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Aircraft Wake Vortices: An Annotated Bibliography (1923 - 1990)

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J.N. Hallock

U.S. Department of Transportation
Research and Special Programs Administration
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National Transportation Systems Center
Cambridge, MA 02142

January 1991

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15. Supplementary Notes

This annotated bibliography consists of abstracts of publications

16. Abstract

This annotated bibliography consists of abstracts of publications on aircraft wake vortices. The material is arranged alphabetically by author(s) and then by month and year of publication. Experimental and theoretical articles are included and consider the formation, structure, motion, and decay of vortices and their effect on penetrating aircraft.

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PREFACE

Like many modern ideas, the earliest known reference to wake vortices appeared in one of the many notebooks of Leonardo da Vinci. After the great Leonardo, little was published until Lord Rayleigh described his "vortexes." However, modern aircraft wake vortex history began with the futile attempts by Lanchester to publish his work in a journal. Fortunately, the material eventually appeared in his book Aerodynamics; one of his figures is still used today.

To make the task of compiling a bibliography a finite one, certain material was not included. To be considered for this document the publication had to possess a possible implication in the setting of separation standards in the Air Traffic Control System. The bibliography includes basic theoretical and experimental work which describes the nature of a vortex (its growth, decay, structure, formation, etc.), the effects of vortices on other aircraft, and the various means to avoid or to alleviate the severity of a vortex encounter. The subject of helicopter vortices has already been summarized in bibliography form ("A Summary of Helicopter Vorticity and Wake Turbulence Publications with an Annotated Bibliography," J. J. Shrager, FAA-RD-74-48, May 1974; "Rotorcraft Wakes - An Annotated Bibliography," J. N. Hallock, FA-427-PM-84, Feb. 1986) and is therefore not included herein except for articles dealing with separation standards. Leading edge or delta wing vortices were excluded except for a few publications which contain relevant theory on vortex decay.

The references are given in the form used by the American Institute of Aeronautics and Astronautics. Since material often appeared in more than one publication (such as first in an AIAA paper, then in one of their archival journals), the more accessible source (usually the refereed journal article) was used in this report. The bibliography is arranged alphabetically by the name(s) of the author(s) and then by month/year of publication. The nucleus of the bibliography was the 1976 report by the author ("Aircraft Wake Vortices - An Annotated Bibliography (1923 - 1975)," FAA-RD-76-43, Jan. 1976), which is superseded by this report.

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METRIC / ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x - 32)(5/9)]$ °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

$[(9/5)y + 32]$ °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

25.40

QUICK FAHRENHEIT-CELCIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and/or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price \$2.50. SD Catalog No. C13 10 286.

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Abbiss, J. B., Sharpe, P. R. and Wright, M. P.,
"EXPERIMENTS USING A THREE-COMPONENT LASER-ANEMOMETRY SYSTEM ON A SUBSONIC FLOW WITH VORTICITY,"
RAE TR-80081, June 1980,
Royal Aircraft Establishment, Farnborough, England.

Experiments with a three-component laser anemometer on the wake and vortex structure behind a model wing at incidence in a 4ft x 3ft subsonic test section are described. Three colors from the output spectrum of an argon-ion laser were used for the three Doppler-difference arrangements. The complete optical system operated in backscatter and was mounted on a single table which could be translated in three orthogonal directions. An integrated data acquisition and reduction system was used incorporating a photon correlator and a Honeywell 6/36 minicomputer. The output data consisted of mean-velocity and turbulence-intensity values for all three components at each measurement point.

Abbott, T. S.,
"COCKPIT-DISPLAY CONCEPT FOR EXECUTING A MULTIPLE GLIDE-SLOPE APPROACH FOR WAKE-VORTEX AVOIDANCE,"
NASA TP-2386, Feb. 1984,
NASA Langley Research Center, Hampton, VA.

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

Abbott, T. S.,
"SIMULATION OF A COCKPIT-DISPLAY CONCEPT FOR EXECUTING A WAKE-VORTEX AVOIDANCE PROCEDURE,"
NASA TP-2300, April 1984,
NASA Langley Research Center, Hampton, VA.

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

Abernathy, F. H. and Menkes, J.,
"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION,"
IEEE Proceedings, Vol. 58, No. 3, March 1970, pp. 326-327.

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

Abernathy, F. H., Menkes, J. and Uberoi, M. S.,
"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION,"
DOT-1081, Dec. 1969,
DOT Air Traffic Advisory Committee, Vol. 2, App. B-4, pp. 55-77.

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

Alferov, V. I., Okerblom, T. I. and Sarantsev, A. I.,
"EXPERIMENTAL INVESTIGATION OF VORTEX FLOWS NEAR LOW-ASPECT-RATIO WINGS AND CIRCULAR CONES AT MACH TWO,"
Akademiia Nauk. SSR, Izvestiia, Mekhanika Zhidkosti I Gaza, Sept.-Oct. 1967, pp. 113-121.

Application of a flow-visualization method to the investigation of the flow pattern resulting from the interaction of wing-tip vortices with the boundary layer. The method employed makes use of a stable luminosity that appears (as a result of a predischarge) when a high voltage is applied to electrodes situated in an airflow. Photographs (on which the shock waves from the electrodes and flow separation region are clearly seen against the interelectrode luminosity) showing the trajectories of the vortex streets are obtained for low-aspect-ratio wings and circular cones situated at various angles of attack in a flow with M=2 and $Re=0.9x10^6$.

Andrews, D. R.,
"A FLIGHT INVESTIGATION OF THE WAKE BEHIND A METEOR AIRCRAFT, WITH SOME THEORETICAL ANALYSIS,"
A.R.C. Current Paper 282, Dec. 1954,
Royal Aircraft Establishment, Farnborough, England.

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

Andrews, W. H.,
"FLIGHT EVALUATION OF THE WING VORTEX WAKE GENERATED BY LARGE JET TRANSPORTS,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 287-288.

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

Andrews, W. H., Drinkwater, F. J., Krier, G. E. and Robinson, G. H.,
"FLIGHT-TEST EVALUATION OF THE WING VORTEX WAKE GENERATED BY LARGE JET-TRANSPORT AIRCRAFT,"
Compilation of Working Papers on Wake Turbulence Tests, April 1970, FAA, Washington, DC.

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

Andrews, W. H., Robinson, G. H. and Larson, R. R.,
"AIRCRAFT RESPONSE TO THE WING TRAILING VORTICES GENERATED BY LARGE JET TRANSPORTS,"
Aircraft Safety and Operating Problems, Vol. 1, NASA SP-270, 1971, pp. 115-126.

The paper summarizes the NASA effort to evaluate the effect of the wing-tip vortex wake generated by large jet transport airplanes on a variety of smaller airplanes. The investigation was designed to obtain data essential to the determination of the wing-wake location relative to the

generating aircraft and the apparent strength and dissipation of the vortex at a specified point along the wake trail. An additional objective was to evaluate the upset potential and subsequent recovery capability of a variety of airplanes penetrating the vortex system.

Andrews, W. H., Robinson G. H. and Larson, R. R.,
"EXPLORATORY FLIGHT INVESTIGATION OF AIRCRAFT RESPONSE TO THE WING VORTEX WAKE GENERATED BY JET TRANSPORT AIRCRAFT,"
NASA TN D-6655, March 1972,
NASA Flight Research Center, Edwards, CA.

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

Andrews, W. H., Tymczyszyn, J. J., Jacobsen, R. A. and Drinkwater, F. J.,
"FLIGHT INVESTIGATION OF THE RESPONSE OF WIDE-BODY TRI-JET TO THE WING VORTEX WAKE GENERATED BY LARGE TRANSPORT AIRCRAFT,"
FWP-35, Feb. 1973,
NASA Flight Research Center, Edwards, CA.

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

Anon.,
"BIG PLANE TURBULENCE CAN CAUSE A FLIGHT HAZARD,"
Safety Suggestions, No. 8, 1952,
Beech Aircraft Corp., Wichita, KS.

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

Anon.,
"A PRELIMINARY STUDY OF THE EFFECT OF JET BLAST OR WAKE ON OTHER AIRCRAFT,"
July 1955,
Beech Aircraft Corp., Wichita, KS.

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

Anon.,
"COMPILATION OF WORKING PAPERS CONCERNING WAKE TURBULENCE TESTS,"
Apr. 1970,
FAA, Washington, DC.

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

Anon.,
"WAKE TURBULENCE IS DANGEROUS,"
Aviation Safety Digest Publication, 1970,
Department of Civil Aviation, Melbourne, Australia.

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

Anon.,
"VORTEX HAZARD INDEX,"
Compilation of Working Papers of Wake Turbulence Tests, April 1970, FAA, Washington, DC.

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

Anon.,
"SYMPOSIUM ON AIRCRAFT WAKE TURBULENCE,"
D1-82-0993, Sept. 1970,
Boeing Scientific Research Labs., Seattle, WA.

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

Anon.,
"AIR VORTEX WAKES AND THEIR CAUSE,"
Verband Deutcher Flugleiter E. V., 1971.

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

Anon.,
"VORTEX WAKE TURBULENCE - FLIGHT TESTS CONDUCTED DURING 1970,"
FAA-FS-71-1, Feb. 1971,
FAA/NASA/Boeing Task Force, Washington, DC.

The summary report covers the 1970 flight test program conducted by the Federal Aviation Administration in joint participation with the National Aeronautics and Space

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

Anon.,
"FAA SYMPOSIUM ON TURBULENCE,"
March 1971,
FAA, Washington, DC.

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

Anon.,
"A LASER-TELESCOPE SYSTEM TO ENHANCE AIRPORT SAFETY,"
Optical Spectra, Sept. 1971, p. 12.

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

Anon.,
"ENGINEERING AND DEVELOPMENT PROGRAM PLAN: AIRCRAFT WAKE VORTEX AVOIDANCE SYSTEM"
FAA-ED-21-1, May 1972,
FAA, Washington, DC.

Efforts to develop a wake Vortex Avoidance System (WVAS) are discussed. The basic objective of the program is the design of a system to increase runway capacity by removing the capacity-restrictive large spacings now required between aircraft to avoid wake vortex hazards. These large spacings will be replaced by separations tailored to aircraft type and prevailing meteorological conditions. In addition, through the use of vortex sensors, safety will be increased in the terminal area by warning of the existence of vortices in the aircraft approach and departure paths. The program consists of three major task areas: sensor development, vortex behavior, and hazard definition. These tasks will be integrated into an overall system design. Although the program will require up to five years to complete, interim capabilities specifically directed toward safety will be available in useable form in advance of the completion date.

Anon.,
"AIR VORTEX WAKES AND THEIR CAUSE,"
NASA-TT-F-14288, June 1972,
Scientific Translation Service, Santa Barbara, CA.

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

Anon,
"AIRCRAFT WAKE TURBULENCE,"
Advisory Circular 90-23D, Dec. 1972,
FAA, Washington, DC.

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

Anon.,
"AIRCRAFT ACCIDENT REPORT: DELTA AIR LINES, INC., MCDONNELL DOUGLAS DC-9-14, N3305L, GREATER SOUTHWEST INTERNATIONAL AIRPORT, FORT WORTH, TEXAS, 30 MAY 1972,"
NTSB-AAR-73-3, March 1973,
NTSB, Washington, DC.

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

Anon.,
"SUBSONIC LIFT-DEPENDENT DRAG DUE TO THE TRAILING VORTEX WAKE FOR WINGS WITHOUT CAMBER OR TWIST,"
ESDU-AERO-W.02.01.02, Oct. 1974,
Engineering Science Data Unit, London, England.

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

Anon.,
"VORTEX WAKES OF LARGE AIRCRAFT,"
AIAA, 1974, New York, NY.

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

Anon.,
"WAKE VORTEX MINIMIZATION,"
NASA SP-409, 1977,
NASA, Washington, DC.

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

aerodynamic means, hopefully to be accomplished by changes on the wake-generating aircraft that are easy to retrofit onto existing aircraft.

Anon.,
"ENGINEERING AND DEVELOPMENT PROGPAM PLAN - WAKE VORTEX,"
FAA-ED-21-1A, Dec. 1977,
FAA, Washington, DC.

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

Anon.,
"AIRCRAFT ACCIDENT REPORT - AIR PENNSYLVANIA 501, PIPER PA-31-350, N5MS, PHILADELPHIA, PENNSYLVANIA, JULY 25, 1980,"
NTSB AAR-81-1, Jan. 1981,
NTSB, Washington, DC.

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

Ashkenas, I. L. and Johnson, W. A.,
"WAKE VORTEX HAZARD DEFINITION PROGRAM,"
TR-1025-3, July 1974,
Systems Tech. Inc., Hawthorne, CA.

This report documents the development of a vortex hazard definition program. The problem is conceptually a simple one: with reduced separations there is a greater potential hazard from vortex encounters; need to assure safe operations with minimum separations that are tailored to the actual hazard. To do this we must consider the possibility of a worst case encounter; and if such encounters are potentially catastrophic, we must assure that the probability of such an event is acceptably small. To do this requires a more precise definition of hazard than simple rules of thumb. The central role of appropriate computer simulation and analysis is emphasized. We must depend on computer modeling because of the many possible critical situations; we must consider the pilot's probable (recovery) control behavior; and we must predict vortex location and strength with minimum uncertainty. Then we must establish realistic, tailored hazard volumes.

Ashmore, B. R., Kimura, A. and Skeith, R. W.,
"DATA PROCESSING AND DISPLAY OF LASER DOPPLER EXPERIMENTAL RESULTS, VOLUME I,"
NASA-CR-150441, Sept. 1976,
Arkansas Univ., Fayetteville, AR.

Contract activities performed in developing a laser Doppler system for detecting, tracking, and measuring aircraft wake vortices are summarized. Program listings are included in the appendix.

Atias, M. and Weihs, D.,
"MOTION OF AIRCRAFT TRAILING VORTICES NEAR THE GROUND,"
J. Aircraft, Vol. 21, No. 10, Oct. 1984, pp. 783-786.

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

Attwooll, V. W.,
"THE EFFECTS OF TRAILING VORTICES ON THE SAFE CAPACITY OF AIR ROUTES AND AIRPORTS,"
Tech. Memo. Math 6702/2, July 1967,
Royal Aircraft Establishment, Farnborough, England.

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

Azuma, A., Saito, S. and Kawachi, K.,
"RESPONSE OF A HELICOPTER PENETRATING THE TIP VORTICES OF A LARGE AIRPLANE,"
Vertica, Vol. 11, No. 1/2, 1987, pp. 65-76.

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

B

Back, L. H.,
"OPTICAL AND PHYSICAL REQUIREMENTS FOR FLUID PARTICLES MARKING TRAILING VORTICES FROM AIRCRAFT,"
J. Aircraft, Vol. 13, No. 7, July 1976, pp. 483-489.

A theoretical study of the optical and physical requirements of marking trailing vortices that emanate from aircraft wings was carried out by considering particulate light-scattering properties, ability of particles to follow trailing vortices, and survival time of particles to vortex dissipation. Liquid droplets undergoing evaporation and molecular dispersion were investigated. Droplets should have lifetimes of about 300 sec. Droplet size should be about 1μ to maximize light scattering with the minimum mass of liquid required. Droplets of this small size would spiral outward very slowly and essentially remain in the vortex cores. Nontoxic hygroscopic liquids, having an affinity for moisture in the air, have been identified. These liquids have relatively low vapor pressures of order 10^{-5} mm Hg that would insure droplet persistence long enough to mark trailing vortices.

Bailey, Jr., W. H. and Durham, T. A.,
"B-52 WAKE INVESTIGATION,"
LOG-C3932, March 1980,
Air Force Academy, Colorado Springs, CO.

The wake characteristics of a B-52 in flight are determined. Of specific concern is the fact that variations in the ambient atmosphere introduced by an aircraft wake manifested by increased wind velocities and gas constituents can cause fluctuations in laser beam propagation. By flying a B-52 upwind of a highly instrumented meteorological tower, wake vortex wind speeds and gas concentrations of the exhaust were obtained. The test was conducted in crosswinds as high as 80 ft/sec which allowed the inspection of wakes 5 seconds in age and 2000 feet behind the aircraft. In this region, it was found that the vortex contained: (1) wind speeds in excess of 210 ft/sec and (2) a 250 percent increase in the concentrations of CO_2. The implication of these results is that propagation of high energy lasers through aircraft wakes could be seriously degraded.

Bailey, Jr., W. H. and Durham, T. A.,
"AIRCRAFT WAKE INVESTIGATION,"
J. Aircraft, Vol. 18, No. 2, Feb. 1981, pp. 67-68.

The Air Force Weapons Laboratory conducted a test to determine the wake characteristics of a B-52 in flight. Variations in the ambient atmosphere introduced by an aircraft wake manifested by increased wind velocities and gas constituents can cause fluctuations in laser beam propagation. By flying a B-52 upwind of a highly instrumented meteorological tower, wake vortex wind speeds and gas concentrations of the exhausts were obtained. The test was conducted in crosswinds as high as 80 ft/s which allowed the inspection of wakes 5 s in age and 2000 ft behind the aircraft. In this region it was found that the vortex contained: 1) wind speeds in excess of 210 ft/s and 2) a 250% increase in the concentrations of CO_2. The implication of these results is that propagation of high-energy lasers through aircraft wakes could be seriously degraded.

Bailey, Jr., W. H., Durham, T. A. and Start, G. E.,
"B-52 TOWER FLYBY,"
AFWL-TR-78-162, April 1979,
Air Force Weapons Lab., Kirtland AFB, NM.

A tower flyby test was conducted to determine the wake characteristics of the B-52 bomber. Such information was required for Air Force Weapons Laboratory studies on laser beam propagation. Of particular interest were wake velocities, engine exhaust composition and general wake geometry. The approach was to fly a B-52 crosswind and upstream of an instrumented tower. Measurements were then made as the wake was transported through the tower by the crosswind - its magnitude, direction and chemical composition - together with the flight trajectory of the airplane then allows a spatial sampling of the wake. In addition, a series of flow visualization runs were made using tower and airplane smoke to characterize wake geometry. Crosswinds on the order of 80 feet per second allowed penetrations as close as 2000 feet behind the aircraft. Peak wake velocities of 210 feet per second and CO_2 exhaust concentrations of 250 percent above the ambient condition were recorded.

Baker, G. R.,
"ROLL UP OF A VORTEX SHEET USING THE "CLOUD-IN-CELL" TECHNIQUE,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68,
edited by J. Hallock, DOT Transportation Systems Center, Cambridge,
June 1977, pp. 124-135.

The problem of the roll up of a two dimensional vortex sheet generated by a wing in an ideal fluid is phrased in terms of the streamfunction and the vortex sheet strength. A numerical method is used to calculate the time evolution of the vortex sheet by adapting the "Cloud-In-Cell" technique introduced in solving many particle simulations in plasma physics. Two cases are considered for the initial distribution of circulation, one corresponding to an elliptically loaded wing and the other simulating the wing with a flap deployed. Results indicate that small scale behavior plays an important part in the roll up. Typically, the small scale perturbations evolve into ever increasing larger structures by vortex amalgamation. Small scale perturbations are introduced artificially by the grid, but the emerging large scale behavior is relatively insensitive to it. Since clearly defined structures result from the application of this method, it promises to aid considerably in understanding the behavior of vortex wakes.

Baker, G. R., Barker, S. J., Bofah, K. K. and Saffman, P. G.,
"LASER ANEMOMETER MEASUREMENTS OF TRAILING VORTICES IN WATER,"
J. Fluid Mech., Vol. 65, Part 2, Aug. 1974, pp. 325-336.

A series of measurem nts of trailing vortices behind lifting hydrofoils is described. These measurements were made in the Caltech Free-Surface Water Tunnel, using a laser-Doppler velocimeter to measure two components of velocity in the vortex wake. Two different model planforms were tested, and measurements were made at several free-stream velocities and angles of attack for each. Velocity profiles were measured at distances downstream of the model of from five to sixty chord lengths. The theory of trailing vortices is discussed. The effects of 'vortex wandering' upon the measurements are computed, and the corrected results are seen to be in reasonable agreement with the theory.

Balcerak, J. C. and Zalay, A. D.,
"INVESTIGATION OF THE EFFECTS OF MASS INJECTION TO RESTRUCTURE A TRAILING TIP VORTEX AT TRANSONIC SPEEDS,"
RASA-73-03M, Feb. 1973,
Rochester Applied Science Assoc., Rochester, NY.

This report describes the results of an experimental research program which was conduced to assess the effects of mass injection in the tip vortex on airfoil performance in transonic flow. Balance data and Schlieren photographs were taken for a rectangular semispan model with a full-span aspect ratio of 7.35 in the Mach number range of 0.553 to 1.0. The results of the investigation indicates that mass injection of the concentrated tip vortex does not generate any significant change in airfoil performance at transonic speeds for the configuration tested. Schlieren photographs of the compressible flow field showed that the near field flow characteristics of the airfoil were not influenced by mass injection or by passive nozzle characteristics at transonic speeds.

Baldwin, B. S., Chigier, N. A. and Sheaffer, Y. S.,
"DECAY OF FAR-FLOWFIELD IN TRAILING VORTICES,"
AIAA Journal, Vol. 11, No. 12, Dec. 1973, pp. 1601-1602.

Methods for reduction of velocities in trailing vortices of large aircraft are of current interest; finite-difference calculations of the flow in turbulent wake vortices were done as an aid to interpretation of wind-tunnel and flight experiments directed toward that end.

Baldwin, B. S., Chigier, N. A. and Sheaffer, Y. S.,
"DECAY OF FAR FLOW FIELD IN TRAILING VORTICES,"
NASA TN D-7568, Feb. 1974,
NASA Ames Research Center, Moffett Field, CA.

A finite difference machine code is used in the wake vortex problems in the quasi-cylindrical boundary layer approximation. A turbulent energy model containing new features is developed that accounts for the major effects disclosed by more advanced models in which the parameters are not yet established. Several puzzles that arose in previous theoretical investigations of wake vortices are resolved.

Baldwin, B. S., Sheaffer, Y. S. and Chigier, N. A.,
"PREDICTION OF FAR FLOW FIELD IN TRAILING VORTICES,"
AIAA Paper No. 72-989,
Palo Alto, CA, 1972.

A finite-difference machine code is brought to bear on the wake-vortex problem in the quasi-cylindrical boundary-layer approximation. A turbulent-energy model containing new features is developed. Parameters of the model are evaluated by comparison of calculated velocities and turbulent intensities with measurements in an axisymmetric wake. Comparisons are made with a previous calculation of the decay of an isolated vortex and with wind tunnel and flight measurements in trailing vortices. A self-similar solution develops at large axial distance that decays with the square root of distance. A slower decay occurs in the preceding transition region.

Ball, C. T.,
"CHICAGO O'HARE INTERNATIONAL AIRPORT CAPACITY ANALYSIS,"
FAA-RD-75-205, Nov. 1975,
FAA, Washington, DC.

A task force comprised of representatives from the FAA, airlines, and the City of Chicago was formed in December of 1974 to study the present and future capacity and delay of the Chicago O'Hare International Airport. The task force effort concentrated on two future air traffic control environments: One consisting of basic metering and spacing and a wake vortex predictive system; the other consisting of advance metering and spacing, a discrete address beacon system, and a wake vortex predictive system. January 1975 schedule information was used to determine the present future capacity of the airport.

Balser, M., McNary, C. A. and Nagy, A. E.,
"ACOUSTIC ANALYSIS OF AIRCRAFT VORTEX CHARACTERISTICS,"
FAA-RD-72-81, July 1972,
Xonics Inc., Van Nuys, CA.

A program of field measurements at NAFEC and related analysis has been carried out as part of the development of acoustic radar for aircraft vortex turbulence detection. Spectra of acoustic signals scattered from the vortices were found to agree in form with those derived from a model, and yielded velocities that generally agreed with those observed by the NAFEC tower instrumentation. Consistent quantitative measurements of circulation, the quantity most closely related to hazard, were obtained for a number of different aircraft. Confident vortex tracks were obtained for aircraft (a DC-6) altitudes up to 1500 ft, with the vortex detected at about 1300 ft and tracked for about a minute until it passed out of the coverage region.

Balser, M., McNary, C. A. and Nagy, A. E.,
"ACOUSTIC BACKSCATTER RADAR SYSTEM FOR TRACKING AIRCRAFT TRAILING VORTICES,"
J. Aircraft, Vol. 11, No. 9, Sept. 1974, pp. 556-562.

The safety hazard posed by potential encounters with invisible vortices from preceding aircraft imposes stringent limitations on aircraft spacing in the terminal area, hence on traffic-handling capacity. An acoustic back-scatter radar system has been developed to detect and track such vortices, and thereby provide the information for more advanced air traffic procedures that would eliminate the uncertainty and delay caused by vortices. The system is fully engineered and operates in real time. Examples of the real-time display and of vortex tracks from Boeing 747's landing at the Los Angeles International Airport are given in the paper.

Balser, M., Nagy, A. E. and Proudian, A. P.,
"VORTEX OBSERVATIONS BY THE XONICS ACOUSTIC RADAR AT NAFEC,"
FAA-RD-71-103, Dec. 1971,
Xonics Inc., Van Nuys, CA.

A series of flight tests was conducted in order to demonstrate feasibility of the concept of the Xonics acoustic vortex detector. The first tests consisted of simultaneous observations in close proximity by both the Xonics equipment and the instrumented tower of vortices shed by a low-flying aircraft. Except for the few cases where data was lost through equipment misalignment or malfunction or operator error, vortex returns were observed on virtually all of the runs. A total of 55 runs, which represents a substantial fraction of all of the data gathered, were selected for analysis. The vortex velocity measurements exhibit a clear correlation with aircraft configuration, and appear to confirm their use as a valid indicator of vortex intensity.

Balser, M., Nagy, A. E. and Proudian, A. P.,
"AIRCRAFT VORTEX DETECTION SYSTEM,"
US Patent 3,735,333, May 1973.

An improved system for detection and measurement of aircraft wing tip vortices over a wide area. An acoustic echo system with transmitter and receiver spaced from each other in a plane perpendicular to the flight path for illuminating the vortex and picking up scattering of the transmitter signal produced by the vortex, using Doppler frequency spectrum analysis with the maximum and minimum frequencies providing measure of vortex intensity. A plurality of receivers operating with a common transmitter providing coverage of an area of interest along a flight path. A transmitter covering a broad area by a broad beam acoustic transducer or a plurality of narrow beams, and means for identifying a specific zone within the broad area occupied by the vortex being analyzed.

Barber, M. R., Kurkowski, R. L., Garodz, L. J., Robinson, G. H., Smith, H. J., Jacobsen, R. A., Stinnett, Jr., G. W., McMurtry, T. C., Tymczyszyn, J. J., Devereaux, R. L. and Bolster, A. J.,
"FLIGHT TEST INVESTIGATION OF THE VORTEX WAKE CHARACTERISTICS BEHIND A BOEING 727 DURING TWO-SEGMENT AND NORMAL ILS APPROACHES,"
FAA-NA-75-151, Jan. 1975,
NASA Dryden Flight Research Center, Edwards, CA.

A series of flight tests were performed to evaluate the vortex wake characteristics of a B727-200 aircraft during conventional and two-segment ILS approaches. Twelve flights of the B727, equipped with smoke generators for vortex marking, were flown and its vortex wake was intentionally encountered by a Lear Jet model 23 (LR-23) or a Piper Twin Comanche (PA-30); and its vortex location was measured using a system of photo-theodolites. At a given separation distance there were no readily apparent differences in the upsets resulting from deliberate vortex encounters during the two types of approaches. Timed mappings of the position of the landing configuration vortices showed that they tended to descend approximately 300 feet below the flight path of the B727. The flaps of the B727 have a dominant effect on the character of the wake vortex. The clean wing produces a strong, concentrated vortex. As the flaps are lowered the vortex system becomes more diffuse. Pilot opinion and roll acceleration data indicate that 4.5 nm would be a minimum separation distance at which roll control could be maintained during parallel encounters of the B727's landing configuration wake by small aircraft. This minimum separation distance is generally in scale with results determined from previous tests of other aircraft using the same roll control criteria.

Barber, M. R., Hastings, Jr., E. C., Champine, R. A. and Tymczyszyn, J. J.,
"VORTEX ATTENUATION FLIGHT EXPERIMENTS,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, Washington, 1977, pp. 369-403.

Flight tests evaluating the effects of altered span loading, turbulence ingestion, combinations of mass and turbulence ingestion, and combinations of altered span loading turbulence ingestion on trailed wake vortex attenuation were conducted. Span loadings were altered in flight by varying the deflections of the inboard and outboard flaps on a B-747 aircraft. Turbulence ingestion was achieved in flight by mounting splines on a C-54G aircraft. Mass and turbulence ingestion was achieved in flight by varying the thrust on the B-747 aircraft. Combinations of altered span loading and turbulence ingestion were achieved in flight by installing a spoiler on a B-747 aircraft. The characteristics of the attenuated and unattenuated vortexes were determined by probing them with smaller aircraft. Acceptable separation distances for encounters with the attenuated and unattenuated vortexes are presented.

Barber, M. R. and Tymczyszyn, J. J.,
"WAKE VORTEX ATTENUATION FLIGHT TESTS: A STATUS REPORT,"
1980 Aircraft Safety and Operating Problems Conf., Part 2, NASA Langley Research Center, March 1981, pp. 387-408.

Flight tests were conducted to evaluate the magnitude of aerodynamic attenuation of the wake vortices of large transport aircraft that can be achieved through the use of static spoiler deflection and lateral control oscillation. These methods of attenuation were tested on Boeing B-747 and Lockheed L-1011 commercial transport aircraft. Evaluations were made using probe aircraft, photographic and visual observations, and ground based measurements of the vortex velocity profiles. The magnitude of attenuation resulting from static spoiler deflection was evaluated both in and out of ground effect. A remotely piloted QF-86 drone aircraft was used to probe the attenuated vortices in flight in and out of ground effect, and to make landings behind an attenuated B-747 airplane at reduced separation distances.

Barker, S. J. and Crow, S. C.,
"CORE INSTABILITIES OF A VORTEX PAIR,"
Bull. Am. Physical Society, Vol. 20, No. 11, Nov. 1975, p. 1428.

Aircraft wake vortices have stimulated great interest in the means by which vortex pairs decay. The mechanism of vortex decay outside ground effect can be divided into two classes: mutual induction instability and vortex core instability. The present study looks at the second class both experimentally and analytically. By the Rayleigh criterion, isolated vortices are stable to small axisymmetric disturbances. However, it is shown that a wrapped-up vortex sheet is unstable to helical disturbances having azimuthal wavenumbers greater than three. Any tangential velocity distribution with an inflection point in the rotational region is unstable to such disturbances. The experiment used to visualize the instabilities is a two-dimensional analog of the vortex wake, in which distance behind the aircraft is represented by time from the creation of the vortex pair. The experiment takes place in a water tank of dimensions 0.5 by 4 by 8 feet. The vortices are oriented across the 0.5 feet width of the tank, visualized by dye injection, and photographed by a high-speed movie camera.

Barker, S. J. and Crow, S. C.,
"THE MOTION OF TWO-DIMENSIONAL VORTEX PAIRS IN GROUND EFFECT,"
PR-4, May 1976,
Poseidon Research, Sherman Oaks, CA.

A new technique for generating a pair of line vortices in the laboratory has been developed. The mean flow of these vortices is highly two-dimensional, although most of the flow field is turbulent. This two-dimensionality permits the study of vortex motions in the absence of the Crow mutual induction instability and other three-dimensional effects. The vortices are generated in a water tank of dimensions 15 x 122 x 244 cm. They propagate vertically and their axes span the 15 cm. width of the tank. One wall of the tank is transparent, and the flow is visualized using fluorescein dye. High speed photography is used to study both the transition to turbulence during the vortex formation process and the interaction of the turbulent vortices with a simulated ground plane. The interaction of the vortex pair with the ground plane does not follow the predictions of potential flow theory for line vortices. Although total circulation is apparently conserved, the vortices remain at a larger distance from the ground than expected and they eventually "rebound" or move away from the ground. Differences between a free surface boundary condition and a smooth or rough ground plane are discussed.

Barker, S. J. and Crow, S. C.,
"THE MOTION OF TWO-DIMENSIONAL VORTEX PAIRS IN A GROUND EFFECT,"
J. Fluid Mech., Vol. 82, Part 4, 1977, pp. 659-671.

A new technique for generating a pair of line vortices in the laboratory has been developed. The mean flow of these vortices is highly two-dimensional, although most of the flow field is turbulent. This two-dimensionality permits the study of vortex motions in the absence of the Crow mutual induction instability and other three-dimensional effects. The vortices are generated in a water tank of dimensions 15 x 122 x 244 cm. They propagate vertically and their axes span the 15 cm width of the tank. One wall of the tank is transparent, and the flow is visualized using fluorescein dye. High speed photography is used to study both the transition to turbulence during the vortex formation process and the interaction of the turbulent vortices with a simulated ground plane. Transition occurs first in an annular region surrounding the core of each vortex, starting with a shear-layer instability on the rolled-up vortex sheet. The turbulent region then grows both radially inwards and radially outwards until the entire recirculation cell is turbulent. A 'relaminarization' of the vortex core appears to take place somewhat later. The interaction of the vortex pair with the ground plane does not follow the predictions of potential-flow theory for line vortices. Although the total circulation is apparently conserved, the vortices remain at a larger distance from the ground than is expected and eventually 'rebound' or move away from the ground. Differences between a free-surface boundary condition and a smooth or rough ground plane are discussed. The ground-plane interaction is qualitatively similar to that of aircraft trailing vortices observed in recent flight tests.

Barnes, J. R.,
"SIDE FORCE ON A WING BODY COMBINATION DUE TO TRAILING VORTICES,"
ARC Report CP-669, July 1962,
Royal Aircraft Establishment, Farnborough, England.
(Also, RAE Tech. Note Aero. 2834)

A long cylindrical body has two wings attached symmetrically but set at equal and opposite angles relative to its axis. When this system is placed at incidence in a uniform flow a side force is experienced. The purpose of this note is to make some estimate of the magnitude of this side force. The vortices shed by the wings are assumed to have rolled up at the trailing edge and their paths are calculated using slender body theory. Expressions are given for the forces experienced by the body aft of the wings, and some numerical calculations made.

Baronti, P. and Elzweig, S.,
"FOG FORMATION AND DISPERSAL BY TRAILING VORTICES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 561-573.

A model is presented to explain why fogs can be maintained for extended periods of time. The model considers fog as a dynamical system whereby droplets depletion through fall is balanced by a continuous process of evaporation and condensation. Possible means of fog dispersal by the velocity field induced by trailing vortices are suggested.

Barrer, J. N.,
"CONCEPT FOR USING MULTIPLE GLIDE SLOPE ANGLES FOR WAKE VORTEX AVOIDANCE ON PARALLEL IFR APPROACHES,"
FAA-DL5-86-3, Nov. 1986,
Mitre Corp., McLean, VA.

For parallel runways separated by less than 2500 feet, the longitudinal separation between aircraft on adjacent approaches must be maintained at the same distance as if the aircraft were on a single runway. The hazard associated with trailing wing tip vortices is the major hindrance to reducing separation distances during instrument approaches. This report shows how separations can be safely reduced on closely spaced parallel runways. The analysis exploits the use of staggered runway thresholds, multiple glide slope angles, and wind measurement devices to ensure vortex avoidance. The analysis is applied to Denver Stapleton International Airport.

Barrows, T. M.,
"SIMPLIFIED METHODS OF PREDICTING AIRCRAFT ROLLING MOMENTS DUE TO VORTEX ENCOUNTERS,"
J. Aircraft, Vol. 14, No. 5, May 1977, pp. 434-439.

Computational methods suitable for fast and accurate prediction of rolling moments on aircraft encountering wake vortices are presented. Appropriate modifications to strip theory are developed which account for the effects of finite wingspan. It is shown that in the case of an elliptic wing the aspect ratio correction to the lift curve slope should be based on the semispan. A reciprocal theorem is used to relate the rolling moment on a wing in an arbitrary downwash field to that on a wing in steady rolling motion. Calculations are presented for a wing encountering a vortex with a Betz velocity distribution. It is shown that the ratio of the spans of the generating and encountering aircraft is the most significant parameter in determining the possible hazard.

Batchelor, G. K.,
"AXIAL FLOW IN TRAILING LINE VORTICES,"
J. Fluid Mech., Vol. 20, Part 4, April 1964, pp. 645-658.

A characteristic feature of a steady trailing line vortex from one side of a wing, and of other types of line vortices, is the existence of strong axial currents near the axis of symmetry. The purpose of this paper is to account in general terms for this axial flow in trailing line vortices. The link between the azimuthal and axial components of motion in a steady line vortex is provided by the pressure; the radial pressure gradient balances the centrifugal force, and any change in the azimuthal motion with distance X downstream produces an axial pressure gradient and consequently an axial acceleration. The concept of drag associated with the core of a trailing vortex is introduced, and the drag is expressed as an integral over a transverse plane which is independent of X.

Bate, Jr., E. R.,
"A STUDY TO DETERMINE THE STRUCTURE OF TRAILING VORTICES FROM FULL SCALE FLIGHT TEST DATA,"
AV-FR-441, July 1974,
AeroVironment Inc., Pasadena, CA.

Computerized data reduction techniques were applied to high resolution velocity measurements obtained during full-scale aircraft wake probing experiments. The desired results were the determination of vortex circulation and core size as a function of wake age. Data scatter prevented the desired results from being fully achieved; it is suggested that the data scatter represents real effects and that these effects are produced by turbulence.

Bate, Jr., E. R.,
"AIRCRAFT WAKE MODELING: PRELIMINARY DESIGN ASPECTS,"
AV-FR-445, Aug. 1974,
AeroVironment Inc., Pasadena, CA.

The design of a scale model with a 6 foot wingspan which simulates the wake flow of a full-size airplane (B-747) is described. The wake is modeled to a full-scale downstream distance of 5 miles. The situation with respect to the simulation of wake instabilities is discussed. Only by the actual experiment that is planned for the model can the relationship between core bursting and vortex linking be established. If core bursting terminates the wake of the model too abruptly, the experimental situation might not

adequately represent the full-scale case, where it is anticipated that linking due to the sinuous wake instability predominates.

Bates, Jr., G. P.,
"A SELECTED BIBLIOGRAPHY PERTAINING TO THE AIRCRAFT WAKE VORTEX PROBLEM,"
AGARD, Symposium on Flight in Turbulence,
Bedfordshire, England, May 1973.

A bibliography pertaining only to available papers directly concerning the development of a trailing vortex flow behind an aircraft and the effects of this flow on a following aircraft.

Bedard, Jr., A. J.,
"MEASUREMENTS OF AN AIRCRAFT WAKE VORTEX SYSTEM USING A METEOROLOGICAL TOWER,"
Proceedings 9th Conf. on Aerospace and Aeronautical Meteorology,
American Meteorological Society, Omaha, June 1983, pp. 252-256.

The experiment for the data presented here involved flybys near the Boulder Atmospheric Observatory (BAO), which provided real-time outputs of various parameters, including wind speed, wind direction, and temperature. These data are used to predict the motion of the vortex system and to guide the aircraft height, bearing, and position in relation to the tower and the radar. The results of the experiment, which focused chiefly on the evaluation of an FM/CW radar for wake vortex detection, are seen as providing an interesting case study of vortex impingement upon a well-instrumented meteorological tower. The horizontal and vertical wind speed measurements are compared with those expected from the passage of a wake vortex system. The temperature perturbation obtained gives a data set indicating the temperature distribution in a wake vortex system.

Benjamin, T. B.,
"THEORY OF THE VORTEX BREAKDOWN PHENOMENON,"
J. Fluid Mech., Vol. 14, June 1962, pp. 38-44.

The phenomenon examined is the abrupt structural change which can occur at some station along the axis of a swirling flow, notably the leading-edge vortex formed above a delta wing at incidence. Contrary to previous attempts at an explanation, the belief demonstrated herein is that vortex breakdown is not a manifestation of instability or of any other effect indicated by study of infinitesimal disturbances alone. It is instead a finite transition between two dynamically conjugate states of axisymmetric flow, analogous to the hydraulic jump in open-channel flow. A set of properties essential to such a transition, corresponding to a set shown to provide a complete explanation for the hydraulic jump, is demonstrated with wide generality for axisymmetric vortex flows; and the interpretation covers both the case of mild transitions, where an undular structure is developed without the need arising for significant energy dissipation, and the case of strong ones where a region of vigorous turbulence is generated.

Benjamin, T. B.,
"SIGNIFICANCE OF THE VORTEX BREAKDOWN PHENOMENON,"
J. Basic Engineering, Vol. 87, June 1965, pp. 518-522.

The essential points in the author's published theory of the vortex breakdown phenomenon are summarized, and their implications with regard to longitudinal vortex flows in general are reviewed. It is proposed that the physical principles serve to rationalize a wide variety of possible behavior in swirling flows.

Benjamin, T. B.,
"SOME DEVELOPMENTS IN THE THEORY OF VORTEX BREAKDOWN,"
J. Fluid Mech., Vol. 28, Part 1, April 1967, pp. 65-84.

This analysis consolidates the ideas of the "conjugate-flow" theory, which proposes that vortex breakdown is fundamentally a transition from a uniform state of swirling flow to one featuring stationary waves of finite amplitude. The original flow is assumed to be supercritical (i.e., incapable of bearing infinitesimal stationary waves), and the mechanism of the transition is explained on the basis of physical principles that are well established in relation to the analogous supercritical flow phenomenon of the hydraulic jump or bore.

Benner, M. S., Dunham, Jr, R. E. and Verstynen, Jr., H. A.,
"EXPLORATORY STUDY OF C-130 AND C-47 AIRCRAFT TRAILING VORTICES IN GROUND EFFECT,"
LWP-1040, March 1972,
NASA Langley Research Center, Hampton, VA.

In the development and checkout of an instrumented tower which is to be used to measure the velocity characteristics of aircraft trailing vortices, some measurements were made of trailing vortices shed by a NASA C-47 airplane and an Air Force C-130 airplane. The report describes the instrumentation and testing technique used and presents some preliminary results on the vortex characteristics of the C-47 and C-130 aircraft shed in close proximity to the ground.

Bennett, W. J.,
"STATE-OF-THE-ART SURVEY FOR MINIMUM APPROACH, LANDING, AND TAKE-OFF INTERVALS AS DICTATED BY WAKES, VORTICES, AND WEATHER PHENOMENA,"
RD-64-4, Jan. 1964,
Boeing Comp., Renton, WA.

This report is a study of the generation and decay of the wake behind an aircraft, both in free air and ground effect, and its effect on following aircraft. An analysis is presented for both fixed and rotary-wing aircraft which defines the wake movement with time and the wake-induced velocities. The influence of atmospheric parameters such as wind, temperature, and turbulence is discussed as it applies to the generation and decay of the wake.

Bennett, W. J.,
"ANALYTICAL DETERMINATION OF THE VELOCITY FIELDS IN THE WAKES OF SPECIFIED AIRCRAFT,"
RD-64-55, May 1964,
Boeing Comp., Renton, WA.

This report documents a study for the prediction of the velocity fields in the wakes of fixed-wing and rotary-wing aircraft. Thirty-three aircraft currently operating within the Air Traffic Control system are analyzed. Numerical data are presented for eleven of the aircraft, defining their respective wake velocity fields. A discussion of the assumptions and limitations of the analytical models used is included along with a discussion of possible correlation of the calculated values with test results.

Bera, R. K.,
"CALCULATION OF INITIAL VORTEX ROLL-UP IN AIRCRAFT WAKES,"
J. Aircraft, Vol. 13, No. 1, Jan. 1976, pp. 58-59.

The intention of this note is to rederive the results of Yates by using a Fourier sine series for the lift distribution instead of the Chebyshev polynomials he has used, and to complete the analysis by also considering nonsymmetric flight conditions. These results may be used as the first step in the use of the extended Betz theory for rollup calculations.

Beran, D. W.,
"ACOUSTIC RADAR DETECTION TECHNIQUES,"
Symposium on Turbulence, FAA, Washington, DC, 1971, p. 27.

Acoustic radar or echo sounding has the potential of providing a solution to both the wake vortex and low level wind shear monitoring problems, at a cost which is realistic in terms of equipping most large airports with an operational system. Such a system would be based on the demonstrated ability to make Doppler wind measurements with an acoustic sounder (for monitoring strong shear layers) and the amplitude and phase scintillation of an acoustic wave when it is transmitted through a turbulent medium (for detecting wake vortices).

Beran, D. W.,
"ACOUSTICS: A NEW APPROACH FOR MONITORING THE ENVIRONMENT NEAR AIRPORTS,"
J. Aircraft, Vol. 8, No. 11, Nov. 1971, pp. 934-936.

The note describes a relatively new device, an acoustic echo sounder, which has the potential to not only indicate the presence or absence of wake vortices, but to act as a continuous monitor of other important meteorological parameters (wind, wind shear, and thermally generated turbulence). A fixed, vertically pointing antenna, in conjunction with two orthogonally positioned scanning antennas could provide a continual real time record of the inversion height, the turbulent intensity, an indication of the presence of wing tip vortices, and the vertical profile of the total wind vector.

Bernstein, S.,
"ANALOG COMPUTER SIMULATION OF TRAILING VORTEX EFFECTS ON FOLLOWING AIRCRAFT,"
MS Thesis, May 1971,
Iowa State University, Ames, IA.

The vortex effects on a penetrating aircraft are simulated using an analog computer. The mode of penetration considered is in an along-track fashion in which the following aircraft flies parallel to the trail of the vortices. A C-130 aircraft probing the vortex wake of another C-130 and the wake of a C-5A was investigated. It was found that the encounter aircraft experienced the largest violent response when the initial positioning of the aircraft was at approximately 0.4 wing span to the right or to the left of the vortex center. A sharp decrease in the response was experienced when the aircraft was initially displaced above or below the vortex trail.

Bernstein, S. and Iversen, J. D.,
"DYNAMIC SIMULATION OF AN AIRCRAFT UNDER THE EFFECT OF VORTEX WAKE TURBULENCE,"
Proceedings of 2nd Atmospheric Flight Mechanics Conf., NASA Ames Research Center, Moffitt Field, Sept. 1972, pp. 29.1-29.9.

A technique is developed to simulate the response of a trailing aircraft due to the induced rolling moments and loss of lift imposed by the vortices. Results of such a simulation for the case of a C-130 behind another C-130 and behind a C-5A are presented.

Betz, A.,
"BEHAVIOR OF VORTEX SYSTEMS,"
Zeit. für angewandte Math. und Mech., Vol. 12, No. 3, June 1932, pp. 164-174.
(Also, NACA TM-713, June 1933).

Progressive application of the Kutta-Joukowsky theorem to the relationship between airfoil lift and circulation affords a number of formulas concerning the conduct of vortex systems. The application of this line of reasoning to several problems of airfoil theory yields an insight into many hitherto little observed relations. The report is confined to plane flow, hence all vortex filaments are straight and mutually parallel.

Bierach, K. F.,
"WAKE VORTEX SENSING, PROCESSING AND DISPLAY,"
Proceedings of 19th International Aerospace Instrumentation Symposium, Instrument Society of America, Vol. 19, 1973, Las Vegas, pp. 153-164.

The FAA has embarked on a program to develop a wake vortex avoidance system to permit airport operations to function at optimum capacity commensurate with safety requirements. Computer modeling has identified a system concept based upon vortex prediction and detection in a closed-loop configuration. In concept, the vortex position, in defined arrival and departure corridors, is predicted from existing and projected meteorological conditions. The vortex movement is sensed within specified vertical scan planes to update this prediction. Aircraft arrivals or departures are then scheduled according to the prevailing vortex predictions and knowledge of the aircraft involved. The paper describes the system concept and potential techniques that are available to satisfy the sensor, data processing, and display subsystems requirements.

Bilanin, A. J.,
"WAKE MECHANICS OF LINE VORTICES,"
PhD Thesis, June 1973,
Mass. Inst. of Technology, Cambridge, MA.

Wave propagation on a vortex with a uniform axial vorticity core and a top-hat axial velocity distribution is studied and the results are a dispersion relation from which group velocities of the various modes can be calculated. A new definition of sub- and supercritical vortices based on group velocity is developed. This definition eliminates the difficulties encountered by others in determining sub- and supercritical states for asymmetric waves. Wave propagation along a vortex with slight axial inhomogeneity is developed for axisymmetric waves to introduce kinematic wave theory to vortices. Critical conditions exist along the slowly varying vortex which block the upstream propagation of waves.

Bilanin, A. J.,
"COMPUTER TECHNOLOGY TO EVALUATE AIRCRAFT VORTEX WAKE INTENSITY,"
SBIR-198, May 1985,
Continuum Dynamics, Princeton, NJ.

Existing analytical models of aircraft vortex wake dynamics have been assembled to predict the evolution and decay of two commercial jet liner wakes. The calculations undertaken demonstrate that aircraft configurational characteristics, such as engine placement and wing load distribution, can significantly influence the early stages of wake decay. This study concludes that it is currently possible and practical to develop a computer design tool capable of assessing wake intensity for existing and future jet liners. This tool could be utilized by FAA regulators in an evaluation of separation standards for current and future aircraft, and allows airframe manufacturers to factor wake intensity into their design.

Bilanin, A. J. and Donaldson, C. duP.,
"ESTIMATION OF VELOCITIES AND ROLL-UP IN AIRCRAFT VORTEX WAKES,"
J. Aircraft, Vol. 12, No. 7, July 1975, pp. 578-585.

A nonlinear model is developed which determines the swirling and axial velocities in an aircraft vortex wake, given wing lift and drag distributions. The model is shown to reduce to that given by Betz when the axial velocity is the freestream value. The nonlinear interaction of swirling and axial velocities may lead to velocity distributions which are different from those previously calculated. Qualitatively, drag reduces the axial velocity in the vortex and results in an enlarged vortex radius and, therefore, a reduction in swirl velocity. The inviscid model that predicts that significant changes in the structure of the vortex wake, brought about solely by modification of the drag distribution, may require prohibitively large drag penalties. Theoretical results compare favorably with measurements made by Orloff and Grant. A model is developed to estimate the time to roll up a two-dimensional vortex sheet. Results are presented for the cases of linear, parabolic, and elliptic wing loading.

Bilanin, A. J., Donaldson, C. duP. and Snedeker, R. S.,
"CALCULATION OF THE INVISCID WAKE OF A BOEING 747 AIRCRAFT,"
ARAP Rept. No. 224, Aug. 1974,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A wake model based on an extension of the inviscid method of Betz used to calculate the rolled up wake structure behind a Boeing 747 aircraft. Two aircraft flight configurations, at a lift coefficient of 1.2, are analyzed and it is shown that the inviscid wake is markedly different in structure. Comparisons between calculated and measured rolling moment on a penetrating wing show that the inviscid model provides useful estimates. When the generating aircraft is in other than the clean configuration, accurate predictions of the rolling moment will require a wake model which includes turbulent transport.

Bilanin, A. J., Donaldson, C. duP. and Snedeker, R. S.,
"AN ANALYTIC AND EXPERIMENTAL INVESTIGATION OF THE WAKES BEHIND FLAPPED AND UNFLAPPED WINGS,"
AFFDL-TR-74-90, Sept. 1974,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

An analytic and experimental program was undertaken to define the near wake structure behind flapped and unflapped wings. The vortex wake structure is determined, given the wing lift and drag distributions with models developed in the spirit of Betz. A procedure to estimate the turbulent kinetic energy distribution in the vortex is also given, as well as a method to determine discrete vortex positions in the downstream wake.

Bilanin, A. J., Hirsh, J. E., Teske, M. E. and Hecht, A. M.,
"ATMOSPHERIC-WAKE VORTEX INTERACTIONS,"
ARAP-331, April 1978,
Aeronautical Research Associates of Princeton, Princeton, NJ.

The interactions of a vortex wake with a turbulent stratified atmosphere are investigated with the computer code WAKE. It is shown that atmospheric shear, turbulence, and stratification can provide the dominant mechanisms by which vortex wakes decay. Computations included the interaction of a vortex wake with a viscous ground plane. The observed phenomenon of vortex bounce is explained in terms of secondary vorticity produced on the ground. This vorticity is swept off the ground and advected about the vortex pair, thereby altering the classic hyperbolic trajectory. The phenomenon of the solitary vortex is explained as an interaction of a vortex with crosswind shear. Here, the vortex having the sign opposite that of the sign of the vorticity in the shear is dispersed by a convective instability. This instability results in the rapid production of turbulence which in turn disperses the smoke marking the vortex.

Bilanin, A. J., Snedeker, R. S., Sullivan, R. D. and Donaldson, C. duP.,
"EXPERIMENTAL AND THEORETICAL STUDY OF AIRCRAFT VORTICES,"
AFOSR-TR-75-0664 and ARAP No. 238, Feb. 1975,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A review is given of development during the past five years in ARAP's study of the aircraft wake turbulence problem. Significant results are described including the successful application of the Betz roll-up method to inviscid wake calculations and its extension to multivortex wakes. Also discussed are effects due to viscous and induced drag, as well

as the role of turbulence in the wake decay process. Recent results of an experimental study of a vortex flow in ARAP's vortex tube tunnel are presented including measurements of mean and turbulent velocity profiles and turbulent correlations.

Bilanin, A. J., Snedeker, R. S. and Teske, M. E.,
"INTERACTIONS AND MERGING OF LINE VORTICES,"
ARAP-276, Feb. 1976,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

The results of a theoretical and experimental study of the interaction between adjacent line vortices are presented. Particular emphasis is given to the process of merging or pairing in which two vortices of like sign coalesce to form a single vortex. Merging is discussed in terms of its importance to the growth and aging of turbulent shear layers and aircraft wakes. Flow visualization experiments are described in which merging was observed by means of smoke injected into a wind tunnel flow. Vortex pairs of like sign and equal strength, varying sign and strength, and opposite sign and equal strength were studied. Good qualitative agreement is found between the observed flow patterns and those calculated by means of a computer code.

Bilanin, A. J. and Teske, M. E.,
"NUMERICAL STUDIES OF THE DEPOSITION OF MATERIAL RELEASED FROM FIXED AND ROTARY WING AIRCRAFT,"
NASA CR-3780, March 1984,
Continuum Dynamics, Princeton, NJ.

The computer code AGDISP (Agricultural Dispersal) has been developed to predict the deposition of material released from fixed and rotary wing aircraft in a single-pass, computationally efficient manner. The formulation of the code is novel in that the mean particle trajectory and the variance about the mean resulting from turbulent fluid fluctuations are simultaneously predicted. The code presently includes the capability of assessing the influence of neutral atmospheric conditions, inviscid wake vortices, particle evaporation, plant canopy and terrain on the deposition pattern. In this report, the equations governing the motion of aerially released particles are developed, including a description of the evaporation model used. A series of case studies, using AGDISP, are included.

Bilanin, A. J., Teske, M. E., Donaldson, C. duP. and Snedeker, R. S.,
"VISCOUS EFFECTS IN AIRCRAFT TRAILING VORTICES,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, Washington, 1977, pp. 61-128.

The mechanism of merging of like-signed aircraft vortices leads to a rapid redistribution of trailed vorticity in a wake through both convective and turbulent processes. Merging is investigated experimentally in a small wind tunnel and analytically through the use of a code which computes turbulent transport using a second-order closure turbulent model. Computations are reported which demonstrate the merging phenomenon, and comparisons are made with experimental results. The usefulness of point vortex computations in predicting merging is explored. Limited computations have shown that jet exhaust does not appreciably alter the merging phenomenon. The effect of ambient atmospheric turbulence on the aging of an aircraft wake is investigated at constant turbulent dissipation rate. It is shown that under stable atmospheric conditions, when atmospheric macroscales are less than or equal to the vortex spacing, misleading results may be obtained. This conclusion cautions against using one parameter to characterize the ability of the atmosphere to dissipate aircraft wake vortices.

Bilanin, A. J., Teske, M. E., Donaldson, C. duP. and Williamson, G. G.,
"VORTEX INTERACTIONS AND DECAY IN AIRCRAFT WAKES,"
NASA CR-2870, Sept. 1977,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

The dynamic interaction of aircraft wake vortices was investigated using both inviscid and viscous models. For the viscous model, a computer code was developed using a second-order closure model of turbulent transport. The phenomenon of vortex merging which results in the rapid aging of a vortex wake was examined in detail. It was shown that the redistribution of vorticity during merging results from both convective and diffusive mechanisms.

Bilanin, A. J., Teske, M. E. and Hirsh, J. E.,
"DEINTENSIFICATION AS A CONSEQUENCE OF VORTEX BREAKDOWN,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 283-296.

The physical mechanisms underlying the phenomenon of vortex breakdown have been the subject of speculation for nearly 20 years. What has become clear from numerous observations of the phenomenon on aircraft trailing vortices is that breakdown can be violently turbulent. This conclusion is drawn from the observation of smoke in the center of the vortex being dispersed with the passage of breakdown along the vortex. The question that has been asked repeatedly by those concerned with the vortex wake hazard is: Does the vortex breakdown phenomenon provide a mechanism of sufficient magnitude to be of aid in lessening the hazard of an aircraft vortex wake? The work reported herein is an attempt to answer this question. Since the vortex breakdown phenomenon is decidedly nonlinear and from observation, violently turbulent, a numerical approach has been undertaken to define the breakdown flowfield. Donaldson's second-order closure turbulent transport model has been coded in circular cylindrical coordinates. The result is an axisymmetric elliptic code in the radial and axial coordinates with time as the marching direction. The code has the capability of computing dispersal of a passive tracer.

Bilanin, A. J., Teske, M. E. and Williamson, G. G.,
"VORTEX INTERACTIONS AND DECAY IN AIRCRAFT WAKES,"
AIAA J., Vol. 15, No. 2, Feb. 1977, pp. 250-260.

The dynamic interactions of aircraft wake vortices are investigated using both inviscid and viscous models. The phenomenon of vortex merging resulting in the rapid aging of a vortex wake is examined in detail. It is shown that the redistribution of vorticity from convection and diffusion during merging is a mechanism effective in reducing the hazard of a wake. Inviscid computations show that the merging phenomenon may be sensitive to small changes in spanwise load distribution and that the fuselage vortex shed from the wing-fuselage junction can play a significant role in promoting merging of wing tip and flap vortices. Vortex wake merging computations using a second-order closure model of turbulent transport indicate that a low hazard wake occurs when the generating aircraft trails flap and wing tip vortices of the same strength and sign. This optimum is achieved when the flap vortex is located outboard approximately 40% of the distance to the tip vortex.

Bilanin, A. J. and Widnall, S. E.,
"AIRCRAFT WAKE DISSIPATION BY SINUSOIDAL INSTABILITY AND VORTEX BREAKDOWN,"
AIAA Paper No. 73-107,
Washington, DC, Jan. 1973.

Sinusoidal instability of aircraft trailing vortices was induced by differentially oscillating inboard and outboard flaps on a model wing in a ship towing tank. Measured amplification rates qualitatively agree with theoretical predictions. Axial velocities in the vortex core were directed toward the wing and measured to be approximately 25% of the tow speed. Vortex breakdown was observed to occur along trailers undergoing sinusoidal instability near but ahead (toward the wind) of positions of maximum trailer separation. It is shown that axisymmetric pressure gradients are imposed along the vortex core by the other sinusoidally deformed trailer and are responsible for the observed changes in core diameter. A theoretical model predicts the short-time behavior of the vortex core and shows that the response of the vortex depends crucially on the axial velocity in the vortex.

Bilbro, J. W., Craig, G. D., George, R. W., Jeffreys, H. B., Marrero, P. J., Weaver, E. A., Krause, M. C., Dunn, T. L., DiMarzio, C. A., Harris, C. E., Sonnenschein, C. M. and Toomey, D. W.,
"LASER DOPPLER VORTEX MEASUREMENTS AT JOHN F. KENNEDY INTERNATIONAL AIRPORT,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 81-93.

Marshall Space Flight Center in cooperation with the FAA has developed a Scanning Laser-Doppler Velocimeter System which has been used to detect, track, and measure the velocity flow fields of wake vortices of aircraft landing at Kennedy International Airport. The tests were performed with the cooperation of the Transportation Systems Center and the National Aviation Facilities Experiment Center, and resulted in detailed velocity and track data on the vortices generated by over 1600 landings of 13 different aircraft types. The paper describes the overall operation and performance of the system as well as the operation of the individual components. It discusses the data-handling capabilities of the system and the algorithms used in processing the laser-Doppler data, both in real time and in post analysis. Selected runs are examined for the spectral characteristics of vortices, their transport, velocity flow fields, and circulation. A summary of the results and a description of the tests are also provided.

Bilbro, J. W., Jeffreys, H. B., Weaver, E. A., Huffaker, R. M., Craig, G. D., George, R. W. and Marrero, P. J., "LASER DOPPLER VELOCIMETER WAKE VORTEX TESTS," FAA-RD-76-11, March 1976, NASA Marshall Space Flight Center, Huntsville, AL.

A scanning laser Doppler velocimeter (SLDV) was installed at John F. Kennedy (JFK) International Airport and was operated for six months collecting data on vortices generated by landing aircraft. A description of the SLDV system, a summary of the JFK test operations, an analysis of selected portions of the data, and recommendations for improvements to the SLDV are presented. The vortex information, including track and velocity data, on over 1600 aircraft landings is contained in the appendices.

Bird, J. D. and Riley, D. R., "SOME EXPERIMENTS ON VISUALIZATION OF FLOW FIELDS BEHIND LOW ASPECT RATIO WINGS BY MEANS OF A TUFT GRID," NACA TN-2674, May 1952, Langley Aeronautical Lab., Langley Field, VA.

A technique for obtaining a physical picture of the flow behind lifting surfaces is described wherein the action of a large number of tufts of uniform length attached to a wire grid are photographed from far downstream. The procedure yields, with a minimum of labor, an approximate vector plot of the flow field in a plane normal to the air stream. The flow fields behind a rectangular wing and several triangular wings were investigated through the angle-of-attack range. The effects of tip-control deflection, sideslip, and oscillation in sideslip on the flow field behind a 60° triangular wing were also determined.

Bisgood, P. L., "IN-FLIGHT STUDIES OF VORTEX WAKES, 1970-73," TM AERO-1554, Nov. 1973, Royal Aircraft Establishment, Farnborough, England.

In-flight studies of vortex wakes made in the UK during 1970-73 are described together with some discussion of the results, so far as the latter are available.

Bisgood, P. L., Maltby, R. L. and Dee, F. W.,
"SOME WORK AT THE ROYAL AIRCRAFT ESTABLISHMENT ON THE BEHAVIOR OF VORTEX WAKES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 171-206.

The paper reviews the work done at the Royal Aircraft Establishment on the behaviour of vortex wakes. Measurements of the development of wakes behind straight and swept wings are described. The results of observations on the formation of loops in a vortex wake, on the behaviour of the wakes close to the ground, and on the development of the wake from a slender wing are given in some detail.

Bliss, D. B.,
"THE DYNAMICS OF FLOW WITH HIGH CONCENTRATIONS OF VORTICITY,"
PhD Thesis, June 1973,
Mass. Inst. of Technology, Cambridge, MA.

A general method is developed for predicting the dynamics of curved rotational vortex lines with axial flow. The vortex core size must be much smaller than both the local radius of curvature and the length scale for axial variation. The self-induced motion is characterized by the size and energy content of the rotational core, as well as the filament geometry. The presence of axial flow diminishes the self-induced motion. The Biot-Savart law can be used to find the motion of a vortex filament, if the proper cut-off distance is used. A general formula for cut-off distance, depending only on local core structure, is derived. Results for a sinusoidally perturbed vortex line are compared with the solution of the dispersion relation for a hollow core vortex in order to ascertain the limits of validity of the solution. The prospect of finding higher order solutions is investigated and the additional effects that can arise are identified.

Bliss, D. B.,
"EFFECT OF UNSTEADY FORCING ON THE SINUSOIDAL INSTABILITY OF VORTEX WAKES,"
J. Aircraft, Vol. 19, No. 9, Sept. 1982, pp. 713-721.

An analytical model of the vortex wake instability subject to forcing by unsteady lift fluctuations has been developed. These lift fluctuations can be caused either by variations in angle of attack or by flying through atmospheric turbulence. The effect of turbulence in the fluid itself, already studied by Crow and Bate, has been reviewed and incorporated into the analysis. A simple procedure is provided to estimate the time at which contact occurs between the two wake vortices as a function of certain characteristics of the forcing inputs. The behavior of the instability is somewhat altered by these forcing terms. In particular, it was found that contact between vortices can occur at much shorter wavelengths than predicted for the unforced case. Furthermore, in the presence of forcing, the minimum completion time for the instability does not correspond to the wavenumber for which the amplification rate is a maximum because the length of the vortex trajectories is also an important factor. Finally, the stability boundary is extended to larger wavenumbers by the presence of forcing, and the boundary location depends on the forcing level.

Bloom, A. M. and Jen, H.,
"ROLL-UP OF AIRCRAFT TRAILING VORTICES USING ARTIFICIAL VISCOSITY,"
J. Aircraft, Vol. 11, No. 11, Nov. 1974, pp. 714-716.

A study was made of the roll-up characteristics of aircraft trailing vortices applying the artificial viscosity method of Kuwahara and Takami to a number of practical aerodynamic configurations and comparing the results for the core location with existing experimental data where possible.

Boatwright, D.,
"A STUDY OF THE INFLUENCE OF WING-TIP VORTICES ON THE TRAJECTORIES OF PARTICLES RELEASED FROM AIRCRAFT,"
Journal No. 1702A, Dec. 1968,
Miss. State U. Agriculture Experiment Station, State College, MS.

This report describes results of tests conducted to determine if radar reflective chaff injected at the wing tip of an aircraft would be ingested into the vortex structure and sufficiently distributed to allow velocity profiles to be measured by a Doppler radar. The results are presented in the form of flow field visualization results and an analysis of radar returns.

Bofah, K. K.,
"SOME REMARKS ON AIRCRAFT WAKE VORTEX ANALYSIS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 31-46.

Analysis techniques for aircraft trailing vortices are presented. Employing vortex theories by Saffman and Moore, predictive methods for vortex-induced rolling moments and coalescence time for a vortex pair are obtained. The predictions compare favorably with published data in the far field.

Bollman, J. R.,
"WAKE VORTEX ADVISORY SYSTEM OPERATIONAL TEST AND EVALUATION,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 335-341.

The objectives of the operational test and evaluation of the Vortex Advisory System (VAS) are described. The critical issues on the operational test and evaluation of VAS may be simplified as: what are the procedural implications of the system and how will operating efficiency of the airport facilities be affected?

Borough, C. K.,
"ELECTRO-OPTICAL VORTEX STUDIES FOR LARGE AIRCRAFT,"
TR 1976, Jan. 1976,
Naval Electronics Lab. Center, San Diego, CA.

Several promising approaches to the wake vortex problem have been recommended by electro-optical industries. Most of them recommend taking advantage of the concentration of CO_2 in the 14 to 16 micron region.

Bossel, H. H.,
"INVISCID AND VISCOUS MODELS OF THE VORTEX BREAKDOWN PHENOMENON,"
PhD Thesis, Report No. A.S. 67-14, Aug. 1967,
University of California, Berkeley, CA.

In the case of high swirl and large Reynolds number, the Navier-Stokes equations for rotationally symmetric incompressible flow are shown to reduce to (1) a viscous parabolic system for slender (quasicylindrical) flows and (2) an inviscid elliptic system for expanding (or contracting) flows. The inviscid system is solved for the case of flow with initial rigid rotation in a cylindrical stream surface. Assuming different downstream boundary conditions, Fourier-Bessel series solutions are computed for the supercritical (nonoscillatory) case and plotted. For very high swirl values, closed and open bubbles of recirculating fluid are obtained for certain cases, where the closed bubbles resemble those observed in vortex tube experiments. The viscous slender problem is formulated in an integral method using approximating functions for axial velocity and circulation which satisfy boundary and asymptotic requirements. Weighting functions are used to generate a linearly independent set of equations of sufficient number to determine the coefficients in the velocity and circulation approximations as functions of one (the axial) coordinate. The formulation is for any order of approximation. Computational difficulties appear near the suspected breakdown point. Flows resembling breaking flows are obtained.

Bossel, H. H.,
"VORTEX BREAKDOWN FLOWFIELD,"
Physics of Fluids, Vol. 12, No. 3, March 1969, pp. 498-507.

The Navier-Stokes equations for incompressible rotationally symmetric vortex flow at high swirl and large core Reynolds number are shown to approximate to the equation of inviscid rotating flow in regions where rigid rotation results from viscous action. Series solutions at high supercritical swirl values near the critical one under the condition of flow retardation near the axis are found to exhibit the experimentally observed features of vortex breakdown flows: bulges of decelerated flow, or bubbles of recirculating fluid, with reversed axial and swirl velocities near the axis. It is concluded that the vortex breakdown in vortex tubes and on delta wings is neither due to hydrodynamic instability, nor is it a phenomenon akin to the hydraulic jump. Rather it is a regular feature of the solution of the equations of motion under the given conditions.

Bossel, H. H.,
"VORTEX EQUATIONS: SINGULARITIES, NUMERICAL SOLUTION, AND AXISYMMETRIC VORTEX BREAKDOWN,"
NASA CR-2090, July 1972,
University of California, Santa Barbara, CA.

A method of weighted residuals for the computation of rotationally symmetric quasi-cylindrical viscous incompressible vortex flow is presented and used to compute a wide variety of vortex flows. The method approximates the axial velocity and circulation profiles by series of exponentials having (N+1) and N free parameters, respectively. Formal integration results in a set of (2N+1) ordinary differential equations for the free parameters. The governing equations are shown to have an infinite number of discrete singularities corresponding to critical values of the swirl parameter. The computations point to the controlling influence of the inner core flow on vortex behavior. They also confirm the existence of two particular critical swirl parameter values: one separates vortex flow which decays smoothly from vortex flow which eventually breaks down, and the second is the first singularity of the quasi-cylindrical system, at which point physical vortex breakdown is thought to occur.

Boswinkle, Jr., R. W.,
"AIRCRAFT VORTEX WAKES,"
Proceedings of Annual Corporate Aircraft Safety Seminar, Flight Safety Foundation, Wichita, May 1970.

An aircraft which is producing lift leaves a rotating flow field behind each wing as it flies forward. There is usually one pair of oppositely rotating flow fields, or vortices, extending downstream from each wing tip and moving downward. Each vortex has a core region in which the rotational velocities build up from zero in the center to some maximum velocity at the edge of the core. If another aircraft crosses laterally through the core of each vortex, it will be subjected to an up-flow, a down-flow, and then another up-flow. Hazards connected with these air motions for a light aircraft are discussed.

Boswinkle, Jr., R. W.,
"VORTEX WAKE TURBULENCE,"
23rd International Air Safety Seminar, Flight Safety Foundation, Washington, DC, 1970.

The talk highlighted the status of the vortex wake problem from the aircraft operator's standpoint. The vortex wake is described, accident statistics discussed, status of knowledge of vortex wake turbulence indicated, and example results of some measurements presented.

Bradley, R. G. and Wray, W. O.,
"A CONCEPTUAL STUDY OF LEADING-EDGE-VORTEX ENHANCEMENT BY BLOWING,"
J. Aircraft, Vol. 11, No. 1, Jan. 1974, pp. 33-38.

A conceptual wind-tunnel-test program has been conducted to verify that blowing a stream of high pressure air over a swept-wing surface in a direction roughly parallel to the leading edge enhances the vortex system. The blowing is shown to intensify the leading-edge vortex and thus delay the deleterious effects of vortex breakdown to higher angle of attack. As a result, the vortex-lift is significantly increased and, as the blowing rate is increased, appears to approach the value predicted by the Polhamus suction-analogy for thin wings.

Brandt, S. A. and Iversen, J. D.,
"MERGING OF AIRCRAFT TRAILING VORTICES,"
J. Aircraft, Vol. 14, No. 12, Dec. 1977, pp. 1212-1220.

A merging distance criterion for equal-strength corotational vortices is derived from low-turbulence wind tunnel flow visualization data. The vortex separation distance is normalized by defining a vortex core diameter based on circulation defect and angular momentum defect. Merging may take place for larger separation distances than predicted from earlier two-dimensional inviscid calculations, which indicates that viscosity and possibly three-dimensional effects are important factors in the merging phenomenon. Hot-wire velocity distributions and rolling moment measurements show that attenuation of the vortex hazard is associated with vortex merging.

Brashears, M. R. and Hallock, J. N.,
"A PREDICTIVE MODEL OF WAKE VORTEX TRANSPORT,"
Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, El Paso, 1974, pp. 387-392.

An aircraft wake vortex transport model has been developed which includes meteorological and fluid mechanic mechanisms. It has been applied to the prediction of the location of aircraft vortices relative to an approach corridor; comparisons of predicted tracks with measured vortex tracks show excellent agreement. The effects of wind shear and the Ekman spiral on vortex transport are discussed, and it is shown that the combination of wind shear and ground effect may be possible mechanisms underlying the tilting of vortices. The application of Pasquill class criteria is shown to be an effective technique to describe the wind profile in the absence of detailed wind data.

Brashears, M. R. and Hallock, J. N.,
"AIRCRAFT WAKE VORTEX TRANSPORT MODEL,"
J. Aircraft, Vol. 11, No. 5, May 1974, pp. 265-272.

A wake vortex transport model has been developed which includes the effects of wind and wind shear, buoyancy, mutual and self-induction, ground plane interaction, viscous decay, finite core, and Crow instability effects. Photographic and ground-wind vortex tracks obtained from DC-6, B-747, B-707, and CV-880 aircraft flybys are compared with predicted vortex tracks computed using meteorological and aircraft data as inputs to the transport model. A parametric analysis of the effects of the aircraft, fluid mechanic, and meteorological parameters shows the relative magnitude of each transport mechanism. The study constitutes the first detailed comparison of vortex transport theory with experimental data.

Brashears, M. R. and Hallock, J. N.,
"ANALYSIS OF PREDICTED AIRCRAFT WAKE VORTEX TRANSPORT AND COMPARISON WITH EXPERIMENT,"
J. Aircraft, Vol. 12, No. 7, July 1975, pp. 619-620.

An aircraft wake vortex transport model has been developed which combines fluid mechanic representations of the various vortex-induced and atmospheric effects. A series of flight tests was conduced to verify the model using B-747, B-707, CV-880 and DC-6 aircraft in which both the motion of the vortices and the attendant meteorological conditions were recorded. The differences between predicted and measured vortex tracks consistently fell within the computed uncertainty in the transport due to random fluctuations in the wind field.

Brashears, M. R. and Hallock, J. N.,
"PREDICTIVE MOTION OF WAKE VORTICES,"
Proceedings Int. Conf. on Future of Aircraft All-Weather Operations, Inst. Electrical Engineers, London, Nov. 1976, pp. 42-45.

Predictive models for the motion of wake vortices are considered as a contribution to vortex avoidance strategy. Four stages are envisaged in the construction of a predictive model: a mathematical model of vortex behavior based on aerodynamics and fluid mechanics; verifying the model against controlled flight test data; refining the model to account for deviations; verification of the model under operational conditions. Each stage is discussed separately. A geometrical approach to vortex detrainment in an approach zone with wind velocity taken into account is sketched.

Brashears, M. R. and Hallock, J. N.,
"THE MEASUREMENT OF WIND SHEAR AND WAKE VORTICES BY LASER VELOCIMETRY,"
Proceedings 7th Conf. on Aerospace and Aeronautical Meteorology,
AIAA/AMS, Melbourne, Nov. 1976, pp. 175-181.

The Laser Doppler Velocimeter (LDV) discussed was developed to measure three-dimensional wind and corresponding wind shear at heights below 500 m, and the location and persistence of aircraft wake vortices in the terminal environment. In particular, the Vertical Azimuth Display mode of operation is shown to be an extremely accurate technique. The measurement accuracy of + or - 0.5 m/sec in wind speed and + or - 2.5 deg in wind direction has been further improved by using least-squares techniques in data processing.

Brashears, M. R., Hallock, J. N. and Logan, N. A.,
"ANALYSIS OF PREDICTED AIRCRAFT WAKE VORTEX TRANSPORT AND COMPARISON WITH EXPERIMENT,"
AIAA Paper No. 74-506,
Palo Alto, CA, June 1974.

Predicted vortex tracks from a wake vortex transport model previously developed (including the effects of wind and wind shear, buoyancy, mutual and self-induction, ground plane interaction, viscous decay, and finite core and Crow instability effects) have been compared with vortex tracks obtained from B-747, B-707, CV-880 and DC-6 aircraft flybys. Excellent agreement was found between prediction and measurement when sufficient wind data were available. A detailed explanation of vortex tilting is given along with observations concerning the mechanism itself.

Brashears, M. R., Lawrence, T. R. and Zalay, A. D.,
"MOBILE LASER DOPPLER SYSTEM CHECKOUT AND CALIBRATION,"
FAA-RD-77-48, June 1977,
Lockheed Missiles & Space Co., Huntsville, AL.

A program has been carried out to make modifications to the Lockheed-Huntsville Mobile Laser Doppler Velocimeter (LDV) system; to calibrate and operate the system at the John F. Kennedy (JFK) Airport; to obtain a data base of wind, wind shear, and wake vortex measurements; and to assess the basic operational capabilities of the system based on these measurements. The basic operational capabilities, resolution, and integrity of a scanning LDV for the remote sensing of winds, wind shear, and wake vortices at terminal areas has been established.

Brashears, M. R., Logan, N. A. and Hallock, J. N.,
"THE EFFECT OF WIND SHEAR AND GROUND PLANE ON AIRCRAFT WAKE VORTICES,"
J. Aircraft, Vol. 12, No. 10, Oct. 1975, pp. 830-833.

A previous comparison of predicted wake vortex transport with experiment revealed two consistent sources of discrepancy, namely, lower predicted sink rates of the vortex pair relative to observed and a lagging of the predicted upwind vortex transport compared with the measured values. It was hypothesized that either a wake tilting or a decrease in circulation was occurring to account for this lagging. Accordingly, an analysis was performed to determine the streamlines associated with the presence of a vortex pair in a shear near the ground and the movement of the stagnation points in such a region. It was found that the upper and lower stagnation points rise or sink relative to their shearless location, depending upon the magnitude of non-dimensional parameters defining ground proximity and wind shear to circulation.

Brashears, M. R., Logan, N. A., Robertson, S. J., Shrider, K. R. and Walters, C. D.,
"ANALYSIS OF PREDICTED AIRCRAFT WAKE VORTEX TRANSPORT AND COMPARISON WITH EXPERIMENT,"
FAA-RD-74-74.I and 74.II, April 1974,
Lockheed Missiles & Space Company, Huntsville, AL.

A unifying wake vortex transport model is developed and applied to a wake vortex predictive system concept. The fundamentals of vortex motion underlying the predictive model are discussed including vortex decay, bursting and instability phenomena. A parametric and sensitivity analysis is presented to establish baseline uncertainties in the algorithm to allow meaningful comparison of predicted and measured vortex tracks. A detailed comparison of predicted vortex tracks with photographic and groundwind vortex data is presented. Excellent agreement between prediction and measurement is shown to exist when sufficient wind data are available. Application of the Pasquill class criteria is shown to be an effective technique to describe the wind profile in the absence of detailed wind data. The effects of wind shear and the Ekman spiral on vortex transport are discussed. It is shown that the combination of wind shear and ground plane may be possible mechanisms underlying vortex tilting and a theoretical explanation is advanced that is somewhat supported by comparison with the experimental data. Finally, recommendations for further vortex data collection in the vicinity of an airport are presented.

Brashears, M. R., Robertson, S. J., Johnson, B. C., Fan, C. and Shrider, K. R.,
"WAKE VORTEX TRANSPORT CONSIDERATIONS AND METEOROLOGICAL DATA ANALYSIS,"
LMSC-HREC TR D390424, Nov. 1974,
Lockheed Missiles & Space Company, Huntsville, AL.

Comparisons were made between predicted wake vortex motions and vortex tracks measured by propeller anemometers arrayed in baselines oriented perpendicularly to the aircraft flight path. The effect of buoyancy in ground plane on the predicted vortex transport was described. Meteorological data processing computer routines were developed to provide a detailed atmospheric characterization.

Brashears, M. R., Robertson, S. J., Love, D. A., Shrider, K. R. and Zalay, A. D.,
"ANALYSIS OF WAKE VORTEX MEASUREMENTS,"
LMSC-HREC TR D496558, Sept. 1975,
Lockheed Missiles & Space Company, Huntsville, AL.

Wake vortex measurements obtained by DOT-TSC at John F. Kennedy (JFK) International Airport have been reduced, analyzed, and correlated with a theoretical vortex transport model. The predictive wake vortex transport model has been updated so that detailed on-site meteorological measurements can be interpreted and utilized to predict more accurately the vortex transport and decay characteristics. A discussion of the wake vortex test data analysis and software development is presented including a description of the JFK wake vortex test program, the computer processing of wake vortex measurements, the analysis of ground wind sensor measurements, and the analysis of meteorological measurements.

Brashears, M. R., Shrider, K. R., Love, D. A., Robertson, S. J. and Zalay, A. D.,
"WAKE VORTEX AND GROUNDWIND METEOROLOGICAL MEASUREMENTS,"
FAA-RD-76-93, May 1976,
Lockheed Missiles & Space Company, Huntsville, AL.

Wake vortex groundwind and meteorological measurements obtained by DOT-TSC at John F. Kennedy (JFK) International Airport have been reduced, analyzed, and correlated with a theoretical vortex transport model. The predictive Wake Vortex Transport Model has been updated so that detailed on-site meteorological measurements can be interpreted and utilized to predict more accurately the vortex transport and decay characteristics. A discussion of the wake vortex test data analysis and software development is presented, including a description of the JFK wake vortex test program, the computer processing of wake vortex measurements, the analysis of ground wind sensor measurements, and the analysis of meteorological measurements.

Brashears, M. R. and Zalay, A. D.,
"LASER DOPPLER VELOCIMETER MEASUREMENTS OF B-747 WAKE VORTEX CHARACTERISTICS,"
FAA-RD-77-85, Sept. 1977,
Lockheed Missiles & Space Company, Huntsville, AL.

To determine the behavior of the wake vortices of a B-747 at low altitudes and to measure the vortex-decay process behind the B-747 as a function of altitude above ground, flap and spoiler settings, and different flight configurations, a B-747 aircraft flew 54 passes at low level over a ground-based laser Doppler velocimeter (LDV) system. From the LDV measurements, the location and flow field of the wake vortices and the general vortex roll-up, transport, and decay trends were obtained. Results of the study indicated that the deployment of spoilers and flaps enhanced the decay of the vortex peak tangential velocity in the near wake while aircraft altitude, glide slope, and landing gear deployment had little effect. The report discusses the LDV wake vortex measurements including the instrumentation used, the experimental test sequence, the results of the wake measurements in terms of the vortex roll-up, transport, and decay trends, and a comparison of the wake vortex characteristics for different configurations.

Brashears, M. R., Zalay, A. D., Chou, L. C. and Shrider, K. R.,
"DEVELOPMENT OF PREDICTIVE WAKE VORTEX TRANSPORT MODEL FOR TERMINAL AREA WAKE VORTEX AVOIDANCE,"
FAA-RD-76-94, May 1976,
Lockheed Missiles & Space Company, Huntsville, AL.

The wake vortex transport program has been expanded to include viscous effects and the influence of initial roll-up, atmospheric turbulence, and wind shear on the persistence and motion of wake vortices in terminal areas. Analysis of wake characteristics has shown that changes in the spanwise loading due to flaps increase the initial sink rate, decrease the separation, and initiates the circulation decay process earlier. Buoyancy due to jet exhaust entrainment and ambient stratification retards vortex spreading and increases descent. Atmospheric turbulence and shear promote a more rapid decay reducing the late-time descent and spread rates of vortices.

Vortex tilting has been related to an interaction involving the wind shear, ground plane, and the vorticity detrainment process. Recognition of the effects of tilting, spanwise loading, vorticity detrainment, burst/sink instabilities, and atmospheric conditions has resulted in an analytic wake transport and decay model with increased accuracy and improved predictive capabilities.

Brashears, M. R., Zalay, A. D. and Eberle, W. R., "PREDICTED AND MEASURED WAKE VORTEX MOTION NEAR THE GROUND," Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 316-325.

Vortex track and meteorological measurements obtained by the Transportation Systems Center at Kennedy International Airport have been processed and cataloged in a computerized data management system. A total of 1320 flybys have been cataloged. A calculated vortex track using meteorological data measured concurrently with the measured vortex track has been generated and placed in the data management system for each flyby. An analysis of measured vortex parameters and corresponding vortex parameters generated from the analytic model was performed. A comparison of calculated vortex residence time and measured vortex residence time is presented. The reasons for deviations between the calculated residence time and measured residence time are discussed. Design considerations for a wake vortex avoidance system are also discussed.

Brashears, M. R., Zalay, A. D., Hallock, J. N. and Burnham, D. C., "LASER DOPPLER FLIGHT TEST MEASUREMENTS OF B-747 WAKE VORTEX CHARACTERISTICS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 106-113.

In order to determine the behavior of aircraft wake vortices at low altitudes and to measure the wake vortex decay process behind a wide-body transport aircraft as a function of altitude above ground, flap and spoiler settings, and different flight configurations; a B-747 aircraft flew 54 passes at low level over a ground-based laser-Doppler velocimeter (LDV) system. From the LDV measurements, the location and velocity distribution of the wake vortices and the general vortex roll-up, transport, and decay trends were obtained. Results of the study indicated that the deployment of spoilers and flaps enhanced the decay of the vortex peak tangential velocity in the near wake while aircraft altitude, flight path angle, and landing gear deployment had little effect. The paper discusses the LDV wake vortex measurements including the instrumentation used, the experimental test sequence, and the results of the wake measurements in terms of the vortex rollup, transport and decay trends. A comparison of the wake vortex characteristics for different aircraft configurations is also presented.

Britton, J. W.,
"SOME OBSERVATIONS OF THE BEHAVIOR OF THE VORTEX WAKE OF A VC 10 AIRCRAFT,"
TM FS-105, Feb. 1977,
Royal Aircraft Establishment, Farnborough, England.

Some observations of the nature and persistence of the trailing vortices of a VC 10 aircraft are presented. Particular attention is drawn to the difference between the wakes for the aircraft in the cruise and approach/landing configurations. The effects of thermals and of the wakes of airfield buildings on the position and persistence of the wake are also described.

Britton, J. W.,
"SOME REMARKS ON EN-ROUTE VORTEX ENCOUNTERS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 243-246.

Encounters with vortex wakes can and have occurred during cruising flight on airways. Observations at RAE Bedford indicate that trailing vortices may persist for more than two minutes after the passage of an intercontinental airliner in cruising flight at high altitude.

Brown, C. E.,
"THE USE OF SHIP MODEL BASINS FOR THE STUDY OF VORTEX WAKE PHENOMENA,"
AFOSR-TR-73-0567, March 1973,
Hydronautics, Laurel, MD.

The basic differences between test in air and in water are discussed relative to the study of aircraft vortex wake phenomena. It is shown that use of large ship model basins is valid for simulation up to critical Mach numbers of flight. Free surface interference is shown to be negligible for tests made at sufficient towing depths and it is concluded that cavitation must and can easily be avoided entirely at typical towing speeds. Effects of Reynolds number mismatch on the test results is analyzed and it is concluded that wing profile drag coefficients should be matched between full and model scale. Finally, consideration is given to the problem of stopping and starting disturbances in towed-model testing.

Brown, C. E.,
"AERODYNAMICS OF WAKE VORTICES,"
AIAA Journal, Vol. 11, No. 4, April 1973, pp. 531-536.

The effect of wing span loading on the development of fully rolled-up wing trailing vortices is discussed. It is shown that parabolic wing loadings produce potential flow maximum core rotary speeds which are finite and less than 50% greater than the downwash speeds at the plane of symmetry. The development of turbulent cores is analyzed and core growth is predicted to occur as the two-thirds power of time, whereas the peak velocities fall off as the inverse one-third power. Axial flow effects of the wing profile drag and lifting system are shown to lead to axial jets on the vortex axis which may either follow the aircraft or exceed the freestream velocity, depending on the ratio of profile drag to induced drag.

Brown, C. E.,
"WAKE TURBULENCE IN A WATER ENVIRONMENT,"
Proceedings of the AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Lab., Wright-Patterson AFB, 1974, pp. 43-49.

A review of NASA tests conducted in the Hydronautics Ship Model Basin was given along with experiments with a thermally stratified environment. Vortices showed a definite slowing in their descent in a water environment even without stratification; this was probably related to the observed bursting and fringing of vortices. The tests with a stratified environment definitely showed an additional slowing effect on vortex descent; the vortices leveled off sooner and even bounced back up in some cases.

Brown, C. E.,
"PRESSURE FIELD OF A VORTEX WAKE IN GROUND EFFECT,"
J. Aircraft, Vol. 12, No. 2, Feb. 1975, pp. 120-121.

The ground pressures under a descending pair of vortices such as might be generated by aircraft either landing or taking off are computed. It is found that as the vortices first approach the ground, only positive pressures are produced; however, as the descent continues the high velocity field of the vortices makes itself apparent in dips to subatmospheric pressure which lie closely beneath the vortex center. Nevertheless, a substantial positive pressure hill precedes the path of the vortex as it moves laterally in the "ground effect". The level of pressures produced is dependent only on the flight speed, lift coefficient and aspect ratio while the length scale of the pressure distribution is proportional to the span. These results may be useful in the development of systems to monitor multiple aircraft take-off and/or landing operations.

Brown, C. E. and Kirkman, K. L.,
"SIMULATION OF WAKE VORTICES DESCENDING IN A STABLY STRATIFIED ATMOSPHERE,"
FAA-RD-74-116, July 1974,
Hydronautics Inc., Laurel, MD.

An experimental simulation of aircraft wake vortices descending in a stable atmosphere has shown that the atmospheric stability stops the downward movement and in some cases produces a subsequent rebound. The tests were carried out in a large ship model basin using a rectangular planform wing. Lift coefficients of 0.4 and 1.0 were selected and stable atmospheric conditions were obtained by temperature (density) stratification of the towing basin. Test conditions corresponding to Vaisala-Brunt periods of infinity, 109, and 51 seconds were obtained. The model parameters and stability conditions covered the most extreme cases to be expected in full scale flight.

Brown, C. E. and Miller, Jr., E.,
"EXPERIMENTAL STUDY OF TRAILING VORTEX WAKES USING A LARGE TOWING TANK,"
Tech Report 7105-1, Aug. 1971,
Hydronautics, Laurel, MD.

An experimental study of the trailing vortex wake behind a 0.03 scale model of a Boeing 747 transport aircraft was carried out in the Hydronautics Ship Model Basin. The experimental equipment and techniques used are described in detail. Data are presented on vortex trajectories, core diameter and growth, and tangential and axial velocity profiles for the cruise and flaps 30 configuration. Distances behind the model equivalent to 3 miles full scale were achieved before disturbances due to stopping the model affected the results. It was concluded that the techniques developed were suitable for studying devices intended to speed vortex decay and that the results to date show good quantitative agreement with full scale observations.

Brown, C. E. and Van Dyke, P.,
"HIGH SPEED COMPUTER STUDIES OF VORTEX MOTIONS IN RELATION TO AIRCRAFT WAKE TURBULENCE,"
AFOSR-TR-76-0481, Jan. 1976,
Hydronautics Inc., Laurel, MD.

Computations are presented and compared with experimental data from other sources for basic and advanced problems in aircraft - wake vortex interactions. Results are presented for coalescence of corotation and counterrotating vortex groups and finally a complete high speed computer method is developed for simulating the roll reaction of an aircraft to the wake produced by a large aircraft with flaps deployed. Suggestions for improved experimental approaches are also appended.

Brown, C. E., Van Dyke, P. and Kloetzli, J. W.,
"MEASUREMENTS AND ANALYSIS OF THE FORCES ACTING ON A SMALL AIRCRAFT FLYING IN THE UPWASH OF A LARGE AIRCRAFT,"
AFOSR-TR-78-0903, April 1978,
Hydronautics Inc., Laurel, MD.

A study has been made of the forces and moments acting on a small aircraft while it is flying in the upwash field adjacent to and behind the wing tip of a larger airplane. Preliminary analysis of the expected ranges of forces and moments were made using available theoretical methods and confirming experiments were performed in the Hydronautics Ship Model Basin. The tests used a large model of the Boeing 747 transport aircraft and a smaller model typifying a fighter-type aircraft. The range of positions of the small model relative to the large model extended laterally 30 full-scale feet from the wing tip or from the tip vortex and downstream roughly 80 feet behind the wing tip. The model tests have shown that an increase of 50% in L/D can be obtained by a small fighter-type aircraft fling close to the tip trailing vortex of a larger aircraft. Higher increases in L/D for the same relative aircraft positions would result if the smaller aircraft exhibited higher performance (maximum L/D was 8.9 in free air). Calculations made for the models tested indicate that control power of typical fighters would be sufficient to maintain level flight in the favorable positions close to a tip vortex.

Brune, G. W. and Hallstaff, T. H.,
"WING SPAN LOADS OF COMPLEX HIGH-LIFT SYSTEMS FROM WAKE MEASUREMENTS,"
J. Aircraft, Vol. 22, No. 9, Sept. 1985, pp. 831-832.

This note presents wake data of a twin-engine transport in a takeoff configuration and outlines a method of calculating wing loads based on well-known concepts that relate loading to the strength of trailing vortices. The measuring system consisted of a single five-hole conical probe (0.25-in. diameter) mounted on a mechanical traverse in the Boeing Transonic Wind Tunnel. The measured test data included total pressure and three components of wake velocity.

Burnham, D. C.,
"EFFECT OF GROUND WIND SHEAR ON AIRCRAFT TRAILING VORTICES,"
AIAA Journal, Vol. 10, No. 8, August 1972, pp. 1114-1115.

In ground effect, when the wind blows across the aircraft path, one often observes that the up-wind wake vortex consistently descends to a lower altitude than the down-wind vortex. The relationship of this effect to wind shear is illustrated by a simple calculation where the wind shear layer near the ground is modeled as a row of line vortices.

Burnham, D. C.,
"WAKE VORTEX CIRCULATION MEASUREMENTS,"
Third Workshop on Atmospheric Acoustics, York University,
Toronto, Canada, June 1975.

An acoustic sounder with separate transmitting and receiving antennas is used to measure the vertical wind profile of an aircraft wake between 20 and 150 feet. The velocity data are processed with correlation techniques to find the vortex locations. The vortex strength and core radius are obtained by fitting the data to a simple model.

Burnham, D. C.,
"CHARACTERISTICS OF A WAKE-VORTEX TRACKING SYSTEM BASED ON ACOUSTIC REFRACTIVE SCATTERING,"
J. Acoustical Soc. America, Vol. 61, March 1977, pp. 647-654

The theory of acoustic-ray bending by aircraft-generated vortices is developed in a form convenient for application to a practical vortex tracking system. The maximum scattering angle is proportional to the vortex circulation divided by the average core radius. Since the circulation for commercial jet transports is roughly proportional to the wingspan, the value of the maximum scattering angle depends little on aircraft size but strongly on the ratio of the core size to the wingspan. For landing aircraft the maximum scattering angle varies from 0.5 to 1.4 rad depending upon the engine placement. The capabilities of a pulsed acoustic vortex tracking system depend strongly upon the maximum scattering angle and therefore upon aircraft type. The effects of timing errors, both vortex induced and random, on tracking accuracy are derived.

Burnham, D. C.,
"REVIEW OF VORTEX SENSOR DEVELOPMENT SINCE 1970,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 47-66.

The various sensing techniques developed since 1970 and used for studying aircraft wake vortices are described. The inherent advantages and limitations of each technique are discussed. Emphasis is placed on those sensors used for data collection at airports.

Burnham, D. C.,
"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME I: DATA COLLECTION AND REDUCTION,"
FAA-RD-79-103,I, Oct. 1979,
DOT Transportation Systems Center, Cambridge, MA.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60 m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. This volume describes the MAVSS principles of operation, the hardware developed, and data reduction methods employed.

Burnham, D. C.,
"B-747 VORTEX ALLEVIATION FLIGHT TESTS: GROUND-BASED SENSOR MEASUREMENTS,"
FAA-RD-81-99, Jan. 1982,
DOT Transportation Systems Center, Cambridge, MA.

In 1979, a series of B-747 flight tests were carried out to study the wake-vortex alleviation produced by deploying spoilers in the landing configuration. The alleviation achieved was examined by encounters of probe aircraft and by velocity profile measurements made by a ground-based Laser Doppler Velocimeter. For the first time these two types of measurements were analyzed in a way which allowed direct comparison; they showed reasonable agreement. The velocimeter measurements can be used to evaluate the vortex-induced rolling moment on any following aircraft at any separation. The spoiler alleviation was found to be insufficient to assure safe landings of small aircraft at reduced separation behind the B-747. The persistence of the alleviated vortices appears to be due to the wing-tip vortices which dominate the roll-up of the spoiler-alleviated wake. The addition of rapid roll inputs to the spoiler deployment produced much more effective alleviation, but at the expense of an unacceptable ride quality in the generating aircraft.

Burnham, D. C., Gorstein, M., Hallock, J. N., Kodis, R. D., Sullivan, T. E. and McWilliams, I. G.,
"AIRCRAFT WAKE VORTEX SENSING SYSTEMS,"
DOT-TSC-FAA-72-13, June 1971,
DOT Transportation Systems Center, Cambridge, MA.

The report summarizes and analyzes techniques, both active and passive, that could be used to detect and measure air movements associated with wingtip vortex generation within an area or throughout a volume of terminal airspace. The study indicates useable techniques with an appraisal of expected performance and inherent limitations. Results of preliminary feasibility tests employing available technology are presented. The report also discusses the systems studies to be performed on the wake vortex sensing problem.

Burnham, D. C. and Hallock, J. N.,
"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME II: DECAY OF B-707 AND DC-8 VORTICES,"
FAA-RD-79-103,II, Sept. 1971,
DOT Transportation Systems Center, Cambridge, MA.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. In this volume, the data are analyzed to examine whether landing B-707 and DC-8 aircraft need to be divided into heavy and non-heavy categories on the basis of wake vortex hazard.

Burnham, D. C. and Hallock, J. N.,
"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME III: EXECUTIVE SUMMARY: DECAY OF B-707 AND DC-8 VORTICES,"
FAA-RD-79-103,III, Jan. 1982,
DOT Transportation Systems Center, Cambridge, MA.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive antennas in the array. In this volume, the results of Volume II are summarized in terms of the safety implications of categorizing all landing B-707s and DC-8s as Large aircraft.

Burnham, D. C. and Hallock, J. N.,
"CHICAGO MONOSTATIC ACOUSTIC VORTEX SENSING SYSTEM, VOLUME IV: WAKE VORTEX DECAY,"
FAA-RD-79-103,IV, July 1982,
DOT Transportation Systems Center, Cambridge, MA.

A Monostatic Acoustic Vortex Sensing System (MAVSS) was installed at Chicago's O'Hare International Airport to measure the strength and decay of aircraft wake vortices from landing aircraft. The MAVSS consists of an array of acoustic antennas which measure the vertical profile up to 60-m altitude of the vertical component of the wind. The decay in wake vortex strength is measured as the vortex passes over successive

antennas in the array. In this volume, the statistical methods used to understand wake vortex decay are described and the data on all common jet transport aircraft are presented.

Burnham, D. C., Hallock, J. N., Kodis, R. D. and Sullivan, T. E.,
"VORTEX SENSING TESTS AT NAFEC,"
DOT-TSC-FAA-72-2, Jan. 1972,
DOT Transportation Systems Center, Cambridge, MA.

This report describes the results of a series of tests conducted for the FAA at NAFEC by the DOT/Transportation Systems Center. The test objectives were to determine and evaluate some of the characteristics of three experimental techniques for the remote sensing of the wing-tip vortices generated by heavy commercial and military aircraft. These techniques involved (1) a pulsed, bistatic acoustic detection and ranging system (referred to as an acoustic radar); (2) a ground level pressure sensor; and (3) a ground level hot-wire anemometer. The tests were conducted both in conjunction with the instrumented tower and at the end of runway 13. Data were obtained and analyzed for a variety of aircraft including the DC-7, B-747, C-141 and C-5A. Results in the form of altitudes and times of tower hits and vortex tracks are presented and compared to the tower data wherever possible.

Burnham, D. C., Hallock, J. N., Tombach, I. H., Brashears, M. R. and Barber, M. R.
"GROUND-BASED MEASUREMENTS OF THE WAKE VORTEX CHARACTERISTICS OF A B-747 AIRCRAFT IN VARIOUS CONFIGURATIONS,"
FAA-RD-78-146, Dec. 1978,
DOT Transportation Systems Center, Cambridge, MA.

A Boeing 747 aircraft flew 54 passes at low altitude over ground-based sensors. Vortex velocities were measured by a laser Doppler velocimeter, an array of monostatic acoustic sounders, and an array of propeller anemometers. Flow visualization of the wake was achieved using smoke and balloon tracers and was recorded photographically. Data were obtained on vortex velocity fields, vortex decay, and the effects of spoilers and differential flap settings on the dissipation and structure of the vortices.

Burnham, D. C., Hallock, J. N., and VanDuyne, E.,
"SUMMARY OF WAKE VORTEX SENSOR RESEARCH AND DEVELOPMENT,"
Proceedings NASA Wake Vortex Detection Technology Workshop, Langley Research Center, Hampton, VA, Sept. 1983.

In this summary paper the status of the wake vortex program from the FAA perspective is reviewed. Special attention is given to the vortex sensor technology as this is an area that NASA may be able to apply expertise gained in other similar programs. This paper first reviews what is and is not known about vortex behavior as one must know its behavior to mitigate its influence. Next, sensors that were developed to collect data on vortex behavior are discussed. Possible problems with an airborne sensor are noted. The paper concludes with a description of the current FAA wake vortex program where short-term solutions are being evaluated as well as the development of long-term research projects.

Burnham, D. C., Kodis, R. D. and Sullivan, T. E.,
"OBSERVATIONS OF ACOUSTIC RAY DEFLECTION BY AIRCRAFT WAKE VORTICES,"
J. Acoustical Soc., Vol. 52, No. 1, Part 2, March 1972, pp. 431-433.

Acoustic ray deflection by aircraft wake vortices has been observed during landing operations by large aircraft. The phenomenon has been used to detect and locate vortex tracks in a plane perpendicular to the runway centerline. The maximum deflection angles observed for a variety of aircraft show qualitative agreement with values predicted for a viscous core.

Burnham, D. C. and Sullivan, T. E.,
"INFLUENCE OF FLAPS AND ENGINES ON AIRCRAFT WAKE VORTICES,"
J. Aircraft, Vol. 11, No. 9, Sept. 1974, pp. 591-592.

Observed differences in aircraft wake vortex core structure are related to engine placement, engine thrust, and wing flap deflection angle. The vortices are divided into two main categories, tubular and non-tubular by two methods: visual observations and results from a pulsed bistatic acoustic vortex sensing system. The major difference is observed in landing configurations between aircraft with and without engines located very close to the outboard flap edge.

Burnham, D. C. and Sullivan, T. E. and Wilk, L. S.,
"MEASUREMENT OF WAKE VORTEX STRENGTH BY MEANS OF ACOUSTIC BACK SCATTERING,"
J. Aircraft, Vol. 13, No. 11, Nov. 1976, pp. 889-894.

A simple acoustic sounder is shown to produce reliable velocity profiles of aircraft wakes at altitudes below 50m. Data collection during normal airport landing operations was feasible because the sensor does not intrude into the airspace being measured. A spatial scan through the wake is obtained when the ambient wind transports the wake through the sounder beam. The data are processed to yield the radial dependence of the velocity and circulation in the wake vortices. The circulation data are fitted to a simple model with two parameters: *strength and core radius*. The spatial and velocity resolution of the sounder is adequate to measure vortex strength but not to probe details of the core structure.

Butter, D. J. and Hancock, G. J.,
"A NUMERICAL METHOD FOR CALCULATING THE TRAILING VORTEX SYSTEM BEHIND A SWEPT WING AT LOW SPEED,"
Aero. Journal, Vol. 75, Aug. 1971, pp. 564-568.

A method is presented for the prediction of the spatial distribution of the trailing vorticity during the rolling up process, thus giving the overall downwash field behind the wing.

Butterworth, P. J.,
"FLOW MEASUREMENTS IN THE WAKE OF A WING FITTED WITH A LEADING-EDGE ROOT EXTENSION (STRAKE),"
RAE TR-79120, Sept. 1979,
Royal Aircraft Establishment, Farnborough, England.

In a low-speed wind tunnel measurements have been taken of the velocity vector in the flow field behind the wing of a combat aircraft model. The wing was fitted with a leading-edge root extension (strake) and could have either a plain leading edge or a deployed slat outboard. Four flow investigations were made; at three angles of incidence with the plain leading edge and at one angle of incidence with the slat deployed. The data from each of these tests have been analyzed to give the distribution of the total head deficit, the streamwise component of vorticity and a measure of the circulation distribution in the wake of the wing.

C

Caiger, B. and Gould, D. G.,
"AN ANALYSIS OF FLIGHT MEASUREMENTS IN THE WAKE OF A JET TRANSPORT AIRCRAFT,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 125-136.

Peak velocity vectors measured in the transverse plane of the wake of a Convair 880 aircraft were found to be four times as high as anticipated. The peak velocities are shown to occur in small intense vortices which are separate from the main tip vortices. These exist up to 30 seconds after generation. The main tip vortices are shown to have a core size which is roughly of the size anticipated but whose diameter does not increase significantly up to 30 seconds after generation.

Campbell, J. F., Chambers, J. R. and Ramsey, C. L.,
"OBSERVATION OF AIRPLANE FLOWFIELDS BY NATURAL CONDENSATION EFFECTS,"
J. Aircraft, Vol. 26, No. 7, July 1989, pp. 593-604.

Flight condensation patterns illustrate a variety of airplane flowfields, such as attached and separated flows, vortex flows, and expansion and shock waves. Analysis shows vortex cores have a low relative humidity which may help explain the voids in condensed vortex flows.

Cann, S. R.,
"AIRCRAFT VORTEX WAKE,"
Shell Aviation News, No. 394, 1971, pp. 8-9.

Consideration is given to the trailing vortices shed by the lifting surfaces of an aircraft. Vortex strength varies directly with the lift being produced by the wing and inversely as the speed and the span. Thus it is that at low speeds - i.e., in control zones - that wake effects become important. Encounters of aircraft with wakes produced by other aircraft can result in uncontrollability. Current UK separation standards are summarized.

Caram, J. M. and Ahmed, A.,
"EFFECTS OF RIBLETS ON THE WAKE CHARACTERISTICS OF AN AIRFOIL,"
AIAA Paper No. 89-2199,
Seattle, WA, Aug. 1989.

Near- and intermediate-wake region boundary layer profile and skin friction coefficient measurements have been conducted for a NACA 0012 airfoil incorporating 0.0229, 0.076, and 0.152 mm symmetric v-groove riblets at a freestream Reynolds number of 250,000. While the growth of the wake was found to be similar for both the clean and the riblet-surfaces airfoils, riblet effectiveness in drag reduction was indicated by a significant decrease in wake turbulence levels. A drag reduction of as much as 13.3 percent was achieved, perhaps due to a combination of skin friction diminution in the riblet valleys and a decrease in turbulent shear stress.

Carpenter, A. G.,
"SUMMARY AND EVALUATION OF THEORETICAL DEVELOPMENTS RELATING TO TRAILING WING TIP VORTICES GENERATED BY AIRCRAFT,"
SAC-NR-76-01, May 1976,
Strategic Air Command, Offutt AFB, NB.

This report presents a summary of theories and measurements which are believed to be applicable to the prediction of details concerning the structure and behavior of wing tip vortices created by large aircraft. Emphasis is placed upon the chronological development of theories, their comparison, and the selection of those which are believed to be most useful in predicting detailed velocity profiles of and within vortices from the moment of wing tip shedding until considerable trailing distances have been established with the passage of time.

Carr, J. W.,
"SURFACE VELOCITIES AND TEMPERATURE CHANGES FOR C-130, C-141, AND C-5A EXHAUST BLASTS AND C-5A WING-TIP VORTEX,"
AEWES-S-73-61, June 1973,
Army Engineer Waterways Experiment Station, Vicksburg, MS.

The report describes a series of field investigations conducted to determine exhaust-blast velocities and temperatures at the ground level for various aircraft and the wing-tip vortex velocity of the C-5A. Measurements of exhaust-blast velocities and temperature rise during static conditions were collected for C-130, C-141, and C-5A aircraft. Taxi, breakway, and liftoff tests were conducted with the C-141 and C-5A to record velocity during actual aircraft operations. Wind velocity created by the wing-tip vortex of the C-5A was recorded during actual aircraft operations. Results of these tests indicate that temperature increases from engine exhaust blasts are not sufficient to cause detrimental effects on runway surfacing in use to date.

Carten, Jr., A. S.,
"WARNING: WAKES,"
Astronautics and Aeronautics, Vol. 8, No. 4, April 1970, pp. 76-81.

This paper is written from the point of view of the airfield meteorological equipment designer. It considers the new problems associated with the just-introduced wide-body jet aircraft and assesses their probable impact on airfield meteorological equipment performance and siting requirements. Jet exhaust wakes caused by taxiing and takeoff operations are treated in detail. Wing tip vortex characteristics are discussed, citing the findings of other authors.

Carten, Jr., A. S.,
"AIRCRAFT WAKE TURBULENCE - AN INTERESTING PHENOMENON TURNED KILLER,"
Air Univ. Review, Vol. XXII, No. 5, July/Aug. 1971, pp. 12-24.

The Aircraft Wake Turbulence problem is described in operational terms and is compared with another environmentally oriented problem: Clear Air Turbulence. The history of the investigation of wing tip vortices is traced from the earliest days of manned flight to the present time of crisis. A simplified theoretical explanation (based on the work of Spreiter and Sacks) is given for the phenomenon. Various possible methods of alleviation and problem control are described along with current on-going research efforts by various concerned groups.

Carten, Jr., A. S.,
"THE AIRCRAFT WAKE TURBULENCE PROBLEM,"
AIAA Student Journal, Vol. 10, No. 4, Dec. 1972, pp. 8-13.

This paper reports on the potential hazard resulting from the wake vortices generated by the heavy aircraft. An account is given of the conventional theory used to describe the vortex.

Chadwick, R. E., Moran, K. P., Campbell, W. C., Earnshaw, P. B. and Detman, T. R.,
DEVELOPMENT OF A CLEAR AIR RADAR TO DETECT METEOROLOGICAL HAZARDS AT AIRPORTS,"
AFGL TR-81-0268, Sept. 1981,
NOAA Wave Propagation Lab., Boulder, CO.

To be useful in detecting meteorological hazards such as low-level wind shear near airports, a radar must be able to: (1) detect backscatter from both clear air and rain; (2) operate at short ranges and low elevation angles; and (3) measure Doppler frequencies caused by air motion. The results of testing such a radar at airports are presented. Special emphasis is placed on the problems of low elevation angle operation and clutter suppression. The importance of proper siting is pointed out. In addition, it is demonstrated that the radar can readily detect the turbulent wakes of large jet aircraft.

Champniss, G. A.,
"AIR TRAFFIC MANAGEMENT - THE IMPACT AT THE AIRPORT,"
Proceedings of Spring Convention, Royal Aeronautical Society, London, England, May 1982.

The introduction of wide bodied aircraft has led to the adoption of increased separation standards in order to minimize the effects of wake turbulence. This use of increased separation standards, while of relatively minor significance when the total number of movements by wide bodied aircraft is low, results in a significant reduction in the sustainable capacity of a dedicated landing runway as the proportion of such aircraft increases. The reduction of separation standards currently in use without adverse effects on safety may be achieved by means of more efficient airport surface movement guidance and control, which optimizes the capacity of a given runway. The aircraft whose impact will be most strongly felt are the 757, 767, and 737, all new generation airliners capable of Category III visibility conditions operations which will require airport facilities to accommodate their expanded capabilities.

Chevalier, H. L.,
"FLIGHT TEST STUDIES OF THE FORMATION AND DISSIPATION OF TRAILING VORTICES,"
J. Aircraft, Vol. 10, No. 1, Jan. 1973, pp. 14-18.

A flight test program has been conducted to measure experimentally parameters which describe the characteristics of vortex behavior and their instability. Three basic atmospheric flight conditions were investigated: steady level flight in calm air, steady level flight in light gusting air and light winds, and unsteady flight produced by control surface oscillations in calm air. A DeHavilland Beaver DHC-2 airplane and a Beechcraft T-34B airplane were used in the investigation. Smoke grenades were located near the wing tips of each airplane so that the vortices could be seeded with smoke and thus made visible. This made it possible to photograph the vortices and make measurements from the photographs obtained. The experimental results show wavelengths of vortex instabilities, dissipation time of trailing vortices, effects of atmospheric current or gust, and the effect of control surface oscillation. These results provide additional experimental verification of the existence of vortex wake instability predicated by theory and show that small oscillations in pitch at a critical frequency accelerate the dissipation of high-intensity vortices.

Chigier, N. A.,
"EXPERIMENTAL STUDIES OF TURBULENT AIRCRAFT WAKES,"
Israel J. of Technology, Vol. 11, No. 6, Dec. 1973, pp. 367-372.

A review of wind tunnel test data obtained for tip vortex studies on a square-tipped rectangular wing. The results include wing surface pressure distributions, three-dimensional velocity components in the wake, and principal vortex characteristics such as peak tangential velocity and core size distribution. The wind tunnel measurements are compared with flight test data. These comparisons show that the magnitudes of circumferential velocities, normalized by flight speed and lift coefficient, as well as the vortex core radius, normalized by wing span, are in close agreement. The data obtained make possible the calculation of turbulence stress distributions and the formulation of models for the prediction of down stream flow field.

Chigier, N. A.,
"VELOCITY MEASUREMENT IN VORTEX FLOWS,"
<u>Flow: Its Measurement and Control in Science and Industry,</u>
Vol. 1, Part 1, edited by R. B. Dowdell, Instrument Society of America, 1974, pp. 399-408.

Measurements have been made in swirling circular and annular free jets using five hole pressure probes and a disk static pressure probe for determination of mean flow and static pressure fields. A 3-wire, hot wire anemometer probe has been used for measuring velocity components in wing tip trailing vortices. Turbulence measurements in recirculation zones of a swirl generator have been made by placing hot wire anemometers in six different orientations, plus or minus 45 degrees to each of the coordinate axes. Details of measuring systems and instruments are discussed and examples of measurements in vortex flows are presented.

Chigier, N. A.,
"MEASUREMENT OF VORTEX BREAKDOWN OVER A DELTA WING USING A LASER ANEMOMETER,"
NEAR TR-62, Jan. 1974,
Nielsen Eng. and Research Inc., Mountain View, CA.

A preliminary experimental study has been made on vortex breakdown over and in the wake of a slender delta wing at low speed. The investigation was made in the NASA/Ames 7- by 10-Foot Wind Tunnel on a slender sharp-edged delta wing with aspect ratio of 1.56 and sweep angle of 70°. Smoke visualization showed the presence and structure of the vortex core and feeding sheet over the wing surface. Vortex breakdown occurred in the wake of the wing at an angle of attack of 20°. Photographs show a clear distinction between the core structure in the pre- and post-breakdown conditions. As the angle of attack was increased further to 35°, the location of vortex breakdown moved upstream over the wing surface. Secondary vortices could be clearly distinguished, formed at the trailing edge near the wing tips. Wind-tunnel balance measurements of lift and drag forces show reduction in lift and drag coefficients due to vortex breakdown for angles of attack above 20°. The NASA/Ames two-color laser Doppler velocimeter was used to measure streamwise and circumferential velocity distributions through the vortex centers at various planes over the wing surface and at a distance of half-chord downstream of the wing trailing edge.

Chigier, N. A.,
"VORTEXES IN AIRCRAFT WAKES,"
Scientific American, Vol. 230, No. 3, March 1974, pp. 76-83.

The advent of the jumbo jets has turned the well-known aerodynamic phenomenon of trailing-vortex air turbulence into a potentially serious hazard to smaller following aircraft. The three main objectives of current research programs are reviewed: (1) ascertaining the nature, strength and persistence of the vortexes for various kinds of aircraft; (2) developing a practical means of reducing the hazard on existing aircraft by artificially inducing the vortexes to break up; and (3) setting up monitoring and control systems at airports in order to prevent aircraft from entering the vortex-wake turbulence of larger aircraft.

Chigier, N. A. and Corsiglia, V. R.,
"TIP VORTICES-VELOCITY DISTRIBUTIONS,"
NASA TM X-62887, Sept. 1971,
NASA Ames Research Center, Moffett Field, CA.

Detailed measurements of velocity distributions have been made in vortices generated at the tip of a square-tip, 18-inch-chord, 48-inch semispan blade mounted in the NASA-Ames 7-by 10-foot wind tunnel. Time-mean-average velocity components were measured using a triple-sensor hot wire probe operated by three separate anemometers. The dimensions of the vortex increase with distance downstream over the blade surface, and at X/C=4 the vortex core radius is 1.7% of the span.

Chigier, N. A. and Corsiglia, V. R.,
"WIND TUNNEL TEST DATA FOR WING TRAILING VORTEX FLOW SURVEY,"
NASA TM X-62148, May 1972,
NASA Ames Research Center, Moffett Field, CA.

Data are presented on velocity measurements made with hot wire anemometers in the wake of a model of the CV-990 aircraft and a rectangular wing in the NASA-Ames 7- by 10-foot wind tunnel. Variables included angle of attack, tunnel speed and axial distance up to 12 chord lengths downstream from the wing trailing edge. Effects of deflecting trailing edge flaps and small spoiler panels are shown.

Chigier, N. A. and Corsiglia, V. R.,
"WIND TUNNEL STUDIES OF WING WAKE TURBULENCE,"
J. Aircraft, Vol. 9, No. 12, Dec. 1972, pp. 820-825.

Velocity measurements have been made in the wake of wings in the Ames 7- by 10-foot Wind Tunnel. Distributions of velocity components were measured with a three-wire anemometer up to 12 chord lengths downstream of a CV-990 aircraft model and a rectangular wing. Results show that increasing the drag increases the vortex core radius, reduces the maximum tangential velocities and increases the magnitude of axial velocity defects.

Chorin, A. J. and Bernard, P. S.,
"DISCRETIZATION OF A VORTEX SHEET WITH AN EXAMPLE OF ROLL UP,"
FM-72-5, Nov. 1972,
Univ. of California, Berkeley, CA.

The point vortex approximation of a vortex sheet in two space dimensions is examined and a remedy for some of its shortcomings is suggested. The approximation is then applied to the study of the roll-up of a vortex sheet induced by an elliptically loaded wing.

Christiansen, J. P.,
"VORTEX: A 2-DIMENSIONAL HYDRODYNAMICS SIMULATION CODE,"
CLM-R-106, July 1970,
United Kingdom Atomic Energy Authority, Culham, England.

Program VORTEX is a computer code which simulates the behavior of an incompressible, inviscid homogeneous fluid in two dimensions by following the motion of a large number of point vortices. The theory behind the program and the program itself are described.

Ciffone, D. L.,
"CORRELATION FOR ESTIMATING VORTEX ROTATIONAL VELOCITY DOWNSTREAM DEPENDENCE,"
J. Aircraft, Vol. 11, No. 11, Nov. 1974, pp. 716-717.

The wake velocity profile was examined up to 200 span lengths in a water tank, and comparisons were made of measured and predicted maximum tangential velocities downstream. Two characteristic flow regions were identified. First, a "plateau" region with little if any change in maximum tangential velocity downstream as great as 100 span lengths. This is followed by a decay region in which the maximum tangential velocity decreases with downstream distance at a rate nominally proportional to the inverse one-half power.

Ciffone, D. L.,
"VORTEX INTERACTIONS IN MULTIPLE VORTEX WAKES BEHIND AIRCRAFT,"
J. Aircraft, Vol. 14, No. 5, May 1977, pp. 440-446.

A flow visualization technique has been developed that allows the nature of lift-generated wakes behind aircraft models to be investigated. The technique is applicable to models being towed underwater in a ship model basin. Several different configurations of a 0.61-m (2-ft) span model of a Boeing 747-

type transport aircraft were tested to allow observation of typical vortex interactions and merging in multiple vortex wakes. The vortices were identified by emitting tracer dyes from selected locations on the model. Their trajectories were obtained from photographs of the wake. Wingspan loading and model attitude were found to effect both vortex motions within the wake and resulting far-field wake velocity. Landing-gear deployment caused a far-field reformation of vorticity behind a model configuration which dissipated concentrated vorticity in the near-field wake. Circulation from the wing always caused a downward movement of the horizontal tail vortices, which merged with wing vortices. A modified landing configuration was developed that appeared to significantly alleviate the concentrated wake vorticity associated with the current landing configuration.

Ciffone, D. L.,
"MEASUREMENTS OF AIRCRAFT WAKE ALLEVIATION AND GROUND PLANE EFFECTS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 173-182.

In support of the NASA wake vortex alleviation program, vortex trajectories and velocity profiles were measured in lift-generated wakes. The wakes were generated by towing 2-ft span models of B-747 and DC-10-30 aircraft under water in a ship model basin. The effects of flaps, spoilers, and ground plane on these wakes were investigated. A laser velocimeter was used to measure vertical (tangential) velocity profiles through primary vortices from 5- to 100-wingspan lengths behind the generating model. A 45° deflection of the two outboard flight spoilers on the B-747 model in the landing configuration resulted in a 40% reduction in wake maximum tangential velocity, in altered velocity profiles, and in erratic vortex trajectories. Similar reductions in maximum tangential velocity were obtained for this model when the outboard flaps were retracted. Presence of a ground plane used to simulate full-scale distances above the ground of 125 ft and 70 ft modified the vortex trajectories but did not appreciably change vortex interactions and merging. However, at 70 ft above the ground plane, the alleviation appeared to be enhanced due to vortex viscous interactions with the ground plane.

Ciffone, D. L. and Lonzo, C.,
"FLOW VISUALIZATION OF VORTEX INTERACTIONS IN MULTIPLE VORTEX WAKES BEHIND AIRCRAFT,"
NASA TM X-62459, June 1975,
NASA Ames Research Center, Moffett Field, CA.

A flow visualization technique has been developed which allows the nature of lift-generated wakes behind aircraft models to be investigated. The technique has been applied to models being towed underwater in a ship model basin. Seven different configurations of a small-scale model of a 747 transport aircraft were used to allow observation of typical vortex interactions and merging in multiple vortex wakes. It was established that the motion of the wake vortices is often sensitive to small changes in either wing span loading or model attitude. Landing gear deployment was found to cause a far-field reformation of vorticity behind a model configuration which dissipated concentrated vorticity in the near-field wake. Alleviation of wake vorticity is achievable by configuring the wing span loading to cause the wake vortices to move in paths that result in their interactions and merging.

Ciffone, D. L., Orloff, K. L.,
"AXIAL FLOW MEASUREMENTS IN TRAILING VORTICES,"
AIAA Journal, Vol. 12, No. 8, Aug. 1974, pp. 1154-1155.

A scanning laser Doppler velocimeter was used to measure the axial velocity defect in the cores of trailing vortices behind a lifting airfoil of rectangular planform. Data were obtained at several different angles of attack and downstream distances ranging from 30 to 10^3 chord lengths.

Ciffone, D. L. and Orloff, K. L.,
"FAR-FIELD WAKE-VORTEX CHARACTERISTICS OF WINGS,"
J. Aircraft, Vol. 12, No. 5, May 1975, pp. 464-470.

Velocity measurements have been made in the wake of wings that were being towed underwater. As the wake aged, measurements of the tangential and axial velocity profiles were made with a two-dimensional scanning laser velocimeter at downstream distances of 5 to 200 span lengths behind wings with different span loadings. The results identify two characteristic flow regions for the dependence of vortex maximum tangential velocity on downstream distance. The first, a region with little, if any change in maximum tangential velocity, extends from wake rollup to downstream distances as great as 100 span

lengths, depending on span loading and angle of attack. This is followed by a decay region in which the maximum tangential velocity decreases with downstream distance at rates nominally proportional to the inverse one-half power. It is shown that tailoring the wingspan loading by either planform or flap deflection can reduce the maximum vortex tangential velocity by a factor of 2 and thus broaden the vortex core. Vortex mutual interactions and instabilities were introduced by alternate up-down flap deflections, delaying vortex rollup to downstream distance of 45 spans.

Ciffone, D. L. and Orloff, K. L.,
"APPLICATION OF LASER VELOCIMETRY TO AIRCRAFT WAKE-VORTEX MEASUREMENTS,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, Washington, 1977, pp. 157-192.

The theory and use of a laser velocimeter that makes simultaneous measurements of vertical and longitudinal velocities while rapidly scanning a flow field laterally are described, and its direct application to trailing wake-vortex research is discussed. Pertinent measurements of aircraft wake-vortex velocity distributions obtained in a wind tunnel and water towing tank are presented. The utility of the velocimeter to quantitatively assess differences in wake velocity distributions due to wake dissipating devices and span loading changes on the wake-generating model is also demonstrated.

Ciffone, D. L., Orloff, K. L. and Grant, G. R.,
"LASER DOPPLER VELOCIMETER INVESTIGATION OF TRAILING VORTICES BEHIND A SEMI-SPAN SWEPT WING IN A LANDING CONFIGURATION,"
NASA TM-X-62294, Aug. 1973,
NASA Ames Research Center, Moffett Field, CA.

Measured axial and tangential velocity profiles in the near wake vortices of a semi-span model of the Convair 990 wing in the NASA-Ames 7- by 10-foot wind tunnel are presented. A scanning laser Doppler velocimeter was used to obtain data at two different downstream stations (0.49 and 1.25 wing spans) at various angles of attack and configurations from wing alone to wing plus nacelles, anti-shock bodies, and flaps deflected 27 deg (landing configuration). It is shown that the velocity distributions within the wake are quite sensitive to span loading. Specifically, it is illustrated that an aircraft flying at given lift coefficient (C_L), can substantially reduce its trailing vortex upset potential by deploying its flaps and altering its flight attitude to maintain the same C_L. This might be taken into consideration along with performance and noise considerations in the selection of aircraft approach lift over drag.

Ciffone, D. L. and Pedley, B.,
"MEASURED WAKE-VORTEX CHARACTERISTICS OF AIRCRAFT IN GROUND EFFECT,"
J. Aircraft, Vol. 16, No. 2, Feb. 1979, pp. 102-109.

In support of the NASA wake vortex alleviation program, measurements were made of the influences of a ground plane on vortex trajectories and velocity profiles within lift-generated wakes. The wakes were generated by towing 0.61-m span models of a B-747 and DC-10-30 under water in a ship model basin. The models were configured with landing flaps and flight spoilers to investigate the wake characteristics of these aircraft in ground effect at simulated full-scale distances of 19-116 m above the ground. The ground plane caused modifications in the vortex trajectories but did not alter vortex interactions and merging patterns in these multiple vortex wakes. Some distortions in vortex vertical (tangential) velocity profiles were recorded as a result of vortex lateral motions and vortex interactions with the viscous boundary layer on the ground plane; however, maximum tangential velocities remained unchanged.

Clark, M.,
"WAKE TURBULENCE - GONE WITH THE WIND,"
J. Air Traffic Control, Vol. 19, Oct.-Dec. 1977, pp. 10-12.

In May 1976 a Vortex Advisory System (VAS) was installed at Chicago's O'Hare airport. The VAS is based on wind measurements around the airport which make it possible to predict movement and behavior of aircraft generated wake vortices. The VAS installation includes a network of meteorological towers sited near the middle marker locations. The wind data from the anemometers on the towers are transmitted to a central computer. The computer transmits through a digital display to the controller advising whether he can use reduced (3 n mi) separations in place of standard separation between arriving aircraft. NASA has been engaged in an extensive research program for the aerodynamic alleviation of wake vortices. Aerodynamic alleviation is a general term describing modifications to the aircraft or airfoil to alter the vortex structure and thereby minimize the adverse effects of the wake.

Clements, R. R. and Maull, D. J.,
"THE ROLLING UP OF A TRAILING VORTEX SHEET,"
Aeronautical Journal, Vol. 77, No. 745, Jan. 1973, pp. 46-51.

The investigation is oriented towards finding circulation distributions which alter the rolling up characteristics of the sheet in such a way as to retard the rolling up and decrease the vorticity finally contained in such rolled up vortex cores. Because the aircraft concerned have, typically, aspect ratios of about 7 and lift coefficients of about 1.0, the Westwater model was used.

Condit, P. M.,
"RESULTS OF THE BOEING COMPANY WAKE TURBULENCE TEST PROGRAM,"
Compilation of Working Papers Concerning Wake Turbulence Tests, FAA, Washington, April 1970.

The results of a flight test investigation of vortex wake turbulence generated by large jet transport aircraft are presented. Test results showing the dynamic response of aircraft which were flown in the wakes of large jet transports, are discussed. Experimental results are compared to theoretical predictions. Test program results are applied to the problem of air traffic control and specific recommendations are presented for air traffic separations.

Condit, P. M.,
"SUMMARY OF PANEL STATEMENT REGARDING WAKE TURBULENCE,"
FAA Symposium on Turbulence, FAA, Washington, March 1971, p. 20.

The Boeing Wake Turbulence Test Program is presented; the goal was to provide a comparison between the 747 wake and the wake of a smaller jet transport and to provide insight into the factors which are important when defining the hazards associated with wake turbulence. A B-737 and a CV-990 were flown behind a B-747 and a B-707. Little differences in the responses of the encountering aircraft were observed. It was concluded that: (1) the relative size of the generating and encountering airplanes is important and (2) the span ratio is the best parameter for defining "hazard".

Condit, P. M. and Tracy, P. W.,
"RESULTS OF THE BOEING COMPANY WAKE TURBULENCE TEST PROGRAM,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 473-508.

The Boeing Company initiated a study of large jet aircraft wake turbulence in mid 1969. The Boeing flight test program was undertaken to evaluate the behavior of trailing vortices and to obtain a direct comparison between the turbulent wakes of the 747 and a 707-320C. A fully instrumented Boeing 737-100 was used as the primary wake probing aircraft. Additional probes were made with the Boeing owned F-86 and NASA's CV-990. It was found that the dynamic response of the chase airplanes was essentially the same when flying in the turbulent wakes of either the 747 or 707. It was observed that the wake leveled off and never descended more than 900 feet below the generating airplane. In the approach and landing tests it was found that the wake generated in ground effect does not "roll up" into strong trailing vortices.

Cone, Jr., C. D.,
"A THEORETICAL INVESTIGATION OF VORTEX-SHEET DEFORMATION BEHIND A HIGHLY LOADED WING AND ITS EFFECT ON LIFT,"
NASA TN-657, April 1961,
NASA Langley Research Center, Langley Field, VA.

The induced drag polar is developed for wings capable of attaining extremely high loadings while possessing an elliptical distribution of circulation. This development is accomplished through a theoretical investigation of the vortex-wake deformation process and the deduction of the airfoil forces from the impulse and kinetic energy contents of the ultimate wake form. The investigation shows that the induced velocities of the wake limit the maximum lift coefficient to a value of 1.94 times the wing aspect ratio, for aspect ratios equal to or less than 6.5, and that the section properties of the airfoil limit the lift coefficient to 12.6 for aspect ratios greater than 6.5. Relations are developed for the rate of deformation of the vortex wake. It is also shown that linear wing theory is applicable up to lift coefficients equal to 1.1 times the aspect ratio.

Connor, A. B. and O'Bryan, T. C.,
"A BRIEF EVALUATION OF HELICOPTER WAKE AS A POTENTIAL OPERATIONAL HAZARD TO AIRCRAFT,"
NASA TN D-1227, March 1962,
NASA Langley Research Center, Langley AFB, VA.

Flight tests with a single-rotor helicopter and a fixed-wing airplane are reported which show that helicopter wake presents a potential hazard to aircraft operating near the wake, particularly in regard to airport traffic situations. Operating practices suggested for reducing this hazard potential include reminding pilots of aircraft following a helicopter to remain above the helicopter flight path and to extend the separation interval between aircraft. An exact time interval was not determined, but a separation estimated to be about 1 minute appears to be a reasonable time with most of the present generation helicopters.

Conway, R., Matuck, G. N., Roe, J. M., Taylor, J. and Turner, A.,
"VORTEX INFORMATION DISPLAY SYSTEM PROGRAM DESCRIPTION MANUAL - DATA ACQUISITION FROM LASER DOPPLER VELOCIMETERS AND REAL TIME OPERATION,"
NASA CR-120703, Feb. 1975,
M&S Computing, Huntsville, AL.

A vortex information display system is described which provides flexible control through system user interaction for collecting wing-tip-trailing vortex data, processing this data in real time, displaying the processed data, storing raw data on magnetic tape, and post processing the raw data. The data is received from two asynchronous laser Doppler velocimeters and includes position, velocity, and intensity information. Both raw data and processing can be continually upgraded during flyby testing to improve vortex behavior studies.

Corsiglia, V. R. and Dunham, Jr., R. E.,
"AIRCRAFT WAKE-VORTEX MINIMIZATION BY USE OF FLAPS,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, 1977, pp. 305-338.

A survey of research on the alleviation of the trailing vortex hazard by altering span loading with flaps on the generator airplane. Flap configurations of the generator that shed multiple vortices were found to have wakes that dispersed by vortex merging and sinusoidal instability. Reductions of approximately 50% in both the wake rolling moment imposed on a following aircraft and the aircraft separation requirement were achieved in the ground and flight test experiments by

deflecting the trailing edge flaps more inboard than outboard. Significantly, this configuration did not increase the drag or vibration on the generating aircraft compared to the conventional landing configuration. Ground based results of rolling moment measurement and flow visualization are shown, using a water tow facility, an air tow facility, and a wind tunnel. Flight test results are shown, using a full scale B-747 airplane. General agreement was found among the results of the various ground based facilities and the flight tests.

Corsiglia, V. R., Iversen, J. D. and Orloff, K. L.,
"LASER-VELOCIMETER SURVEYS OF MERGING VORTICES IN A WIND TUNNEL,"
J. Aircraft, Vol. 15, No. 11, Nov. 1978, pp. 762-768.

The merger of two vortices was studied with a laser velocimeter designed to measure the two cross-stream components of velocity. Measurements were made at several downstream distances in the vortex wake shed by two semispan wings mounted on the wind tunnel walls. The velocity data provided well-defined contours of cross-flow velocity, stream function, and vorticity. Downstream of the merger point the vorticity was shown to be independent of the downstream distance for small radii. Upstream of the merger point a multicell vorticity pattern was shown.

Corsiglia, V. R., Jacobsen, R. A. and Chigier, N. A.,
"AN EXPERIMENTAL INVESTIGATION OF TRAILING VORTICES BEHIND A WING WITH A VORTEX DISSIPATOR,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 229-242.

An experimental study was done on a rectangular wing in the NASA Ames 7x10-foot Wind Tunnel. Flow visualization studies were made using a tuft grid and smoke. Studies showed that a small vertical panel, termed a vortex dissipater, mounted on the wing upper surface near the wing tip caused a modification of the vortex. Both the smoke and tuft grid visualization studies indicated that the dissipater caused a significant reduction in the maximum tangential velocities in the trailing vortex. Additional studies using a hot wire anemometer showed significant reductions in the magnitude of the tangential velocities, increases in the cross-sectional dimensions of the core of the dissipated vortex and changes in the turbulence structure. Limited flight tests with a dissipator fitted to a CV-990 wing tip and using a Learjet as a probe indicated that the rolling acceleration and the degree of roll control required was less in the modified vortex than in the unmodified vortex.

Corsiglia, V. R. and Orloff, K. L.,
"SCANNING LASER-VELOCIMETER SURVEYS AND ANALYSIS OF MULTIPLE VORTEX WAKES OF AN AIRCRAFT,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 114-123.

A laser velocimeter capable of rapidly scanning a flow field while simultaneously sensing two components of the velocity was used to measure the vertical and streamwise velocity structure 1.5 spans downstream in the wake of a model of a large subsonic transport (B-747). This flow field was modeled by a superposition of axisymmetric vortices with finite cores. The theoretical model was found to agree with the measured velocities everywhere except where two vortices were in close proximity. Vortex strengths derived from the span loading on the wing as predicted by vortex-lattice theory also agree with the present measurements. It was, therefore, concluded that the axisymmetric vortex model used is a useful tool for analytically investigating the vortex wakes of aircraft.

Corsiglia, V. R. and Rossow, V. J.,
"WIND-TUNNEL INVESTIGATION OF THE EFFECT OF POROUS SPOILERS ON THE WAKE OF A SUBSONIC TRANSPORT MODEL,"
NASA TM-X-73091, Jan. 1976,
NASA Ames Research Center, Moffett Field, CA.

Tests were conducted in the Ames Research Center 40- by 80-Foot Wind Tunnel to determine how porosity of wing spoilers on a B-747 airplane would affect the rolling moments imposed on an aircraft following in the wake. It was found that spoilers with 40% porosity and hole diameter to thickness ratio of 1.1 were just as effective in reducing the rolling moment imposed on the follower as solid spoilers, for the case of two spoilers per wing panel (6.4% semispan each) with a following model whose span was 20% of the span of the generator. When a larger following model was tested, whose span was 50% of that of the generator, the effectiveness of the two spoilers per wing was substantially reduced.

Corsiglia, V. R., Rossow, V. J. and Ciffone, D. L.,
"EXPERIMENTAL STUDIES OF THE EFFECT OF SPAN LOADING ON AIRCRAFT WAKES,"
AIAA Paper No. 75-885,
Hartford, CT, 1975.

Experiments were conducted in the Ames 40- by 80 foot Wind Tunnel and a water tow facility using a model of a jumbo jet aircraft to determine whether predicted reductions in vortex wake intensity could be achieved by a redistribution of span loading. Rolling moments were measured on two following aircraft models, and photographs were taken of the vortex wake structure. The measurements showed that the overturning moment on an encountering aircraft is reduced substantially by shedding multiple vortices which destructively interact.

Corsiglia, V. R. and Rossow, V. J. and Ciffone, D. L.,
"EXPERIMENTAL STUDY OF THE EFFECT OF SPAN LOADING ON AIRCRAFT WAKES,"
J. Aircraft, Vol. 13, No. 12, Dec. 1976, pp. 968-973.

Measurements of the rolling moment induced on a wing trailing in the wake 13.6 spans behind a subsonic transport model were made in the NASA-Ames 40-by 80-Foot Wind Tunnel. It was found that the rolling moment induced on the trailing wing was reduced substantially by reshaping the span loading on the generating model. This was accomplished by retracting the outboard trailing edge flaps. It was concluded from wind tunnel and water tow facility flow visualization studies that this flap arrangement redistributes the vorticity shed by the wing along the span to form three vortex pairs that interact to disperse the wake.

Corsiglia, V. R., Schwind, R. G. and Chigier, N. A.,
"RAPID SCANNING, THREE-DIMENSIONAL HOT-WIRE ANEMOMETER SURVEYS OF WING-TIP VORTICES,"
J. Aircraft, Vol. 10, No. 12, Dec. 1973, pp. 752-757.

A rapid-rotation arm traversing mechanism with a three-wire, hot-wire anemometer at the tip was developed for surveying trailing vortices whose paths were distorted over long distances by wind-tunnel turbulence. Measurements were obtained behind two geometrically similar rectangular wings up to 31 span lengths in the Ames 40- by 80-foot wind tunnel. Peak tangential velocities normalized by free-stream velocity and lift coefficient decreased from 0.8 at the trailing edge to 0.6 at 31 span lengths downstream while the circulation within the core remained constant. Measured tangential velocity distributions had the same functional form as that determined by Hoffmann and Joubert.

Costen, R. C.,
"AN EQUATION FOR VORTEX MOTION INCLUDING EFFECTS OF BUOYANCY AND SOURCES WITH APPLICATIONS TO TORNADOES,"
NASA TN D-5964, Oct. 1970,
NASA Langley Research Center, Hampton, VA.

A new equation is derived for the motion of vorticity in a general fluid, including the effects of viscosity, compressibility, nonhomogeneity, and nonconservative forces. The equation holds, in particular, for vortices which may not move with the fluid. A linearized form of the equation is applied to tornado cyclones.

Costen, R. C.,
"NONLINEAR EFFECTS OF THE DRIFT OF BUOYANT VORTICES,"
AIAA Paper NO. 71-604,
Palo Alto, CA, 1971.

A new equation is formulated for the motion of buoyant free vortices in an inviscid fluid. Such vortices have fluid in the core of lower density than the surrounding fluid. A criterion is given for such vortices to persist. A method is outlined for obtaining approximate solutions of the equation of motion, and results are presented for a number of cases. A horizontal buoyant vortex with positive circulation in an unbounded fluid subject to gravity drifts horizontally toward the left when viewed along its axis. Aircraft trailing vortices, if made buoyant by injection of hot gas into the vortex cores, are shown to approach each other as they descend, unless they are near the ground in which case the ground effect dominates and makes them separate. Twin buoyant vortices of like sense revolve about each other with a slower revolution rate than nonbuoyant twin vortices. Formulas are presented for calculating each of these effects.

Costen, R. C.,
"DRIFT OF BUOYANT WING-TIP VORTICES,"
J. Aircraft, Vol. 9, No. 6, June 1972, pp. 406-412.

An exact solution is derived for the trochoidal motion of a single horizontal buoyant vortex drifting under gravity, and a criterion is given for such vortices to persist. Approximate solutions are obtained for the two-dimensional drift of buoyant wing tip vortices descending in a neutrally stable atmosphere where the buoyancy is achieved by injecting hot gas from the engine exhaust or auxiliary burners into the vortex cores. The vortices are found to approach each other as they descend. At low altitudes the effect may accelerate their breakup and thus reduce the period of time when wake from a large aircraft is dangerous to other aircraft. At low altitudes the ground effect may dominate and cause buoyant wing-tip vortices to separate instead of approach each other. A weakly stable atmosphere should increase the buoyancy and the convergence rate of descending wing-tip vortices, and a method is presented for calculating the combined effect of core heating and atmospheric stability.

Costen, R. C., Davidson, R. E. and Rogers, G. T.,
"WIND-TUNNEL TESTS AND COMPUTER SIMULATIONS OF BUOYANT WING-TIP VORTICES,"
Proceedings Sixth Conf. on Aerospace and Aeronautical Meteorology, American Meteorology Society, El Paso, 1974, pp. 378-386.

Wind-tunnel tests have demonstrated that buoyant fluid ejected downstream at a wing tip or flap tip will enter the core of the trailing vortex and cause it to drift horizontally in accordance with the theory for buoyant-core vortices. These tests have also confirmed the results of previous experimenters that sufficiently high injection rates cause the vortices to undergo transition from small laminar cores to diffuse turbulent cores. Also, the thrust of the injection jets for this transition was shown to be less than the induced drag of the wings tested. These results indicated that placing the propulsion engines of a jet aircraft at the wing tips and flap tips would aid in alleviating the aircraft wake (1) by causing the vortices from the two wings to drift toward each other as they descend and thus break up more quickly through the Crow or burst instability, and (2) by making the vortex cores more diffuse and turbulent. Computer simulations showed that buoyant wing-tip vortices in near proximity continue to be driven together despite elongation of the cores parallel to the symmetry plane. They also showed that engine placement is critical if jet exhaust is to drive the vortices together. Random engine placement and buoyancy obtained by descent of the wake in a stable atmosphere will, in general, not promote this drift because the buoyant fluid, while wrapping around the vortices, does not always converge on their cores.

Costen, R. C., Davidson, R. E. and Rogers, G. T.,
"WIND-TUNNEL TESTS AND COMPUTER SIMULATIONS OF BUOYANT WING-TIP VORTICES,"
J. Aircraft, Vol. 13, No. 7, July 1976, pp. 495-499.

Wind-tunnel tests have demonstrated that buoyant fluid ejected downstream at a wing tip or flap tip will enter the core of the trailing vortex and cause it to drift horizontally in accordance with the theory for buoyant-core vortices. This result indicates that locating the propulsion engines of a jet aircraft at the wing-tips and/or flaptips would cause the vortices from the two wings to drift toward each other as they descend, and thus break up more quickly through the Crow or burst instability. Two-dimensional computer simulations showed that engine placement is critical because distributed buoyancy resulting from general engine placement or from descent of the wake in a stable atmosphere does not promote this drift.

Credeur, L.,
"BASIC ANALYSIS OF TERMINAL OPERATION BENEFITS RESULTING FROM REDUCED VORTEX SEPARATION MINIMA,"
NASA TM-78624, Oct. 1977,
NASA Langley Research Center, Hampton, VA.

The impact of reducing the wake vortex minimum separation required behind heavy jets on terminal area operation rate was analyzed. The effect on arrival saturation and steady state average delay was determined for various percentages mix of heavy and large jet traffic samples operating under various precision of interarrival spacing. Benefits increase with percentage of heavy aircraft and with precision of control. These results demonstrate the payoff possible from research to reduce the severity of the trailing vortex by aerodynamic means.

Croom, D. R.,
"LOW-SPEED WIND-TUNNEL INVESTIGATION OF FORWARD-LOCATED SPOILERS AND TRAILING SPLINES AS TRAILING-VORTEX HAZARD-ALLEVIATION DEVICES ON AN ASPECT-RATIO-8 WING MODEL,"
NASA TM X-3166, Feb. 1975,
NASA Langley Research Center, Langley Station, VA.

An investigation was made in the Langley V/STOL tunnel in order to determine, by the trailing-wing sensor technique, the effectiveness of either a forward-mounted spoiler or a tip-mounted spline as trailing-vortex attenuation devices on an upswept aspect-ratio-8 wing model. The trailing-wing rolling-moment data taken in the tunnel diffuser section show good agreement with the data taken in the tunnel test section. This agreement indicates that reasonable results may be obtained in the Langley V/STOL tunnel in experimental investigations of the trailing-vortex hazard at relatively great distances behind aircraft models.

Croom, D. R.,
"THE DEVELOPMENT AND USE OF SPOILERS AS VORTEX ATTENUATORS,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, Washington, 1977, pp. 339-368.

This paper presents the results of groundbased and flight investigations performed at NASA to develop spoilers as trailing vortex alleviation devices. Based on the results obtained in these investigations, it was found that the induced rolling moment on a trailing model can be reduced by spoilers located near the midsemispan of a vortex-generating wing. Substantial reductions in induced rolling moment occur when the spoiler vortex attenuator is located well forward on both unswept and swept wing models. In addition, it was found that existing flight spoilers on the jumbo-jet transport aircraft can be effective as trailing vortex attenuators.

Croom, D. R.,
"DEVELOPMENT OF SPOILERS AS TRAILING-VORTEX HAZARD ALLEVIATION DEVICES,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 217-228.

This paper presents the results of groundbased and flight investigations that have been performed at NASA for the purpose of development of spoilers as trailing-vortex hazard alleviation devices. Based on the results obtained in these investigations, it was found that the induced rolling moment on a trailing model can be reduced by spoilers located near the midsemispan of a vortex-generating wing. Substantial reductions in induced rolling moment occur when the spoiler vortex attenuator is located well forward on both unswept and swept wing models. In addition, it was found by groundbased model tests and verified by full-scale flight tests that the existing flight spoilers on the B-747 aircraft are effective as trailing vortex attenuators. Based on the results of wind-tunnel investigations of the DC-10-30 and L-1011 airplane models, the existing flight spoilers on both the DC-10-30 and L-1011 airplanes may also be effective trailing vortex attenuators.

Croom, D. R.,
"EVALUATION OF FLIGHT SPOILERS FOR VORTEX ALLEVIATION,"
J. Aircraft, Vol. 14, No. 8, Aug. 1977, pp. 823-825.

The strong vortex wakes generated by large transport aircraft are a potential hazard to smaller aircraft, and so NASA is involved in a program of model tests, flight tests, and theoretical studies to determine the feasibility of reducing this hazard by aerodynamic means. This note summarizes the wind tunnel and full-scale flight investigations of the flight spoilers that exist on the wide-bodied transport jet aircraft when used as trailing vortex hazard alleviation devices. Existing flight spoilers on the B-747 airplane were found to be effective as trailing vortex attenuators.

Croom, D. R.,
"LOW-SPEED WIND-TUNNEL PARAMETRIC INVESTIGATION OF FLIGHT SPOILERS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON A TRANSPORT AIRCRAFT MODEL,"
NASA TP-1419, April 1979,
NASA Langley Research Center, Hampton, VA.

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of 11 combinations of the existing flight-spoiler segments on a jumbo-jet transport aircraft model when they were deflected as trailing-vortex-alleviation devices. All 11 of the flight-spoiler configurations investigated were effective in reducing the induced rolling moment on the trailing model by as much as 18 to 67% at a distance of 7.8 wing spans behind the transport aircraft model. Essentially all of the reduction in induced rolling moment on the trailing-wing model was realized at a spoiler deflection of 45° for single-spoiler configurations, 30° for two-spoiler configurations, and 15° for both the three- and four-spoiler configurations. Of the 11 flight-spoiler configurations, the most promising configuration for trailing-vortex abatement on the jumbo-jet aircraft appears to be the three inboard flight spoilers deflected 15°. This configuration reduced induced rolling moment on the trailing-wing model by 65% and increased drag coefficient on the transport aircraft model by about 0.012 at a trim lift coefficient of 1.2.

Croom, D. R. and Dunham, Jr., R. E.,
"LOW-SPEED WIND-TUNNEL INVESTIGATION OF SPAN LOAD ALTERNATION, FORWARD-LOCATED SPOILERS, AND SPLINES AS TRAILING-VORTEX-HAZARD ALLEVIATION DEVICES ON A TRANSPORT AIRCRAFT MODEL,"
NASA TN D-8133, Dec. 1975,
NASA Langley Research Center, Hampton, VA.

An investigation was made in the Langley V/STOL tunnel to determine the effectiveness of a forward-located spoiler, a spline, and a span load alteration due to a flap configuration change as trailing-vortex-hazard alleviation methods. For the transport aircraft model in the normal approach configuration, the results indicate that either a forward-located spoiler or a spline is effective in reducing the trailing-vortex hazard. The results also indicate that large changes in span loading, due to retraction of the outboard flap, may be an effective method of reducing the trailing-vortex hazard.

Croom, D. R. and Holbrook, G. T.,
"LOW-SPEED WIND-TUNNEL INVESTIGATION OF WING FINS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON A TRANSPORT AIRPLANE MODEL,"
NASA TP-1453, June 1979,
NASA Langley Research Center, Hampton, VA.

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the trailing-vortex-alleviation effectiveness of both a one- and a two-fin configuration (semicircular with a radius of 0.043 semispan) on a jumbo-jet transport airplane model in its landing configuration. The fins were located on the upper surface of the transport model wing along the 30%-chord line. The fin configurations were effective in reducing the vortex-induced rolling moment, by amounts varying from 28 to 60%, on the trailing wing model located at a distance of 7.8 model wing spans downstream of the transport model. The flow over the fins and over the transport airplane model wing downstream of the fins was observed to be separated and turbulent. All fin configurations caused a reduction in maximum lift coefficient, a positive increment in drag coefficient, and an increment in nose-up pitching-moment coefficient on the transport airplane model.

Croom, D. R., Vogler, R. D. and Thelander, J. A.,
"LOW-SPEED WIND-TUNNEL INVESTIGATION OF FLIGHT SPOILERS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON AN EXTENDED-RANGE WIDE-BODY TRI-JET AIRPLANE MODEL,"
NASA TN D-8373, Dec. 1976,
NASA Langley Research Center, Hampton, VA.

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of various segments of the existing flight spoilers on an extended-range wide-body tri-jet transport airplane model when they were deflected as trailing-vortex-alleviation devices. On the transport model with the approach flap configuration, the four combinations of flight-spoiler segments investigated were effective in reducing the induced rolling moment on the trailing wing model by as much as 25 to 45% at downstream distances behind the model of 9.2 and 18.4 transport wing spans. On the model with the landing flap configuration, the four combinations of flight-spoiler segments investigated were effective in reducing the induced rolling moment on the trailing wing model by as much as 35 to 60% at distances behind the model of from 3.7 to 18.4 transport wing spans, 18.4 spans being the downstream limit of distances used in this investigation.

Croom, D. R., Vogler, R. D. and Williams, G. M.,
"LOW-SPEED WIND-TUNNEL INVESTIGATION OF FLIGHT SPOILERS AS TRAILING-VORTEX-ALLEVIATION DEVICES ON A MEDIUM-RANGE WIDE-BODY TRI-JET AIRPLANE MODEL,"
NASA TN D-8360, Nov. 1976,
NASA Langley Research Center, Hampton, VA.

An investigation was made in the Langley V/STOL tunnel to determine, by the trailing-wing sensor technique, the effectiveness of various segments of the existing flight spoilers on a medium-range wide-body tri-jet transport airplane model when they were deflected as trailing-vortex-alleviation devices. The four combinations of flight-spoiler segments investigated were effective in reducing the induced rolling moment on the trailing wing model by as much as 15 to 60% at distances behind the transport model of from 3.9 to 19.6 wing spans, 19.6 spans being the downstream limit of distances used in this investigation. Essentially all of the reduction in induced rolling moment on the trailing wing model was realized at a spoiler deflection of about 45°.

Crow, S. C.,
"STABILITY THEORY FOR A PAIR OF TRAILING VORTICES,"
AIAA Journal, Vol. 8, No. 12, Dec. 1970, pp. 2172-2179.

Trailing vortices do not decay by simple diffusion. Usually they undergo a symmetric and nearly sinusoidal instability, until eventually they join at intervals to form a train of vortex rings. The present theory accounts for the instability during the early stages of its growth. The vortices are idealized as interacting lines; their core diameters are taken into account by a cutoff in the line integral representing self-induction. The equation relating induced velocity to vortex displacement gives rise to an eigenvalue problem for the growth rate of sinusoidal perturbations. Stability is found to depend on the products of vortex separation b and cutoff distance d times the perturbation wavenumber. Depending on those products, both symmetric and antisymmetric eigenmodes can be unstable, but only the symmetric mode involves strongly interacting long waves. An argument is presented that d/b = 0.063 for the vortices trailing from an elliptically loaded wing. In that case, the maximally unstable long wave has a length 8.6b and grows by a factor e in a time $9.4(A_R/C_L)$times (b/V_o), where A_R is the aspect ratio, C_L is the lift coefficient, and V_o is the speed of the aircraft. The vortex displacements are symmetric and are confined to fixed planes inclined at 48° to the horizontal.

Crow, S. C.,
"MOTION OF A VORTEX PAIR IN A STABLY STRATIFIED FLUID,"
Research Report No. 1, May 1974,
Poseidon Research, Santa Monica, CA.

A theory is developed for the descent of a vortex pair in a stably stratified fluid. The stratification is assumed to be weak, and the evolution of vorticity is traced without recourse to assumptions about turbulent mixing. The conclusion is that the vortices draw together and accelerate downward under the influence of stable stratification, contrary to the intuition that the recirculation cell might buoy upward. Fluid particles do rebound to their original levels, but in the form of a buoyant upwash above a diminishing cell. Eventually the vortex cores overlap, and their impulse radiates away on internal waves.

Crow, S. C. and Bate, Jr., E. R.,
"LIFESPAN OF TRAILING VORTICES IN A TURBULENT ATMOSPHERE,"
Research Report No. 2, Dec. 1974,
Poseidon Research, Sherman Oaks, CA.

The lifespan of aircraft trailing vortices is controlled by a mutual induction instability excited by atmospheric turbulence. The instability itself is well understood. The purpose here is to incorporate the effects of turbulence and thereby predict wake lifespan as a function of meteorological conditions. In the limit vertical currents are the chief excitors of instability. The paper concludes with a review of a practical method for actively exciting the mutual induction instability. The method would shorten the typical lifespan of a 747 wake by a factor of three.

Crow, S. C. and Bate, Jr., E. R.,
"LIFESPAN OF TRAILING VORTICES IN A TURBULENT ATMOSPHERE,"
J. Aircraft, Vol. 13, No. 7, July 1976, pp. 476-482

The lifespan of aircraft trailing vortices is controlled by a mutual induction instability excited by atmospheric turbulence. The instability itself is well understood. The purpose here is to incorporate the effects of turbulence and thereby predict wake lifespan as a function of meteorological conditions. Eddies of the relevant size are assumed to lie in the Kolmogorov inertial subrange. A statistical definition of lifespan is proposed. The paper concludes with a review of a practical method for actively exciting the mutual induction instability. The method would shorten the typical lifespan of a 747 wake by a factor of 3.

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Daiutolo, H.,
"DEVELOPMENT AND EVALUATION OF A WAKE VORTEX ADVISORY SYSTEM,"
Proceedings 22nd Annual Meeting, Air Traffic Control Assoc.,
Las Vegas, Oct. 1977, pp. 155-170.

A prototype wake vortex advisory system, presently being tested at Chicago O'Hare International Airport, is examined. The system utilizes a predictive algorithm described by an elliptical boundary drawn about the cross wind and head or tail wind. System testing procedures are outlined noting simulated and on-site evaluations of procedural implications, capacity gains, delay decreases, reliability, and maintenance. Preliminary results are presented.

Damania, R. B.,
"INVESTIGATION OF NEAR FIELD WAKES BEHIND HIGH-LIFT WINGS,"
PhD Thesis, 1973,
Mississippi State Univ., State College, MS.

An experimental study was made of the partially rolled up vortex behind a high lift wing. Specifically, the velocity vector behind a STOL airplane was measured in flight. The data were obtained at two measurement planes behind the wing in the range of 3.0 to 0.85 for flapped and unflapped conditions. Wing surface pressure distribution and wake vorticity were also measured. Results are presented in the form of contour plots of vorticity and velocity components.

Daugherty, J. W.,
"STUDY OF THE ELECTROSTATIC FIELD AND CHARGE DISTRIBUTION IN A VORTEX SEEDED WITH DUST,"
PhD Thesis, June 1973,
Ohio State Univ., Columbus, OH.

An experimental program was undertaken to investigate the vortex geometry, particle distribution and electric field distribution in a trailing vortex shed from an airfoil tip placed in a dust laden flow. A differential airfoil, positioned in a subsonic wind tunnel, generated the trailing vortex. Vortex geometry, particle distribution and electric field intensity were measured throughout the plane normal to the wind tunnel axis at several locations downstream from the airfoil.

Dee, F. W. and Nicholas, O. P.,
"FLIGHT MEASUREMENTS OF WING-TIP VORTEX MOTION NEAR THE GROUND,"
ARC Paper CP-1065, Jan. 1968,
Royal Aircraft Establishment, Bedford, England.

Tests have been made to measure the movement of the wing tip vortices from a Hunter aircraft flying at 170 knots approximately 35 feet above a runway, in a variety of wind conditions. Measurements were limited to a maximum time of 20 seconds after vortex generation. During this period the theoretical predictions presented are in good general agreement with the observed motions; however significant differences did occur. There was no clear indication as to whether the vortices decayed more rapidly in the presence of the ground and atmospheric turbulence, than would have been expected from the ground in calm air. Limited tests were also made to study the vortex mutual interaction away from the ground.

Delaney, B. T.,
"AIRCRAFT VORTEX EFFECTS ON GROUND LEVEL POLLUTANT CONCENTRATION AND TRACKING OF VORTEX MOVEMENT IN THE AIRPORT ENVIRONMENT,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 264-282.

The effect on ground level pollutant concentrations of including a mechanism to consider the transport of aircraft-generated pollutants captured in the trailing vortex system is examined by coupling a three-dimensional vortex transport program with a line source dispersion routine. It was found that not only would the ground level concentrations of oxides of nitrogen change but so would the spatial distribution. Echos recorded by a FM-CW radar are shown to be the result of water vapor and pollutants trapped in a descending vortex system.

Delaney, B. T. and Ledbetter, J. O.,
"AIRCRAFT VORTEX EFFECTS ON GROUND LEVEL POLLUTANT CONCENTRATION,"
Air Pollution Control Assoc., Paper 77-41,5,
Toronto, Canada, June 1977.

The effect of aircraft wake vortex transport on airport air pollution models is assessed. In particular, the emission of nitrogen oxides by aircraft during one segment of the takeoff phase (i.e., during the first 943 m of climb) is not adequately simulated by models adopted by the U.S. Air Force and the Environmental Protection Agency. In a study conducted at a major airport, inclusion of the effects of a rolled up contrarotating vortex pair generated by aircraft in the takeoff phase is found to improve the nitrogen oxides prediction capability of a conventional airport air quality model.

Delaney, B. T., Noonkester, R. V. and Ledbetter, J. O.,
"REMOTE SENSING OF AIRCRAFT WAKE VORTEX MOVEMENT IN THE AIRPORT ENVIRONMENT,"
Air Pollution Control Assoc., Paper 77-41,4,
Toronto, Canada, June 1977.

The use of FM-CW radar to track aircraft wake vortices at airports is discussed; remote tracking of vortices may aid in studying ground level pollution dispersion and the effects of vortex trails on encountering aircraft. Results are reported for a month-long test of a FM-CW radar system placed at the edge of a runway at Lindbergh Field, San Diego. V-echoes detected by the FM-CW radar appear to reflect the water and/or exhaust products trapped in the descending vortex trails of aircraft departing from the runway. Thus FM-CW radar detection seems a possible alternative to vortex sensing systems based on acoustic energy, anemometers, or laser backscatter.

Delisi, D. P., Robins, R. E. and Fraser, R. B.,
"THE EFFECTS OF STRATIFICATION AND WIND SHEAR ON THE EVOLUTION OF AIRCRAFT WAKE VORTICES NEAR THE GROUND,"
NWRA-87-R006, April 1987,
Northwest Research Associates, Bellevue, WA.

We have performed a feasibility study of how stratification and shear affect the evolution of aircraft trailing-tip vortices as they approach the ground and how they evolve when they are generated near the ground. The study incorporates both laboratory experiments and numerical modeling, matching model Froude numbers and shear parameters with their full-scale values. Results indicate that stratification and shear can have significant effects on the evolution of the vortex system. In nonstratified, nonsheared flow, vortex evolution is symmetric, each vortex decaying at the same rate. Adding stratification maintains the symmetry but inhibits the vertical migration. In ground effect, stratification also inhibits horizontal migration and cancels the rebound effect (observed in the nonstratified, nonsheared case). In a nonstratified flow with shear, vortex evolution is asymmetric; in ground effect, the shear also acts to severely reduce the rebound effect. With stratification and shear (Richardson number equal to one), the flow is asymmetric, and two effects are observed. When the vortex pair is weak relative to the shear (strong crosswind condition), the weaker downwind vortex is closer to the ground than the stronger upwind vortex. (If the vortex pair is far from the ground, a solitary vortex develops.) If the vortex is stronger relative to the shear (weak crosswind conditions), the weaker downwind vortex is further from the ground than the stronger upwind vortex.

Deptula, D. A.,
"NASA/FRC WAKE TURBULENCE FLIGHT TEST PROGRAM: RIDE QUALITY ASPECTS,"
NASA CR-145700, Nov. 1975,
Univ. of Virginia, Charlottesville, VA.

To determine how much the ride quality of the Shuttle Carrier (B-747) Aircraft is affected at various spoiler settings, the PEMS II (Portable Environmental Measuring System) was used to measure onboard motion during a test flight October 15, 1975. The PEMS II measures acceleration in the vertical, transverse and longitudinal directions as well as angular rates of pitch, roll, and yaw. The data acquired by this instrument, combined with an airline passenger comfort model, gives an indication of how passengers would react to the motion induced by flying in a vortex alleviation configuration.

DeSantis, G. C. and Goodrick, T. F.,
"WAKE SURVEY OF POWERED AND UNPOWERED C-5A AIRCRAFT MODELS,"
AIAA Paper No. 68-931,
El Centro, CA, 1968.

As part of the development program to airdrop 50,000 pound unit loads from the C-5A aircraft, a wind tunnel study was initiated to investigate the flow characteristics in the wake of the aircraft during airdrop. Two models of the C-5A were used in the study, a 1/2 scale unpowered model and a 1/17 scale powered model. By using both the powered and unpowered models it was possible to completely determine the C-5A wake characteristics and to isolate the variations in the wake which were caused by the interaction of the engine discharge and the aircraft wake.

Deyst, Jr., J. J. and Serben, S.,
"AUTOMATIC TRACKING OF WAKE VORTICES USING GROUND-WIND SENSOR DATA,"
FAA-RD-77-11, Jan. 1977,
Charles Stark Draper Lab., Cambridge, MA.

Algorithms for automatic tracking of wake vortices using ground-wind anemometer data are developed. Methods of bad-data suppression, track initiation, and track termination are included. An effective sensor-failure detection-and-identification system is also documented. System performance is verified using actual sensor data. Computer requirements for implementing the system in the field are summarized, and a plan for developing a general-purpose vortex-tracking simulation is presented.

DiMarzio, C. A., Sonnenschein, C. M. and Jeffreys, H. B.,
"AIRCRAFT WAKE VORTEX VELOCITY MEASUREMENTS USING A SCANNING CO_2 LASER DOPPLER VELOCIMETER,"
Electro-Optics '75 International Laser Conf.,
Anaheim, CA, 1975, pp. 391-397.

Aircraft wake vortex flow fields have been studied using a scanning laser Doppler velocimeter located adjacent to runway 31R at Kennedy International Airport in New York. Data has been obtained on vortex location, transport, and flow fields for a variety of aircraft. The data which has been analyzed was recorded with a one-dimensional laser Doppler system capable of measuring only the magnitude of a single velocity component. Although the optical range resolution determines the spatial resolution of the velocity profile in one direction, the laser system's excellent angular resolution makes it possible (assuming circular symmetry of the vortex) to obtain the tangential vortex velocity flow field. The resolution with which this function is obtained depends on the angular scan rate. With the present scan configurations, data points are obtained at approximately 1 degree intervals, corresponding to a resolution of 2 to 3 meters at ranges of 100 to 150 meters.

Donaldson, C. duP.,
"A BRIEF REVIEW OF THE AIRCRAFT TRAILING VORTEX PROBLEM,"
AFOSR-TR-71-1910, May 1971,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

In this paper, an attempt will be made to review the simplest theory of the wake, as well as to bring to attention a more detailed description of vortex roll-up that has been available for many years. This more complete description of the wake is in far better agreement with experimental results than the conventional description and may be used to illustrate several problems that face the experimentalist in the interpretation of this data. Once the roll-up problem has been discussed, the ways in which trailing vortex systems may be dissipated are reviewed. Finally, a system for evaluating the danger potential of aircraft wakes is discussed and the wake characteristics of a representative selection of present-day aircraft are presented in terms of this method of classifying aircraft wakes.

Donaldson, C. duP.,
"CALCULATION OF TURBULENT SHEAR FLOWS FOR ATMOSPHERIC AND VORTEX MOTIONS,"
AIAA Journal, Vol. 10, No. 1, Jan. 1972, pp. 4-14.

The basic ideas behind methods for computing the transport properties of turbulent shear flows for the past several decades are reviewed. Their shortcomings, insofar as computing a number of problems that arise in nature, are discussed. Particular emphasis is given to the case of vortex flows and atmospheric motion. The results of several years' effort toward establishing a general method for computing turbulent shear flows which does not suffer from the shortcomings of the older methods are reviewed, and a new method for the calculation of turbulent shear flows is suggested. The new results obtained when this method is applied to the computation of simple atmospheric motions and to vortex flows are presented and discussed in some detail.

Donaldson, C. duP.,
"VORTICES AND AIRCRAFT PERFORMANCE,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 11-17.

A review is given on ARAP's work on the roll-up and initial organization of vorticity shed by the wing of an aircraft and on the aging effects in the far wake due to viscosity (molecular and turbulent). The modified Betz model was shown to be an effective approach to the roll-up problem; it includes the effect of distributed wing drag on vortex structure. In considering the far-field flow, a detailed second-order numerical closure model has been developed for the axisymmetric vortex under the assumptions of equilibrium between the production and convection of turbulent energy.

Donaldson, C. duP. and Bilanin, A. J.,
"VORTEX WAKES OF CONVENTIONAL AIRCRAFT,"
AGARDograph No. 204, May 1975,
Aero. Research Assoc. of Princeton, Princeton, NJ.

A review is made of the present state of our knowledge of the vortex wakes of conventional aircraft. Included are discussions of wake roll-up, geometry, instability, and turbulent aging. In the light of these discussions, a brief review is made of the persistence of vortices in the atmosphere and design techniques which might be used to minimize wake hazard are considered.

Donaldson, C. duP., Bilanin, A. J. and Crow, S. C.,
"VORTEX WAKES OF LARGE AIRCRAFT,"
Notebook for AIAA Professonal Study Seminar, June 1974,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A compendium of lecture notes on the subject of vortex wakes of large aircraft. The notes include the following topics: rollup of shed vorticity, new roll-up models, comparison of rollup computations with experiments, interactive motion of shed vorticity, aging of vortices, vortex breakdown, mutually induced instabilities, atmospheric effects, and the impact on aircraft design.

Donaldson, C. duP., Snedeker, R. S. and Sullivan, R. D.,
"CALCULATION OF THE WAKES OF THREE TRANSPORT AIRCRAFT IN HOLDING, TAKEOFF, AND LANDING CONFIGURATIONS AND COMPARISON WITH EXPERIMENTAL MEASUREMENTS,"
FAA-RD-73-42, March 1973,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A method is described for the calculation of the initial form and location of the inviscid rolled-up wake vortices behind wings having both simple and complex load distributions such as those which occur when the wing is highly flapped. The method makes use of the Betz theorems of conservation of vorticity and moments of vorticity in the wake. It is found that a simple relationship exists between the radial distribution of vorticity concentrated in the wake vortices and the spanwise distribution of vorticity shed from the wing. Velocity profiles computed for the vortices of several aircraft in holding, takeoff, and landing configurations are shown to compare favorably with those measured at times up to one minute after fly-by during full-scale experiments.

Donaldson, C. duP., Snedeker, R. S. and Sullivan, R. D.,
"CALCULATION OF AIRCRAFT WAKE VELOCITY PROFILES AND COMPARISON WITH EXPERIMENTAL RESULTS,"
J. Aircraft, Vol. 11, No. 9, Sept. 1974, pp. 547-555.

A method is developed for the circulation of the initial inviscid form of rolled-up wake vortices behind a wing having arbitrary lift distribution. The method makes use of the Betz assumptions of conservation of wake vorticity and moments of vorticity. It is found that a simple relationship exists between the radial distribution of vorticity in the rolled-up wake and the spanwise lift distribution. Computed tangential velocity profiles for DC-7, DC-9, and C-141 aircraft are shown to compare favorably with profiles measured by the FAA during tower flyby tests of these aircraft in both flapped and unflapped configurations.

Donaldson, C. duP. and Sullivan, R. D.,
"DECAY OF AN ISOLATED VORTEX,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 389-411.

The effect of turbulent shear on the decay of a single vortex is considered. The ultimate aim of the program is the development of a method by which the effects of turbulence, whether introduced initially in the center of a vortex or contained in the fluid in which the vortex is formed, could be calculated.

Donaldson, C. duP., Williamson, G. C., Bilanin, A. J. and Snedeker, R. S.,
"STUDY OF THE FEASIBILITY OF CONDUCTING A WAKE-RIDING EXPERIMENT USING A T-2 AIRCRAFT BEHIND TWO P-3 AIRCRAFT,"
ARAP-287, Aug. 1976,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A study has been made of a T-2 aircraft attempting to establish a wake-riding position behind two P-3 aircraft. The major objectives were to estimate structural loads in the wake rider and to evaluate wake entry and station keeping control techniques. The results of the study indicate that the root-bending load on the tail of the T-2 aircraft would be of the order of the design load if the aircraft were to inadvertently pass directly through the center of a trailing vortex from one of the P-3's. Thus the flight tests, as originally envisaged, must be considered as high risk experiments unless the tail of the T-2 were to be strengthened. If wake riding experiments are carried out, approach to the wake-riding position should be made from above using a reduced-power, constant-airspeed approach. In calm air the piloting task appears reasonable if the trailing vortices are marked by smoke or condensation.

Dosanjh, D. S., Gasparek, E. P. and Eskinazi, S.,
"DECAY OF A VISCOUS TRAILING VORTEX,"
Aero. Quarterly, Vol. 13, May 1962, pp. 167-188.

An experimental investigation of the viscous decay of a steady three-dimensional helical vortex is presented. The vortex was generated by a rectangular, symmetrical half aerofoil, cantilevered from the wall of the circular test section of a low-speed wind tunnel. Only the local total head and flow directions were measured with a five-hole pressure sensitive probe at one to eight chord lengths behind the trailing edge of the aerofoil and the radial, tangential and axial velocity distributions in the trailing vortex were derived. The static pressure variation on the vortex flow and the difficulties in its accurate measurement are discussed.

Dunham, Jr., R. E.,
"VORTEX DISSIPATION TESTS CONDUCTED AT NASA LANGLEY RESEARCH CENTER,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 29-35.

The major interest in vortices at Langley lies in the far wake aspect of the problem, and especially in the possibility of enhancing the rate of far wake dissipation. Three separate facilities are used to conduct tests on wake vortex behavior and possible dissipation devices: the Vortex Flow Facility (an 1800 foot track), the Langley V/STOL wind tunnel, and the Hydronautics water tank facility. An overall summary of NASA Langley experiments with hazard reduction techniques was presented; the manipulation of span loading appears to be the most promising hazard reduction technique.

Dunham, Jr., R. E.,
"SUMMARY OF NASA WAKE-VORTEX MINIMIZATION RESEARCH,"
Proceedings Aircraft Safety and Operating Problems, NASA, Washington, 1976, pp. 303-318.

NASA's effort in the area of wake-vortex minimization are reviewed. The results presented at a NASA symposium on wake-vortex minimization are summarized and additional results obtained since the symposium are included. Theoretical and experimental techniques for assessing the effectiveness of various wake-vortex minimization techniques are described. Three methods of reducing the effect of aircraft trailing vortices and a preliminary assessment of the operational suitability of employing wake-vortex minimization techniques are discussed. The application of one wake-vortex minimization technique to DC-10 and L-1011 aircraft is presented.

Dunham, Jr., R. E.,
"UNSUCCESSFUL CONCEPTS FOR AIRCRAFT WAKE VORTEX MINIMIZATION,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, Washington, 1977, pp. 221-250.

Exploratory concepts are described which were investigated to achieve a reduction in the vortex induced rolling upsets produced by heavy aircraft trailing vortexes. The initial tests included the use of mass injection, oscillating devices, wingtip shape design, interacting multiple vortexes, and end plates. Although later refinements of some of these concepts were successful, initial test results did not indicate a capability of these concepts to significantly alter the vortex induced rolling upset on a following aircraft.

Dunham, Jr., R. E., Barber, M. R. and Croom, D. R.,
"WAKE VORTEX TECHNOLOGY,"
CTOL Transport Technology, 1978, pp. 757-771.

A brief overview of NASA's wake vortex minimization program is presented. The significant results of this program are summarized as follows: (1) it is technically feasible to reduce significantly the rolling upset created on a trailing aircraft; (2) the basic principles or methods by which reduction in the vortex strength can be achieved have been identified; and (3) an analytical capability for investigating aircraft vortex wakes has been developed.

Dunham, Jr., R. E., Verstynen, Jr., H. A. and Banner, M. S.,
"PROGRESS REPORT ON WING-TRAILING-VORTEX STUDIES,"
NASA Aircraft Safety and Operating Problems, Vol. 1, NASA SP-270, 1971, pp. 101-113.

The paper summarizes the activities of NASA in three major areas of vortex research. The first area is concerned with the measurement of the characteristics of full-scale aircraft vortices to obtain an understanding of the behavior of vortices at altitude and near the ground. Of particular interest are the velocities and their distributions, and the vortex persistence. The second area involves investigations of possible techniques to effect a more rapid breakdown or decay of vortices; the deployment of wing flaps create a vortex system which is less intense and decays more rapidly than vortices created in a flaps-up condition. The third area concerns an investigation of the feasibility of remotely detecting the presence of wing trailing vortices in the terminal area.

Dunham, Jr., R. E., Verstynen, Jr., H. A. and Banner, M. S.,
"PRELIMINARY RESULTS OF A FLIGHT INVESTIGATION OF THE TRAILING VORTICES GENERATED BY A C-5A HEAVY JET TRANSPORT,"
LWP-969, June 1971,
NASA Langley Research Center, Hampton, VA.

Some exploratory flight tests were conducted to investigate the strength and persistence characteristics of the vortices generated by a C-5A jet transport. The tests were conducted using an instrumented T-33 aircraft to probe the vortices of the C-5A while ranging information was provided by ground based radars. The results are presented in terms of tabulated maximum measured tangential velocities and radii of maximum velocities, vortex positions as a function of distance behind the C-5A, and maximum recorded velocity as a function of vortex age.

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Earnshaw, P. B.,
"MEASUREMENTS OF VORTEX-BREAKDOWN POSITION AT LOW SPEED ON A SERIES OF SHARP-EDGED SYMMETRICAL MODELS,"
ARC Paper CP-828, Nov. 1964,
Royal Aircraft Establishment, Farnborough, England.

Measurements have been made at low speed of vortex-breakdown positions on a series of five, symmetrical wings, using a schlieren system to detect the position of breakdown. The results suggest that the modification of a delta planform to incorporate streamwise tips has little effect on breakdown position when this is forward of the modified tip. Examination of the large differences between these measurements and those from other sources suggests that the influence of cross-sectional shape even on nominally thin wings may be larger than expected and merits further investigation.

Easterbrook, C. C. and Joss, W. W.,
"THE UTILITY OF DOPPLER RADAR IN THE STUDY OF AIRCRAFT WING-TIP VORTICES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 97-112.

The feasibility of utilizing a special purpose Doppler radar to investigate air motions in aircraft wakes is explored and tested. One method involves the injection of radar reflecting chaff into the wing-tip vortex of an aircraft in flight, and subsequently recording the Doppler spectrum of the return from the chaff packet as obtained by the radar looking normal to the flight path. The second method consists of Doppler measurements in the wake behind aircraft on the approach to an airport during snow conditions, where natural snow crystals and flakes assume the role of radar reflecting tracers of air motion. The power spectra derived from both techniques reflect the distribution of velocities of scatterers in the direction of the radar, weighted by the spatial distribution of the scatterers contained in the radar sensitive volume.

Easterbrook, C. C., Joss, W. W. and Prinsen, H. W.,
"AN EXPERIMENTAL INVESTIGATION AND EVALUATION OF A DOPPLER RADAR TECHNIQUE FOR THE MEASUREMENT OF THE FLOW GENERATED BY WING TIP VORTICES,"
CAL-AF-3015-1, Jan. 1971,
Cornell Aeronautical Lab., Buffalo, NY.

Results are described of tests conducted to determine if radar reflective chaff injected at the wing tip of an aircraft would be ingested into the vortex structure and sufficiently distributed to allow velocity profiles to be measured by a Doppler radar. The results are presented in the form of flow field visualization results and an analysis of radar returns. The data show that individual chaff filaments dispensed at the wing tips of an Aztec aircraft are entrained by the wing tip vortices. An examination of the radar returns reveals the presence of large Doppler spreads in relatively small regions of the vortices. It was also found that a substantial percentage of the chaff had a tendency to form clumps which hampered the determination of the detailed velocity profiles.

Eberle, W. R., Brashears, M. R., Zalay, A. D., Shrider, K. R. and Love, D. A.,
"AIRCRAFT WAKE VORTEX CHARACTERISTICS FROM DATA MEASURED AT JOHN F. KENNEDY INTERNATIONAL AIRPORT,"
FAA-RD-78-47, March 1978,
Lockheed Missiles & Space Co., Huntsville, AL.

Data from 1320 aircraft flybys at Kennedy International Airport, Jamaica, New York, in 1975 were processed and stored in a computerized vortex data management system. The data were selectively recalled to determine vortex characteristics pertinent to the design of an effective wake vortex avoidance system. Vortex and meteorological characteristics which are relevant to the design of an effective wake vortex avoidance system are discussed from an analytical viewpoint as well as from an analysis of the data. Several formulations for feedback of vortex sensor information to provide vortex prediction are presented. Several wake vortex avoidance system designs are shown.

Eberle, W. R., McCutcheon, W. A. and Shrider, K. R.,
"WAKE TURBULENCE INVESTIGATION AT NEW YORK'S LA GUARDIA AIRPORT,"
LMSC-HEC TR F225747-B, Dec. 1988,
Lockheed Missiles & Space Co., Huntsville, AL.

The intent of the study was the development of a rationale for increased airport capacity by eliminating the extra space required for aircraft landing behind heavy takeoff aircraft at La Guardia airport. The study considered two approaches: (1) demonstration that a vortex encounter would not occur for the runway configuration of interest (takeoff on runway 31 and landing on runway 22), and (2) demonstration that if a vortex encounter occurred where the flight path of the following aircraft is perpendicular to the flight path of the generating aircraft, it would not be hazardous to the landing aircraft.

Edwards, B. B. and Coffey, E. W.,
"DEVELOPMENT AND TESTING OF LASER DOPPLER SYSTEM COMPONENTS FOR WAKE VORTEX MONITORING; VOL. 2: SCANNER OPERATIONS MANUAL,"
NASA CR-120467, Aug. 1974,
Lockheed Missiles & Space Company, Huntsville, AL.

This manual describes the theory and operation of the scanner portion of the Laser Doppler system for detecting and monitoring aircraft trailing vortices in an airport environment. Included in the manual are schematics, wiring diagrams, component values, and operation and check out procedures.

Eisenhuth, J. J., McCormick, B. W., Nelson, R. C. and Garodz, L. J.,
"ANALYSIS OF EXPERIMENTAL MEASUREMENTS OF TRAILING VORTEX SYSTEMS OF LARGE JET TRANSPORT AIRCRAFT,"
Proceedings of the National Aerospace Electronics Conf., IEEE, Dayton, 1971, pp. 28-35.

This paper presents an analysis of data obtained by the Federal Aviation Administration related to the characteristics of trailing vortex systems generated by large jet aircraft. Difficulty was experienced in analyzing the data because of the comparatively large spacing of sensors, but some significant information and conclusions can be derived from the analysis. It was found that the velocity field around a vortex produced by a large jet aircraft is defined by a logarithmic variation of circulation with radius. For a lift coefficient of unity, the core diameter was found to be approximately 5% of the mid-span chord while the maximum tangential velocity at the edge of the core was about 70% of the aircraft velocity. Both the diameter and core appear to change in proportion to the lift coefficient. Expressions are developed for predicting the velocity field produced by the trailing vortices from large aircraft. These should be used with caution, however, until additional and more precise data are obtained.

Eliason, B. G., Gartshore, I. S. and Parkinson, G. V.,
"WIND TUNNEL INVESTIGATION OF CROW INSTABILITY,"
J. Aircraft, Vol. 12, No. 12, Dec. 1975, pp. 985-988.

The mutual instability of a trailing vortex pair has been studied in a large wind tunnel. The vortices were visualized using helium-filled soap bubbles and the cores probed with a hot-wire anemometer. Measurements were made to permit calculation of the wing lift, the circulation of the trailing vortices, the diameter of the vortex cores, and the wavelength and plane of oscillation of the unstable vortices. The results show that the linear theories of either Crow or Parks closely predict the characteristics of the instability, the agreement depending on the definition of vortex core diameter.

El-Ramly, Z.,
"AIRCRAFT TRAILING VORTICES - A SURVEY OF THE PROBLEM,"
ME/A 72-1, Nov. 1972,
Carleton University, Ottawa, Canada.

A survey of the trailing vortices problem is presented. In this report only the work related to vortices shed from high aspect ratio straight or sweptback wings is considered. The survey covers the initial formation and roll-up of trailing vortices, their steady motion and decay, the stability of a trailing vortex pair, atmospheric and ground effects, and vortex breakdown. Experimental results, both full scale and subscale are also reviewed and a survey of the work describing the hazards to aircraft encountering a trailing vortex system is included.

El-Ramly, Z.,
"INVESTIGATION OF THE DEVELOPMENT OF THE TRAILING VORTEX SYSTEM BEHIND A SWEPTBACK WING,"
ME/A 75-3, Oct. 1975,
Carleton University, Ottawa, Canada.

Measurements of the trailing vortex system behind a 35° sweptback wing have been made in a low speed wind tunnel at a mean chord Reynolds number $R\bar{c}$, of about 0.5 x 10^6 with vortex Reynolds numbers, $\Gamma_\infty/_\nu$, up to about 0.25 x 10^6. Spanwise and chordwise loading on the main wing as obtained from pressure distributions, and the character of the boundary layer flow was explored using oil-dot flow visualization and limited hot wire measurements. Mean flow properties of the vortex field have been measured, using a non-nulling 5-hole probe, at two stations 2-1/2 and 5 main wing spans downstream

(17.5 and 35° respectively). Using a simple strain-gauged balance, the induced rolling moment on two trailing wings (of representative relative scale and aircraft geometry), which intercepted the main wing vortex system, was also measured. Maximum induced rolling moments as well as variation with lateral and vertical position was found.

El-Ramly, Z.,
"INDUCED ROLLING MOMENT ON TRAILING WINGS,"
AIAA Paper No. 77-663,
Albuquerque, NM, June 1977.

An experimental wind tunnel test program has been conducted to investigate possible scaling parameters for the prediction of the maximum induced rolling moment on a trailing wing. Detailed variation of the induced rolling moment on a following wing in the wake of a generating wing is measured for several lead/trailing combinations. With five wings used ten different combinations were possible covering the trailing/generating span ratio of 0.24 to 1.22. The wings include both straight and swept configurations and the aspect ratio varies between 4 and 8.5. The results show that the maximum induced rolling coefficient depends on the trailing wing aspect ratio and is proportional to both the lift coefficient of the generating aircraft divided by its aspect ratio and to the square root of generating/trailing span ratio. The effect of trailing wing incidence is also examined.

El-Ramly, Z. and Rainbird, W. J.,
"EFFECT OF SIMULATED JET ENGINES ON THE FLOWFIELD BEHIND A SWEPT-BACK WING,"
J. Aircraft, Vol. 14, No. 4, April 1977, pp. 343-349.

Measurements of the vortex behind a swept-back wing have been made in a low-speed wing tunnel. Results have been taken with a clean wing, with engines mounted in representative positions, and with and without jet exhaust simulation. Only cruising flight conditions are simulated. Loading on the wing has been obtained from pressure distribution measurements. Flowfield properties and the rolling moment on a trailing wing have been measured at 2-1/2 and 5 wing spans downstream. The concentrated tip vortex structure is essentially unaffected by the engines but the remaining shear layers are considerably distorted by the pylon-nacelles. The maximum induced rolling moment on the trailing wing is only slightly reduced by the present engine installation or the simulated jet exhaust.

El-Ramly, Z. and Rainbird, W. J.,
"EFFECT OF WING-MOUNTED DEVICES ON THE TRAILING VORTEX SYSTEM IN THE NEAR FIELD,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 194-206.

The paper examines the results of an extensive wind tunnel test program aimed at evaluating the effect of several devices mounted on a wing on the near field trailing vortex system. The devices used include different wing tip modifications, several spoilers, simulated flap-track fairings, as well as two simulated engines with and without air injection. Only practical tip modifications and spoilers have been incorporated, i.e., only those that appear to be structurally possible with reasonable drag penalties. The devices have been tried first individually and then in combination to see if the reduction in rolling moment is cumulative. Assessment of the effectiveness of the devices, in reducing vortex hazard, is measured as a reduction in the maximum induced rolling-moment coefficient on a following wing of fixed span ratio of 0.24, representative of a light aircraft. All devices tested have resulted in decreases of the vortex hazard. However, no single device produced a substantial decrease in maximum induced rolling moment.

El-Ramly, Z. and Rainbird, W. J.,
"COMPUTER-CONTROLLED SYSTEM FOR THE INVESTIGATION OF THE FLOW BEHIND WINGS,"
J. Aircraft, Vol. 14, No. 7, July 1977, pp. 668-674.

A completely computer-controlled wind-tunnel test facility for measurements of the vortical flowfield behind a lifting swept-back wing is described. The vortex generator model is a pressure-plotted root-mounted half-wing. Flowfield measurements were made using a precalibrated non-nulling blunted conical five-hole probe. The program developed can calculate and plot, on-line, the three components of velocity and vorticity, the total pressure loss coefficient, and the circulation distribution. As a result of these automated flowfield measurements, it was possible to account for almost all of the vorticity shed from the wing.

El-Ramly, Z. and Rainbird, W. J.,
"FLOW SURVEY OF THE VORTEX WAKE BEHIND WINGS,"
J. Aircraft, Vol. 14, No. 11, Nov. 1977, pp. 1102-1108.

Flowfield surveys of the wake behind three different wings have been carried out in a low-speed wind tunnel. The mean flow properties have been measured using a small non-nulling five-hole probe. The results include the three mean velocity components, complete definition of the viscous wake, and detailed loading on one of the wings. The three components of vorticity were calculated and the vortical wake completely defined. It was found that the vortical wake always is contained within the viscous wake (region of total pressure loss). The vortex system is never fully rolled up, in the traditional sense, within the reasonably large downstream distance tested of 13 wing spans. The overall lift coefficient calculated from the distribution of streamwise component of vorticity is found to be smaller (87-100%) than that measured directly on the wing. The total circulation accounted for, at any streamwise station, decreases slightly with downstream distance. Comparison was made between the measured tangential velocity profiles and circulation distribution and those calculated using Betz theory, based on measured spanwise loading. Agreement is reasonable over a radius more or less equal to that of the vortex viscous core ($<0.25\ b/2$). Outside of this region, the Betz model assumes that roll-up is complete when, in fact, it is not. Agreement is also poor very near the vortex center because of the strong viscous effects there.

El-Ramly, Z., Rainbird, W. J. and Earl, D. G.,
"WIND TUNNEL MEASUREMENTS OF ROLLING MOMENT IN A SWEPT-WING VORTEX WAKE,"
J. Aircraft, Vol. 13, No. 12, Dec. 1976, pp. 962-967.

Some measurement of the trailing vortex system behind a 35° sweptback, tapered wing have been made in a low-speed tunnel at a chord Reynolds number of 0.5×10^{6}. Detailed wing loading was obtained from pressure distributions. Mean flow properties have been measured, using a non-nulling 5-hole probe, at two stations 2-1/2 and 5 main wing spans downstream. Induced rolling moment on two trailing wings, which intercepted the main wing vortex system was also measured. Judged by the circulation around the core, the shear layers had not fully rolled up at the 2-1/2*b* station. Also no further appreciable roll-up occurred at the 5*b* station. Furthermore, there was very little difference between the induced rolling moments measured at the two stations.

Emmer, D. S.,
"EXPERIMENTAL STUDIES OF TRANSONIC AIRFOIL TRAILING EDGE AND WAKE FLOWFIELD PROPERTIES,"
PhD Thesis, 1984,
Ohio State University, Columbus, OH.

An experimental investigation of several of the trailing edge and wake turbulence properties for a NACA 84A010 airfoil section was completed. The experiment was conducted at The Ohio State University Aeronautical and Astronautical Research Laboratory in the 6 x 22 inch transonic flow facility. For both angles of attack, the turbulence intensities and turbulence kinetic energy were observed to decay in the streamwise direction. In the fair wake, the turbulence intensities were nearly isotropic for the nonlifting case. For the two degree case, the horizontal component of the turbulence intensity was observed to be substantially higher than the vertical component. For each survey, the data demonstrated excellent repeatability with a high degree of spatial resolution. The results of this research should provide guidance for the development, verification, and improvement of turbulence modeling.

Evans, P. F. and Hackett, J. E.,
"NUMERICAL STUDIES OF THREE-DIMENSIONAL BREAKDOWN IN TRAILING VORTEX WAKES,"
NASA CR-137888, June 1976,
Lockheed-Georgia Co., Marietta, GA.

Finite element, three-dimensional relaxation methods are used to calculate the development of vortex wakes behind aircraft for a considerable downstream distance. The inclusion of a self-induction term in the solution, dependent upon local curvature and vortex core radius, permits calculation of finite lifetimes for systems for which infinite life would be predicted two-dimensionally. The present report describes the associated computer program together with single-pair, twin-pair, and multiple-pair studies carried out using it. It is found, in single-pair studies, that there is a lower limit to the wavelengths at which the "Crow"-type of instability can occur. Below this limit, self-induction effects cause the plane of the disturbance waves to rotate counter to the vortex direction. Self induction in two dimensionally generated twin spiral waves causes an increase in axial length which becomes more marked with decreasing initial wavelength. The time taken for vortex convergence toward the center plane is correspondingly increased. The limited parametric twin-pair study performed suggests that time-to-converge increases with increasing flap span. Limited studies of Boeing 747 configurations show correct qualitative response to removal of the outer flap and to gear deployment, as compared with wind tunnel and flight test experience.

Evett, R. C., Jagodnick, A. J. and Zimmer, J. T.,
"SIGNAL PROCESSING AND DISPLAY INTERFACE STUDIES,"
NAS-8-29822, Sept. 1975,
Raytheon Company, Sudbury, MA.

The report discusses the principles of operation and the design and testing of a digital signal processor to be used with a laser system in the detection and tracking of vortices. The processor is basically a spectrum analyzer with thresholding, frequency and time integration, and outputs to recorders and computer interfaces.

F

Faery, Jr., H. F.,
"THE EFFECT OF WHITCOMB WINGLETS AND OTHER WINGTIP MODIFICATIONS ON WAKE VORTICES,"
PhD Thesis, 1975,
Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

Wind tunnel experiments were conducted on six wingtip configurations to determine their wake vortex characteristics. The trailing wingtip vortex was probed by a 1/8 inch diameter five hole yawhead pressure probe. The vortex tangential and axial velocity profiles are compared at five and twenty chordlengths downstream. The Whitcomb winglet and the upper winglet configuration both produce two distinct vortices of the same rotation. The maximum tangential velocity in each is about 64 percent less than that produced by a conventional wingtip configuration. The lift and drag characteristics of the wingtip configurations are compared. The aerodynamic force effects of the wing on the winglet and the winglet on the wing. The downwash distribution on the wing both with and without winglets, and the effect of different winglet dihedral angles on the wing downwash pattern are discussed.

Faery, Jr., H. F and Marchman, III, J. F.,
"EFFECT OF WHITCOMB WINGLETS AND OTHER WINGTIP MODIFICATIONS ON WAKE VORTICES,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 207-216.

Experimental studies of the wake vortices generated behind 6 different wingtip configurations are presented. It is shown that the Whitcomb winglet configuration produces two distinct wingtip vortices, each of approximately 65% less swirl velocity than that produced by a rounded-tip configuration. Strong axial velocity deficits are shown to be characteristic of these vortices with reduced maximum swirl velocities.

Fage, A. and Simmons, L. F.,
"AN INVESTIGATION OF THE AIR-FLOW PATTERN IN THE WAKE OF AN AEROFOIL OF FINITE SPAN,"
Proc. Royal Soc., Vol. 225, No. A632, Dec. 1925, pp. 303-330.

By means of precise measurements of the wind speed and direction, a picture of the disturbance behind an aerofoil of finite span is presented. Changes in the extent and distribution of the vorticity in the wake as it passes downstream are mapped out. The measured vorticity is considered in relation to the circulation around the aerofoil. The work provides an experimental verification of the theoretical relation that the total strength of the vorticity leaving a semi-span of an aerofoil, as obtained by integration over a transverse plane close behind the aerofoil, is equal to the circulation around the median section. It also shows that the distribution of vorticity behind the aerofoil is closely connected with the distribution of lift on the span.

Farlow, N. H., Watson, V. R., Loewenstein, M., Chan, K. L., Hoshizaki, H., Conti, R. J. and Meyer, J. W.,
"MEASUREMENTS OF SUPERSONIC JET AIRCRAFT WAKES IN THE STRATOSPHERE,"
International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, American Meteorological Society, July 1974, pp. 53-58.

Progress is reported in an experimental program consisting of making supersonic aircraft wakes visible in the stratosphere so that photographs can be taken which yield wake dimensions vs time, and so that aircraft equipped with instruments which measure key exhaust species can find and penetrate the wakes. The object is to provide verification of fluid dynamic and chemical models. Three available models are summarized, and the experimental methods used are described. The Lockheed model predictions correspond in general most closely to experimental wake cross-sectional area. NO data are in reasonable agreement with NO predictions, but chemical models are relatively undeveloped, and additional measurements of exhaust products are needed before verification of chemical models becomes possible. However, the overall feasibility of wake visualization for model verification is substantiated. It is emphasized that significant model differences exist that must be resolved before reliable predictions can be made in the wake regimes studied.

Fay, J. A.,
"BUOYANT PLUMES AND WAKES,"
<u>Ann. Rev. Fluid Mechanics</u>, Vol. 5, Annual Reviews Inc., Palo Alto, CA, 1973, pp. 151-160.

A review is given of the theories of the motion of buoyant plumes and the dispension of exhaust gases in vehicular and aircraft wakes. Models for estimating the effects of downwash on the growth of buoyant aircraft trails are presented.

Fernandez, F. L. and Lubard, S. C.,
"TURBULENT VORTEX WAKES AND JETS,"
AIAA Paper No. 71-615,
Palo Alto, CA, 1971.

The turbulent viscous core of a potential vortex with axial velocity excess or defect is considered. An integral method is used with quasi-cylindrical flow approximations to describe the flow in the core of the vortex. Models are postulated for both axial and swirl mixing. The resulting equations are shown to possess both regular wake-like and jet-like solutions and solutions which become singular indicating vortex breakdown. The singular solutions are found only for single vortex cores with a net axial momentum deficiency which implies a net drag for the vortex generator.

Fidler, J. E.,
"APPROXIMATE METHOD FOR ESTIMATING WAKE VORTEX STRENGTH,"
AIAA Journal, Vol. 12, No. 5, May 1974, pp. 633-635.

An approximate method is presented for estimating the strength of slender-body wake vortices. The method is shown to yield good accuracy for the case of asymmetric vortices in the wake of a body at high angles of attack.

Francis, D. G.,
"DEVELOPMENT OF A VORTEX LASER DOPPLER VELOCIMETER,"
Proceedings of the National Aerospace Electronics Conf., IEEE, Dayton, 1971, pp. 36-40.

The paper describes basic laser Doppler velocimeter theory and outlines the vortex laser Doppler velocimeter program at the Arnold Engineering Development Center. The object of the program is to design, develop, and place into operation a three component laser Doppler velocimeter system capable of mapping velocity profiles of aircraft wake turbulence at altitudes up to 1000 feet.

Francis, M. S.,
"AN EXPERIMENTAL INVESTIGATION OF WING TRAILING VORTEX FORMATION,"
FJSRL TR-76-0013, Aug. 1976,
US Air Force Academy, Colorado Springs, CO.

The incompressible flowfield in the vicinity of a lifting rectangular finite wing is investigated experimentally to ascertain the nature and detailed characteristics of the

formation and early development of a trailing vortex. The apparatus was designed and fabricated to facilitate a direct comparison of real flow data with existing theories and flow models. The inboard potential flow region was observed to exhibit the simplifying characteristic of a spanwise cross-flow velocity component which is independent of the surface normal coordinate. As a result, a possible ambiguity in the determination of the stream-wise vorticity component was removed. Graphs of the near-surface (bound) vorticity distribution are presented along with a map of Prandtl bound vortex filaments. The associated bound circulation function could be expressed approximately as the product of two separable functions of the planform spatial coordinates. Measurement at the wing trailing edge are employed to show that the properly non-dimensionalized characteristic vorticity distribution in this region is independent of angle of attack.

Francis, M. S. and Kennedy, D. A.,
"FORMATION OF A TRAILING VORTEX,"
J. Aircraft, Vol. 16, No. 3, March 1979, pp. 148-154.

The incompressible flowfield in the vicinity of a lifting rectangular finite wing is investigated experimentally to ascertain the nature and detailed characteristics of the formation of a trailing vortex. The mean velocity field was mapped directly using a linearized constant temperature hot-wire anemometry probe in conjunction with a precision wind-tunnel traversing mechanism. The associated vorticity field was inferred from these measurements through a spatial contour integration procedure. The existence of several identifiable flow regions exhibiting similar characteristics was established and verified with both hot-wire and flow visualization data. The nature of the near surface bound vorticity distribution is described including a map of the Prandtl-bound vortex filaments. Measurements at the wing trailing edge show that the properly nondimensionalized characteristic vorticity distribution in this region is independent of angle of attack. Shed vorticity emanating from the lower aerodynamic surface near the wing tip was observed to roll up adjacent to the tip and roll over onto the upper wing surface at a chordwise location which depends on the wing orientation. The presence and behavior of this structure which possesses an identifiable core is suggested as the cause of the modified pressure distribution (lift increment) normally observed in this region.

Freymuth, P.,
"THREE-DIMENSIONAL VORTEX SYSTEMS OF FINITE WINGS,"
J. Aircraft, Vol. 25, No. 10, Oct. 1988, pp. 971-972.

The vortex strands of a finite three-dimensional vortex system must be connected in accordance with Helmholtz's law. It is shown that flow visualization documents the connecting and reconnecting of the strands.

Freymuth, P., Finaish, F. and Bank, W.,
"VISUALIZATION OF WING TIP VORTICES IN ACCELERATING AND STEADY FLOW,"
J. Aircraft, Vol. 23, No. 9, Sept. 1986, pp. 730-733.

A streakline method was used to visualize complex two- and three-dimensional vortical structures over an airfoil. The method was extended to visualize wing tip vortices in unsteady and steady flows.

Fridman, J. D.,
"AIRBORNE WAKE VORTEX DETECTION,"
FAA-RD-74-46, March 1974,
Raytheon Company, Sudbury, MA.

Active and passive remote sensing systems were assessed to determine the feasibility of detecting aircraft trailing vortices using instrumentation on-board an aircraft. It was found that a modification of the front-end receiver of a 10 GHz weather radar system or a change of frequency to 35 GHz may allow vortex identification over a range of several kilometers. The CO_2 laser coherent Doppler radar technique and passive radiometric techniques (8-14 microns) show considerable promise. Other airborne systems (incoherent Lidar, Raman shift techniques, fluorescence scattering, acoustic radar, ultraviolet emissions) were shown not to possess sufficient sensitivity.

Fridman, J. D. and Hallock, J. N.,
"AIRBORNE WAKE VORTEX DETECTION,"
Proceedings Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, El Paso, 1974, pp. 399-404.

Active and passive remote sensing systems have been assessed to determine the feasibility of detecting aircraft trailing

vortices using instrumentation on-board an aircraft. A front-end modified millimetric wave weather radar may allow vortex identification over a range of several kilometers for a sufficiently large target cross-section. A 10.6 micron coherent Doppler optical radar detects the presence of a trailing vortex over a range of several miles. A passive radiometric technique in the 8-14 micron range also shows considerable promise.

Fuller, C. E.,
"A STUDY OF TURBULENCE MEASUREMENTS USING LASER DOPPLER SYSTEM,"
NASA CR-119804, June 1971,
Remtech Inc., Birmingham, AL.

The object of the wing tip vortex test is to demonstrate the extent with which the Laser Doppler Velocimeter system can be used for the measurement of gas velocities with high spatial and temporal resolution. This test was planned to provide three dimensional mean velocity data of the vortex pattern shed from a wing tip at an angle of attack. These measurements are being conducted at the MSFC 7 x 7 inch wind tunnel facility. The test plan and procedure as well as the measurements that were made are included. In addition, data on several measurements of the system's operating parameters which are important to these tests are also given.

Fuller, C. E.,
"WING TIP DOPPLER MEASUREMENTS WITH LASER DOPPLER SYSTEMS,"
RTR-002-3, April 1973,
Remtech Inc., Huntsville, AL.

The vortex velocity field produced by a rectangular wing in a subsonic wind tunnel was measured using two laser Doppler velocimeter systems. One system made three-dimensional mean velocity measurements and the other made one-dimensional turbulence measurements. The systems and test procedures are described and the measurements presented. The data defined a strong spiral motion in the vortex formation process.

Funk, B. H. and Johnston, K. D.,
"LASER NET - A SYSTEM FOR MONITORING WINGTIP VORTICES ON RUNWAYS,"
NASA TM X-64525, June 1970,
NASA Marshall Space Flight Center, Huntsville, AL.

A laser schlieren method is proposed which potentially provides a means for monitoring the strength of vortex wakes on and near runways. The method could provide a gross, continuous assessment of the intensity of disturbances over airport runways and aircraft carriers. Preliminary measurements behind a wingtip mounted on the wall of a small subsonic wind tunnel indicate that wingtip vortices are readily detectable with this simple system.

Funston, N. L. and Koob, S. L.,
"A TRAILING VORTEX MODEL AND ITS EFFECT ON A PENETRATING AIRCRAFT," Proceedings of the National Aerospace Electronics Conf., IEEE, Dayton, 1971, pp. 23-27.

The high strength of the trailing vortex system produced by the new jumbo jet aircraft has renewed interest in the study of the vortex phenomenon and its effect on proximate aircraft operations. In the present study, the trailing vortex system produced by an aircraft in flight and penetration of the system by a second aircraft are modeled mathematically. The effect of turbulent mixing on the persistence of the intact trailing vortices is modeled by modifying the similar solution for a decaying laminar vortex. The correction is made by introducing an effective turbulent viscosity which is determined empirically. The vortex induced velocity is superimposed on the free stream velocity of a penetrating aircraft to determine a total velocity vector and angle of attack history. Separation times and distances required for safe operation in traffic pattern conditions are predicted using a gust load formula and maximum incremental load factors. Calculations were performed for several generator/penetrator aircraft combinations.

G

Gados, R. G. and Amodeo, F. A.,
"PROCEDURAL FEASIBILITY OF REDUCED SPACING UNDER WAKE VORTEX AVOIDANCE SYSTEM OPERATION, WITH APPLICATIONS TO ATLANTA AND O'HARE,"
FAA-EM-79-18, Aug. 1979,
Mitre Corp., McLean, VA.

A Wake Vortex Avoidance System (WVAS) may provide increased airport capacity by allowing for reduced aircraft separation standards on final approach under certain meteorological conditions. Three sets of reduced separation standards have been hypothesized in order to describe the operational characteristics of potential WVAS systems. Analyses develop several operational schemes which allow aircraft to transition to reduced separation standards when under WVAS coverage, while maintaining larger terminal area standards prior to intercepting that coverage. Specific applications of these schemes to Atlanta Hartsfield and Chicago O'Hare International Airports are also described. Other analyses investigate procedures for and dynamics of transitioning between different sets of separation standards. Capacity benefits corresponding to the utilization of the different sets of separation standards, under various operational procedures, are estimated for Chicago and Atlanta.

Garodz, L. J.,
"MEASUREMENTS OF THE VORTEX WAKE CHARACTERISTICS OF THE BOEING 747, LOCKHEED C5A AND OTHER AIRCRAFT,"
FAA Data Report, Project 177-621-03X, April 1970,
NAFEC, Atlantic City, NJ.

Flight tests were conducted at the Environmental Services Sciences Agency (ESSA) Site, Idaho Falls, Idaho, to investigate the vortices of the Boeing 747, 707, 727, Douglas DC-8 and DC-9, and the Lockheed C5A using the tower fly-by technique and a 200-foot tower. Flow visualization was provided by smoke grenades on the tower. In addition, CORVUS smoke oil was used on the B-747 and B-707 for vortex marking. Three-dimensional airflow measurement hot-wire sensors were mounted at 25-foot intervals up the tower. Atmospheric measurements were performed by ESSA. These tests revealed that (1) vortex core diameters are much smaller (almost an order of magnitude) than certain existing theories predicted; (2) vortex characteristics are significantly affected by air plane configuration with the exception of the clean wing B-727/DC-9. For the former, the vortex tangential velocities decreased with an increase in flap deflection. For the latter, the tangential velocities were fairly independent of airplane configuration. $V_{\Theta max}$ was about 140 ft/sec for the B-747/707/C5A in clean/low flap setting configuration and decreased to 60-100 ft/sec for the landing configuration, full flaps; (3) the B-727 vortices produced a distinct artillery shell-type whine as they passed overhead; (4) the primary vortex dissipation mode appeared to be bursting; (5) the vortices persisted for less than 2 minutes regardless of aircraft and configuration.

Garodz, L. J.,
"INVESTIGATION OF THE RELATIVELY LONG TIME-HISTORY CHARACTERISTICS OF THE CV-880 AIRPLANE IN TERMINAL AREA-TYPE FLIGHT OPERATIONS,"
FAA Data Report, Project 504-303-03X, Nov. 1970,
NAFEC, Atlantic City, NJ.

The CV-880 vortex characteristics were investigated using the tower fly-by and aircraft-mounted vortex flow visualization techniques. Tests were performed in takeoff, landing and holding (clean) configurations. General results were (1) vortex characteristics; i.e., intensity, persistence, and movement followed the same pattern with regard to aircraft configuration effects as noted and reported on previously for other aircraft; (2) vortex lateral movement in ground effect was about 47 feet AGL which approximates $(\pi/8)$ b for the CV-880; (3) the automatic 8-degree spoiler deflection on the top of the wing combined with landing flap deflection of 55 degrees appeared to assist in producing low V_{Θ} and in accelerating vortex dissipation; (4) an ambient wind velocity of 3 to 7 mph appears to be most conducive to vortex persistence within the first 100 feet above ground for takeoff and landing configurations; (5) vortices changed from an orderly to a random, turbulent-type flow in less than 2 minutes with some degree of flap deflection; and (6) CV-880 vortices for the conditions of these tests, were considered to have dissipated to insignificant velocities in less than 2,500 feet lateral travel under crosswind conditions.

Garodz, L. J.,
"INVESTIGATION OF JET TRANSPORT AIRCRAFT VORTEX SYSTEMS DESCENDING INTO AND GENERATED IN GROUND EFFECT,"
FAA Data Report, Project 504-303-03X, Nov. 1970,
NAFEC, Atlantic City, NJ.

Flight tests were performed with B-707, B-727, DC-9 and CV-880 to investigate the characteristics of vortex systems generated within ground effect and those generated out of but descending into ground effect. The tower fly-by technique was used. Aircraft passed upwind of the tower in takeoff, holding and landing configuration with the latter on a 2.75-degree glide-slope at 20-, 40-, 60-, 80- and 100-foot altitudes above ground level (AGL). General results were (1) vortices generated by aircraft with some degree of flap deflection tended to become unstable and degenerate to discontinuous, segmented-type vortices or a random-type motion in about 90 seconds; (2) a pulsating axial flow appears to signal the onset of vortex core disintegration; (3) for identical ages, there appears to be a drop-off in vortex tangential velocities as they are generated closer to the ground; (4) airflow sensors which were spaced at 10-foot intervals on the 100-foot tower were too far apart; and (5) with the exception of the DC-9/B-727 aircraft, flap deflection had a significant effect on $V_{\Theta max}$, vortex structure and life-span. As with previous tests, DC-9/B-727 vortex characteristics appeared to be independent of aircraft configuration and produced the highest V_{Θ}, about 200 feet per second for the B-727.

Garodz, L. J.,
"FEDERAL AVIATION ADMINISTRATION FULL-SCALE AIRCRAFT VORTEX WAKE TURBULENCE FLIGHT TEST INVESTIGATIONS: PAST, PRESENT, FUTURE,"
AIAA Paper No. 71-97,
New York, NY, 1971.

This is a brief summary/status report on flight test programs which are designed to gather quantitative data on aircraft vortex characteristics for air traffic control application. Aircraft tested to date include the Sikorsky S-58 helicopter; the Boeing 747, 727 and 707; the Douglas DC8-63, DC8-33 and DC9-10; the Lockheed C5A, C-141; and the Convair CV-880 aircraft. Future vortex investigation flight tests will include the Douglas DC-10, Lockheed L1011 and the Concorde aircraft. Test techniques discussed are the aircraft tower fly-bys, vortex penetrations with suitably instrumented probe aircraft and vortex probing with an airborne rake-type airflow measurement system suspended from a second aircraft.

Garodz, L. J.,
"MEASUREMENTS OF BOEING 747, LOCKHEED C5A AND OTHER AIRCRAFT VORTEX WAKE CHARACTERISTICS BY TOWER FLY-BY TECHNIQUES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 265-285.

Flight tests have been conducted by the FAA at both the

ESSA/AEC facility, Idaho Falls, Idaho, and the NAFEC, Atlantic City, New Jersey, during the period 18 February 1970 through 3 August 1970 to gather quantitative data on aircraft vortex wake characteristics using the tower fly-by technique. Aircraft tested included the Boeing 747, 707-300, and 727-100; the Douglas DC-8-63F, DC-8-33, and DC-9-10; the Lockheed C5A; the Convair 880; and the Learjet 24. A 200-foot and a 100-foot tower was used at the ESSA and NAFEC test sites, respectively. Vortex flow velocities were obtained using hot-film/hot-wire sensors.

Garodz, L. J., Barber, M. R. and Kurkowski, R. L.,
"FLIGHT TEST INVESTIGATION OF THE VORTEX WAKE CHARACTERISTICS BEHIND A BOEING 727 DURING TWO-SEGMENT AND NORMAL ILS APPROACHES,"
FAA-NA-75-151, Oct. 1975,
NAFEC, Atlantic City, NJ.

A series of flight tests were performed to evaluate the vortex wake characteristics of a Boeing 727 (B727-200) aircraft during conventional and two-segment ILS approaches. Twelve flights of the B727, equipped with smoke generators for vortex marking, were flown wherein its vortex wake was intentionally encountered by a Lear Jet model 23 (LR-23) or a Piper Twin Comanche (PA-30); and its vortex location during landing approach was measured using a system of photo-theodolites. The tests showed that at a given separation distance there were no readily apparent differences in the upsets resulting from deliberate vortex encounters during the two types of approaches. Timed mappings of the position of the landing configuration vortices showed that they tended to descend approximately 91 meters (300 feet) below the flight path of the B727. The flaps of the B727 have a dominant effect on the character of the trailed wake vortex. The clean wing produces a strong, concentrated vortex. As the flaps are lowered, the vortex system becomes more diffuse. Pilot opinion and roll acceleration data indicate that 4.5 nautical miles would be a minimum separation distance at which roll control could be maintained during parallel encounters of the B727's landing configuration wake by small aircraft. This minimum separation distance is generally in scale with results determined from previous tests of other aircraft using the same roll control criteria.

Garodz, L. J., Hanley, W. J. and Miller, N. J., "ABBREVIATED INVESTIGATION OF THE LOCKHEED L1011 AIRPLANE VORTEX WAKE CHARACTERISTICS IN TERMINAL AREA-TYPE OPERATIONS," FAA Data Report, Project 214-741-04X, July 1972, NAFEC, Atlantic City, NJ.

A brief flight test investigation was performed at the National Aviation Facilities Experimental Center (NAFEC) to investigate the time-history characteristics of the vortex system of the Lockheed L1011 Tri-Star jet transport airplane in terminal area-type operations using a 140-foot high instrumented tower. Vortex rotational flow velocities were measured by hot-film anemometers, vortex flow visualization as outlined by tower-mounted smoke grenades was documented and meteorological data was recorded. Although only 19 tower fly-by passes were made, the test results showed that (1) the L1011 vortex system was more persistent and intense than other heavy jet transport (>300,000 lbs.) aircraft tested by NAFEC but did not persist for more than 2 minutes; (2) vortex dissipation was primarily due to vortex instability (bursting); vortex core diameters were on the average of 5, 4 and 2 feet in diameter for the landing, approach and takeoff configurations, respectively; (4) peak-recorded tangential velocities V_Θ were 126, 135, and 224 feet per second for these same respective configurations; (5) the math model $V_\Theta=(r_c/r)V_{\Theta max}[\ln(r/r_c)+1]$ appeared to best describe the radial distribution of tangential velocities; (6) the upwind vortex was more intense and persistent than the downwind vortex for crosswind tests; (7) vortex lateral movement in ground effect was about $(\pi/6.6)b$ above ground level; and (8) average vortex descent velocities approached 6 feet per second out of ground effect.

Garodz, L. J., Hanley, W. J. and Miller, N. J., "ABBREVIATED INVESTIGATION OF THE DOUGLAS DC-10 AIRPLANE VORTEX WAKE CHARACTERISTICS IN TERMINAL AREA-TYPE OPERATIONS," FAA Data Report, Project 214-741-04X, Aug. 1972, NAFEC, Atlantic City, NJ.

The Douglas DC-10 Series 10 vortex characteristics were investigated using the tower fly-by technique. NAFEC's 140-foot high vortex test tower was used. Hot-film airflow sensors at 1-foot intervals on the tower were used for tangential velocity measurements and smoke grenades for flow visualization. Wind velocity/direction and temperature were measured at 5 points on the tower. Twenty tower fly-bys were conducted in takeoff, approach and landing configurations. Results indicated that (1) DC-10 vortex characteristics were similar to another widebodied jet, the L1011 which was previously tested; (2) multiple vortices were noted in the recorded data; (3) visually, vortex flow visualization revealed that the vortices underwent an instability mode and dissipated, primarily by bursting, in less than 2 minutes; (4) vortex tangential velocities of up to 192 feet per second were recorded (takeoff configuration); and (5) core diameters were relatively small - about 8 to 10 feet.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.,
"THE MEASUREMENT OF THE MCDONNELL-DOUGLAS DC-9 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE,"
FAA-RD-74-173, Nov. 1974,
NAFEC, Atlantic City, NJ.

The results are presented of a series of low-altitude (approximately 200 feet above ground level) flight tests performed at NAFEC, Atlantic City, N.J., in which the trailing vortices of the McDonnell-Douglas DC-9 airplane were investigated, using a 140-foot instrumented tower. Flow visualization (colored smoke streams) was employed and film records made. The airplane was tracked by the NAFEC phototheodolite facility. Data presented consists of plots of vortex tangential velocity distribution, peak velocity as a function of time, airplane configuration and wind speed, vortex descent rates, and lateral transport rates. Principal findings were that (1) within the time period 30-100 seconds after vortex generation, the peak velocities within the vortices were bounded by the function $V_\Theta=396\exp(-.0347t)$, with a half-life of 20 seconds; (2) vortex cores were uniformly small (1-2 feet) in both configurations tested (takeoff and landing), and little or no growth with time was found; (3) vortex lateral transport velocities correlated well with the crosswind measured at 140 feet; and (4) the presence of a temperature inversion markedly retarded the vortex descent rates. The highest peak recorded tangential velocity was 120-130 feet per second, found to occur in both configurations tested.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.,
"THE MEASUREMENT OF THE BOEING 747 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE,"
FAA-RD-73-156, June 1974,
NAFEC, Atlantic City, NJ.

The characteristics of the trailing vortex system of the Boeing 747 airplane have been investigated by the National Aviation Facilities Experimental Center (NAFEC), Atlantic

City, N.J., during a series of flight tests conducted in September and October 1972. This investigation is part of a long-term program, started in February 1970 with flight tests conducted by NAFEC at the Atomic Energy Commission site at Idaho Falls, Idaho, devoted to the study of the overall wake turbulence problem. The present tests were conducted using improved flow measurement and meteorological instrumentation, permitting greater resolution than had been possible in earlier testing. Principal findings were that the peak tangential velocity decays as the reciprocal of the square root of the time elapsed since vortex generation; that the peak velocity is unaffected by the throttling back of the adjacent outboard engine; and that the lateral transport velocities correlate quite well with theory. Vortex descent rates did not correlate with theory, being up to three times greater than theoretical values.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.,
"THE MEASUREMENT OF THE BOEING 727 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE,"
FAA-RD-74-90, Aug. 1974,
NAFEC, Atlantic City, NJ.

The results are presented of a series of low altitude (100-300 feet above ground level) flight tests performed at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, in which the trailing vortices of the Boeing 727 airplane were investigated, using a 140-foot tower instrumented with air velocity, direction, temperature, and humidity sensors. Flow visualization was also employed, using colored smoke streams and film records made. The airplane was tracked by the NAFEC Phototheodolite Facility. The data presented consists of plots of vortex tangential velocity distribution, peak tangential velocity as a function of time, airplane configuration, windspeed, and airplane altitude in proximity to the tower, vortex descent rates, lateral transport velocities, and specimen time histories of the velocities measured by individual sensors.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.,
"THE MEASUREMENT OF THE BOEING 707 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE,"
FAA-RD-75-15, March 1975,
NAFEC, Atlantic City, NJ.

The results are presented for a series of low altitude (160-240 feet above ground level) flight tests performed at the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, New Jersey, in which the trailing vortices of the Boeing 707 airplane were investigated using a 140-foot tower instrumented with airspeed, velocity, direction, temperature, and humidity sensors. Flow visualization was employed and motion picture records made. The airplane was tracked by the NAFEC Phototheodolite Facility.

Garodz, L. J., Lawrence, D. M. and Miller, N. J.,
"MEASUREMENT OF THE TRAILING VORTEX SYSTEMS OF LARGE TRANSPORT AIRCRAFT USING TOWER FLY-BY AND FLOW VISUALIZATION (SUMMARY, COMPARISON AND APPLICATION),"
FAA RD-75-127, May 1975,
NAFEC, Atlantic City, NJ.

Full-scale flight test investigations have been made of the characteristics, persistence and movement of the trailing vortices generated by propeller and jet transport aircraft. The tests were performed by NAFEC, Atlantic City, N.J., during the period 1970-1973 using tower fly-by and vortex flow visualization. The results are summarized and comparisons made of the vortices of the Douglas DC-10, DC-9, and DC-7; Boeing 747, 727 and 707; Lockheed C5A, C141, and L1011; and the Convair 880 aircraft. Vortex mathematical models and decay mechanisms are discussed and their effects (upset potential) on encountering aircraft are investigated for possible air traffic control application.

Garodz, L. J. and Miller, N. J.,
"INVESTIGATION OF THE VORTEX WAKE CHARACTERISTICS OF JET TRANSPORTS DURING CLIMBOUT AND TURNING FLIGHT,"
FAA AEQ-75-1, May 1975,
NAFEC, Atlantic City, NJ.

The characteristics of the trailing vortices of several large propeller and jet transport aircraft have been investigated by the National Aviation Facilities Experimental Center (NAFEC), Atlantic City, N.J. This investigation centered around jet transport vortex persistence and movement during noise abatement-type departure operations at the Los Angeles International Airport and how approaching aircraft could avoid these vortices, however, it is concluded that the results and conclusions would be applicable to similar operations at other airports. The study is primarily based upon full-scale flight tests of vortex characteristics and their effect on encountering aircraft, conducted by NAFEC, NASA, Boeing, and the Royal Aircraft Establishment (RAE). Special flight tests for vortex investigations of the B-727 during noise abatement climbouts, straightaway and turning flight, in takeoff and clean configuration are included. Vortex-generating aircraft included C5A, B-747, B-707, B-727, DC-7, CV-880 and Lincoln; vortex probe aircraft included CV-990, B-737, Learjet 23, DC-9 and Devon. A vortex avoidance zone was developed which has an active life of 2 min when below 5,000 ft above ground level and 2.6 min when higher than 5,000 ft above ground level.

Garodz, L. J., Miller, N. J. and Lawrence, D. M.,
"THE MEASUREMENT OF THE DC-7 TRAILING VORTEX SYSTEM USING THE TOWER FLY-BY TECHNIQUE,"
FAA-RD-73-141, Nov. 1973,
NAFEC, Atlantic City, NJ.

This report describes the technique and presents the results of a series of fullscale flight tests performed at NAFEC in September 1971, in which the wing trailing vortices of the Douglas DC-7 airplane were investigated by flying the airplane at low altitude, upwind of, and in close proximity to a 140-foot instrumented tower. Tower instrumentation consisted of hot-film anemometers located at 4-foot intervals and wind velocity and direction sensors. Vortex air flow visualization was by use of colored smoke. The aircraft was tracked by the National Aviation Facilities Experimental Center's Phototheodolite Facility. The data consists of tangential velocity distribution plots, peak recorded velocity as a function of time, airplane configuration and wind; vortex vertical and lateral transport velocities, and specimen time histories of the velocities recorded at individual sensors. The principal findings were: (1) Peak absolute velocity, associated with the vortex core decays exponentially; (2) Vertical transport velocities of the vortices do not correlate well with those predicted by potential flow theory; (3) Lateral transport velocities correlate fairly well with values obtained from theory; and (4) The resolution possible with 4-foot spacing of the hot-wire anemometer is insufficient to precisely define vortex core size of the subject airplane.

Garodz, L. J. and Schutz, C. M.,
"ANALYSIS OF LOW ATMOSPHERIC DENSITY WAKE TURBULENCE CHARACTERISTICS FOR JET TRANSPORT CATEGORY AIRCRAFT,"
FAA Data Report, Project 177-621-04X, Feb. 1968,
NAFEC, Atlantic City, NJ.

The characteristics of the trailing vortices of several large jet transport aircraft operating at high altitudes at enroute speeds over the ocean were investigated by vortex flow visualization and penetration techniques. Flight tests were conducted from 29,000 to 38,000 feet. Vortex generators were a Lockheed C141, CV-880, Boeing C-135. Vortex penetrators included a C141, CV-880, Boeing C-135 and two specially instrumented Lockheed T-33 aircraft, one from National Aeronautical Establishment, Canada, and the other from NASA-Langley Research Center. Contrails were the primary means of vortex flow visualization except for the CV-880 wherein dumped dyed fuel was used. Separation distances between generator and penetrator ranged from 1,000 feet up to 8 nautical miles. It was found that (1) the contrails when they existed did indeed mark the trailing vortices for these model aircraft; (2) vortex turbulence induced on the probe aircraft ranged from moderate to severe; (3) discrete vortices in the form of toroids, with high energy content, were observed and felt by the probe aircraft; and (4) compressor stall was experienced on three of the four C141 engines, and the fourth flamed out during an encounter at 1 nautical mile separation.

Gartrell, L. R. and Rhodes, D. B.,
"A SCANNING LASER-VELOCIMETER TECHNIQUE FOR MEASURING TWO-DIMENSIONAL WAKE-VORTEX VELOCITY DISTRIBUTIONS,"
NASA TM-1661, May 1980,
NASA Langley Research Center, Hampton, VA.

A rapid scanning two dimensional laser velocimeter (LV) has been used to measure simultaneously the vortex vertical and axial velocity distributions in the Langley Vortex Research Facility. This system utilized a two dimensional Bragg cell for removing flow direction ambiguity by translating the optical frequency for each velocity component, which was separated by band-pass filters. A rotational scan mechanism provided an incremental rapid scan to compensate for the large displacement of the vortex with time. The data were processed with a digital counter and an on-line minicomputer. Vaporized kerosene (0.5 micron to 5 micron particle sizes) was used for flow visualization and LV scattering centers. The overall measured mean-velocity uncertainty is less than 2 percent. These measurements were obtained from ensemble averaging of individual realizations.

Gartrell, L. R. and Jordan, Jr., F. L.,
"DEMONSTRATION OF RAPID-SCAN TWO-DIMENSIONAL LASER VELOCIMETRY IN THE LANGLEY VORTEX RESEARCH FACILITY FOR RESEARCH IN AERIAL APPLICATIONS,"
NASA TM 74081, Aug. 1977,
NASA Langley Research Center, Hampton, VA.

Tests were conducted to demonstrate a rapid scan two dimensional laser velocimeter (LV) measurement technique for aerial applications research. The LV system is capable of simultaneously measuring both vertical and axial flow velocity components in a near or far field vortex system. Velocity profiles were successfully measured in the wake vortex of a representative agricultural aircraft model, with the vortex system rapidly transporting in ground effect. Results indicate that the laser velocimetry technique can provide quantitative information of wake vortex characteristics in ground effect.

Gee, D., Paillet, F. L. and Kurylowich, G.,
"ANALYSIS OF A WAKE TURBULENCE HAZARD IN USAF OPERATIONS (T-39 ACCIDENT),"
AFFDL-TM-75-19-FGC, Jan. 1975,
Wright-Patterson Air Force Base, OH.

Analyses related to the investigation of a T-39 accident are presented which appeared caused by an encounter with the wake of a DC-10. Wake propagation and dynamic encounter numerical simulations are compared to the pilots' statements and other relevant facts. The necessary existence of an inversion layer which could prevent the rapid descent of the DC-10 wake is also noted.

Georges, T. M.,
"ACOUSTIC RAY PATHS THROUGH A MODEL VORTEX WITH A VISCOUS CORE,"
J. Acoustical Society, Vol. 51, No. 1, Jan. 1972, pp. 206-209.

Angular deflection and the formation of a line caustic are examined for acoustic waves passing through a cylindrical vortex with a viscous core. Ray paths are displayed in normalized form and appear to be applicable to the aircraft-wake problem as well as to long-distance sound propagation through synoptic weather features.

Gessow, A.,
"AIRCRAFT WAKE TURBULENCE MINIMIZATION BY AERODYNAMIC MEANS,"
Sixth Conference on Aerospace and Aeronautical Meteorology,
American Meteorology Society, El Paso, 1974.

The paper reviews NASA's efforts on wake vortex turbulence minimization by aerodynamic design or retrofit modifications to large aircraft. Theoretical and experimental (ground-based and flight) results are presented which show that the adverse effects of a vortex wake produced by a large aircraft on a small following aircraft can be reduced significantly.

Gilliam, Jr., F. T.,
"INVESTIGATION OF THE EFFECTS OF DISCRETE WING TIP JETS ON WAKE VORTEX ROLL UP,"
PhD Thesis, Aug. 1983,
Air Force Inst. of Tech., Wright-Patterson AFB, OH.

A water tunnel experiment and a computational flow field model show that discrete wing tip jets can strongly affect the roll up of the wing tip vortex and apparently decrease its rolled up strength at moderate levels of blowing. The key factor in vortex alleviation was the extent of the local flow interactions between the discrete jets and the developing wing tip vortex. Vortex trajectory in both the spanwise and vertical directions was influenced by the jets. An outboard shift of the wing tip vortex indicated that discrete wing tip jets may be able to produce improved wing aerodynamics during cruise flight. The counterrotating pair of vortices generated by a jet in a cross flow were clearly seen in the water tunnel and appeared to be very effective in reducing the intensity of the wing vortex system. Two types of periodic secondary vortices were also observed in the water tunnel for heavy jet blowing. These were spin-off vortices which periodically developed in the rolling up tip vortex but rapidly spun outboard and above the wing; and entrained vortices which was a set of periodic vortices laterally connecting the wing tip vortex to the vortices embedded in the jet. These secondary vortices are oriented such that they will greatly accelerate the spreading of wake vorticity through the vortex stretching term of the Helmholtz equation. This influence was confirmed in the water tunnel tests.

Goff, R. W.,
"STUDY OF THE PERFORMANCE REQUIREMENTS OF A VORTEX MONITORING SYSTEM,"
DOT-TSC-141-1, March 1972,
Raytheon Company, Sudbury, MA.

This study involved four basic task items. The first was a general review of the characteristics of trailing vortex wakes. The second task item involved the generation of envelopes showing the expected vortex drift for the Boeing 747 and 727 aircraft. The third task item was an investigation of the environmental factors with which a vortex monitoring system would interact. The final task item was the application of the vortex drift data and operational usage considerations to the investigation of the performance requirements for a vortex monitoring system.

Goff, R. W.,
"AIRCRAFT WAKE VORTEX BEHAVIOR STUDY, VORTICES AND RUNWAY UTILIZATION,"
ER73-4300, July 1973,
Raytheon Company, Sudbury, MA.

This report contains a survey and description of Air Traffic Control equipment which may be modified to provide the warning signal for a vortex detection system (the vortex warning device will alert landing aircraft of a vortex hazard). Since an important aspect of implementing new Air Traffic Control equipment is its integration with existing equipment and procedures, general information relevant to that problem is also provided.

Goff, R. W.,
"AIRCRAFT WAKE VORTEX BEHAVIOR STUDY,"
ER73-4319, Aug. 1973,
Raytheon Company, Sudbury, MA.

This report presents an analysis of the variations in wind magnitude and direction occurring at various times of day at Logan and Kennedy Airports, and an analysis of the aircraft spacing required to preclude an aircraft-vortex encounter in the approach corridor beyond the middle marker.

Goldstone, L.,
"AN INVESTIGATION INTO WAKE TURBULENCE INCIDENTS,"
CAA Report DTRD/7301, Nov. 1973,
Civil Aviation Authority, London, England.

A working group was set up in March 1972 by the Director of Technical Research and Development to consider wake turbulence incidents reported in the United Kingdom from January 1972. The paper contains an analysis of these incidents and presents certain conclusions regarding factors which are relevant to the formation and persistence of the wake.

Goodman, T. R.,
"THE VORTEX CORE JET NEAR THE POINT OF GENERATION,"
72-91, April 1972,
Oceanics Inc., Plainview, NY.

Near the point of generation of a wing tip vortex the axial velocity in the vortex core can be considerably greater than the free stream velocity. The present analysis describes the velocity field under these circumstances and shows that a self-similar solution exists that satisfies all the boundary conditions. The resulting two-point boundary value problem is solved on a digital computer and shows qualitative agreement with experiments.

Gorstein, M.,
"WAKE VORTEX DETECTION AND AVOIDANCE SYSTEMS,"
USSR/US Aeronautical Technology Symposium, Moscow, USSR, July 1973.

A Wake Vortex Avoidance System (WVAS) to improve air transport safety and airport efficiency is being developed by the Transportation Systems Center for the FAA. The WVAS will detect and/or predict the current movement of vortices in nearby airport corridors, assess them as potential hazards to following aircraft, and provide warning to controllers and pilots to prevent hazardous encounters. The paper briefly discusses vortex behavior characteristics, vortex sensors, an in-process experimental program and several possible wake vortex avoidance system concepts.

Gorstein, M., Hallock, J. N., McWilliams, I. G. and Goff, R. W.,
"SYSTEM PERFORMANCE REQUIREMENTS FOR MONITORING TRAILING VORTICES IN A TERMINAL ENVIRONMENT,"
National Aerospace Electronics Conf., NAE/IEEE, Dayton, OH, 1971.

The paper discusses the performance requirements for systems capable of monitoring trailing vortices in three situations: (1) the approach and departure corridors, (2) between adjacent runways, and (3) at runway intersections. The monitoring requirements are shown to depend upon the vortex characteristics, the airport-runway geometry, and the operations characteristics of the airport (separation standards, runway usage and runway selection based upon the wind velocity). The significance of these factors are discussed and examples are given for several vortex monitoring situations at Logan Airport in Boston.

Gorstein, M., Hallock, J. N. and McWilliams, I. G.,
"AIRCRAFT WAKE VORTEX AVOIDANCE SYSTEMS,"
Proceedings of Electronics and Aerospace Systems Convention, IEEE, Washington, 1972, pp. 64-69.

The behavior, detection, and prediction of the motion of aircraft wake vortices in the airport environment is discussed. Preliminary designs of wake vortex avoidance systems based upon the current assessment of aircraft vortex hazards are presented.

Govindaraju, S. P. and Saffman, P. G.,
"FLOW IN A TURBULENT TRAILING VORTEX,"
Physics of Fluids, Vol. 14, No. 10, Oct. 1971, pp. 2074-2080.

The structure of turbulent line vortices is examined. A general argument is constructed to show that the vortex must develop an overshoot of circulation if it entrains fluid at a rate greater than that due to molecular diffusion. A weak hypothesis on the distribution of Reynolds stress leads to the logarithmic profile of Hoffman and Joubert and an estimate of the maximum Reynolds stress. The results of a turbulence model due to Saffman are presented and shown to be poor.

Grabowski, W. J. and Berger, S. A.,
"SOLUTIONS OF THE NAVIER-STOKES EQUATIONS FOR VORTEX BREAKDOWN,"
J. Fluid Mech., Vol. 75, Part 3, June 1976, pp. 525-544.

A numerical investigation of vortex breakdown has been undertaken in an attempt to understand its properties, and the mechanisms responsible for it. Solutions of the full steady axisymmetric Navier-Stokes equations for breakdown in an unconfined viscous vortex have been obtained for core Reynolds numbers up to 200, for a two-parameter family of assumed upstream velocity distributions. Diffusion and convection of vorticity away from the vortex core, and the strong coupling between the circumferential and axial velocity fields in highly-swirling flows, are shown to lead to stagnation and reversal of the axial flow near the axis. The various theories of vortex breakdown are considered in light of the present numerical solutions.

Graham, J. A. H., Newman, B. G. and Phillips, W. R.,
"TURBULENT TRAILING VORTEX WITH CENTRAL JET OR WAKE,"
International Council of the Aeronautical Sciences Paper 74-40, Haifa, Israel, 1974.

The concentrated trailing vortices from the wing of heavy aircraft contain significant rotational velocities which may persist for minutes. To reduce this time, the turbulence level in the core of the vortex may be increased by superimposing a longitudinal jet or wake. A series of experiments have been conducted in a circular wind tunnel with a trailing vortex along the center line. Jets or wakes of varying momentum were added to the center of the vortex. The mean velocity and the complete Reynolds stress tensor were measured at various azimuthal positions.

Graham, J. A. H. and Phillips, W. R.,
"REYNOLDS STRESS AND VELOCITY MEASUREMENTS IN A TURBULENT TRAILING VORTEX,"
TN-75-1, Apr. 1975,
McGill Univ., Montreal, Canada.

The results of a series of experiments conducted in a circular blower wind tunnel on a turbulent trailing vortex of Reynolds number Gamma sub infinity/nu = 57000 are given. The results include the rotational and axial velocity components and the complete Reynolds stress tensor, for five cases of axial momentum, two jets, two wakes and a case of zero momentum increment. All measurements were made with a hot wire anemometer linked to an on-line digital computer. Results are given at three downstream locations, x/c = 45, 76 and 109 where c is the average chord width of the vortex generator.

Grahame, W. E.,
"A PRELIMINARY METHOD FOR THE PREDICTION OF MINIMUM INTERVAL TAKEOFF (MITO),"
TM 80-9.2/1, Feb. 1980,
Calspan Corp., Los Angeles, CA.

Methodology to predict minimum interval takeoff (MITO) has been developed by Calspan from full-scale flight test wake vortex data and from analytical procedures which determine aircraft roll characteristics due to wake vorticity. The method has been applied to SAC-based aircraft, including the FB-111, KC-135, B-52 and B-1, which were "flown" behind a 747 (E-4) aircraft to determine MITO time sequences. Appropriate expressions for circulation and vortex peak vorticity decay based on 747 flight test data were applied. From these expressions, values of vortex core radius were calculated and applied in a roll moment function to determine variations of the vortex-induced roll moment coefficient with time. Values of vortex-induced rolling moment as a function of time were calculated and compared against maximum roll capability to indicate "safe" time intervals for MITO.

Granger, R.,
"STEADY THREE-DIMENSIONAL VORTEX FLOW,"
J. Fluid Mech., Vol. 25, Part 3, July 1966, pp. 557-576.

A theory is developed for an incompressible fluid in a steady three-dimensional rotational flow. Solutions are obtained subject to the restriction of small perturbations and are determinant provided that the vorticity distribution along the axis of rotation is known. Effects of viscosity are included.

Greene, G. C.,
"WAKE VORTEX ALLEVIATION,"
AIAA Paper No. 81-0798,
Atlantic City, NJ, May 1981.

This paper describes some of the National Aeronautics and Space Administration's (NASA's) recent and current research on aerodynamic techniques for minimizing the aircraft trailing vortex hazard. The potential benefits and operating problems of the more promising concepts are discussed. Recent flight-test results are presented which show that essentially total vortex alleviation can be achieved at a 3 nautical mile separation distance by oscillating the aircraft's lateral-control surfaces. While not operationally practical, these results suggest that it may be possible to minimize the wake hazard by exciting longitudinal instabilities.

Greene, G. C.,
"AN APPROXIMATE MODEL OF VORTEX DECAY IN THE ATMOSPHERE,"
J. Aircraft, Vol. 23, No. 7, July 1986, pp. 566-573.

An approximate analysis of atmospheric effects on wake vortex motion and decay is presented. The effect of density stratification, turbulence, and Reynolds number are combined in a single model so that the relative importance of different parameters can be estimated. Predicted wake motion is shown to be in good agreement with limited data from ground facility and flight test measurements taken under low-turbulence conditions. Wake decay was found to depend strongly on both density stratifications and turbulence. For typical levels of turbulence, wake decay was found to result from the Crow instability except under strongly stratified conditions.

Greene, G. C., Lamar, J. E. and Kubendran, L. R.,
"AIRCRAFT VORTICES - JUNCTURE, WING, AND WAKE,"
AIAA Paper 88-3742,
Cincinnati, OH, July 1988.

Many real aircraft flows contain regions of three-dimensional separation with vortices. This paper presents selected results for three representative flows: juncture vortex, lifting-wing vortex, and wake vortex. Due to the difficulty of studying vortices, flow visualization was used as a primary research tool. Vortices are found to depend in subtle ways on details of the configuration, Reynolds number, or the environment. Examples showing the effect of filleting on the juncture flow, Reynolds number on the wing flow, and density gradients on the wake flow are presented.

Groenenboom, J. and Ievalts, J.,
"WING VORTEX VISUALIZATION AND INTERFERENCE PATTERNS,"
AIAA Paper No.77-309,
Washington, DC, 1977.

Two symmetrical airfoils with an elliptical lift distribution were tested in the Iowa State University low-turbulence wind tunnel to determine through visualization the effects of vortex interaction. The first portion of the study was devoted to determining the best method of vortex visualization. It was found that steam injected into the flow forward of the airfoils gave the best delineation. The two wings were tested to determine what effect circulation strength and direction and separation distance had on the vortices at various downstream locations. Test results showed that the vortices interacted by wrapping around one another and merging. The degree of interaction was primarily dependent on separating distance and circulation strength.

Grow, T. L.,
"THE EFFECT OF WING GEOMETRY AND LOWER SURFACE BOUNDARY LAYER ON THE ROLLED-UP TIP VORTEX,"
MS Thesis, June 1967,
Penn. State Univ., University Park, PA.

A theoretical and an experimental analysis were performed to determine the effect the wing geometry and the boundary layer on the lower surface of the wing have on the size and strength of the rolled-up tip vortex. The theoretical analysis was limited by the inherent three-dimensional properties of the flow. An extensive experimental investigation provided results which adequately described the vortex strength and geometry for the many wing configurations which were tested. From these results the size and strength of the rolled-up tip vortex can be predicted for any wing with similar geometry and Reynolds number.

Grow, T. L.,
"EFFECT OF A WING ON ITS TIP VORTEX,"
J. Aircraft, Vol. 5, No. 2, March-April 1968, pp. 37-41.

A theoretical and an experimental analysis was performed to determine the effect that the wing geometry and the boundary layer on the lower surface of the wing have on the trailing rolled-up tip vortex. Model test results are presented for the vortex structure downstream of wings of varying aspect ratio and taper ratio. The geometry and strength of the rolled-up tip vortices were measured over a range of lift coefficients. In general, it was found that the strength of the vortex is less than one would predict on the basis of the midspan circulation about the wing. Conclusions are given with regard to the size and strength of a vortex as they relate to the wing aspect ratio, taper ratio, and lift coefficient.

Gupta, V. P.,
"VORTEX-RELATED ACCIDENTS OVER THE TEN YEAR PERIOD 1964-1973,"
FAA-EM-75-6, April 1975,
MITRE Corp., McLean, VA.

Out of the approximately 45,000 aviation accidents that occurred over the ten-year period 1964-73, in the conterminous United States, wake vortices have been cited as a cause or as factor in 147 accidents by the National Transportation Safety Board. These "vortex-related" accidents have been studied and categorized (by flight phases of the vortex-generating aircraft and the accident aircraft, and other pertinent factors) in the report with the objective of providing historical insight to the Wake Vortex Avoidance System development program. The vortex problem was found to be largely confined to small general aviation aircraft landing or taking off close behind air carrier aircraft under VFR conditions.

Gustafson, W. A. C., Davis Jr., D. W. and Deffenbaugh, F. D., "ANALYSIS OF THE TURBULENT WAKE OF A CASCADE AIRFOIL," J. Aircraft, Vol. 14, No. 4, April 1977, pp. 350-356.

The structure of the wake in an incompressible, turbulent fluid behind an airfoil in a cascade is investigated. Boundary-layer equations containing longitudinal curvature terms are applied to the problem and the similarity properties of the equations are developed. Local similarity solutions are determined for mean velocity profiles at several wake positions, and these results are compared with experimental data for two incidence angles. Good correlation between theory and experiment is obtained beyond approximately a tenth of a chord downstream of the airfoil at small incidence angles.

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Habercom, Jr., G. E.,
"AIRCRAFT WAKE VORTICES - A BIBLIOGRAPHY WITH ABSTRACTS,"
PB-82-809112, June 1982,
NTIS, Springfield, VA.

Wake vortices and turbulent flow across aircraft lifting surfaces were investigated. Aerodynamic characteristics of vortices were reviewed with special attention made to trailing aircraft and aviation safety.

Hackett, J. E.,
"LOCKHEED TECHNICAL EFFORTS IN WAKE TURBULENCE,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 19-27.

An overview is presented of the current wake turbulence research being conducted at Lockheed-California and Lockheed-Georgia. The effects of variations in span loading were examined by solving the general vorticity equation through the superposition of Lamb vortices and extended by allowing the eddy viscosity to vary in the downstream direction. The initial Lamb vortex profile was superimposed on various axial flows, and the second order boundary layer equations integrated to demonstrate how the different axial flows affected vortex decay. Results of a fixed-base simulation of a C-130 encountering a vortex were discussed.

Hackett, J. E. and Evans, M. R.,
"VORTEX WAKES BEHIND HIGH-LIFT WINGS,"
J. Aircraft, Vol. 8, No. 5, May 1971, pp. 334-340.

At high wing lift coefficients pertinent to STOL operation, the conventional neglect of vortex roll-up effects can lead to errors when calculating downwash at the tail plane and in the presence of ground or wind-tunnel walls. A classical unsteady treatment in the cross-flow plane, which calculates the roll-up of an initial spanwise row of point vortices, has been modified to allow for the influence of the wing. Additional meaning is thereby given to the streamwise length dimension and hence to aspect ratio and sweep. The effects of height-above-ground and of various tunnel heights and widths are discussed. Under certain limited conditions, notably with part-span flaps or too narrow a tunnel, part or all of the trailing vortex system may move upwards. Consequent changes in the vertical velocity field are additional to conventional estimates, involving only the appropriate image system.

Hackett, J. E. and Evans, P. F.,
"NUMERICAL STUDIES OF THREE-DIMENSIONAL BREAKDOWN IN TRAILING VORTEX WAKES,"
J. Aircraft, Vol. 14, No. 11, Nov. 1977, pp. 1093-1101.

Finite-element 3-D relaxation methods are used to calculate the development of vortex wakes behind aircraft for a significant downstream distance. The inclusion of a self-induction term in the solution, dependent upon local curvature and vortex core radius, permits calculation of finite lifetimes for systems for which infinite life would be predicated two-dimensionally. Single-pair, twin-pair, and multiple-pair studies are described. It is found, in single-pair studies, that there is a lower limit to the wavelengths at which the "Crow"-type of instability can occur. Below this limit, self-induction effects cause the plane of the disturbance waves to rotate counter to the vortex direction. Self-induction in 2-D generated twin spiral waves causes an increase in axial length, which becomes more marked with decreasing initial wavelength and the time taken for vortex convergence toward the center plane is correspondingly increased. In many cases designed to produce early vortex convergence at the center plane, it is found that the surviving vortex is sufficiently strong for significant hazard to remain. Such cases, which have low flap span, are also characterized by long-wavelength spirals, for which the potential for self-induced wake dispersion is small. There may therefore be a maloptimum flap-span ratio, in the mid-semispan range, for which time-to-converge maximizes. Limited studies of B-747 configurations show correct qualitative response to removal of the outer flap and to gear deployment, as compared with wind-tunnel and flight-test experience.

Hackett, J. E., Scruggs, R. M., Lyman, V. and Theisen, J. G.,
"THEORETICAL ANALYSIS AND DATA INTERPRETATION TO ASSIST THE GOVERNMENT IN EVALUATING THE VARIOUS DEVICES PROPOSED FOR ENHANCING VORTEX DECAY AND EXTRAPOLATION OF LABORATORY RESULTS TO FULL-SCALE APPLICATION,"
Report LG74ER0152, Oct. 1974,
Lockheed-Georgia, Marietta, GA.

The efforts briefly described herein evaluated methods for alleviating the aircraft vortex wake hazard problem.

Lockheed-Georgia Company scientists and consultants have used both theoretical means (hopefully to predict a physical mechanism for causing premature vortex decay) and correlation with IR&D scaled model tests on aero-mechanical devices or energizing techniques (vortex generators, jets, etc.) to modify the vortex wake without unacceptable compromise in aircraft performance. Principal tasks include: a) Theoretical study of jet and wake effects on vortex decay; b) Provide span-load distributions for Boeing 747 using potential flow model; c) Study the distortion of a vortex by a lifting surface immersed in the vortex; d) Feasibility study of using a vortex roll-up program iteratively with a vortex-lattice program to determine mutual interaction effect; e) Continuing consultation on a moving-base simulator program at NASA (Ames) jointly with the FAA.

Hackett, J. E. and Theisen, J. G.,
"VORTEX WAKE DEVELOPMENT AND AIRCRAFT DYNAMICS,"
Aircraft Wake Turbulence and Its Detection, edited bu J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 243-263.

Calculations of the sinuous instability of a trailing pair are extended, using a nonlinear vortex modeling technique, and the effects of initial parameters are examined, particularly the initially assumed wavelengths. More complex modes of vortex decay may be demonstrated by flow visualization in water, using the hydrogen bubble technique; vortex bursting is shown to be possible before and/or after the "wavy" mode. These small-scale measurements are shown to be consistent with flight measurements. In another series of experiments, smoke injected into the core of the trailing vortex behind a 13-foot-span C-130 wind-tunnel model, mounted in a 23-foot by 16-foot working section, showed remarkable coherence until the adverse pressure gradient in the wind-tunnel diffuser caused vortex bursting. The results of a computer simulation are discussed concerning the dynamic response and loads on an aircraft which enters the trailing vortex of a lead aircraft of large size.

Haines, A. L.,
"CONCEPTS FOR DETERMINATION OF LONGITUDINAL SEPARATION STANDARDS ON FINAL APPROACH,"
MTR-7047, Oct. 1975,
Mitre Corp., McLean, VA.

The concept of a longitudinal separation standard on final approach requires precise definitions in order to develop an analytical structure. These are developed in this paper with a view toward identifying the relationships between separation standards and the variables describing the final approach environment. This provides a basis for systematic evaluation of changes in separation standards due to changes in the environment, particularly through Engineering and Development products. Analytical relationships are developed primarily for IFR conditions, represented by strict adherence to all applicable ATC rules and procedures. For modeling purposes, relationships are also developed for 'standards' for VFR conditions, represented by visual approaches from an IFR flight plan.

Hall, D. L. and Amodeo, F. A.,
"OPPORTUNITIES ANALYSIS OF POTENTIAL ADVANCED VORTEX SYSTEMS SEPARATION STANDARDS,"
FAA-EM-79-17, July 1979,
Mitre Corp., McLean, VA.

The purpose of this study is to provide first order estimates of the benefits of reduced separation standards under Advanced Vortex System (AVS) operations. Benefits associated with conceptual Advanced Vortex Systems (AVS) are quantified from a delay reduction viewpoint. The study is equally applicable to airborne vortex alleviation technology or to ground or air-based vortex avoidance systems. Conducted as a first cut, exploratory analysis, the research compares the delay consequences of three sets of successively closer interarrival standards against the option of maintaining today's rules or a combination of today's and 3 nmi separations. The analysis was performed for only IFR weather conditions, since minimum required separation standards are not defined for VFR conditions. Three sets of standards were selected as representative of possible AVS capabilities. Substantial delay savings are shown to be possible even with demand growth below that projected to occur across the 1985 through 1995 analysis time period. The benefits are sufficiently large as to warrant a substantial research and development investment into an AVS program.

Hall, M. G.,
"A THEORY FOR THE CORE OF A LEADING-EDGE VORTEX,"
J. Fluid Mech., Vol. 11, Part 2, Sept. 1961, pp. 209-228.

In the flow past a slender delta wing at incidence one can observe a roughly axial symmetric core of spiralling fluid, formed by the roll-up of the shear layer that separates from a leading edge. The aim of this paper is to predict the flow field within this vortex core, given appropriate conditions at its outside edge. A sample calculation yields results which are in good qualitative and fair quantitative agreement with experimental measurements.

Hall, M. G.,
"A NUMERICAL METHOD FOR SOLVING THE EQUATIONS FOR A VORTEX CORE,"
ARC-R&M-3467, May 1965,
Royal Aircraft Establishment, Farnborough, England.

A method is presented for calculating steady axially symmetric spiralling motions of an incompressible fluid at large Reynolds numbers. By making approximations of the boundary-layer type the Navier-Stokes equations are reduced essentially to a pair of non-linear parabolic equations. Initial conditions are specified on some upstream cross-section, and boundary conditions on the axis of symmetry and on some bounding surface of revolution.

Hall, M. G.,
"THE STRUCTURE OF CONCENTRATED VORTEX CORES,"
Progress in the Aeronautical Sciences, Vol. VII, edited by D. Kucheman, Pergamon Press, 1966, pp. 53-110.

In a vortex we often observe an approximately axially symmetric core of spiralling fluid in which the vorticity is high. A review is given of recent work on the structure of such vortex cores. It begins with a discussion of the equations of motion and the appropriate boundary conditions, and continues with a description in general terms of the vigorous but highly responsive character of the flow, of the effects of compressibility and turbulence and of the phenomenon of energy separation. A discussion is given of the phenomenon of stagnation in the axial flow, spiral instability and finite transition, any of which may destroy the typical core of high vorticity or prevent its maintenance.

Hall, M. G.,
"A NEW APPROACH TO VORTEX BREAKDOWN,"
Proceedings of 1967 Heat Transfer and Fluid Mechanics Institute, edited by P. Libby, D. Olfe and C. Van Atta, Stanford Univ. Press, 1967, pp. 319-340.

Comparison between a practical example of vortex breakdown and a computed failure of the quasi-cylindrical approximation, and description of evidence that failure actually corresponds to breakdown. The theory for viscous axisymmetric quasi-cylindrical flows including the governing equations and boundary conditions, and the numerical method of solving the equations, is outlined. A simple model of a vortex core is set up which depends on only two parameters, representing the magnitude of the swirl and the shape of the bounding stream surface.

Hall, M. G.,
"VORTEX BREAKDOWN,"
Annual Review of Fluid Mechanics, Vol. 4, Ann. Rev. Inc., Palo Alto, 1972, pp. 195-218.

A study was made of the breakdown feature of the vortex core. The vortex core was set up by drawing fluid through a duct and imparting swirl with a set of vanes at entry. The spiral was followed along the duct and it was found that the structure of the vortex varied slowly in the axial direction, and then, unexpectedly, there is an abrupt change in the structure with a very pronounced retardation of the flow along the axis and a corresponding divergence of the stream surfaces near the axis.

Hallock, J. N.,
"PRESSURE MEASUREMENTS OF WAKE VORTICES NEAR THE GROUND,"
J. Aircraft, Vol. 9, No. 4, April 1972, pp. 311-312.

A simple barocel pressure sensor was tested to determine whether it could detect the presence of aircraft wake vortices. Pressure differentials in excess of 0.1 millibars were consistently measured when the vortices from DC-7, B-747, B-707, DC-8, C-141, and DC-3 aircraft were below 100 feet in altitude.

Hallock, J. N.,
"AIRCRAFT WAKE VORTICES: *THEIR MOTION AND DECAY,*"
AIAA Seminar,
Boston University, Boston, MA, Jan. 1973.

A review of the physics of aircraft wake vortices was presented considering the formation of vortices and their subsequent motion and decay. The experimental and analytical research programs of the Department of Transportation were reviewed; particular emphasis was given to the effects of meteorology on aircraft wakes.

Hallock, J. N.,
"MONITORING THE MOVEMENT OF WAKE VORTICES AT KENNEDY AND STAPLETON AIRPORTS,"
Proceedings Fifth Annual Symposium of the Society of Flight Test Engineers, SFTE, Anaheim, CA, 1974, pp. 4/7-4/12.

During the summer and fall of 1973, the Transportation Systems Center collected an extensive amount of data on the motion of aircraft make vortices. Two test sites were instrumented: the John F. Kennedy International Airport in New York and the Stapleton International Airport in Denver, Colorado. The vortices from over 10,000 landing aircraft were recorded and the motion of the vortices correlated with the ambient meteorological conditions. The results of these measurements coupled with user requirements lead to the description of three basic vortex avoidance systems.

Hallock, J. N.,
"WAKE VORTEX MODELING AND DETECTION,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 59-63.

The FAA program in wake vortices was reviewed and included: the development of reliable vortex prediction methods in terms of meteorological conditions and generator aircraft characteristics, the determination of a hazard criterion regarding how close an aircraft can approach a vortex without experiencing an unacceptable disturbance, and the development of effective vortex detection equipment. The results of over 10,000 vortex observations recorded at Kennedy and Stapleton International Airports were presented as well as possible techniques for eventually decreasing current separations.

Hallock, J. N.,
"WAKE VORTEX DECAY NEAR THE GROUND,"
AIAA Paper No. 75-882,
Hartford, CT, 1975.

The strength of wake vortices is being measured for aircraft landing on runway 31R at JFK International Airport using monostotic acoustic radars. By range-gating and Doppler processing the backscattered acoustic energy from a number of sensors, measurements are made of vortex height, strength or circulation, vertical velocity field, translational velocity, and the circulation distribution within the vortex. Possible decay mechanisms and correlations with meteorological conditions are presented.

Hallock, J. N.,
"AIRCRAFT WAKE VORTICES - AN ANNOTATED BIBLIOGRAPHY (1923-1975),"
FAA-RD-76-43, Jan. 1976,
DOT Transportation Systems Center, Cambridge, MA.

This annotated bibliography consists of 570 abstracts of publications on aircraft wake vortices. The material is arranged alphabetically by year of publication and covers the time period through 1975. Experimental and theoretical articles are included (except for helicopter vortices) and consider the formation, structure, motion, and decay of vortices and their effect on penetrating aircraft.

Hallock, J. N.,
"MONITORING WAKE VORTEX STRENGTH DECAY NEAR THE GROUND,"
J. Aircraft, Vol. 13, No. 10, Oct. 1976, pp. 830-832.

The strength of aircraft wake vortices is being measured for aircraft landing on runway 31R at the John F. Kennedy International Airport using monostatic acoustic radars. By range-gating and Doppler processing the backscattered acoustic energy from a number of sensors, measurements are made of vortex height, strength or circulation, vertical velocity field, translational velocity, and the circulation distribution within the vortex. Possible decay mechanisms and correlations with meteorological conditions are described.

Hallock, J. N.,
"VORTEX ADVISORY SYSTEM SAFETY ANALYSIS, VOLUME I: ANALYTICAL MODEL,"
FAA-RD-78-68,I, Sept. 1978,
DOT Transportation Systems Center, Cambridge, MA.

An analysis was conducted to examine the safety of decreasing landing aircraft separations to three nautical miles between the outer marker and the runway threshold. Such reduced separations would only be used when the Vortex Advisory System indicated that wake vortices would not pose a threat to a following aircraft. Based on state-of-the-art models of vortex and aircraft behavior, the analysis indicates that such reduced interarrival separations may be used safely by Large and Heavy aircraft following Heavies. When the analysis is expanded to include an as yet unproven crosswinds aloft model, the results indicate that reduced separations may be used by all aircraft regardless of leader/follower aircraft type.

Hallock, J. N.,
"VORTEX ADVISORY SYSTEM SAFETY ANALYSIS, VOLUME III: SUMMARY OF LASER DATA COLLECTION AND ANALYSIS,"
FAA-RD-78-68,III, Aug. 1979,
DOT Transportation Systems Center, Cambridge, MA.

A Laser-Doppler Velocimeter was used to monitor the wake vortices shed by 5300 landing aircraft at a point 10,000 feet from the runway threshold. The data were collected to verify the analysis in Volume I of the safety of decreasing interarrival separations to three nautical miles between the outer marker and the runway threshold. Such reduced spacings would only be used when the Vortex Advisory System (VAS) indicated that wake vortices would not pose a threat to a following aircraft. The data show that vortex behavior, during times identified by the VAS, is commensurate with the goal of using uniform three-nautical miles separations from the outer marker to touchdown regardless of leader or follower aircraft type.

Hallock, J. N.,
"VORTEX ADVISORY SYSTEM SAFETY ANALYSIS, VOLUME I: EFFECTIVENESS FOR SELECTED AIRPORTS,"
FAA-RD-80-62,I, May 1980,
DOT Transportation Systems Center, Cambridge, MA.

The Vortex Advisory System (VAS) is based on a wind criterion; when the wind near the runway end is outside of the criterion, all interarrival IFR aircraft separations can be set at 3 nautical miles. Five years of wind data have been obtained for 20 airports. By comparing the VAS wind criterion to the 5 years of wind data, the percentages of time that interarrival separations can be reduced at the 20 airports have been found. The percentages are give on an hourly and a monthly basis.

Hallock, J. N.,
"ANALYSIS OF THE WAKE VORTEX IMPLICATIONS FOR THE PROPOSED LDA/DME APPROACH AT LAMBERT/ST. LOUIS,"
FAA-427-PM-84-1, Dec. 1983,
DOT Transportation Systems Center, Cambridge, MA.

The proposed simultaneous use of ILS approaches to runway 12R and LDA/DME approaches to runway 12L at St. Louis International (Lambert Field) is analyzed from a wake turbulence perspective. Although the two runways are only 1300 feet apart, their staggered thresholds mitigate the wake turbulence problem. To preclude a vortex encounter, certain restrictions must be imposed: all Heavy-category aircraft must be confined to runway 12R, all Small-category aircraft must be confined to runway 12L, no aircraft larger than a B-727 may use runway 12L, and an MDA must be established for the 3-nm DME fix on runway 12L.

Hallock, J. N., editor,
"PROCEEDINGS OF THE AIRCRAFT WAKE VORTICES CONFERENCE,"
FAA-RD-77-68, June 1977,
DOT Transportation Systems Center, Cambridge, MA.

This volume contains the proceedings of a conference on aircraft wake vortices held at the DOT Transportation Systems Center on March 15-17, 1977. The contributed papers discuss technological advances in the knowledge of the phenomenon, its effects on aircraft, alleviation techniques, and vortex avoidance systems designed to permit decreases in delays at major airports.

Hallock, J. N.,
"AIRCRAFT WAKE VORTICES: AN ASSESSMENT OF THE CURRENT SITUATION,"
DOT-FAA-RD-90-29, Oct. 1990,
DOT Volpe National Transportation Systems Center, Cambridge, MA.

The state of knowledge about aircraft wake vortices in the summer of 1990 is summarized. With the advent of a new FAA wake vortex program, the current situationwas assessed by answering five questions: (1) what do we know about wake vortices, (2) what don't we know about wake vortices, (3) what are the requirements and limitations for operational systems to solve the wake vortex problem, (4) where do we go from here, and (5) why do we need to collect more wake vortex data.

Hallock, J. N., Burnham, D. C., Tombach, I. H., Brashears, M. R.,
Zalay, A. D. and Barber, M. R.,
"GROUND-BASED MEASUREMENTS OF THE WAKE VORTEX CHARACTERISTICS OF A B747 AIRCRAFT IN VARIOUS CONFIGURATIONS,"
AIAA Paper No. 77-9,
Los Angeles, CA, Jan. 1977.

A Boeing 747 aircraft flew 54 passes at low level over ground-based sensors. Vortex velocities were measured by a laser-Doppler velocimeter, an array of monostatic acoustic sounders, and an array of propeller anemometers. Flow visualization of the wake was achieved using smoke and balloon tracers.

Preliminary results were obtained on the initial downwash field, the time for merging of the multiple vortices, the velocity fields, vortex decay, and the effects of spoilers and differential flap settings on the dissipation and structure of vortices.

Hallock, J. N. and Eberle, W. R., editors,
"AIRCRAFT WAKE VORTICES: A STATE-OF-THE-ART REVIEW OF THE UNITED STATES R&D PROGRAM,"
FAA-RD-77-23, Feb. 1977,
DOT Transportation Systems Center, Cambridge, MA.

The report summarizes the current state-of-the-art understanding of the aircraft wake vortex phenomenon and the results of the United Sates program to minimize the restrictions caused by aircraft wake vortices in the terminal environment. The vortex phenomenon, vortex avoidance systems, and vortex alleviation techniques are discussed.

Hallock, J. N. and Goldstone, L.,
"US/UK VORTEX MONITORING PROGRAM AT HEATHROW AIRPORT,"
Proceedings of 20th Symposium of Guidance and Control Panel, Plans and Developments for Air Traffic Systems, AGARD, Cambridge, 1975, pp. 24-1 to 24-9.

Vortices shed from aircraft landing on Runway 28R at Heathrow Airport are being monitored in a joint US/UK program. Over 9100 vortex pairs have been recorded and analyzed and their motion correlated with the ambient meteorological conditions. It is shown that if the crosswind component measured near the runway threshold exceeds five knots, vortices linger near the extended runway centerline for a time in excess of one minute for less than 0.5 percent of the landings. This small percentage is almost entirely due to vortices from the heavy wide-body jets - the B-747, DC-10, and L-1011.

Hallock, J. N., Goldstone, L., Nevill, R. G. and Cooper, D. C.,
"MONITORING OF AIRCRAFT WAKE VORTICES AT HEATHROW AIRPORT,"
Proceedings Int. Conf. on Future of Aircraft All-Weather Operations, Inst. Electrical Engineers, London, Nov. 1976, pp. 38-41.

Aircraft separation to avert entrainment in wake vortices is weighed against loss of traffic capacity at airports, and meteorological conditions unfavorable to the formation of wake vortices and their attendant hazards are examined; the organization of vortex data collection sites is discussed. Experience with vortex data collection sites at London, New York, and Denver is surveyed. Anemometer baselines and an acoustic Doppler system are described. Delineation of safety zones and determination of the rate at which shed vortices leave the safety zone are discussed.

Hallock, J. N., Spitzer, E. A. and Wood, W. D.,
"VORTEX ADVISORY SYSTEM,"
U.S. Patent 4,137,764, Feb. 1979.

The invention relates to determining the appropriate spacing between fixed-wing aircraft arriving at runways so as to permit the minimum separation commensurate with safe operation as a function of the atmospheric conditions. More specifically, this invention is directed to a vortex advisory system which will enable flight controllers to vary the separation between aircraft as a function of the accurately predicted motion of wake vortices produced by the aircraft.

Hallock, J. N. and Winston, B. P.,
"RUNWAY CONFIGURATION ANALYSIS FOR CHICAGO O'HARE AIRPORT USING VORTEX ADVISORY SYSTEM DATA,"
FA186-PM-81-37, May 1981,
DOT Transportation Systems Center, Cambridge, MA.

Based on an analysis of 14 months of data collected at O'Hare International Airport, it was found that decreased separations between runway threshold and outer marker would be permitted about 25 percent of the time. This figure assumes that the landing runways are selected as they are today without any input from the VAS. On the other hand, if the VAS were used to guide the decision on which runways should be used for landings, decreased separations would have been permitted about 40 percent of the time. This 15 percent increase would lead to large delay-dollar savings; $150 to $200 million in total IFR annual delay savings (1976 dollars) could be saved if VAS standards are applied instead of today's standards at the top 20 airports. The escalation of fuel prices certainly will increase these delay savings dollars.

Hallock, J. N., Winston, B. P., Burnham, D. C., Sullivan, T. E. and McWilliams, I. G.,
"JOINT US/UK VORTEX TRACKING PROGRAM AT HEATHROW INTERNATIONAL AIRPORT, VOLUME II: DATA ANALYSIS,"
FAA-RD-76-58, II, Nov. 1977,
DOT Transportation Systems Center, Cambridge, MA.

From May 1974 through June 1975, the approach region to runway 28R at Heathrow International Airport was equipped with aircraft wake vortex tracking equipment. The vortices from approximately 13,000 aircraft were monitored along with the attendant meteorological conditions. The joint US/UK project represents a major step in learning how vortices move and die in the terminal environment. Volume II describes the entire project from the workings and locations of the equipment to the analysis of the data.

Hallock, J. N., Winston, B. P., Sullivan, T. E. and Burnham, D. C.,
"TSC WAKE VORTEX DATA BASE AND APPLICATIONS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 67-80.

An extensive data base is being compiled on the motion and decay of wake vortices near the ground. To date, data for over 40,000 vortex pairs have been recorded, analyzed, and entered into the data base. The rationale for the data collection program at each site is presented along with a description of the entries into the data base and the results of some preliminary studies using the data base.

Hallock, J. N. and Wood, W. D.,
"STATUS OF THE WAKE VORTEX AVOIDANCE SYSTEM,"
EASCON '74 Record, IEEE Electronics and Aerospace Systems Conference, Washington, 1974, pp. 250-256.

The Federal Aviation Administration is pursuing a dual thrust program toward the solution of the wake vortex problem to be able to increase capacity to meet the air traffic density demands of the future while maintaining a high level of safety. One approach being investigated by NASA is to prevent the generation of a dangerous vortex via modification of the aircraft. The alternate approach, to be discussed herein and being undertaken by the Transportation Systems Center, is the design and development of a wake vortex avoidance system which will be used in the terminal airspace to detect and/or predict the presence of wake vortices, evaluate whether a threat of hazard exists, and command the hazard avoidance action. The

status of the Wake Vortex Avoidance System is presented by briefly examining each of the modules making up a system: the predictive model and data base, vortex detecting and tracking subsystems, the hazard model, and the system concepts.

Hallock, J. N. and Wood, W. D.,
"IMPACT OF WAKE TURBULENCE,"
19th Annual Meeting and Technical Program, Air Traffic Control Association, Las Vegas, NV, Oct. 1974.

The paper presented the status of the Wake Vortex Avoidance System program by briefly reviewing what is known about vortices and the ability to predict their transport and demise; vortex detection and tracking sensors development; hazard definition; vortex data collection at Kennedy, Stapleton, and Heathrow International Airports; and various system concepts.

Hallock, J. N. and Wood, W. D.,
"JOINT US/UK VORTEX TRACKING PROGRAM AT HEATHROW INTERNATIONAL AIRPORT, VOLUME I: EXECUTIVE SUMMARY,"
FAA-RD-76-58.1, March 1976,
DOT Transportation Systems Center, Cambridge, MA.

From May 1974 through June 1975 the approach region to Runway 28R at Heathrow International Airport was equipped with aircraft wake vortex tracking equipment. The vortices from approximately 13000 aircraft were monitored along with the attendant meteorological conditions. The joint US/UK project represents a major step in learning how vortices move and die in the terminal environment. An overview of the Heathrow project is given and it is shown how the project has significantly contributed to the capability to develop a vortex advisory system promising increased capacity through decreased aircraft separations.

Hallock, J. N., Wood, W. D. and Spitzer, E. A.,
"THE MOTION OF WAKE VORTICES IN THE TERMINAL ENVIRONMENT,"
Proceedings Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorology Society, El Paso, 1974, pp. 393-398.

A Wake Vortex Avoidance System (WVAS) is being designed and developed for use in the terminal airspace to detect and/or predict the presence of vortices, to evaluate the threat, and to command the hazard avoidance action. The WVAS will consist of a predictive model and data base, a vortex detection and tracking subsystem, a hazard model, and a data processing and display subsystem. The paper describes the vortex detection and tracking systems (a pulsed acoustic, a Doppler acoustic, a ground wind, and a laser Doppler system), the JFK Vortex Test Site and its extensive meteorological network, and a number of WVAS concepts ranging from a very simple meteorological system to a complex and fully-automated system.

Hallock, J. N., Wood, W. D. and Spitzer, E. A.,
"PREDICTIVE TECHNIQUES FOR WAKE VORTEX AVOIDANCE,"
Proceedings of 20th Symposium of Guidance and Control Panel, Plans and Developments for Air Traffic Systems, AGARD, Cambridge, 1975, pp. 23-1 to 23-11.

Aircraft wake vortices represent a major impediment to increasing runway capacity. Separation criteria are conservative most of the time and thus traffic is unnecessarily delayed by always adhering to the present inflexible regulations. Systems which employ vortex tracking sensors and/or meteorological sensors to determine safe reduced spacings are being designed. Any wake vortex avoidance strategy relies upon the ability to predict vortex transport and decay. The paper discusses vortex behavior, preliminary predictive models based upon the tracking of vortices from over 24,000 landing aircraft and systems and their implementation to provide the capability of using adaptive separations.

Hallock, J. N., Wood, W. D. and Spitzer, E. A.,
"THE WAKE VORTEX ADVISORY SYSTEM,"
Proceedings Int. Conf. on Electronic Navigational Aid Systems for Aircraft, Federation des Industries Electriques et Electroniques, Nov. 1977, Paris, France, pp. 269-273.

The vortices from over 50,000 landing aircraft have been monitored at Kennedy, Stapleton, O'Hare, and Heathrow International Airports. Using this data base, a wind criterion has been defined which can be used as a vortex condition indicator; by measuring the wind velocity in the runway approach zone and comparing the velocity with the wind criterion, the times when the aircraft spacing may be reduced safely to three nautical miles for all aircraft are delineated. A Vortex Advisory System has been implemented at the Chicago O'Hare International Airport and will be fully operational in December 1977.

Hama, F. R.,
"PROGRESSIVE DEFORMATION OF A CURVED VORTEX FILAMENT BY ITS OWN **INDUCTION,"**
Physics of Fluids, Vol. 5, No. 10, Oct. 1962, pp. 1156-1162.

Progressive three-dimensional deformation of an initially parabolic, plane curved vortex due to its own induction is numerically obtained in this paper by the use of the localized-induction concept instead of through the full Biot-Savart law. It is shown that, after the region near the vertex rises up from the plane of the initial orientation, a helical deformation takes place on the legs of the parabola. The helix, which rotates in the direction opposite to the circulatory rotation around the vortex filament, is found to travel away toward the far ends of the parabola as the vertex keeps rising up, while increasing the amplitude and extent of the helical deformation. Similar computations also carried out with a hyperbolic initial shape resulted in essentially the same conclusions as the parabola but with much better numerical stability, as well as with an exponential initial configuration, which grew into somewhat more complicated patterns, yet maintained the essential feature of the helical deformation.

Hancock, G. J.,
"ON THE ROLLING UP OF A TRAILING VORTEX SHEET,"
Aero. Journal, Vol. 74, No. 717, Sept. 1970, pp. 749-752.

This paper looked at the rollup of two vortices behind a wing with an elliptical spanwise load distribution when the standard linear model becomes less valid, for example, at higher wing lift coefficients. The paper assumed that a continuous trailing vortex sheet rolls up into two discrete vortices, and this rolling up process takes place far downstream of the finite wing which generates the trailing vorticity.

Hanson, C. E.,
"AN INVESTIGATION OF THE NEAR WAKE PROPERTIES ASSOCIATED WITH PERIODIC VORTEX SHEDDING FROM AIRFOILS,"
AVL Report 76234-5, Sept. 1970,
Mass. Inst. of Technology, Cambridge, MA.

An investigation of the near wake of airfoils with various trailing edge configurations including splitter plates reveals properties which are conducive to wake periodicity. The frequency of the shedding process is found to scale with the new wake momentum thickness and a wake velocity simply related to the base pressure coefficient. Computer results suggest that the frequency and bandwidth of the vortex shedding process can be predicted by a solution of the complete Orr-Sommerfeld equation.

Harland, R. B. and Madden, S. J.,
"A HAZARD DEFINITION FOR WAKE TURBULENCE ENCOUNTER DURING TERMINAL AREA OPERATIONS,"
RE-81, March 1973,
Mass. Institute of Technology, Cambridge, MA.

A six-degree-of-freedom vortex encounter simulation has been developed for use on a hybrid computer to determine the hazard potential for terminal area operations. Complete trajectory data for landing, horizontal flyby, and climbing flights are presented and conclusions are drawn from these results. A hazardous condition is defined as having the roll angle exceed ten degrees and/or the flight path angle become steeper than -4.5 degrees at any point along the flight path with the aircraft under autopilot control. A simplified sensitivity analysis shows that the controllability of an aircraft is about twice as sensitive to changes in vortex proximity than to changes in wingspan, but if the near wingtip proximity is chosen to be the independent variable, controllability is nearly independent of aircraft size.

Hartman, R. J. and Lewis, H. W.,
"WAKE COLLAPSE IN A STRATIFIED FLUID: LINEAR TREATMENT,"
J. Fluid Mech., Vol. 51, Part 3, 1972, pp. 613-618.

The linear initial-value problem of a partially mixed cylindrical wake in a uniformly stratified fluid is formulated and exact solutions are given for the density and velocity fields inside and just outside the original cylinder. An asymptotic expression for the far-field internal wave radiation is given and the corresponding solutions for a spherical wake geometry are noted. The treatment emphasizes the inadequacy of the usual linear Boussinesq approximation to describe the detailed nature of similar problems, in particular the fully mixed wake-collapse problem.

Harvey, J. K.,
"SOME OBSERVATIONS OF THE VORTEX BREAKDOWN PHENOMENON,"
J. Fluid Mech., Vol. 14, Part 4, Dec. 1962, pp. 585-592.

This paper describes an experiment in which a cylindrical vortex, formed in a long tube, was used to study the 'vortex breakdown' that has been previously reported in investigations of the flow over slender delta wings. By varying the amount of swirl that was imparted to the fluid before it entered the tube, it was found that the breakdown was the intermediate stage between the two basic types of rotating flows, that is, those that do and those that do not exhibit axial velocity reversal. In addition, it was shown that an unusual flow pattern was established after the breakdown and that certain features of this pointed to it being a 'critical' phenomenon. The tests were concluded by measuring the swirl angle distribution a short distance ahead of the breakdown and comparing these results with the prediction of Squire's theory.

Harvey, J. K. and Fackrell, J. E.,
"OBSERVATION OF A MECHANISM CAUSING A TRAILING VORTEX TO BREAK UP,"
IC-AERO-70-08, Dec. 1970,
Imperial College, London, England.

Simple flow visualization experiments have been performed to identify a new form of vortex breakdown which is characterized by the disturbance appearing somewhere near the edge of the core and not on the vortex center line. There is a marked similarity between the disc observed and those seen in condensation trails. In the experiments a towing tank was used which enabled the vortices to be studied within a frame of reference which was stationary with respect to the undisturbed fluid and so their total history could be observed.

Harvey, J. K. and Perry, F. J.,
"FLOWFIELD PRODUCED BY TRAILING VORTICES IN THE VICINITY OF THE GROUND,"
AIAA Journal, Vol. 9, No. 8, Aug. 1971, pp. 1659-1660.

Vortices have been noted to rise again after having descended close to the ground. To attempt to explain this phenomena, a series of total-head surveys in planes across the flow were made in a wind tunnel with a single trailing vortex passing over a moving floor simulating the ground boundary condition. The vortex induces a cross flow on the floor with an attendant suction peak beneath the core. Consequently, the boundary layer resulting from the cross flow has to negotiate an adverse pressure gradient once it has passed under the vortex. When the vortex is sufficiently near the ground, the pressure gradient is strong enough for separation to occur, and a bubble forms containing vorticity of opposite sense to the main vortex. Progressing downstream, the bubble detaches from the floor as a secondary vortex fed by a vortex sheet from the separation point. The subsequent motion of the two vortices is complicated but the secondary vortex can induce an upward velocity on the main vortex.

Hastings, Jr., E. C. and Champine, R. A.,
"RESULTS OF FULL-SCALE VORTEX ATTENUATION FLIGHT EXPERIMENTS,"
Proceedings of the Fifth Annual Symposium of the Society of Flight Test Engineers, SFTE, Anaheim, 1974, pp. 4/26-4/46.

Flight tests have been conducted to evaluate the effectiveness of a wing-tip vortex attenuating device called a spline. Vortex penetrations were made with a PA-28 behind a C-54 aircraft with and without wing-tip splines attached and the resultant rolling acceleration was measured and related to the roll acceleration capability of the PA-28.

Hastings, Jr., E. C., Holbrook, G. T. and Keyser, Jr., G. L.,
"PRELIMINARY RESULTS OF SIMULATED VORTEX ENCOUNTERS BY A TWIN-ENGINE, COMMERCIAL AIRCRAFT DURING FINAL LANDING APPROACH,"
NASA TM-81782, May 1980,
NASA Langley Research Center, Hampton, VA.

Piloted simulations of encounters with vortices of various ages and degrees of attenuation have been performed with the Visual Motion Simulator at the Langley Research Center. In the simulations, a twin-engine, commercial transport on final approach, encountered the modeled vortices of a four-engine, wide-body, commercial transport. Unattenuated vortices (in- and out-of-ground effect) and vortices attenuated by the spoilers of the generating aircraft were used in the simulations. The results show that the upset severity due to encounters with unattenuated vortices out-of-ground effect, decreased very little with vortex aging. The presence of ground effect, or the utilization of spoiler attenuation, had little effect on the upset severity for vortices near 45 seconds of age. The upset severity of the ground effect and 15^{o} spoiler vortex encounters however, diminished more rapidly as the vortices aged.

Hastings, Jr., E. C. and Keyser, Jr., G. L.,
"SIMULATED VORTEX ENCOUNTERS BY A TWIN-ENGINE COMMERCIAL **TRANSPORT AIRCRAFT DURING** FINAL APPROACH,"
SAE Paper No. 800775,
Cincinnati, OH, May 1980.

Piloted simulations of encounters with vortices of various **ages and** degrees of attenuation were performed with the Visual **Motion** Simulator. In the simulations, a twin-engine, **commercial** transport on final approach encountered the modeled **vortices** of a four-engine, wide-body, commercial transport. **The data** in this report show the effect of vortex age and **ground** effect on the severity of the initial upset, as well **as the** effect of the vortex encounters on the landing **capability.**

Hastings, Jr., E. C. and Keyser, Jr., G. L.,
"SIMULATOR STUDY OF VORTEX ENCOUNTERS BY A TWIN-ENGINE, COMMERCIAL, **JET TRANSPORT** AIRPLANE,"
NASA TP-1966, Feb. 1982,
Langley Research Center, Hampton, VA.

An investigation of vortex-induced upset and recovery characteristics was conducted by using a simulated twin-engine, commercial, jet transport airplane with fixed controls **and** with a conventional manual-control system. The piloted simulations were performed with the Langley Vísual/Motion Simulator. Wake vortex encounters were simulated with the airplane in the final-approach configuration at altitudes between 76.2 m and 30.5 m. The investigation consisted of parametric studies of the effects of the lateral and vertical locations of the vortex center, vortex aging in and out of ground effect, approach speed of the simulated following airplane, lift coefficient of the vortex-generating airplane, **and vortex** attenuation by using the flight spoilers of the vortex-generating airplane. In addition, altitude-dependent bank angle and flight-path excursion criteria were used to evaluate the acceptability of the vortex-induced upsets.

Hastings, Jr., E. C., Patterson, Jr., J. C., Shanks, R. E., **Champine,** R. A., Copeland, W. L. and Young, D. C.,
"**DEVELOPMENT** AND FLIGHT TESTS OF VORTEX ATTENUATING SPLINES,"
NASA TN D-8083, Nov. 1975,
NASA Langley Research Center, Hampton, VA.

The **report** describes some of the ground test and full-scale **flight** test conducted by the Langley Research Center during **development** of the vortex-attenuating spline. The flight

tests were conducted using a vortex generating aircraft with and without splines; a second aircraft was used to probe the vortices generated in both cases. The results showed that splines significantly reduced the vortex effects, but resulted in some noise and climb performance penalties on the generating aircraft.

Hastings, Jr., E. C., Shanks, R. E., Champine, R. A., Copeland, W. L., Latham, W. and Young, D. C.,
"PRELIMINARY RESULTS OF FLIGHT TESTS OF VORTEX ATTENUATING SPLINES,"
NASA TMX-71928, March 1974,
NASA Langley Research Center, Hampton, VA.

Flight tests have been conducted to evaluate the effectiveness of a wingtip vortex attenuating device, referred to as a spline. Vortex penetrations were made with a PA-28 behind a C-54 aircraft with and without wingtip splines attached and the resultant rolling acceleration was measured and related to the roll acceleration capability of the PA-28. Preliminary results indicate that the splines led to a significant reduction in the vortex induced roll acceleration experienced by the PA-28 probe aircraft.

Hawkes, J. W.
"A SIMPLE MODEL FOR THE VORTEX BREAKDOWN PHENOMENON,"
MS Thesis, Aug. 1969,
Mass. Inst. of Technology, Cambridge, MA.

Previous experimental and theoretical investigations of vortex breakdown are reviewed. In light of past experimental results, a new model for the vortex breakdown is proposed. It is modelled as a transition from an upstream uniform vortex core to a downstream flow in which there exists a stagnant bubble on the axis. The conservation equations are applied across this transition under the constraint that the pressure jump in the breakdown be a maximum. Model results indicate that a pressure increase in the stagnant bubble of about 75% of the initial maximum swirl dynamic head is to be expected at swirl ratios comparable to those observed experimentally to involve a breakdown. Radii predicted for the breakdown bubbles are compared on a limited basis with experiments and reasonable agreement obtained.

Hay, G. C.,
"FAA R&D OBJECTIVES REGARDING WAKE TURBULENCE,"
Symposium on Turbulence, FAA, Washington, DC, March 1971, p. 26.

The FAA breaks the wake vortices program into three parts, each being examined concurrently. One part is to eliminate or minimize the problem at its sources; NASA has been asked to pursue this effort. Second, real time detection and measurement concepts using present day technology is being examined; this includes system designs, the feasibility of a predictive system, and the identification of hazardous conditions. Third, in concert with the National Airspace System users, current operational procedures need to be updated.

Hecht, A. M., Bilanin, A. J. and Hirsh, J. E.,
"TURBULENT TRAILING VORTICES IN STRATIFIED FLUIDS,"
AIAA Journal, Vol. 19, No. 6, June 1981, pp. 691-698.

The effects of stable atmospheric-density stratification, vortex core size, and turbulent scale on the descent of aircraft-trailing vortices are investigated using numerical solutions of a second-order closure turbulent model. A B-747 vortex descent is simulated numerically and compared to reported measurements of descent distance, velocity, and circulation profiles. It is concluded that the pair was halted in its descent by a diffuse region of countersign vorticity primarily outboard and above the vortex cores. It is shown that the core size and turbulent macroscale have significant effects on vortex behavior through their influence on turbulence production, diffusion, and dissipation.

Hecht, A. M., Bilanin, A. J., Hirsh, J. E. and Snedeker, R. S.,
"INVESTIGATION OF STABLE ATMOSPHERIC STRATIFICATION EFFECT ON THE DYNAMICS OF DESCENDING VORTEX PAIRS,"
FAA-RD-79-4, Feb. 1979,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

The physics of vortex flows in stratified fluids is studied with the objective of determining the influence of stable stratification on the descent of aircraft vortex pairs. Vortex rings descending into linear and discontinuous density stratifications are investigated experimentally and simulated numerically. The computer code is based on a second-order closure turbulence model of the Reynolds stress equations in axisymmetric coordinates. The 2-D version of the code is then used to simulate a measured B-747 vortex descending in stable stratification. The strength and tightness of the measured vortex cores have necessitated development of a new method of numerically calculating strong vortex flows. The comparison of measured with calculated descent velocity, descent distance, swirl velocity, and circulation in the vortex is in agreement. It is concluded that turbulence effects must be accounted for in the study of aircraft vortex behavior. It is found that unalleviated vortices remain strong during descent, that the vortices stop descending due to a diffuse region of countersign vorticity outboard and above the cores, and that core separation does not primarily control descent.

Hecht, A. M., Bilanin, A. J., Hirsh, J. E. and Snedeker, R. S.,
"TURBULENT VORTICES IN STRATIFIED FLUIDS,"
AIAA J., Vol. 18, No. 7, July 1980, pp. 738-746.

The effects of density stratification and turbulence on the behavior of vortex rings and vortex pairs is investigated. The results of a vortex ring experiment, in which rings were injected into linear and discontinuous density stratifications, are compared with calculations of ring behavior made using an axisymmetric, unsteady solution of the mean variable and the modeled Reynolds stress equations. Second-order closure is based upon the invariant modeling technique of Donaldson. Comparisons are made for ring trajectories, radius, and size of the recirculation cell carried along with the ring. Calculations of turbulent vortex pairs descending into a stably stratified atmosphere are presented. The vortex separation for the 2-D calculation is found to be very nearly constant with vortex pair descent, while both the experimental and numerical results for vortex rings give a sharply decreasing radius during descent.

Hedman, S. G.,
"COMPUTATION OF VORTEX MODELS FOR WINGS AT HIGH ANGLE OF ATTACK IN INCOMPRESSIBLE FLOW,"
FFA-AU-653, Feb. 1973,
Aeronautical Research Inst. of Sweden, Stockholm, Sweden.

The vortex lattice method is applied in the solution of the thin wing lifting problem. The strength of the horseshoe vortices and a set of trailing vortex definition points are computed. The flow is required to be tangential in a number of collocation points on the wing and on the trailing vortices. This is expressed in a system of equations. It is shown how the system can be solved in two ways. In the first the system is partitioned into two subsystems, one where the boundary conditions of the wing are used for the determination of the vortex strengths, and one where the boundary conditions of the free vortices determine the positions of the vortices. In the second method the whole system is solved simultaneously by means of Newton-Raphson's rule.

Heyson, H. H.,
"SOME WAKE-RELATED OPERATIONAL LIMITATIONS OF ROTORCRAFT,"
NASA TM-81920, Dec. 1980.
NASA Langley Research Center, Hampton, VA.

Wind tunnel measurements show that the wake of a rotor, except at near hovering speeds, is not like that of a propeller. The wake is more like that of a wing except that, because of the slow speeds, the wake velocities may be much greater. The helicopter can produce a wake hazard to following light aircraft that is disproportionately great compared to an equivalent fixed wing aircraft. This hazard should be recognized by both pilots and airport controllers when operating in congested areas. Ground effect is generally counted as a blessing since it allows overloaded takeoffs; however, it also introduces additional operation problems. These problems include premature blade stall in hover, settling in forward transition, shuddering in approach to touchdown and complications with yaw control. Some of these problems were treated analytically in an approximate manner and reasonable experiment agreement was obtained. An awareness of these effects can prepare the user for their appearance and their consequences.

Hill, F. M.,
"A NUMERICAL STUDY OF THE DESCENT OF A VORTEX PAIR IN A STABLY STRATIFIED ATMOSPHERE,"
J. Fluid Mech., Vol. 71, Part 1, Sept. 1975, pp. 1-13.

Numerical methods are used to investigate the motion of a horizontal vortex pair through a stably stratified atmosphere. The vortices carry with them a mass of fluid whose density differs from that of the air through which it descends, and the surface of this accompanying fluid becomes a vortex sheet, which is modelled by a set of discrete line vortices. It is shown that, at first, the vortex pair slows down with the shape of the envelope of the accompanying fluid remaining constant. Later, vorticity concentrates at the rear, initiating detrainment and causing a downward acceleration of the vortex pair. Throughout the motion, the vortices approach each other.

Hoffman. E. R. and Joubert, P. N.,
"TURBULENT LINE VORTICES,"
J. Fluid Mech., Vol. 16, Part 3, July 1963, pp. 395-411.

An attempt has been made to establish the laws governing the flow in a turbulent line vortex. Up to the present time theoretical solutions for laminar flow have been used for comparison with experimental results for turbulent flow to find an 'eddy viscosity' term and its variation with various parameters. An approach is developed along lines similar to the methods used in turbulent boundary-layer theory and is found to be reasonably successful as far as the work has proceeded. It is predicted by theory, and confirmed by experiment, that the circulation in the vortex is proportional to the logarithm of radius under certain conditions. For the present experimental conditions, the vortices are found to be completely independent of viscosity effects when the parameter WZ/K_0 exceeds 150, and above this value the experimental results may be correlated to give a universal distribution of circulation in the inner region of the vortex. Further experiments are necessary to verify and extend the results of these tests before any definite conclusions may be made regarding the circulation distribution in the outer core region of the vortex and the growth and development of the vortex.

Hoh, R. H.,
"PILOT RATING SCALE FOR VORTEX HAZARD EVALUATION,"
NASA CR-143836, June 1975,
Systems Tech. Inc., Hawthorne, CA.

A pilot rating scale is developed for subjective assessment of hazard resulting from wake vortex encounter upsets. The development of the rating scale is based on a survey of 48 pilots regarding the semantic properties of various phrases and a choice of formats for the rating scale. The rating scale can be used to define a hazard/non-hazard boundary as well as to determine a measure of the hazard.

Holbrook, G. T.,
"VORTEX WAKE HAZARD ANALYSIS INCLUDING THE EFFECT OF THE ENCOUNTERING WING ON THE VORTEX,"
MS Thesis, Aug. 1985,
George Washington Univ., Washington, DC.

This thesis addresses the problem of vortex wakes and their impact on airport capacity. Dynamic vortex simulations were performed over a wide range of vortex generator and following aircraft pairs with, for the first time, an analysis of the effect of the encountering wing on the vortex and the resulting change in the roll response of the wing. The mutual interference between a wing and a vortex was accounted for by coupling the wing and vortex and applying the conservation of angular momentum flux in a control volume enclosing the wing. The following aircraft model incorporated a roll control authority based on minimum design requirements and roll responses to vortex encounters were predicted with and without roll control applied. The predictions were used to produce maps of acceptable vortex generator and following aircraft pairs. This allowed a generalized determination of the effects of the vortex generator span load, wake decay, and the mutual influence of the wing and vortex on predicted roll upsets.

Hoshizaki, H., Conti, R. J., Anderson, L. B., Redler, K. O., Meyer, J. W., McLean, W. J. and Cassady, P. E.,
"STUDY OF HIGH ALTITUDE AIRCRAFT WAKE DYNAMICS: TASK 1, PROBLEM DEFINITION,"
DOT-TST-90-3, Dec. 1972,
Lockheed Research Laboratory, Palo Alto, CA.

The important features of chemically reacting aircraft wakes have been identified. The aircraft wake is modeled in terms of the jet regime (wake age about 10 seconds), vortex regime (wake age about 100 seconds), and the wake dispersion regime (wake age about 100 seconds). The important thermochemical reactions were found to take place in the jet regime.

Hoshizaki, H., Redler, K. O., Meyer, J. W., Conti, R. J. and Anderson, L. B.,
"STUDY OF HIGH ALTITUDE AIRCRAFT WAKE DYNAMICS, MODEL DEVELOPMENT,"
DOT-TST-73-5, Jan. 1973,
Lockheed Palo Alto Research Lab., Palo Alto, CA.

A chemically-reacting wake model computer program has been formulated. The wake model program computes the wake height and width from the jet engine nozzle to the point in time where aerodynamic perturbations are small.

Houbolt, J. C.,
"AIRCRAFT RESPONSE TO TURBULENCE INCLUDING WAKES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 509-522.

The nature of atmospheric turbulence and the means for establishing aircraft response is reviewed, both from discrete-gust and spectral interpretations. Application is then made to the situation of wake turbulence encounter to show the nature and magnitude of the loads that result. Specific cases are treated, with encounters perpendicular to and parallel to the wake, to bring out the main parameters that are significant. General relations are also developed to show how the wake "gust" forces on the encountering airplane are related to the lift on the airplane generating the wake. It is shown that normal loads in excess of 2 g's may be produced by a perpendicular encounter of a wake vortex, and that uncontrollable rolling moments may be caused by encounters along the axis of a vortex.

Hubbard, H. B.,
"TERMINAL AIRSPACE/AIRPORT CONGESTION DELAYS,"
Interfaces, Vol. 8, Feb. 1978, pp. 1-14.

Methods of reducing airport congestion delays are discussed, with particular attention given to an FAA-sponsored program at Chicago's O'Hare Airport. Selection of low-delay runway configurations for the existing wind and weather conditions is found to reduce inbound holding delays by about two to three minutes per arrival. In addition, wake vortex detection systems have been tested as a means to reduce in-trail separations when the wake vortices do not present a problem. More complete real-time air traffic monitoring may also aid in reducing delays.

Huffaker, R. M.,
"LASER DOPPLER SYSTEM FOR AIRCRAFT TRAILING VORTEX TRACKING AND MEASUREMENT,"
Proceedings Second Annual Research and Technology Review, NASA, Washington, Oct. 1974.

MSFC has developed a CO_2 Laser Doppler System for the tracking and measurement of aircraft trailing vortices under an interagency agreement between NASA and the FAA. This system has been installed at Kennedy International Airport after checkout at MSFC. This paper describes the logic for the systems design and outlines some of the hardware

considerations used in the development. Results of system performance in the tracking and measurement of aircraft trailing vortices will be given.

Huffaker, R. M., Jeffreys, H. B., Weaver, E. A., Bilbro, J. W., Craig, G. D., George, R. W., Gleason, E. H., Marrero, P. J., Reinbolt, E. J. and Shirey, J. E.,
"DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION, TRACKING, AND MEASUREMENT OF AIRCRAFT TRAILING VORTICES,"
FAA-RD-74-213, March 1975,
NASA Marshall Space Flight Center, Huntsville, AL.

A Scanning Laser Doppler Vortex System (SLDVS) has been developed for use as an aircraft trailing vortex detection, tracking, and measuring system. The report describes the SLDVS design, development, and checkout at NASA. Previous efforts had demonstrated the capability of laser Doppler systems to accurately measure remote wind velocity and turbulence. To assure the proper overall system design; tradeoff studies were performed to determine the optimum design parameters that met the program objectives. Computer simulations of the SLDVS performance were used in determining the optimum design parameters. The SLDVS scans both in range and angle. A real-time vortex display system is provided which gives the vortices' center positions in the scan plane as a function of time. The SLDVS was integrated and checked out at MSFC. The SLDVS has demonstrated overall systems accuracy against known calibrated targets of ± 3.3 ft at 492 ft (± 1 m at 150 m). During cooperative flybys at MSFC, the SLDVS has located the center positions of the B-737 and B-720 aircraft vortices to within ± 10 ft (± 3 m).

Huffaker, R. M., Jelalian, A. V., Keene, W. H. and Sonnenschein, C. M.,
"APPLICATION OF LASER DOPPLER SYSTEMS TO VORTEX MEASUREMENT AND DETECTION,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 113-124.

A laser Doppler system for the measurement of atmospheric wind velocity and turbulence has been developed. This system utilizes the Doppler frequency shift undergone by a beam of radiation when scattered by particles suspended in the flows. A three-dimensional system has been developed for wind tunnel and jet type flow studies; measurements of velocity have been made with velocities in excess of Mach 2 and compared with theory and hot wire instrumentation. The laser Doppler system has also been applied to the problem of detecting the presence of an aircraft trailing vortex. The results showed that when the vortex was visually sighted and known to be in the sensitive scattering volume of the laser Doppler system, the velocity distribution of the vortex was measured.

Huffaker, R. M., Jelalian, A. V. and Thomson, J. A. L., "LASER-DOPPLER SYSTEM FOR DETECTION OF AIRCRAFT TRAILING VORTICES," Proc. IEEE, Vol. 58, No. 3, March 1970, pp. 322-326

The paper reviews the results of a test program utilizing a CW CO_2 laser-Doppler velocimeter system that has demonstrated the capability of detecting wing tip vortices by the measurement of Doppler shifted back scatter from atmospheric aerosols naturally suspended in the atmosphere. The velocity signatures of vortices generated by a C-47 aircraft making low altitude cooperative flybys are shown. Some considerations of an operational detection system are given.

Israel, D. R.,
"AN OVERVIEW OF THE UPGRADED THIRD GENERATION AIR TRAFFIC CONTROL SYSTEM,"
EASCON '74 Record, IEEE, Washington, 1974, pp. 244-249.

With the continuing growth of aviation, improvements to our current air traffic control system will be required. The system planned for use in the 1980's and beyond is now known as the Upgraded Third Generation System. It is designed to meet the FAA's goals of: (a) maintaining or improving safety, (b) constraining or reducing costs, and (c) increasing or improving performance. The system will be characterized by nine major features - Intermittent Positive Control, the Discrete Address Beacon System, Area Navigation, Microwave Landing System, Increased Automation, Airport Surface Traffic Control, a Wake Vortex Avoidance System, Flight Service Stations, and Aeronautical Satellites.

Israel, D. R.,
"WAKE VORTEX PROGRAM STATUS,"
Inter. Air Trans. Conf., Am. Soc. Civil Engineers, San Francisco, March 1975, pp. 143-160.

The paper describes past results, present status, and future outlook and approaches of programs for studying wake vortex behavior and reduction of its effects. The characteristics of several vortex sensing systems are examined, including a pulsed acoustic vortex sensing system, a Doppler acoustic sensing system, a ground wind sensing system, and a laser Doppler system. Three stages in the life of an aircraft wake have been discerned by recent study: the inviscid wake stage, the entraining wake stage, and the decaying wake stage. A prototype vortex advisory system for a large airport is described.

Iversen, J. D.,
"TRAILING VORTEX EFFECTS ON FOLLOWING AIRCRAFT,"
ISU USAF Operations Analysis Report, ERI-66200, 1971, Iowa State University, Ames, IA.

Wind tunnel tests of two C-130 aircraft models were performed to determine the effect of the wake of a leading aircraft upon the aerodynamic forces experienced by the trailing aircraft. The results of the tests along with theoretical considerations are used to calculate lift forces and rolling moments experienced by the trailing aircraft.

Iversen, J. D.,
"STUDIES OF VORTEX DECAY AND VORTEX ROLLUP,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 50-58.

The effect of generating aircraft span loading on the following aircraft rolling moment is discussed for the particular cases of tailored loading, sawtooth loading and unconventional flap loading on the generating aircraft. A correlation function is introduced with correlates maximum tangential velocity in the vortex with downstream distance for a wide range of Reynolds numbers.

Iversen, J. D.,
"INVISCID TO TURBULENT TRANSITION OF TRAILING VORTICES,"
ISU-ERI-AMES-74241, Nov. 1974,
Iowa State University, Ames, IA.

It has been discovered experimentally that a so-called "plateau" region exists in the vortex system which trails from a lifting wing. The decay of the vortex due to viscous or turbulent shear is very slow in the plateau so that the maximum tangential speed in the vortices remains very nearly constant for some distance downstream of roll-up and then begins to decrease, becoming inversely proportional to the square root of the distance far downstream.

Iversen, J. D.,
"INVISCID TO TURBULENT TRANSITION OF TRAILING VORTICES,"
AIAA Paper No. 75-883,
Hartford, CT, 1975.

The plateau region in which trailing vortices initially exhibit slow decay of maximum tangential speed is demonstrated with the aid of constant and variable eddy viscosity models. The existence of the plateau is explained by the presence of the viscous core and by the necessity for transition of the initial, nearly inviscid profile to similarity far downstream. Span loading is shown to affect the initial maximum tangential speed as well as the duration of the plateau region. Triangular span loading is shown to present less hazard to trailing aircraft, at least in the near field, than elliptic loading because the inviscid profile for triangular loading exhibits a finite tangential speed at the vortex centerline and a large inviscid core.

Iversen, J. D.,
"CORRELATION OF TURBULENT TRAILING VORTEX DECAY DATA,"
J. Aircraft, Vol. 13, No. 5, May 1976, pp. 338-342.

A correlation function, derived on the basis of self-similar variable eddy-viscosity decay, is introduced and utilized to correlate aircraft trailing vortex velocity data from ground and flight experiments. The correlation function collapses maximum tangential velocity data from scale-model and flight tests to a single curve. The resulting curve clearly shows both the inviscid plateau and the downstream decay regions. A comparison between experimental data and numerical solution shows closer agreement with the variable eddy viscosity solution than the constant viscosity analytical solution.

Iversen, J. D. and Bernstein, S.,
"DYNAMIC SIMULATION OF AN AIRCRAFT UNDER THE EFFECT OF VORTEX WAKE TURBULENCE,"
Annales de l'Association Pour le Calcul Analogique, Vol. 14, 1972, pp. 136-144.

The introduction of modern heavy jets poses an increasing hazard to light and moderate weight aircraft due to high-intensity vortex wake turbulence. A technique is developed to simulate the responses of a trailing aircraft due to the induced rolling moments and loss of lift imposed by the vortices. In spite of the nonlinear and complex nature of the problem, the method was applied successfully using an EAI 8812 analog computer with no hybrid facilities. The simulated aircraft was free to roll and move vertically and laterally with respect to the generating aircraft. Results of such a simulation for the case of a C-130 behind another C-130 and behind a C-5A are presented.

Iversen, J. D. and Bernstein, S.,
"TRAILING VORTEX EFFECTS ON FOLLOWING AIRCRAFT,"
J. Aircraft, Vol. 11, No. 1, Jan. 1974, pp. 60-61.

Wind-tunnel tests and a strip-theory analysis are utilized to estimate the change in lift force and rolling moment on an aircraft due to its penetration into the vortex trail of a leading aircraft. Values of lift and rolling moment coefficients on the trailing aircraft are presented as functions of vertical and lateral displacement with respect to the vortex.

Iversen, J. D., Brandt, S. A. and Raj, P.,
"MERGING DISTANCE CRITERIA FOR CO-ROTATING TRAILING VORTICES,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 161-172.

The merging of co-rotational vortices of equal strength is studied by flow-visualization and hot-wire anemometer wind-tunnel experiments and by preliminary numerical calculation of vortex merging. Wind-tunnel experiments and numerical calculations indicate that the effects of turbulence and viscosity are to decrease merging distance from that predicted by inviscid calculations. Hot-wire anemometer measurements of velocity profiles and rolling-moment measurements on a follower model show reduction of the trailing vortex hazard due to merging.

Iversen, J. D., Corsiglia, V. R., Park, S. O., Backhus, D. R. and Brickman, R. A.,
"HOT-WIRE, LASER-ANEMOMETER, AND FORCE MEASUREMENTS OF INTERACTING TRAILING VORTICES,"
J. Aircraft, Vol. 16, No. 7, July 1979, pp. 448-454.

Single and multiple trailing vortices shed from semispan wings and a transport model in a wind tunnel were studied by means of a laser velocimeter, hot-wire anemometer, and trailing model incorporating a six-component force balance. Velocity profile and turbulence data from the laser velocimeter and hot-wire anemometer are presented and shown to compare well with the Betz inviscid circulation model. Lift and rolling moment measurements on the following model are compared with those predicted from the flowfield measurements.

J

Jackson, R. P.,
"AERONAUTICS - THE BIG "A" IN NASA,"
Symposium on Turbulence, FAA, Washington, 1971, pp. 13-18.

The paper presents highlights of the operating systems part of the NASA aeronautics program and where wake turbulence fits into NASA's scale of priorities. The roles of aircraft noise and related research are discussed.

Jacobsen, R. A.,
"HOT-WIRE ANEMOMETRY FOR IN-FLIGHT MEASUREMENT OF AIRCRAFT WAKE VORTICES,"
Proceedings Fifth Annual Symposium, Society of Flight Test Engineers, Anaheim, 1974, pp. 4/13-4/24.

An airborne hot-wire anemometry system capable of providing data with few limitations has been used in several flight studies. The design features of the technique and the operational experience with it are described. The development program has resulted in a flight-test technique that can make accurate velocity measurements in flow regimes where large velocity gradients occur.

Jacobsen, R. A.,
"HOT-WIRE ANEMOMETRY FOR IN-FLIGHT MEASUREMENT OF AIRCRAFT WAKE VORTICES,"
DISA Information, April 1977, pp. 21-27

A development program has demonstrated that hot-wire anemometry can be used successfully on an aircraft in flight to make measurements of wake vortices produced by another aircraft. The probe, whose wires were made of platinum/rhodium, 10 microns in diameter, provides unambiguous results for inflow angles less than about 35 deg. off the probe axis. The high frequency response capability of the hot-wire system allows detailed measurement of the flow structure, and the study of aircraft hazards associated with wake turbulence.

Jacobsen, R. A. and Barber, M. R.,
"FLIGHT TEST TECHNIQUES FOR WAKE-VORTEX MINIMIZATION STUDIES,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, Washington, 1977, pp. 193-220.

Flight test techniques developed for use in a study of wake turbulence and used recently in flight studies of wake minimization methods are discussed. Flow visualization was developed as a technique for qualitatively assessing minimization methods and is required in flight test procedures for making quantitative measurements. The quantitative techniques are the measurement of the upset dynamics of an aircraft encountering the wake and the measurement of the wake velocity profiles. Descriptions of the instrumentation and the data reduction and correlation methods are given.

Jacobsen, R. A. and Drinkwater, F. J.,
"EXPLORATORY FLIGHT INVESTIGATION OF AIRCRAFT RESPONSE TO THE WING VORTEX WAKE GENERATED BY THE AUGMENTOR WING JET STOL RESEARCH AIRCRAFT,"
NASA TM X-62387, May 1975,
NASA Ames Research Center, Moffett Field, CA.

A brief exploratory flight program was conducted at Ames Research Center to investigate the vortex wake hazard of a powered-lift STOL aircraft. The study was made by flying an instrumented Cessna 210 aircraft into the wake of the Augmentor Wing Jet STOL research aircraft at separation distances from 1 to 4 n.mi. Characteristics of the wake were evaluated in terms of the magnitude of the upset of the probing aircraft. Results indicated that within 1 n.mi. separation the wake could cause rolling moments in excess of roll control power and yawing moments equivalent to rudder control power of the probe aircraft. Subjective evaluations by the pilot of the Cessna 210 aircraft, supported by response measurements, indicated that the upset caused by the wake of the STOL aircraft was comparable to that of a DC-9 in the landing configuration.

Jacobsen, R. A. and Short, B. J.,
"A FLIGHT INVESTIGATION OF THE WAKE TURBULENCE ALLEVIATION RESULTING FROM A FLAP CONFIGURATION CHANGE ON A B-747 AIRCRAFT,"
NASA TM-73263, July 1977,
NASA Ames Research Center, Moffett Field, CA.

A flight test investigation was conducted to evaluate the effects of a flap configuration change on the vortex wake characteristics of a Boeing 747 (B-747) aircraft as measured by differences in upset response resulting from deliberate vortex encounters by a following Learjet aircraft and by direct measurement of the velocities in the wake. The flaps of the B-747 have a predominant effect on the wake. The normal landing flap configuration produces a strong vortex that is attenuated when the outboard flap segments are raised; however, extension of the landing gear at that point increases the vortex induced upsets. These effects are in general agreement with existing wind tunnel and flight data for the modified flap configuration.

Jain, A. C.,
"NUMERICAL SOLUTIONS OF NAVIER-STOKES EQUATIONS FOR THE STRUCTURE OF A TRAILING VORTEX,"
NASA TM X-73361, Jan. 1977
NASA Marshall Space Flight Center, Huntsville, AL.

An attempt is made to understand the structure and decay of a trailing vortex through the numerical solutions of the full Navier-Stokes equations. Unsteady forms of the governing equations are recast in terms of circulation, vorticity, and stream function as dependent variables, and a second upwind finite-difference scheme is used to integrate them with prescribed initial and boundary conditions. A discussion of the boundary conditions at the outer edge and at the outflow section of the trailing vortex is included. A parametric study is undertaken with a view to understand the various phenomena that may possibly occur in the trailing vortex. Using the Hoffman and Joubert law of circulation at the inflow section, the results of the present investigation are compared with the experimental data of Chigier and Corsiglia on a CV-990 wing model and a rectangular wing. With an exponentially decaying law of circulation at the inflow section and an adverse pressure gradient at the outer edge of the trailing vortex, solutions depict vortex bursting through the sudden expansion of the core and/or through the stagnation and consequent reversal of the flow on the axis. It is found that this bursting takes place at lower values of the swirl ratio as the Reynolds number increases.

Jarvinen, P. O.,
"AIRCRAFT WING-TIP VORTEX MODIFICATION,"
J. Aircraft, Vol. 10, No. 1, Jan. 1973, pp. 63-64.

The results of a low speed experimental wind tunnel study of the modification of a wing tip vortex using a tip mounted, upstream facing jet are discussed. The tests were performed in the MIT Wright Brothers 7 ft by 10 ft closed return subsonic wind tunnel. The vorticity of the vortex was measured by a vorticity meter located seven chord lengths downstream of the wing trailing edge and in line with the wing tip. A moveable smoke generator unit was used to obtain flow visualization photographs. It was found that the upstream facing jet is more effective in reducing the vorticity at the same value of the jet momentum coefficient (essentially a thrust coefficient) than the downstream facing jet.

Jeffery, R. W., Broadbent, E. G. and Hazell, A. F.,
"WIND-TUNNEL INVESTIGATION OF VORTEX REFRACTION EFFECTS ON AIRCRAFT NOISE PROPAGATION,"
J. Aircraft, Vol. 14, No. 8, Aug. 1977, pp. 737-745.

One possible method for reducing aircraft flyover noise is to site the engines so that the wing vortex can refract sound away from the ground. A series of experiments was carried out in the RAE 24-foot wind tunnel using a model of the HP 115 slender delta research aircraft, which produced a strong leading-edge vortex when set at incidence. The engine noise was simulated by a Hartmann whistle mounted above the engine intake. The results are compared with a theoretical prediction based on ray theory and a simplified representation of the wing vortex structure.

Jeffreys, H. B.,
"SYSTEMS SIMULATION FOR AN AIRPORT TRAILING VORTEX WARNING SYSTEM,"
NASA TM X-64704, Oct. 1972,
NASA Marshall Space Flight Center, Huntsville, AL.

This report documents the approach, development, and limited system studies associated with a system simulation for an Airport Trailing Vortex Warning System (ATVWS). It attempts to show the usefulness of a systems engineering approach to the problem of developing a system, as dictated by aircraft vortices, which will increase air traffic flow in the takeoff/landing corridors of busy airports while maintaining the required safety factor, for each operation.

Jeffreys, H. B. and Bilbro, J. W.,
"DEVELOPMENT OF A LASER DOPPLER SYSTEM FOR THE DETECTION AND MONITORING OF ATMOSPHERIC DISTURBANCES,"
Electro-Optics '75 International Laser Conf., Anaheim, CA, Nov. 1975, pp. 380-390.

The Marshall Space Flight Center has developed a Scanning Laser Doppler System capable of detecting and monitoring atmospheric disturbances. This system has been used successfully to detect and track wake vortices of landing aircraft and to obtain vertical wind profiles in the atmosphere. The laser system, which is installed in a mobile van, is a focused continuous wave, CO_2 system which determines the line-of-sight velocities of particles in the focal volume of the system by measuring the Doppler shift created by these particles. At present, the system has been designed to have a range coverage of approximately 2,000 feet with a vertical angle coverage of approximately 60°. The system can detect Doppler velocities of up to 200 feet/second with a velocity resolution of approximately 1.8 feet/second. A complete velocity profile is provided by the system at each point in space at which it is focused. This information is further processed to provide specific velocity information in regions of interest.

Jeffreys, H. B., Sonnenschein, C. M. and DiMarzio, C. A.,
"PERFORMANCE OF A CO_2 LASER VORTEX DETECTION SYSTEM,"
Conf. on Laser Engineering and Applications, IEEE/OSA, Washington, May 1975.

A scanning CO_2 laser Doppler velocimeter has been used to obtain transport and velocity characteristics of aircraft trailing vortices. System performance and vortex data are presented.

Jelalian, A. V., Keene, W. H., Sonnenschein, C. M. and Huffaker, R. M.,
"LASER DOPPLER SYSTEMS OF REMOTE ATMOSPHERIC MEASUREMENTS,"
Northeast Electronics Research and Engineering Meeting, IEEE, Boston, Nov. 1971.

This paper discusses several field measurements that have been performed with a CO_2 laser Doppler homodyne system sampling the clear atmosphere for the remote measurement of atmospheric winds and aircraft wake vortices. This system makes use of particulate matter normally present in the lower atmosphere to provide backscattering and to act as tracers of air motion.

Jenkins, M. W. M. and Hackett, J. E.,
"A PILOT-IN-THE-LOOP, VISUAL SIMULATION OF TRAILING VORTEX ENCOUNTERS AT LOW SPEED,"
AIAA Paper No. 75-104,
Pasadena, CA, 1975.

A fixed base, visual flight simulator, using a transport cab, was used to explore pilot-in-the-loop encounters of a C-130 type transport flying in the wake of a C-5A. Some 80 flight conditions were flown through a range of vortex strengths, core radii, spatial orientations, direction of rotation, and encounter altitudes. Vortex-lattice modeling techniques were used to update the forces and moments of the penetrating aircraft. It established the feasibility of digitally updating the encounter aerodynamics in real time to permit pilot-in-the-loop visual tasks to be performed. Suggested approaches to regulatory boundaries have been made.

Jenkins, M. W. M. and Meyer, R. T.,
"VORTICAL WAKE HAZARD ADVISORY,"
AFFDL-TR-76-146, Feb. 1977,
Lockheed-Georgia Co., Marietta, GA.

The study reported herein was an analytical effort to define separation criteria for USAF aircraft during landing and taking-off. The approach used was a blend of theoretical and experimental work. Existing theoretical methods, analyses and data were used and the results were conditioned by published flight test and pilot-in-the-loop simulation data. Results from the study are presented as a suggested Interim Advisory for USAF operational aircraft when flying in the terminal area. In this advisory, the current operational fleet has been divided into four classes of vortex-generating and vortex-encountering aircraft. Specific separation recommendations are presented in the form of "avoid volumes" of airspace for each combination of the generating and encountering aircraft. These "avoid volumes" include the effects of aircraft relative speeds, flight paths, local winds and atmospheric conditions.

Jensen, R. J.,
"EXPERIMENTAL STUDY OF FAR-FIELD WING WAKES,"
MS Thesis, Jan. 1973,
Mass. Inst. of Technology, Cambridge, MA.

The results of a flow visualization experiment in the M.I.T. Ship Model Towing Tank show that sinusoidal instability and vortex breakdown in a lifting surface wake can be forced by

differential flap oscillation. A theoretical investigation reveals the driving factors are displacement of the vortex from its mean position, sinusoidal variation of circulation along the trailers, and shed vorticity. Optimum wavelengths at which the sinusoidal instability goes to completion in minimum time are found and indicate that inclusion of the driving factors causes the optimum to diverge substantially from the locus of maximum growth rates as predicted by linear theory. Core axial velocities are also investigated and found to be high compared with previous research.

Jewell, W. F. and Stapleford, R. L.,
"MATHEMATICAL MODELS USED TO SIMULATE AIRCRAFT ENCOUNTERS WITH WAKE VORTICES,"
STI TR-1035-4, Aug. 1975,
Systems Technology Inc., Mountain View, CA.

The mathematical model described herein was used for piloted simulation of aircraft encounters with wake vortices. It was implemented on a large moving base simulator (Flight Simulator for Advanced Aircraft) at National Aeronautics and Space Administration's Ames Research Center. The simulation covered two penetrating aircraft, the Lear-23 and the Boeing 720.

Johannes, R. P.,
"AIRCRAFT WAKE TURBULENCE CONTROLLABILITY EXPERIMENT,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 547-559.

The object of the experiment was to evaluate the effectiveness of a properly mechanized automatic control system in minimizing aircraft upset and improving the controllability which can result from wake turbulence encounter. The in-flight experiment consisted of two flights of approximately three hours duration each, wherein the B-52 test aircraft was flown in formation with a C-141 and explored the wake turbulence generated.

Johnson, D. E.,
"DEVELOPMENT OF A TERMINAL SENSOR FOR HAZARDOUS WEATHER AND WAKE TURBULENCE DETECTION,"
Annual Assembly Meeting and Technical Symposium Proceedings, Radio Technical Commission for Aeronautics, 1984, pp. 149-158.

It is pointed out that real time weather information for Federal Aviation Administration (FAA) air traffic control

(ATC) purposes comes currently from ATC surveillance radars. However, existing surveillance radars have three severe limitations for weather detection use. One limitation is related to an optimization of the radars for aircraft detection, because such an optimization degrades the weather detection capability. The fan beam antenna of the surveillance radars causes inaccuracies in weather indications, while the third limitation is the restriction of the surveillance radars to the provision of reflectivity information. This situation has led the FAA to conduct research and development activities concerning the use of Doppler radars. Attention is given to the FAA weather radar requirements, activities in support of the Next Generation Weather Radar (NEXRAD), wind shear and wake turbulence detection, and aspects of data collection.

Johnson, W. A.,
"MATHEMATICAL MODEL FOR HUMAN PILOT BEHAVIOR DURING A WAKE VORTEX ENCOUNTER UPSET,"
TR-1025-4/2, May 1975,
Systems Tech. Inc., Hawthorne, CA.

This report documents the results of a pilot modeling effort to determine the roll control behavior of a human pilot during a wake vortex encounter upset. Data for the pilot modeling analysis was obtained from a six-degree-of-freedom moving-base, piloted simulation of vortex encounters at NASA Ames Research Center.

Johnson, W. A. and Myers, T. T.,
"A MODEL FOR HUMAN PILOT BEHAVIOR DURING WAKE VORTEX ENCOUNTER UPSETS,"
FAA-RD-76-8, April 1976,
Systems Technology Inc., Hawthorne, CA.

A model for pilot behavior is needed to more completely analyze the consequences (including hazard assessment) of wake vortex encounter upsets during final approach. Such a model has been developed to describe a pilot's roll control behavior during a vortex upsets. This model resulted from abstracting the salient characteristics of the many vortex encounters recorded during two moving-base piloted simulations at NASA Ames Research Center. The model allows for several discrete modes of behavior and includes an associated set of switching logics. The model is the result of a lengthy sequence of analytical steps; however, a retracing of these steps is not included here. Rather, only a description of the resulting model and several example applications are presented.

Johnson, W. A. and Rediess, H. A.,
"STUDY OF CONTROL SYSTEM EFFECTIVENESS IN ALLEVIATING VORTEX WAKE UPSETS,"
AIAA Paper No. 73-833,
Key Biscayne, FL, 1973.

The problem of an airplane being upset by encountering the vortex wake of a large transport on takeoff or landing is currently receiving considerable attention. This paper describes the technique and results of a study to assess the effectiveness of automatic control systems in alleviating vortex wake upsets. A six-degree-of-freedom nonlinear digital simulation was used for this purpose. The analysis included establishing the disturbance input due to penetrating a vortex wake from an arbitrary position and angle. Simulations were computed for both a general aviation airplane and a commercial jet transport. Dynamic responses were obtained for the penetrating aircraft with no augmentation, and with various command augmentation systems. The results of this preliminary study indicate that it is feasible to use an automatic control system to alleviate vortex encounter upsets.

Johnson, W. A. and Teper, G. L.,
"ANALYSIS OF VORTEX WAKE ENCOUNTER UPSETS,"
NASA CR-127491, Aug. 1974.
Systems Tech. Inc., Hawthorne, CA.

The problem of an airplane being upset by encountering the vortex wake of a large transport on takeoff or landing is currently receiving considerable attention. This report describes the technique and result of a study to assess the effectiveness of automatic control systems in alleviating vortex wake upsets. A six-degree-of-freedom nonlinear digital simulation was used for this purpose. The analysis included establishing the disturbance input due to penetrating a vortex wake from an arbitrary position and angle. Simulations were computed for both a general aviation airplane and a commercial jet transport. Dynamic responses were obtained for the penetrating aircraft with no augmentation, and with various command augmentation systems, as well as with human pilot control. The results of this preliminary study indicate that attitude command augmentation systems can provide significant alleviation of vortex wake upsets; and can do it better than a human pilot.

Johnson, W. A., Teper, G. L. and Rediess, H. A.,
"STUDY OF CONTROL SYSTEM EFFECTIVENESS IN ALLEVIATING VORTEX WAKE UPSETS,"
J. Aircraft, Vol. 11, No. 3, March 1974, pp. 148-154.

The problem of an airplane being upset by encountering the vortex wake of a large transport on takeoff or landing is currently receiving considerable attention. This paper describes the technique and results of a study to assess the effectiveness of automatic control systems in alleviating vortex wake upsets. A six-degree-of-freedom nonlinear digital simulation was used for this purpose. The analysis included establishing the disturbance input due to penetrating a vortex wake from an arbitrary position and angle. Simulations were computed for both a general aviation airplane and a commercial jet transport. Dynamic responses were obtained for the penetrating aircraft with no augmentation, and with various command augmentation systems. The results of this preliminary study indicate that it is feasible to use an automatic control system to alleviate vortex encounter upsets.

Jones, D. N.,
"INTRODUCTION TO JET-ENGINE EXHAUST AND TRAILING VORTEX WAKES,"
TR-226, April 1970,
Air Weather Service (MAC), USAF, Scott Air Force Base, IL.

This report is a result of a survey of the immediately available literature on aircraft wakes and is a general representation of techniques and problems involved. Approximate relations are used for their simplicity and to define areas dangerous to flight.

Jones, J. P.,
"THE CALCULATION OF THE PATHS OF VORTICES FROM A SYSTEM OF VORTEX GENERATORS AND A COMPARISON WITH EXPERIMENT,"
ARC Report CP-361, March 1955.
University of Southampton, Southampton, England.

A method is described for the calculation of the paths of the trailing vortices from a system of counter-rotating vortex generators, and a comparison is made with some experimental results obtained in a water tunnel. The method can be adapted to other configurations of generators arranged to produce rows of vortices close to a plane surface.

Jones, R. H.,
"HOW THE COURTS LOOK AT WAKE TURBULENCE,"
Symposium on Turbulence, FAA, Washington, 1971, p. 23.

Wake turbulence aircraft accidents over the years have resulted in law suits against the Government for the alleged negligence of the control tower operator. Recent cases have broadened and extended the liability of the U.S. Government for the negligence of its air traffic controllers in wake turbulence accident cases.

Jones, W. P. and Chevalier, H. L.,
"AIRCRAFT TRAILING VORTEX INSTABILITIES,"
International Council of the Aeronautical Sciences Paper 74-34, Haifa, Israel, 1974.

A brief summary is given of the results of flight test studies of trailing vortices carried out at Texas A&M University. The instability of a pair of trailing vortices due to mutual interaction is fully discussed and theoretical predictions of the wavelength of the vortex oscillations that develop in the far wake of an airplane are compared with values determined from photographic records of the wake behavior of a DeHavilland Beaver DHC-2 aircraft. The different types of instability that can develop with single vortices are also considered, including vortex bursting phenomenon that occurs with vortices that separate from the leading edges of highly swept wings at incidence. A technique for inducing earlier breakdown and dissipation of the vortices than would occur normally is described.

Jones, W. P. and Rao, B. M.,
"AIRLOADS AND MOMENTS ON AN AIRPLANE FLYING OVER A PAIR OF INCLINED TRAILING VORTICES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 523-545.

When an aircraft flies across the wake of a preceding one, it is subjected to changing airloads and moments induced by the trailing vortices of the first aircraft. The purpose of this paper is to investigate the magnitude and characteristics of the time dependent aerodynamic forces so produced. The problem is reduced to finding the appropriate vorticity distribution at each stage of the aircraft's flight over the trailing vortices. This can be done approximately by using a modified lifting line theory or, more accurately, by lifting surface theory.

Jordan, A. R.,
"PRESSURE AND VORTICITY TRANSIENTS FROM SUMMER STORMS AND AIRCRAFT,"
J. Appl. Meteorology, Vol. 19, Oct. 1980, pp. 1223-1233.

Pressure, wind, and vorticity have been studied on the microscale and mesoscale for a variety of features including plumes, vortices, dust devils, and gust front from thunderstorms along with aircraft-generated vortices. Results confirm the fact that negative-pressure pulses result from updrafts associated with convective elements, both rotational and non rotational. It is shown that wake vortices from aircraft at take-off and landing have similar features with naturally occurring vortices even though the axes of the wake vortices are initially almost horizontal. It is also shown that a high-sensitivity pressure sensor in combination with suitable wind sensors can be used to determine the diameter and orbital velocity of the vortex flow near the ground where a potential hazard to flight may exist.

Jordan, Jr., F. L.,
"FLOW VISUALIZATION OF THE WAKE OF A TRANSPORT AIRCRAFT MODEL WITH LATERAL-CONTROL OSCILLATIONS,"
NASA TM-84623, June 1983,
NASA Langley Research Center, Hampton, VA.

An exploratory flow visualization study conducted in the Langley Vortex Research Facility to investigate the effectiveness of lateral control surface oscillations as a potential method for wake vortex attenuation on a 0.03 scale model of a wide body jet transport aircraft is described. Effects of both asymmetric surface oscillation (control surfaces move as with normal lateral control inputs) and symmetric surface oscillation (control surfaces move in phase) are presented. The asymmetric case simulated a flight maneuver which was previously investigated on the transport aircraft during NASA/FAA flight tests and which resulted in substantial wake vortex attenuation. Effects on the model wake vortex systems were observed by propelling the model through a two dimensional smoke screen perpendicular to the model flight path. Results are presented as photographic time histories of the wake characteristics recorded with high speed still cameras. Effects of oscillation on the wake roll up are described in some detail, and the amount of vortex attenuation observed is discussed in comparative terms. Findings were consistent with flight test results in that only a small amount of rotation was observed in the wake for the asymmetric case. A possible aerodynamic mechanism contributing to this attenuation is suggested.

Jordan, P. F.,
"SPAN LOADING AND FORMATION OF WAKE,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 207-227.

Classical analyses of aircraft wake formation assume that the wing span loading is (essentially) elliptic, and that in consequence the wake starts out being (essentially) flat. This assumption is incorrect: actual span loadings contain a logarithmic term, and in consequence there is an infinite upwash directly behind the wing just inside the wing tips. This explains why the aircraft wake rolls up faster than the classical analyses predict.

Jordan, P. F.,
"STRUCTURE OF BETZ VORTEX CORES,"
J. Aircraft, Vol. 10, No. 11, Nov. 1973, pp. 691-693.

In 1932 Betz proposed a principle of momentum conservation which leads to an unambiguous description of the structure of the major (the inviscid) part of the trailing vortex. In the present note, the analysis by which one calculates this structure for a wing with an arbitrary (but known) spanwise lift distribution is drastically simplified. Thus an easier access is provided for discussions of questions like that of single versus multiple vortex pairs, of the effect of the detailed vortex structure on its stability, and such.

Jung, Y. and Seath, D. D.,
"SPANWISE DISPLACEMENT OF A LINE VORTEX ABOVE A WING - A SIMPLE CALCULATION SCHEME,"
J. Aircraft, Vol. 25, No. 5, May 1988, pp. 476-478.

When a wing encounters a concentrated tip vortex, its aerodynamic characteristics are substantially altered due to nonlinear interaction. While the vortex affects the wing loads, the wing in turn affects the vortex path through its vorticity field. It is generally believed that some kind of iteration scheme is necessary to account for the mutual influence between the vortex and the wing trailing vorticity and, thus, to obtain an acceptable vortex path and its effect on induced airloads. The present method is based on the lifting line solution of the spanwise load distribution.

K

Kantha, H. L., Lewellen, W. S., and Durgin, F. H.,
"RESPONSE OF A TRAILING VORTEX TO AXIAL INJECTION INTO THE CORE,"
J. Aircraft, Vol. 9, No. 3, March 1972, pp. 254-256.

The present investigation demonstrates that axial injection into the core of a vortex can indeed beneficially spread out the vorticity concentrated in it and prematurely age it. It further shows that the phenomenon is more nearly governed by the momentum flux of injection than by mass flow. A suitable value of injection for which substantial changes are produced in the vortex core appears to correspond to α of roughly 0.35. Despite the relatively high value of α needed, this provides a possibly feasible way to disperse trailing vortices, since all of the injection required may be obtained by a redistribution of thrust.

Keeffe, B. E.,
"VORTEX ADVISORY SYSTEM SIMULATION OF CHICAGO O'HARE INTERNATIONAL AIRPORT,"
FAA-RD-78-76, July 1978,
NAFEC, Atlantic City, NJ.

This report evaluates, in simulation, the procedural implications of the Vortex Advisory System (VAS) on the Chicago O'Hare terminal air traffic control environment. It also attempts to demonstrate any cost benefits/capacity gains which may accrue using reduced VAS aircraft separation criteria on the final approach course based upon meteorological assurance of vortex dissipation. Utilizing the National Aviation Facilities Experimental Center (NAFEC) Digital Simulation Facility (DSF), a real-time simulation of the Chicago O'Hare International Airport airside operations was conducted between March 28 and June 24, 1977. There were 105 data runs of 1 hour and 20 minutes duration completed during this period. Test results indicate that (1) no procedural implications emerged which would deter the implementation of VAS at Chicago O'Hare Airport, and (2) arrival rate increases are sufficient to support previous cost/benefit analysis studies.

Kelly, A. J. and Handelsman, M.,
"ELECTROMAGNETIC EFFECTS OF AIRCRAFT WAKE-ACTIVE FEUILLET INTERACTION,"
IEEE Trans. Aerospace and Electronic Systems, Vol. AES-10, Jan. 1974, pp. 136-143.

A mechanism by which an aircraft wake can interact strongly with the electromagnetic radiation present in an active elevated anomalous refractivity region (active feuillet) is analyzed. The aircraft wake structure, assumed to consist of twin contrarotating vortices plus entrained irrotational gas, trailing behind the wings of typical large aircraft is shown to be capable of descending a distance of approximately 3 wing span distances and attaining a length of the order of 10 km, prior to instability-induced disruption. The parcel of air such a descending coherent wake structure can convey into an active feuillet is demonstrated to alter significantly the local refractive index of the duct and induce substantial radiation spillage. The general characteristics of the electromagnetic radiation produced by this interaction process (i.e., scattering by diaphanous objects) is described.

Kerr, T. H. and Dee, F. W.,
"A FLIGHT INVESTIGATION INTO THE PERSISTENCE OF TRAILING VORTICES BEHIND LARGE AIRCRAFT,"
ARC Report CP-489, Sept. 1959,
Royal Aircraft Establishment, Farnborough, England. (Also, RAE Tech. Note Aero. 2649.)

A flight investigation into the persistence of trailing vortices has been made by flying a Devon in the wake of a Lincoln. The tests were made in the clean and flaps down configurations. The results indicate that the disturbance decays rapidly after 160 seconds and 105 seconds, respectively, and produces negligible rolling moments after 190 seconds and 120 seconds, respectively. The flight results have been compared with the available theoretical work and the comparison suggests that the theory of Squire holds until the vortices start to decay rapidly.

Kfoury, D. J.,
"A ROUTINE METHOD FOR THE CALCULATION OF AERODYNAMIC LOADS ON A WING IN THE VICINITY OF INFINITE VORTICES,"
TR-133-2, May 1966,
MIT Aeroelastic and Structure Laboratory, Cambridge, MA.

The vortex lattice method for the calculation of loads on a wing advancing in a uniform stream was extended to the case of a wing in the vicinity of infinite vortices. The results in the report were limited to checking the convergence of the calculations.

Kiang, R. L.,
"SUB-SCALE MODELING OF AIRCRAFT TRAILING VORTICES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 81-95.

A pilot study of trailing vortices using a sub-scale model is described. The essential feature of the laboratory facility is to have a vortex-generating wing moving along a pair of elevated rails so that the vortices shed by the wing remain relatively fixed with respect to ground-based instrumentation and can be observed and measured throughout their entire life-span. The vortices are rendered visible by smoke traces and by drifting soap bubbles. Hot-wire anemometer probes are used to study the turbulence nature of the vortices. Geometrically similar wings of different sizes running at various speeds and angles of attack have been tested. A scaling study is also described based on existing theories that predict the decay rate of a turbulent line vortex. None of theories examined is capable of correlating the results of the sub-scale experiments.

Kidd, R. M.,
"WAKE TURBULENCE - THE INVISIBLE KILLER,"
CATCA Journal, Vol. 5, Fall 1973, pp. 4-7.

A number of hazardous takeoff situations and some accidents caused by wake vortices (wing tip vortices) from a preceding aircraft on a congested runway are described. Details are given on a wake vortices accident of June 8, 1966, resulting in a collision of an XB-70 and an F-104 over the Mojave Desert in California, and on the crash of a DC-9 behind a DC-10 at Fort Worth on May 30, 1972. Recommendations made by the ALPA air safety team after the crash are listed.

Kirkman, K. L., Brown, C. E. and Goodman, A.,
"EVALUATION OF EFFECTIVENESS OF VARIOUS DEVICES FOR ATTENUATION OF TRAILING VORTICES BASED ON MODEL TESTS IN A LARGE TOWING BASIN,"
NASA CP-2202, Dec. 1973,
Hydronautics Inc., Laurel, MD.

The effectiveness of various candidate aircraft-wing devices for attenuation of trailing vortices generated by large aircraft is evaluated on basis of results of tests conducted with a 0.03-scale model of a Boeing 747 transport aircraft using a unique technique developed at the Hydronautics Ship Model Basin. Emphasis is on the effects produced by these devices in the farfield where the unaltered vortex wakes could still be hazardous to small following aircraft.

Knox, C. E.,
"AN INVESTIGATION OF AIR TRAFFIC CONTROL PROCEDURES AND PILOT TECHNIQUES IN A HIGH DENSITY TERMINAL AREA,"
PhD Thesis, 1974,
Kansas University, Lawrence, KS.

An investigation was conducted to determine if increases in runway capacity could be achieved through the modification of various air traffic control procedures and pilot techniques. Modified procedures and techniques were to be specified such that equipment not already necessary for IFR and/or VFR flight in a high density, semi-positive controlled airspace would not be required. A summary of pertinent pilot and air traffic controller constraints and airspace structure around the high density terminal area and a review of wake vortex characteristics and avoidance procedures was included in this investigation. Kinematic equations of motion and aircraft performance equations were developed for take-off, landing, and in-flight maneuvering computations.

Kodis, R. D.,
"WAKE VORTEX SENSORS,"
Symposium on Turbulence, FAA, Washington, DC, March 1971, p. 28.

The results obtained to date on the Transportation Systems Center task to identify remote sensing techniques to detect, locate, and measure wake vortices near the ground is presented. A simple bistatic radar that detects pulses of acoustic radiation deflected by a vortex is described and experimental data shown. Sensors that use electromagnetic signals scattered by particulate matter in wake vortices are indicated to be feasible but would probably prove less acceptable at airports due to their cost, potential hazard, and difficult maintenance.

Kodis, R. D.,
"WAKE VORTEX SENSING,"
Proceedings of the 18th International Aerospace Instrumentation Symposium, Instrument Society of America, Vol. 18, 1972, pp. 281-283.

Experimental studies and tests are reported on two wake vortex sensing techniques designed to sense the presence and track the motions of low altitude aircraft wake vortices endangering operations around terminal areas. The techniques studied are based on acoustic pulse deflection and velocity field measurements.

Kodis, R. D.,
"THE DETECTION OF AIRCRAFT WAKE VORTICES,"
Conference Proceedings on Flight in Turbulence, AGARD, Number 140, Cambridge, 1973, pp. 11-1 to 11-9.

The trailing vortices deposited in the wakes of heavy jet aircraft constitute a serious hazard for encountering aircraft. In the terminal area this hazard leads to longer separation standards and reduced runway capacity. In order to shorten the required separations without compromising safety it is necessary to be able to detect the presence and the motion of vortices in regions where they constitute a threat. This paper reviews sensing techniques that have been developed and tested for this purpose. In particular, the characteristics of acoustic and wind pressure sensors developed by the U.S. Transportation Systems Center for the Federal Aviation Administration will be described in detail.

Kodis, R. D.,
"REMOTE SENSING TECHNIQUES FOR OBSERVING WAKE VORTICES NEAR THE GROUND,"
AIAA Paper No. 75-320,
Washington, DC, 1975.

The advent of heavy jet aircraft has made it necessary to develop remote sensors capable of detecting and tracking wake vortices for data collection and traffic control. Active sensors now being evaluated include acoustic and optical radars. Passive wind sensors that respond to the velocity field of a nearby vortex have also proved their usefulness. The full complement of such sensors which have been engineered and installed at the Kennedy International Airport (JFK) are described. Typical data are presented and the performance characteristics and limitations of each sensor technique are discussed.

Kohl, R. E.,
"MODEL EXPERIMENTS TO EVALUATE VORTEX DISSIPATION DEVICES PROPOSED FOR INSTALLATION ON OR NEAR AIRCRAFT RUNWAYS,"
NASA CR-132365, August 1973,
Hydronautics Inc., Laurel, MD.

The effectiveness of various vortex dissipation devices proposed for installation on or near aircraft runways is evaluated on basis of results of experiments conducted with a 0.03-scale model of a Boeing 747 transport aircraft in conjunction with a simulated runway. The test variables included type of vortex dissipation device, mode of operation of the powered devices, and altitude, lift coefficient, and speed of the generating aircraft. A total of fifteen devices was investigated. The evaluation is based on time sequence photographs taken in the vertical and horizontal planes during each run.

König, R.,
"AIRCRAFT RESPONSE AND PILOT BEHAVIOR DURING A WAKE VORTEX ENCOUNTER PERPENDICULAR TO THE VORTEX AXIS,"
Flight in Adverse Environmental Conditions, AGARD, Sept. 1989.

Vortex systems can be hazardous to trailing aircraft which encounter them in flight. The greatest hazard occurs in areas where aircraft from a wide range of classes operate and where the flight paths are close to the ground. Upwash velocities induced by the wake vortices can be equivalent to the design gust velocities. Furthermore, different types of hazardous effects exist when encountering the vortex system, such as imposed rolling and pitching moments, a loss of rate of climb, a loss of altitude and structural loads. Aircraft response and pilot behavior during takeoff are described when a wake vortex is encountered perpendicular to the vortex axis. The aircraft response is calculated by nonlinear digital simulation with a mathematical model of a wake vortex system close to the ground. This real-time vortex model is also used in the Boeing B-737 simulator of Deutsche Lufthansa in order to examine the pilot behavior. Close to the ground, the wake vortex system induces additional horizontal velocities. There exists a critical flight path where very large g-loads are induced by vertical and horizontal vortex velocities and normal vertical acceleration shortly after takeoff. Often the pilot will attempt to counteract these g-loads, but this produces only a small effect.

Koochesfahani, M. M.,
"VORTICAL PATTERNS IN THE WAKE OF AN OSCILLATING AIRFOIL,"
AIAA J., Vol. 27, No. 9, Sept. 1989, pp. 1200-1205.

The vortical flow patterns in the wake of a NACA 0012 airfoil pitching at small amplitudes are studied in a low-speed water channel. It is shown that a great deal of control can be exercised on the structure of the wake by the control of the frequency, amplitude, and also the shape of the oscillation waveform. An important observation in this study is the existence of an axial flow in the cores of the wake vortices. Estimates of the magnitude of the axial flow suggest a linear dependence on the oscillation frequency and amplitude.

Köpp, F. and Krichbaumer, W. A.,
"EXPERIMENTAL AND THEORETICAL DOPPLER-LIDAR SIGNATURES OF AIRCRAFT WAKE VORTICES,"
13th International Laser Radar Conf., NASA Langley, Hampton, Aug. 1986.

The DFVLR laser Doppler anemometer is a CO_2 continuous wave homodyne system designed for boundary layer wind measurements. During the last three years, it was mainly used in the wake-vortex program at Frankfurt airport for determination of vortex strength, transport, and lifetime. The strategy for that special type of measurement was previously reported in detail along with single experimental results. Therefore, herein is given a short summary of the data concerning questions of air traffic control. In addition to the experimental activities a computer model describing wake-vortex behavior was installed. It allows the comparison of the measured data with the hydrodynamically predicted quantities. On the other hand, it leads to an improved procedure for future wake-vortex measurements.

Koziol, Jr., J. S.,
"AN ASSESSMENT OF CURRENT METEOROLOGICAL DATA SYSTEMS AT LARGE AIRPORTS FOR WAKE VORTEX AVOIDANCE SYSTEMS,"
PM-P-8, Sept. 1974,
DOT Transportation System Center, Cambridge, MA.

The objective of this assessment was to determine the extent current airport meteorological data systems can provide a basis for the formulation and implementation of a wake vortex prediction model. This involved an investigation of meteorological data systems at 10 high-traffic airports, weather forecasting services, and prediction requirements.

Kraft, Jr., C. C.,
"FLIGHT MEASUREMENTS OF THE TRAILING VORTICES OF AN AIRPLANE,"
NACA TN-3377, March 1955,
Langley Aeronautical Lab., Langley Field, VA.

The disturbance created by the trailing vortices of an airplane can have a detrimental effect on the flight of another airplane passing through the wake. An attempt has been made to measure the velocity distribution and persistence of the trailing vortices of a propeller-driven fighter-type aircraft. This airplane was equipped with a smoke-generating device to mark the vortices. A jet airplane having a high-frequency angle-of-attack vane and a sensitive total-pressure instrument was used to fly through the vortices.

Krasny, R.,
"Computation OF VORTEX SHEET ROLL-UP IN THE TREFFTZ PLANE,"
J. Fluid Mech., Vol. 184, 1987, pp. 123-155.

Two vortex-sheet evolution problems arising in aerodynamics are studied numerically. The approach is based on desingularizing the Cauchy principal value integral which defines the sheet's velocity. Numerical evidence is presented which indicates that the approach converges with respect to refinement in the mesh-size and the smoothing parameter. For elliptic loading, the computed roll-up is in good agreement with Kaden's asymptotic spiral at early times. Some aspects of the solution's instability to short-wavelength perturbations, for a small value of the smoothing parameter, are inferred by comparing calculations performed with different levels of computer round-off error. The tip vortices' deformation, due to their mutual interaction, is shown in a long-time calculation. Computations for a simulated fuselage-flap configuration show a complicated process of roll-up, deformation and interaction involving the tip vortex and the inboard neighboring vortices.

Krause, M. C., Eberle, W. R., Miller, G. M. and Gorzynkski, E. J.,
"INVESTIGATION OF WIND CONDITIONS DURING EARLY MORNING HOURS AT LOS ANGELES INTERNATIONAL AIRPORT,"
FAA-RD-77-116, Oct. 1977,
Lockheed Missiles & Space Co., Huntsville, AL.

Los Angeles International Airport (LAX) uses a unique runway utilization pattern to minimize noise pollution between midnight and 0600. During these hours, all approaches are conducted to the east, and all takeoffs are conducted to the west. The low-altitude portions of all takeoff and landing operations are thereby conducted over the Pacific Ocean. During these operations, pilots have occasionally reported encountering unusual wind conditions. It is the objective of this study to use the Lockheed-Huntsville mobile laser Doppler unit velocimeter unit to monitor winds and wake vortices in the approach zone of runway 6R to identify the sources of the wind anomalies reported by the pilots. No incidents of pilot-reported wind anomalies occurred during the five-week data collection period.

Krause, M. C., Wilson, D. J., Howle, R. E., Edwards, B. B. and Craven, C. E.,
"REMOTE MEASUREMENT UTILIZING NASA'S SCANNING LASER DOPPLER SYSTEM, VOLUME I: LASER DOPPLER WAKE VORTEX TRACKING AT KENNEDY AIRPORT,"
LMSC-HREC-TR-D496633-V1, March 1976,
Lockheed Missiles & Space Co., Huntsvile, AL.

Test operations of the Scanning Laser Doppler System (SLDS) at Kennedy International Airport (KIA) during August 1974 through June 1975 are reported. A total of 1619 data runs was recorded with a totally operational system during normal landing operations at KIA. In addition, 53 data runs were made during cooperative flybys with the CV-880 for a grand total of 1672 recorded vortex tracks. Test crews were in attendance at KIA for 31 weeks, of which 25 weeks were considered operational and the other six were packing, unpacking, setup and check out. Although average activity equates to 67 recorded landing operations per week, two periods of complete runway inactivity spanned 20 days and 13 days, respectively. The operation frequency therefore averaged about 88 operations per week.

Kuchemann, D. and Weber, J.,
"VORTEX MOTIONS,"
Zeitschrift für Angewandte Mathematik and Mechanik, Vol. 45, No. 7-8, Dec. 1965, pp. 457-474.

This work demonstrated that the key features of the vortex core flows are the same, whether the model used involves a vortex sheet in irrotational flow or a swirling flow with distributed vorticity. Some complete flows are described and the problems involved are briefly discussed, using the example of a lifting slender wing.

Kuhn, G. D.,
"LEAST-SQUARES ANALYSIS OF VELOCITY MEASUREMENTS IN THE WAKE OF AIRCRAFT WITH TAILORED SPAN LOADING,"
NEAR TR-78, Dec. 1974,
Nielsen Eng. and Research Inc., Mountain View, CA.

A method is presented for analyzing experimental velocity measurements behind aircraft with multiple wake vortices. The method assumes the vortices can be represented by inviscid vortices. The nonlinear mathematical expressions so produced are linearized around a "first guess" of the positions and strengths of the vortices. The resulting expressions are solved for the unknown perturbations from linearity by the method of least squares. The "first guess" is updated and the process repeated until the solution converges.

Kuhn, G. D. and Jacobsen, R. A.,
"ANALYSIS OF WAKE VORTEX FLIGHT TEST DATA BEHIND A T-33 AIRCRAFT,"
NASA CR-137669, April 1975,
Nielsen Engineering & Research Inc., Mountain View, CA.

Measurements of the vortex system behind a T-33 aircraft were obtained by a Learjet equipped with a boom carrying a three-wire, hot-wire anemometry probe and other instrumentation. Analysis of the measurements using a computerized geometric method indicated the vortices had a core radius of approximately 0.11 meter with a maximum velocity of 25 meters per second. No longitudinal instabilities, buoyant effects or vortex breakdowns were evident in the data which included vortex wake cross sections from 0.24 to 5.22 kilometers behind the T-33.

Kuhn, G. D. and Nielsen, J. N.,
"ANALYTICAL STUDIES OF AIRCRAFT TRAILING VORTICES,"
AIAA Paper No. 72-42,
San Diego, CA, 1972.

The effects of turbulent mixing and buoyancy on the motion and persistency of a trailing vortex wake behind an aircraft are considered. A model for the characteristics of a turbulent vortex, based on an analogy to a turbulent boundary layer, is presented. A theory of trailing-vortex characteristics behind an aircraft is presented based on considerations of the angular and linear momentum of the vortex and the total pressure variation along the axis. Comparisons between the predictions of the theory and recent NASA wind tunnel data exhibit good agreement. The turbulent shear of the axial flow was shown to be the dominant mechanism for the growth of the core radius, the decay of the peak tangential velocity and the decay of the axial velocity defect.

Kurkowski, R. L., Barber, M. R. and Garodz, L. J.,
"CHARACTERISTICS OF WAKE VORTEX GENERATED BY A BOEING 727 JET TRANSPORT DURING TWO-SEGMENT AND NORMAL ILS APPROACH FLIGHT PATHS,"
NASA TN D-8222, April 1976,
NASA Ames Research Center, Moffett Field, CA.

A series of flight tests was conducted to evaluate the vortex wake characteristics of a Boeing 727 (B727-200) aircraft during conventional and two-segment ILS approaches. Twelve flights of the B727, which was equipped with smoke generators for vortex marking, were flown and its vortex wake was intentionally encountered by a Lear Jet model 23 (LR-23) and a Piper Twin Comanche (PA-30). The tests showed that at a given separation distance there were no readily apparent differences in the upsets resulting from deliberate vortex encounters during the two types of approaches. Timed mappings of the position of the landing configuration vortices showed that they tended to descend approximately 91 m (300 ft) below the flight path of the B727. The flaps of the B727 have a dominant effect on the character of the trailed wake vortex. The clean wing produces a strong, concentrated vortex but as the flaps are lowered, the vortex system becomes more diffuse. Pilot opinion and roll acceleration data indicate that 4.5 n.mi. would be a minimum separation distance at which roll control of light aircraft (less than 5,670 kg (12,500 lb) could be maintained during parallel encounters of the B727's landing configuration wake.

Kurylowich, G.,
"A STUDY OF AIR FORCE WAKE TURBULENCE ACCIDENTS,"
AFFDL-TM-72-3-FGC, March 1972,
Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH.

USAF accident statistics have been analyzed for the 1965-1971 time period. The number of accidents probably caused by wake encounters, as well as the percentage of total and terminal area losses they represent, are given. A short-term program for the study of wake turbulence as related to USAF operations is proposed.

Kurylowich, G.,
"WAKE TURBULENCE ABATEMENT BY BLOWING AND OTHER MEANS,"
Fluid Dynamics Panel, AGARD, 1973.

The current state of knowledge concerning the turbulent breakup and bursting of aircraft trailing vortices is reviewed. Efforts towards the forcing of premature vortex breakup are placed in the context of an Air Force related wake turbulence program.

Kurylowich, G.,
"ANALYSES RELATING TO AIRCRAFT VORTICAL WAKES,"
AFFDL-TM-73-23-FGC, Feb. 1973,
Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH.

A comprehensive literature review of all analyses and experimental investigations related to vortical wake structure is presented. Various mathematical models for the flow field in the far wake are given and then compared to experiment. The possibility of causing premature vortex break-up by such means as wingtip spoilers and mass injection is also discussed.

Kurylowich, G.,
"THE WAKE TURBULENCE RESEARCH PROGRAM AT AFFDL,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 3-9.

A review is given of the Flight Dynamics Laboratory wake turbulence program; the program was prompted by the evaluation of accidents and incidents within the Air Force. A large percentage of the vortex encounters occurred during military operations quite distinct from the usual civil related terminal operations (mid-air refueling, minimum interval takeoff, formation flight, and mixed mode operations with nearby helicopters). Future high performance fighters will be more susceptible to vortex upsets because of their light weight and low moments of inertia. The primary concern of the Air Force is the near wake. The experimental and theoretical efforts on the near wake are reviewed as well as a vortex encounter simulation.

Kurylowich, G.,
"A SIMPLIFIED VORTEX ENCOUNTER MODEL FOR SIMULATING WAKE TURBULENCE ON USAF TRAINERS AND SIMULATORS,"
AFFDL-TM-75-91-FGC, June 1975,
Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH.

A simplified model for the calculation of rolling moment on an aircraft encountering wake turbulence is presented. The model is implemented on appropriate trainers and simulators for the purpose of educating the pilots on the extent of a wake turbulence encounter as part of their training curriculum.

Kurylowich, G.,
"A METHOD FOR ASSESSING THE IMPACT OF WAKE VORTICES OF USAF OPERATIONS,"
AFFDL-TR-79-3060, July 1979,
Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH.

Experience as a consultant to the Safety Office at Norton AFB led to compiling the engineering tools presented so that this report can be used by engineering personnel to investigate future incidents/accidents and existing USAF operations that are impacted by the vortical wake hazard. The approach presented is amenable to easy hand computations. Mixed airplane/helicopter operations can be assessed, since the engineering tools to determine the location and strength of the rotor downwash field behind a helicopter are presented. Finally, a simplified mathematical model is given to represent this hazard for use in USAF simulators, to make pilots aware of the problems associated with operating in wake-contaminated airspace.

Kurylowich, G. and Nelson, R. C.,
"ANALYSIS OF A WAKE TURBULENCE HAZARD IN USAF OPERATIONS (T-38 ACCIDENTS),"
AFFDL-TM-74-132-FGC, June 1974,
Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH.

Analyses related to the investigation of a T-38 accident which appeared to be caused by an encounter with the wake of an L-382 are presented. It is shown that the T-38 could have encountered wake turbulence through modelling the atmospheric propagation of the L-382 wake. The severity of the encounter is estimated through modelling of wake decay and the effects of dynamic encounters.

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Labrujere, T. E. and Devries, O.,
"EVALUATION OF A POTENTIAL THEORETICAL MODEL OF THE WAKE BEHIND A WING VIA COMPARISON OF MEASUREMENTS AND CALCULATIONS,"
NLR TR-74063-U, July 1974,
National Aerospace Lab., Amsterdam, The Netherlands.

The validity of the representation of the wake by discrete trailing vortices as common practice in potential theoretical calculations is considered. Theoretical results, obtained with a method developed at NLR, are compared with experimental results obtained at NLB for a 30 deg sweptback wing. The shape of the vortex sheet as well as the velocity distribution downstream from the wing are predicted reasonably well; however, the wake model appears to be not completely satisfactory in the wing tip region. The numerical method requires improvement with respect to the description of the rolling up process of the vortex sheet.

Lake, H.,
"AIRCRAFT WAKE VORTEX BEHAVIOR STUDY, METEOROLOGY AND AIRCRAFT VORTEX TRANSPORT AND DECAY,"
ER-73-4299, July 1973,
Raytheon Company, Sudbury, MA.

This report identifies and defines the meteorological parameters that have been observed to affect the behavior of aircraft generated vortices. The most commonly observed effect (observed with smoke entrainment) was the drift of vortices with the mean wind. More recently other meteorological parameters have been identified as affecting the manner and rate at which vortices behave.

Lamar, J. E.,
"PREDICTION OF VORTEX FLOW CHARACTERISTICS OF WINGS AT SUBSONIC AND SUPERSONIC SPEEDS,"
J. Aircraft, Vol. 13, No. 7, July 1976, pp. 490-494.

The leading-edge suction analogy of Polhamus, which has been successful in the prediction of vortex lift characteristics on wings with pointed tips at subsonic and supersonic speeds, has recently been extended to account for the vortex flow characteristics for wings with side edges. Comparisons of experimental data and other currently used methods with the extended method are made for wings having side edges at subsonic and supersonic speeds. Recent data obtained for a low-aspect-ratio cropped-delta wing with various amounts of asymmetrical tip rake, simulating a roll control device, are also presented.

Lambourne, N. C.,
"THE BREAKDOWN OF CERTAIN TYPES OF VORTEX,"
ARC-C-915, Sept. 1965,
Aeronautical Research Council, London, England. (Also, NPL-AERO-1166 and ARC-27200).

Two observed forms of vortex breakdown are compared and experimental evidence is presented to suggest that the spiral form is a derivative of the axisymmetric form. Theoretical examination of the effect of an imposed adverse pressure gradient on a vortex core shows that drastic changes of flow structure must occur when certain critical conditions are exceeded. The theoretical predictions are to some extent consistent with the observed breakdown.

Lambourne, N. C. and Bryer, D. W.,
"THE BURSTING OF LEADING-EDGE VORTICES - SOME OBSERVATIONS AND DISCUSSIONS OF THE PHENOMENON,"
ARC-22775, April 1961,
Nat. Phys. Lab., Great Britain. (Also, ARC R&M-3282)

Bursting refers to the abrupt structural change from a regular spiral motion to a weaker turbulent motion which can occur at some position along a vortex generated by a sweptback leading edge of a wing. The phenomenon is examined by flow visualization, its sensitivity to several factors is investigated and the reasons for its occurrence are discussed. The burst is found to be sensitive to several factors, in particular, an increase of pressure gradient along the vortex seems conducive to the occurrence of a burst. It is suggested that a condition essential for the burst to occur is a low total pressure within the vortex core coupled with an adverse pressure gradient along the axis.

Landahl, M. T. and Widnall, S. E.,
"VORTEX CONTROL,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 137-155.

The fluid dynamical aspects of the control of free vortices emanating from the wing or other parts of a flight vehicle are reviewed. Simple calculations based on slender-body theory are used to demonstrate the importance of controlling the strength, position and core stability and thickness of such vortices. From the equations describing vortex motion, conclusions are drawn as to how vortex properties can be influenced. Simple energy arguments are used to clarify the phenomenon of vortex bursting and to draw conclusions as to what can be done to prevent or induce bursting.

Langweil, L.,
"WAKE VORTEX AVOIDANCE SYSTEM PROGRAM,"
Flight in Turbulence, AGARD, CP-140, 1973, pp. 12-1 to 12-9.

The paper describes the Wake Vortex Avoidance System program now being carried out by the FAA. The program's basic objective is to design a predictive system which will increase runway capacity by eliminating the need for the large fixed separations now required between aircraft. These will be replaced by a dynamic safe spacing tailored to the aircraft type and prevailing meteorological conditions. The program consists of three major task areas: sensor development, vortex behavior, hazard definition and the integration of these tasks into an overall system design.

Larson, R. S. and Robbins, K. W.,
"REFRACTION OF SOUND BY AIRCRAFT WING TIP VORTICES,"
AIAA Paper No. 80-0975,
Hartford, CT, June 1980.

A detailed study was conducted to define the effect of a wing tip vortex on aircraft flyover noise, The Lamb vortex, the modified Lamb vortex, and a turbulent vortex were three models used to simulate a wing tip vortex. A theoretical geometrical acoustics model was developed to predict the effect of an aircraft's wing tip vortex on acoustic measurements obtained in typical sideline noise tests. Theoretical predictions demonstrated that the refraction and convective amplification effects from a wing tip vortex can cause large distortions in the acoustic field radiated by an engine.

Lee, G. H.,
"TRAILING VORTEX WAKES,"
Aeronautical Journal, Sept. 1975, pp. 377-388.

It is shown that the trailing vortex wakes generated by large aeroplanes can cause serious upsets (loss of control) to smaller following aircraft that may encounter them and may damage buildings near an airport. The increase in separation behind big aircraft imposed as a safety measure leads to a serious loss of runway capacity. After discussion of the nature of wake vortices, it is demonstrated that they may be attenuated, so avoiding unnecessary separation between aircraft at an airport and, at the same time, obviating ground damage. Discussion of alternative devices available for moderating the vortex wake indicates that practical solutions may be confidently expected.

Lee, H. and Schetz, J. A.,
"EXPERIMENTAL RESULTS FOR REYNOLDS NUMBER EFFECTS ON TRAILING VORTICES,"
J. Aircraft, Vol. 22, No. 2, Feb. 1985, pp. 158-160.

The simulation of vortices by small-scale model testing in wind tunnels and towing ranks presents a problem, since the history of vortices is known to be sensitive to Reynolds number. The near-wake behavior of the vortices trailing from low aspect ratio lifting surfaces mounted on either side of a larger, nonlifting, streamlined strut was investigated in a wind tunnel. The effect of Reynolds number was apparent; an increasing Reynolds number corresponded to a decreasing axial velocity defect and an increasing maximum swirl velocity. Furthermore, this Reynolds number effect was found to be greater than that of downstream distance.

Leibovich, S.,
"WAVE MOTION AND VORTEX BREAKDOWN,"
AIAA Paper No. 69-645,
San Francisco, CA, 1969.

Vortex breakdown is a phenomenon occurring in rotating fluids when there is a component of velocity along the axis of rotation. It occurs in many flows including the conical vortex cores above delta wings on an angle of attack, leading to an abrupt deceleration of the flow and the consequent rapid expansion of stream surfaces. In the original theory, due to Squire, it was suggested that the phenomenon was connected with wave motion along the rotation axis. Squire's theory was for infinitesimal perturbations, and Benjamin pointed out a serious inconsistency which discredited the wave idea. Here the wave theory is re-examined, by taking into account the effects of nonzero wave amplitude. It is found that a nonlinear wave theory is consistent, is easy to calculate, and is quite flexible, allowing treatment of both incompressible and compressible fluids, in either axially-symmetric or spiral wave modes.

Leibovich, S.,
"THE STRUCTURE OF VORTEX BREAKDOWN,"
Annual Review of Fluid Mechanics, Vol. 10, Ann. Rev. Inc., Palo Alto, 1978, pp. 221-246.

A survey of experimental and theoretical work on vortex breakdown published since the 1972 review by Hall. All studies have been carried out at low speeds so only incompressible motions are considered.

Lengendre, R.,
"EFFECT OF WING TIP SHAPE ON VORTEX SHEET ROLLING UP,"
Rech. Aerosp., No. 4, July-Aug. 1971, pp. 227-228.

Laws of separation over a whole wing are applied to study straight or moderately swept back wings. The effect of vortex sheet rolling up can be avoided by tailoring the profile of the trailing edge to the edge of a wing or blade, with constant or zero leading edge sweepback, in such a way as to make a clear distinction between the leading and trailing edges. Break phenomena are studied.

Lennert, A. E., Crosswy, F. L. and Kalb, H. T.,
"APPLICATION OF THE LASER VELOCIMETER FOR TRAILING VORTEX MEASUREMENTS,"
AEDC-TR-74-26, Dec. 1974,
ARO Inc., Arnold Air Force Station, TN.

This report summarized a three-year analytical and experimental program to develop a dual-scatter laser velocimeter system to map the flow field of trailing vortices stemming from the wingtips of flying aircraft. The basic design parameters ascertaining feasibility of the LV-measuring technique are presented. Included is a discussion and evaluation of a newly developed two-dimensional Bragg cell for resolving directional ambiguity. The electronics instrumentation developed for the operation of the Bragg cell is evaluated in detail.

Lessen, M.,
"THE HYDRODYNAMIC STABILITY OF A TRAILING VORTEX,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 37-41.

The results of research being conducted at the University of Rochester on the hydrodynamic stability of swirling flows was presented. There are two basic aspects to the problem: the mathematical solution of the formalized stability theory as applied to wake vortex models, and the extension of results obtained in such investigations to the finite amplitude disturbances and fully turbulent flows encountered in real life.

Lessen, M., DeShpande, N. V. and Hadji-Ohanes, B.,
"STABILITY OF A POTENTIAL VORTEX WITH A NON-ROTATING AND RIGID-BODY ROTATING TOP-HAT JET CORE,"
J. Fluid Mechanics, Vol. 60, Part 3, Sept. 1973, pp. 459-466.

The stability of a potential vortex with a rotating and a non-rotating jet core is analyzed. Eigenvalues are calculated numerically for different values of the ratio of the strength of the vortex to the axial velocity. These results show that the potential vortex becomes unstable in the presence of a jet.

Lessen, M. and Paillet, F.,
"THE STABILITY OF A TRAILING LINE VORTEX, PART 2: VISCOUS THEORY,"
J. Fluid Mech., Vol. 65, Part 4, Oct. 1974, pp. 769-779.

The viscous stability of the Lamb vortex and axisymmetric wake is explored. A locally constant eddy viscosity is used to formulate the full stability equations. Disturbance growth rates are then calculated as a function of Reynolds number, axial and azimuthal periodicity, and intensity of core rotation. It is shown that the initial destabilization by the superposition of stable rotation reduces the minimum critical Reynolds number to half that for the wake alone. All modes are stabilized when the rotation becomes strong, and the increase of minimum critical Reynolds number with increasing rotation is traced.

Lessen, M., Singh, P. and Paillet, F.,
"THE STABILITY OF A TRAILING LINE VORTEX, PART 1: INVISCID THEORY,"
J. Fluid Mech., Vol. 63, Part 4, May 1974, pp. 753-763.

The hydrodynamic stability of a continuous velocity distribution (Lamb vortex and axisymmetric wake) resembling that in a wake vortex is examined, and stability is calculated as a function of the ratio of maximum velocity defect to maximum tangential flow. It is found that rotation can destabilize the axisymmetric wake, but that all instability modes appear stable when the rotation becomes strong enough.

Lewellen, W. S.,
"A SOLUTION FOR THREE-DIMENSIONAL VORTEX FLOWS WITH STRONG CIRCULATION,"
J. Fluid Mechanics, Vol. 14, Part 3, Nov. 1962, pp. 420-432.

The Navier-Stokes equations for a viscous, incompressible fluid is considered for a steady, axisymmetric flow composed of a strong rotation combined with radial sink flow which exhausts axially inside a finite radius. The equations are reduced to two coupled partial differential equations in terms of the stream function and circulation.

Lezius, D. K.,
"WATER TANK STUDY OF THE DECAY OF TRAILING VORTICES,"
AIAA Journal, Vol. 12, No. 8, Aug. 1974, pp. 1065-1071.

Underwater towing experiments were carried out with a rectangular airfoil of aspect ratio 5.3 at 4° and 8° angles of attack and at chord-based Reynolds numbers between 2.2×10^5 and 7.5×10^5. Tangential velocity measurements in the downstream region between 100 and 1000 chord lengths indicate rates of vortex decay proportional to $t^{-7/8}$ at 8°, whereas previous flight tests show that the decay rate approaches $t^{-1/2}$ far downstream. The observed behavior is explained in terms of an analytical solution that includes time dependence of the turbulent eddy viscosity, $\sim t^m$. It shows that, for $m>0$, an isolated turbulent vortex decays faster than $t^{-1/2}$. In this case, the decay is accompanied by increasing turbulent eddy viscosity, or levels of turbulence, which corresponds to turbulent nonequilibrium flow. The special case of vortex decay with equilibrium flow ($m=0$) leads to the well-known decay rate $t^{-1/2}$. Since, in towing tank experiments at low Reynolds number, turbulent vortex decay may occur predominantly in non equilibrium, it is doubtful that such tests correctly predict the late stage of decay of aircraft trailing vortices, when turbulence is the only dissipating mechanism.

Lezius, D. K.,
"ANALYTICAL SOLUTION FOR INVISCID VORTEX ROLLUP FROM ELLIPTICALLY LOADED WINGS,"
J. Aircraft, Vol. 12, No. 11, Nov. 1975, pp. 911-914.

An explicit analytical perturbation solution is presented that is based upon the Betz rollup theory for the vortex circulation after rollup from wings with elliptically distributed span loading. Since the resulting series solution converges rapidly, accurate and uniformly valid results emerge for the complete rollup when only the first three terms of the expansion are retained.

Lissaman, P. B. S., Crow, S. C., MacCready, Jr., P. B., Tombach, I. H. and Bate, Jr., E. R.,
"AIRCRAFT VORTEX WAKE DESCENT AND DECAY UNDER REAL ATMOSPHERIC EFFECTS,"
FAA-RD-73-120, Oct. 1973,
AeroVironment Inc., Pasadena, CA.

Aircraft vortex wake descent and decay in a real atmosphere is studied analytically. Factors relating to encounter hazard, wake generation, wake descent and stability, and atmospheric dynamics are considered. A new analysis for Crow instability in ambient turbulence is given, expressing time-to-linkage as an explicit function of the turbulent dissipation. Wake descent in a stratified inviscid fluid is studied analytically providing new results. According to the new theory, the vortex span reduces upon descent into a stably stratified flow, causing the rate of descent to increase. Exact solutions are derived for vortex cell shapes in a uniformly sheared crosswind, showing that the upwind cell is greatly increased in size. It is believed that this may partly account for the observed unsymmetrical behavior (banking, etc.) in crosswinds.

Liu, H. T.,
"LABORATORY INVESTIGATION OF ATMOSPHERIC EFFECTS ON VORTEX WAKES - A FEASIBILITY INVESTIGATION,"
TR 394, March 1987
Flow Research, Inc., Kent, WA.

Tow tank experiments were successfully conducted to demonstrate the feasibility of investigating atmospheric effects on the evolution of a trailing vortex wake. Atmospheric disturbances simulated in the tank included stable stratification, ambient turbulence, and wind shear. Visualizations of the vortex wakes from several perspectives were conducted using fluorescent dye illuminated by bands of ultraviolet lights and a sheet of laser light. In a quiescent environment, we have established the upper bound of the lifespan of a trailing vortex wake due to essentially self-induced sinusoidal instability. Ambient turbulence reduces the lifespan. Vortex linking is the dominant mode of vortex instability in weak turbulence. As the turbulence intensity or dissipation rate increases, vortex bursting begins to appear and eventually replaces linking as the dominant mode of instability. The wind shear affects the behavior of the vortex wake in two ways. In a longitudinal shear, the inclined trailing vortex pair is stretched, resulting in vortex contraction and leading to speed up of vortex descent and possibly to vortex annihilation prior to the onset of linking or bursting. In a cross shear, the vortex wake is forced to rotate about its axis.

Liu, H. T. and Srnsky, R. A.,
"LABORATORY INVESTIGATION OF ATMOSPHERIC EFFECTS ON VORTEX WAKES,"
TR 497, Feb. 1990,
Flow Research, Inc., Kent, WA.

Tow tank experiments were conducted to investigate atmospheric effects on the evolution of trailing vortex wakes. The atmospheric effects simulated included stable stratification, ambient turbulence, and wind shear. In a quiescent fluid, self-induced sinusoidal instability limits the lifespan of a trailing vortex wake in a neutral or weakly stratified environment. Ambient turbulence reduces the lifespan. For weak turbulence with a large integral scale compared with the vortex separation, vortex linking is the dominant mode of vortex instability. As the turbulence intensity or dissipation rate increases, however, vortex bursting begins to appear and eventually replaces linking as the dominant mode of instability. Existing theory tends to underpredict, by a factor of about 2, the lifespan of the vortex wake in a turbulent environment. For turbulence with a small integral scale compared with the vortex separation, vortex instability is predominantly of the bursting type. In a longitudinal shear, the inclined trailing vortex pair tends to be stretched, resulting in an increase in the dominant wavelength of the linking instability. In a cross shear, one side of the vortex pair is stabilized and the other destabilized by the shear, the formation of a solitary vortex at large times is often observed. Tipping of the vortex wake is observed just below the exit of the 2-D vortex pair due to the presence of a crossflow. The tipping is attributed to the asymmetries of the initial rollup and of the flow generated as the vortex pair is carried by the crossflow across the exit plate. There is no correlation betwe(n the orientation of the tipping and the sign of the shear .w. With respect to ground effects, a vortex wake rebound: after it moves close to the ground. By introducing a solid surface close to the exit of the 2-D vortex pair, the formation of secondary vortices outboard of the main vortices that cause the latter to rebound is evident from the visual results. Trajectories derived from the trailing vortex wake released in the proximity of a simulated ground surface have confirmed that the hyperbolic inviscid solution is incorrect.

Logan, A. H.,
"A SOLUTION TO THE VORTEX BREAKDOWN PHENOMENON IN A TRAILING LINE VORTEX,"
MS Thesis, Dec. 1966,
Penn. State University, University Park, PA.

A theoretical analysis of the vortex burst phenomenon in a trailing line vortex is carried out with the result being the development of a numerical solution to the line vortex behind a lifting surface. The acceleration or retardation of the axial velocity in a vortex in general was also predicted and supported by previous investigations and the present experimental work. Finally, both criteria for predicting vortex breakdown and a numerical program predicting the axial velocity deficit in the wake are developed theoretically and supported by experimental investigation.

Logan, A. H.,
"VORTEX VELOCITY DISTRIBUTIONS AT LARGE DOWNSTREAM DISTANCES,"
J. Aircraft, Vol. 8, No. 11, Nov. 1971, pp. 930-932.

This paper extends the available data on the velocity structure within a trailing line vortex to large distances downstream of the generating wing. Data are presented to show the variation of both axial and tangential velocity with tunnel speed and trailing vortex strength. Specifically, data are presented at downstream distances of 10 and 26 chord lengths behind a semispan wing at 4 and 12 degree angle of attack for tunnel speeds of 50 and 70 mph.

Long, R. R.,
"A VORTEX IN AN INFINITE VISCOUS FLUID,"
J. Fluid Mech., Vol. 11, Part 4, Dec. 1961, pp. 611-624.

A solution is given for a viscous vortex in an infinite liquid. Similarity arguments lead to a reduction of the equations of motion to a set of ordinary differential equations. These are integrated numerically. A uniform feature is the constant circulation K outside the vortex core, which is also a viscous boundary layer. The circulation decreases monotonically towards the axis. The axial velocity profiles and the radial velocity profiles have several characteristic shapes, depending on the value of the non-dimensional momentum transfer M. The solution has a singular point on the axis of the vortex. The radius of the core increases linearly with distance along the axis from the singularity, and, at a given distance, is proportional to the coefficient of viscosity and inversely proportional to K.

Ludwieg, H.,
"ZUR ERKLARUNG DER INSTABILITAT DER ÜBER ANGESTELLTEN DELTAFLUGELN AUFTRETENDEN FREIEN WIRBELKERNE,"
Z. Flugwiss, Vol. 10, No. 6, June 1962, pp. 242-249.

By rolling up the surfaces of discontinuity originating from the leading edge of delta wings, free vortex cores are formed above the wing. In case of greater angles of incidence, the flow in these vortex cores shows an instability which abruptly produces strong turbulence. An explanation is given of this instability being a "frictionless instability" of the vortex core flow by increasing helical interference vortices.

Ludwieg, H.,
"ERKLORUNG DES WIRBELAUFPLATZENS MIT HILFE DER STABILITATSTHEORIE FÜR STROMUNGEN MIT SCHRAUBENLINIEN FORMIGEN STROMLINIEN,"
Z. Flugwiss, Vol. 13, No. 12, Dec. 1965, pp. 437-442.

The breakdown of the vortices over delta wings is interpreted as instability in the sense of the theory of stability of flows. The manner in which the breakdown progress ought to evolve is investigated according to the theory and the results are compared with recent experimental investigations.

Ludwieg, H.,
"VORTEX BREAKDOWN,"
DLR-FB-70-40, Sept. 1970,
Deutsche Forschungs- und Versuchsanstalt für Luft- and Raumfahrt,
Gottingen, West Germany.

Vortex breakdown, an abrupt change in the velocity distribution of a vortex, is often observed under quite different conditions. The various theories for the explanation of the phenomenon are discussed. It is concluded that various physical phenomena may cause a vortex breakdown, so that it is not possible to explain all observed breakdown processes by one theory only.

Luebs, A. B., Bradfute, J. G. and Ciffone, D. L.,
"EFFECTS OF SPOILERS AND GEAR ON B-747 WAKE VORTEX VELOCITIES,"
NASA TM X-73197, Aug. 1976,
NASA Ames Research Center, Moffett Field, CA.

Vortex velocities were measured in the wakes of four configurations of a 0.61-m span model of a B-747 aircraft. The wakes were generated by towing the model underwater in a ship model basin. Tangential and axial velocity profiles were obtained with a scanning laser velocimeter as the wakes aged to 35 span lengths behind the model. A 45 deg deflection of two outboard flight spoilers with the model in the landing configuration resulted in a 36 percent reduction in wake maximum tangential velocity, altered velocity profiles, and erratic vortex trajectories. Deployment of the landing gear with the inboard flaps in the landing position and outboard flaps retracted had little effect on the flap vortices to 35 spans, but caused the wing tip vortices to have: (1) more diffuse velocity profiles; (2) a 27 percent reduction in maximum tangential velocity; and (3) a more rapid merger with the flap vortices.

Luffsey, W. S.,
"AIRCRAFT WAKE TURBULENCE,"
Safe Engineering, Vol. 3, Nov. 1969, pp. 21-22.

Review of the questions posed and tests called for by the problem of aircraft wake turbulence. Available information on wake characteristics is very limited. Tests conducted toward gaining the knowledge required are described. The test methods applied include hot-film anemometry from towers in whose proximity aircraft are flown and wake penetrations by aircraft instrumented with three-axis linear accelerometers, multichannel recording oscillograph, and motion picture cameras providing photo coverage of contrail outlined vortices. It is believed that data from planned testing should ultimately result in a meaningful and practical solution to the problem.

Lundry, J. L.,
"INITIAL DEVELOPMENT OF A WAKE TURBULENCE ASSESSMENT SYSTEM,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 183-193.

The initial development of a computer software system for wake vortex technology is discussed. The system is intended for use in the preliminary design of new airplanes. Several overall objectives are listed, including the prediction of hazard as a function of geometry and flight conditions of the wake-producing and wake-penetrating airplanes, low cost of use, adaptability to new technology, and an explanation of currently known alleviation concepts. Essential elements of a Wake Turbulence Assessment System are listed, and an upper level system design is presented. Candidate technology for system elements is discussed. Prototype code has been produced for the initial wake rollup and for the wake penetration. Initial results of these two modules are compared with experimental data, and are promising. The comparisons also show the importance of considering the low Reynolds number at which model studies of wake penetration are conducted.

Lush, P. A.,
"THE PRESSURE AND VELOCITY FIELDS OF CONVECTED VORTICES,"
J. Sound and Vibration, Vol. 27, No. 2, Feb. 1973, pp. 266-270.

The pressure and velocity fields of convected vortices are calculated for irrotational, incompressible, and inviscid flow and assuming the vortex strength and convection velocity are constant. The case of a single vortex filament and the case of two contrarotating line vortices of equal strength are considered.

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MacCready, Jr., P. B.,
"AN ASSESSMENT OF DOMINANT MECHANISMS IN VORTEX-WAKE DECAY,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 289-304.

Predicting the transport and decay of the organized vortex system for various aircraft types, flight modes, and meteorological conditions requires clear identification of the various significant factors and mechanisms involved in the transport/decay process. Outside of the ground effect, the dominant factors include the circulation and core characteristics of the vortices, the turbulence in the wake and in the environment, and the thermal stability of the environment. The environmental factors are sometimes dominant; the vortex wakes from an airplane operating in two different meteorological regimes can differ by an order of magnitude in decay and by an order of magnitude in decent distance.

MacCready, Jr., P. B. and Bate, Jr., E. R.,
"AIRCRAFT VORTEX-WAKE EFFECTS ON PARTICLE TRANSPORT, BREAKUP, AND COALESCENCE,"
AV FR-301, Jan. 1973,
AeroVironment Inc., Pasadena, CA.

The vortex sheet from an aircraft wing and the associated organized vortex pair in the aircraft's wake constitute a flow field with strong shears and accelerations which may have important consequences on the local microphysics of natural clouds and on certain cloud seeding techniques. Calculations are made of the trajectories of small (5μm radius) droplets and large (50μm radius) droplets released in the cores of two representative vortex situations (corresponding to a C-130 and a Piper Aztec). The small droplets only move out to a radius of 1m or so before their outflow speed is down to negligible value (assumed to be 20 cm/sec, comparable to the cloud turbulence). The large droplets are spun out about 5m for the C-130 and 1-1/2m for the Apache. The speed of the droplets relative to the air is everywhere too slow to cause droplet breakup.

MacCready, Jr., P. B. and Lissaman, P. B. S.,
"ASSESSMENT OF ATMOSPHERIC EFFECTS ON THE BEHAVIOR OF AIRCRAFT WAKE VORTICES,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 310-315.

The transport and decay of an aircraft-generated vortex system depends on the characteristics of the generating aircraft, the proximity to the ground, and on atmospheric factors - the turbulence field, thermal stability, and mean wind shears throughout the region traversed by the vortex system. The number of variables involved, the statistical nature of the phenomena, and the difficulty of performing definitive field tests make the development of a comprehensive theory of vortex transport and decay an elusive goal, but significant strides have been made. This paper seeks to illuminate some of the main points, with more emphasis on dominant factors than on completeness or rigorousness.

MacCready, Jr., P. B. and Tombach, I. H.,
"INFLIGHT VALIDATION OF VORTEX BEHAVIOR AND HAZARD MODELS IN THE VORTEX WAKES OF JET TRANSPORT AIRCRAFT,"
AV-FR-502, Jan. 1975,
AeroVironment, Pasadena, CA.

A plan is presented for an experimental program to validate three models - flow field, vehicle response, hazard region - which give (respectively) the vortex flow field as a function of generating aircraft characteristics and atmospheric characteristics; the response of an aircraft, with certain stability and control characteristics, to an encounter with the vortex system; and the limits of the hazard volume to be avoided by a specific aircraft.

Madden, S. J. and Harlan, R. B., editors,
"A PROGRAM TO ANALYZE AND MODEL TRAILING VORTICES ON AIRPORTS,"
RN-69, October 1971,
MIT Measurement Systems Laboratory, Cambridge, MA.

Three specific areas related to the wake turbulence hazard problem are studied. An examination of vortex formation, structure, and decay leads to appropriate mathematical models for use in simulation studies. The effects of atmospheric turbulence and meteorological conditions on the stability and persistence of vortices in close proximity to the airports are assessed. Development and application of a three-degree-of-freedom computer simulation program provides an understanding of the hazard potential under a variety of encounter situations in which the aircraft, its approach to the vortex, and the vortex strength are varied. Vortex circulation is shown to be the paramount characteristic relating to the dhazard potential.

Mager, A.,
"SOLUTION ACROSS THE VORTEX BREAKDOWN,"
ATR-71 (9999)-1, April 1971,
Aerospace Corporation, Los Angeles, CA.

The solutions of the quasi-cylindrical, momentum-integral equations for the incompressible, viscous core of a vortex embedded in constant-velocity, axial flow are obtained in a closed form. These solutions are shown to be discontinuous when the axial flux of the axial momentum deficiency and the circumferential-to-axial velocity ratio at core boundary are larger than certain values. Since the axial gradients on both sides of the discontinuity are shown to be infinite and since the solutions are shown to disappear at one side of the discontinuity, and reappear on the other, vortex breakdown is assumed to occur in the region where the quasi-cylindrical approximation fails to describe the flow. Transition across the vortex breakdown is provided by the connection between the two separated parts of the solution having the same total axial flux of the axial momentum deficiency. The vortex breakdown is conceived as being equivalent to a sudden increase in the dissipation of the swirling motion. No additional constraints are required for the determination of the flow conditions on both sides of the vortex breakdown which indicate a steep increase of the static pressure axis, an enlargement of the core area, and usually, a reversal of the axial flow on the axis.

Mager, A.,
"DISSIPATION AND BREAKDOWN OF A WING-TIP VORTEX,"
J. Fluid Mech., Vol. 55, Part 4, Oct. 1972, pp. 609-628.

The solutions of the incompressible, quasi-cylindrical momentum-integral equations of describing the flow in the viscous core of a wing tip vortex are obtained in a closed form and are shown to have two distinct branches. The discontinuities of these solutions have infinite axial gradients and therefore, following Hall, are assumed to signal the inception of the vortex breakdown. Benjamin's finite transition, with its excess flow force dissipated, is shown to give results equivalent to a sudden cross-over, upstream of the discontinuity, from one branch solution to another.

The critical point of such a cross-over is downstream from the cross-over, at the discontinuity. Sarpkaya's experimental data, and the nature of the solutions ahead of the discontinuity, suggest that the physical manifestation of the discontinuity is the spiral breakdown, whereas the cross-over seems to be related to the rapidly expanding and subsequently contracting axisymmetric bubble. This therefore implies that the beginning of the spiral breakdown is the all important disturbance which triggers off not only the downstream asymmetric departure of the flow from its quasi-cylindrical form but also the formation of the upstream axisymmetric cross-over bubble. Solutions for the turbulent flow downstream from the spiral breakdown indicate that the wing-tip vortex breakdown can result in an appreciable reduction of the maximum circumferential velocity and should thus lessen the danger that trailing vortices present to following aircraft.

Maltby, T. L.,
"A GENERAL DISCUSSION OF THE DISTURBANCES IN THE WAKE AREA OF A JET AIRCRAFT AND THE EFFECTS OF A SHOCK WAVE INTERCEPTING A SMALL AIRCRAFT,"
General Structural Report No. 241, July 1955,
Beech Aircraft Corp., Wichita, KS.

The purpose of the report is twofold: to investigate the disturbances in the wake area of a jet aircraft that affects the controllability and air loads on a small aircraft entering this region, and to investigate the effect on small aircraft of shock waves generated by supersonic aircraft. The wake area is divided into three areas: the jet engine wake, trailing vortices off the wing tips of the jet aircraft, and residual turbulence.

Mantay, W. R., Holbrook, G. T., Campbell, R. L., and
Tomaine, R. L.,
"HELICOPTER RESPONSE TO AN AIRPLANE'S TRAILING VORTEX,"
J. Aircraft, Vol. 14, No. 4, April 1977, pp. 357-363.

A flight investigation was conducted to determine quantitatively the response of a medium-weight helicopter to the trailing-vortex system of a fixed-wing aircraft. Both flight tests and analytical tools were utilized in the investigaiton. The flight tests involved an extensively instrumented UH-1H helicopter and a C-54 aircraft. Penetrations of the vortex system by the UH-1H were made at the following nominal conditions: the C-54 flew at 5500-ft altitude at a nominal gross weight of 58,000 lb and an indicated airspeed of 115 knots in a cruise configuration; the UH-1H, nominally 7200-lb gross weight, flew at 60-knots indicated airspeed during the penetration at separation distances of 6.64 nautical miles to 0.42 nautical mile between aircraft. In general, the data analyzed for these tests indicated that no unsafe penetration occurred. Further, penetrating vehicle attitude changes and structural loads were nominal. In addition, the response of the helicopter did not change appreciably with decreased separation distance.

Marchman, III, J. F.,
"WAKE TURBULENCE AND ITS ELIMINATION,"
SAE Paper No. 730294,
Wichita, KS, 1973.

The results of a detailed wind tunnel study of the structure of the trailing vortex to distances of 30 chord lengths downstream of the wing are reported. Five different means of reducing the dangerous high-swirl velocities in a vortex are described and their effects on the wake are illustrated. The effects of these possible vortex "fixes" on the wing itself as well as the possibility of using these or other devices to accelerate the dissipation of wake turbulence are discussed.

Marchman, III, J. F., Manor, D. and Faery, Jr., H. F.,
"WHITCOMB WINGLET APPLICATIONS TO GENERAL AVIATION AIRCRAFT,"
AIAA Paper No. 78-1478,
Los Angeles, CA, Aug. 1978.

A study was conducted to examine several of the aspects of Whitcomb winglet applications to low speed, general aviation aircraft. Both supercritical and laminar flow airfoil section winglets were tested on straight and tapered symmetrical wings. Aerodynamic parameters were measured for a wide range of wing angles of attack and for several winglet angles. Tests were run to determine the low speed effect of the wing on the winglet and of the winglets on the wing. Towing tank and wind tunnel tests were run to examine the trailing vortices from the wing-winglets combinations. The tests showed that winglets are effective at low speeds, however a tapered wing planform results in a reduction of the winglet effectiveness. Symmetrical winglets were shown to be effective at low speed. Tests showed that a proper choice of winglet angle can reduce the strength of the wake turbulence.

Marchman, III, J. F. and Marshall, J. R.,
"VORTEX AGE AS A WAKE TURBULENCE SCALING PARAMETER,"
AIAA Paper No. 74-36,
Washington, DC, 1974.

Tests were conducted in the Virginia Tech Stability Wind Tunnel to determine the significance of vortex age as a scaling parameter in wake turbulence development and dissipation. Vortex structure was measured over a range of three angles of attack, three free-stream speeds, and seven downstream positions from 2 to 30 chordlengths using an NACA 0012 wing and a five hole yawhead probe. The resulting data indicates that vortex age is not a self-sufficient scaling parameter but a free-stream velocity influence also exists at higher angles of attack which cannot be explained in terms of Re or M.

Marchman, III, J. F. and Uzel, J. N.,
"EFFECT OF SEVERAL WING TIP MODIFICATIONS ON A TRAILING VORTEX,"
J. Aircraft, Vol. 9, No. 9, Sept. 1972, pp. 684-686.

Several different wing-tip modifications were used to alter the characteristics of an airfoil trailing vortex. Preliminary photographs were taken using a tuft-grid to visually determine the effects of the various tip configurations. Detailed mean flow measurements were then made at ten and thirty chordlengths downstream of the wing. As a first approximation, the static pressure was assumed to be constant. The results show a definite decrease in the tangential velocity of the vortex and a spreading out of the core for all modifications tested.

Maskew, B.,
"ON THE INFLUENCE OF CAMBER AND NON-PLANAR VORTEX WAKE ON WING CHARACTERISTICS IN GROUND EFFECT,"
ARC CP-1264, 1973,
Loughborough Univ. of Technology, Loughborough, England.

The theoretical influence of camber and non-planar wake on the change of lift, vortex drag and centre of pressure of a wing with ground effect is examined. Potential flow calculations are performed for both 2- and 3-dimensional conditions, the former using a multi-vortex method and the latter using an arbitrary geometry quadrilateral vortex-ring method with a vortex wake relaxation iterative scheme. The results show the importance of including the influence of camber, incidence and non-planar wake in practical ground effect calculations.

Mason, W. H. and Marchman, III, J. F.,
"INVESTIGATION OF AN AIRCRAFT TRAILING VORTEX USING A TUFT GRID,"
VPI-E-71-17, Sept. 1971,
Virginia Polytechnic Inst. and State University, Blacksburg, VA.

A study of the trailing vortex of a wing has been made using a tuft grid in the Virginia Tech 6 Foot Wind Tunnel. The study included an investigation of the use of mass injection at the wing tip as a means of destroying the vortex. Test results show that a fully developed, stable, vortex exists at least a distance of thirty chord lengths downstream of the wing, and that the "swirl" of the vortex can be reduced or eliminated by mass injection at the wing tip.

Mason, W. H. and Marchman, III, J. F.,
"FAR-FIELD STRUCTURE OF AIRCRAFT WAKE TURBULENCE,"
J. Aircraft, Vol. 10, No. 2, Feb. 1973, pp. 86-92.

Detailed mean flow measurements were obtained at stations up to thirty chordlengths downstream in an airfoil trailing vortex using a yawhead pressure probe in the Virginia Tech Six-Foot Subsonic Tunnel. Mass injection at the wingtip was shown to hasten the vortex decay. A theoretical method has been developed to show the effect of wing circulation distribution on the structure of the outer portion of the vortex and excellent agreement with the experimental data is demonstrated.

Mason, W. H. and Marchman, III, J. F.,
"FAR-FIELD STRUCTURE OF AN AIRCRAFT TRAILING VORTEX, INCLUDING EFFECTS OF MASS INJECTION,"
NASA CR-62078, April 1972,
Virginia Polytechnic Inst. and State Univ., Blacksburg, VA.

With the introduction of the "Jumbo Jet" class of aircraft it has become important to predict the aircraft wake turbulence due to the tip trailing vortex accurately. A yawhead pressure probe has been used in the Virginia Tech 6-Foot Subsonic Tunnel to obtain detailed mean flow measurements at stations up to thirty chordlengths downstream in an aircraft trailing vortex. Mass injection at the wingtip has been shown to hasten the decay of the trailing vortex. A theoretical method has been given to show the effect of the circulation distribution on the wing on the structure of the outer portion of the vortex, and excellent agreement with experiment has been shown. Experimental results indicate a much slower decay and higher tangential velocities than previously expected.

Mather, G. K.,
"A NOTE ON SOME MEASUREMENTS MADE IN VORTEX WAKES BEHIND A DC-8," National Research Council (Canada), Division of Mechanical Engineering and National Aeronautical Establishment, Quarterly Bulletin, No. 2, 1967, pp. 45-54.

A discussion of measurements of maximum circumferential velocities obtained by the NAE T-33 when flying 3500 and 1000 feet directly behind a DC-8, seeking the wing tip vortices. It is found that the measured maximum velocities of these vortices are substantially higher than those predicted by accepted theory. No reduction in vortex strength due to dissipative effects was observed.

Mattei, A. and Santoro, E.,
"NUMERICAL COMPUTATIONS OF WAKE VORTICES BEHIND LIFTING SURFACES," International Council of the Aeronautical Sciences Paper 74-28, Haifa, Israel, 1974.

A numerical method is developed for the calculation of the wake vortices behind lifting wings. According to modern three-dimensional methods, discrete vortices are distributed on the camber surface of the wing and upon the wake. The rolled-up vortex sheet is obtained by a convergent interactive procedure. Different numerical schemes investigated are compared for obtaining smooth solutions and minimizing computer time.

Maxworthy, T.,
"THE STRUCTURE AND STABILITY OF VORTEX RINGS,"
J. Fluid Mech., Vol. 51, Part 1, 1972, pp. 15-32.

A series of observations on experimentally produced vortex rings is described. The flow field, ring velocity and growth rate were observed using dye and hydrogen-bubble techniques. It was found that stable rings are formed and grow in such a way that most of their vorticity is distributed throughout a fluid volume which is larger than and moving with the visible dye core. As the vorticity diffuses out of this moving body of fluid into the outer irrotational fluid, it has two effects. It causes some of the fluid, with newly acquired vorticity, to be entrained into the interior of the bubble, while the rest is left behind and accounts for the appearance of ring vorticity in a wake. It was found that the velocity of translation U of these stable rings varies as t^{-1}, at high Reynolds number, where t is the time measured from the start of the motion at a virtual origin at downstream infinity. A simple theoretical model is presented which explains all of these features of the observed stable flow. Rings of even higher Reynolds number become unstable and shed significantly more vorticity into the wake. Observations of the interaction between two nearly identical rings travelling a common path showed that, contrary to popular belief, rings do not pass back and forth through one another, but that the rearward one becomes entrained into the forward one. Only when the rearward ring has a much higher velocity than its partner can it emerge from the joining process and leave a slower-moving ring behind.

Maxworthy, T.,
"THE MOTION OF AIRCRAFT TRAILING VORTICES,"
J. Applied Mechanics, Vol. 42, No. 2, June 1975, pp. 279-282.

Knowledge of the motion of turbulent vortex rings is used to speculate upon the dynamical characteristics of the trailing vortex pair which forms the wake of a lifting surface. An interpretation is presented of common observations which suggests that the gross features of the two systems are similar, at least before the aircraft wake distorts due, among other things, to a self-induced instability. The theory presented by Maxworthy (1974) is extended to the two-dimensional case and predictions of the shape of aircraft trails are displayed in nondimensional form. As a special case a preliminary prediction is given for the wake shape of a 747, in cruise condition, for a set of parameters that are only approximately correct. Only comparison with actual observations can further refine these guesses.

McConville, R. P.,
"INSTALLATION AND TEST OF DOPPLER ACOUSTIC SENSOR,"
FAA-RD-76-223, Oct. 1977,
Avco, Wilmington, MA.

This report presents details of the installation of a Doppler acoustic vortex sensing system at JFK Runway 31R, the hardware and software improvements made since installation, vortex diagnostic and tracking data and analysis, and conclusions and recommendations.

McConville, R. P.,
"DOPPLER ACOUSTIC VORTEX SENSING SYSTEM,"
FAA-RD-75-28, Oct. 1978,
Avco, Wilmington, MA.

This is the final report on the Doppler Acoustic Vortex Sensing System, (DAVSS) program carried out by Avco Corporation's Systems Division for the U.S. Department of Transportation, Transportation Systems Center. The objective of the program was the design of an engineered DAVSS capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. Problems related to such vortices are currently under intensive study by the U.S. Department of Transportation for the Federal Aviation Administration. This report presents hardware and software design aspects of the system. The design of the acoustic antennas and transducers is described. System control, computer hardware and software, and system/subsystem interfaces are discussed.

McConville, R. P. and Pfeiffer, G.,
"A DOPPLER ACOUSTIC VORTEX SENSING SYSTEM FOR AUTOMATIC REAL TIME TRACKING OF AIRCRAFT TRAILING VORTICES,"
Third Workshop on Atmospheric Acoustic, York University,
Toronto, Canada, June 1975.

An automatic real time vortex tracking system using Doppler acoustic scattering techniques has recently been built and installed at the J. F. Kennedy International Airport. The system is capable of operating in either the pulsed or cw mode and in the monostotic backscatter or the bistatic forward scatter configuration. Acoustic signals in the band 3-6 KHz are transmitted from fan beam antennas. The vortex scattered signals with their characteristic Doppler spectra are received in any of four receiving antennas each consisting of 12 pencil beams. The scattered signals are Doppler processed to determine the angle and, in the case of pulsed signals, the range of the scattering center. The angle or range-angle estimates are automatically interpreted using the actual geometry of the antenna elements to form vortex altitude-displacement tracks.

McCormick, B. W.,
"A STUDY OF THE MINIMUM PRESSURE IN A TRAILING VORTEX SYSTEM,"
PhD Thesis, June 1954,
Penn. State Univ., University Park, PA.

Theoretical, experimental, and semi-empirical investigations of the minimum pressure in trailing vortex systems of elliptic, rectangular, and delta wings are presented. The magnitude of the minimum pressure coefficient in the trailing vortex system of a wing increases nearly linearly with the angle of attack of the wings. This magnitude is almost independent of aspect ratio for elliptic wings but for rectangular wings is slightly higher, the greater the aspect ratio, for a given angle of attack. At a given angle of attack the magnitude of the minimum pressure coefficient increases with increasing Reynolds number. The thickness of the tip-vortex core, or the thickness of the edge of the trailing vortex sheet is determined by the thickness of the boundary layer on the lower surface of the wing at the trailing edge of the tip and not by any considerations of induced drag and kinetic energy of the vortex sheet itself.

McCormick, B. W.,
"AIRCRAFT WAKES: A SURVEY OF THE PROBLEM,"
Symposium on Turbulence, FAA, Washington, DC, March 1971.

A large aircraft generates a vortex system which can present a hazard to lighter aircraft. The rollup, geometry, decay and instabilities of trailing vortices are discussed. Their effect on other aircraft is considered and it is concluded on the basis of a simplified analysis and accident records that relatively large aircraft can be susceptible to vortices from large jet transports. A brief history of the problem is included as well as an extensive bibliography covering the behavior of vortex systems and aircraft response.

McCormick, B. W.,
"AN ASSESSMENT OF THE EFFECT OF A TRAILING VORTEX ON A FOLLOWING AIRCRAFT,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, pp. 65-69.

The various factors affecting the static rolling moment on an aircraft encountering wake turbulence are considered. The expressions for the total rolling moment are derived for a logarithmic velocity profile and for a Lamb or Rankine vortex.

McCormick, B. W. and Padakannaya, R.,
"THE EFFECT OF A DROPPED WING TIP ON ITS TRAILING VORTEX SYSTEM," Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 157-169.

The effect of wing tip droop on the structure and position of its trailing vortex is studied. Spanwise load distributions determined by vortex lattice theory show that the stronger vortex moves from the tip of the wing to the hinge of the drooped tip as the droop angle increases. Experimental results on model wings are given which present the strength and the induced velocity profiles of the rolled-up vortex as a function of tip geometry. It is concluded that a droop angle approximately 90 degrees is optimum and results in a maximum induced velocity which is half of that produced by a plane wing.

McCormick, B. W. and Schumacher, W. J.,
"AN INVESTIGATION OF THE TRAILING VORTEX SYSTEM GENERATED BY A JET FLAPPED WING OPERATED AT HIGH WING LIFT COEFFICIENTS,"
AFFDL-TR-70-90, June 1970,
Penn. State Univ., University Park, PA.

The purpose of the investigation was to measure the geometry of the trailing vortex generated behind a jet flapped wing. Such vortices can pose a serious hazard to aircraft that penetrate them. Previous investigations performed on conventional wings indicate that these vortices persist for some time and have maximum tangential velocities which increase linearly with the lift coefficient. As future aircraft may employ high lift devices such as jet-flapped wings, the vortices generated could be even stronger. Two semispan models of a jet-flapped wing were tested in a subsonic wind tunnel. Parameters varied during testing included the jet flap angle, angle of attack, aspect ratio and jet momentum coefficient. Vortex measurements were obtained using a vortex meter which measured the rotational speed of the fluid within the vortex. Values obtained were numerically integrated to yield the tangential velocity and circulation distributed through the vortex. Experimental results indicate that the maximum tangential velocity increases to a maximum and then decreases with continually increasing jet blowing. At high values of jet blowing, the vortex was found to decay rapidly downstream.

McCormick, B. W., Tangler, J. L., and Sherrieb, H. E.,
"STRUCTURE OF TRAILING VORTICES,"
J. Aircraft, Vol. 5, No. 3, May-June 1968, pp. 260-267.

A study of aircraft trailing vortex systems, involving actual flight testing as well as model testing and analytical considerations, has resulted in a method for predicting the vortex geometry and velocity field downstream of an aircraft. It is found that the vortex decay can be described by geometric similarity considerations and not by any modification of the Navier-Stokes equations. This conclusion is based on detailed velocity measurements made through the vortex immediately behind a test aircraft up to distances of approximately 1000 chord lengths downstream of the aircraft. This report includes a presentation of the data on which the conclusions are based, as well as a description of test equipment and procedures.

McGowan, W. A.,
"CALCULATED NORMAL LOAD FACTORS ON LIGHT AIRPLANES TRAVERSING THE TRAILING VORTICES OF HEAVY TRANSPORT AIRPLANES,"
NASA TN D-829, May 1961,
NASA Langley Research Center, Langley Station, VA.

Results are presented of normal-load-factor calculations made for a light normal-category airplane and a light transport-category airplane traversing the trailing vortices generated by each of three heavy transport airplanes. With each light airplane, the normal load factors were determined for several penetration paths lying in a plane perpendicular to the trailing vortices and for three center-of-gravity locations and velocities. Also determined for the light normal-category airplane were the elevator deflection required to maintain 1 g flight and the vertical displacements of the airplane from the prescribed penetration paths while traversing the vortices. The results indicate that light airplanes traversing the wakes of currently operational heavy transport airplanes can experience loading conditions that exceed the design limit and, in some cases, the design ultimate load factors. For light airplanes traversing the wake generated by a proposed supersonic transport airplane the design ultimate load factors can be greatly exceeded. It was also shown that load factors imposed by the vortex system could be alleviated by elevator deflection; however, because of inherent pilot and control-system lag, the load factors would almost certainly be aggravated rather than alleviated.

McGowan, W. A.,
"TRAILING VORTEX HAZARD,"
SAE Paper No. 680220,
Wichita, KS, April 1968.

Light aircraft that encounter the trailing vortex system generated by heavy transport aircraft can experience high roll rates, loss of altitude, and large structural loads. Envelopes of vortex system velocities, duration and movement for various wind conditions have been determined. Specific operational procedures for the take-off, landing, and enroute phases of flight are suggested to enable the light aircraft pilot to avoid the wake turbulence of heavy aircraft.

McGowan, W. A.,
"AVOIDANCE OF AIRCRAFT TRAILING VORTEX HAZARDS,"
AGARD, Flight Mechanics Panel,
Baden-Baden, Germany, October 1970.

Aircraft trailing vortex systems are made up of two counter-rotating cylindrical air masses, about a wing span apart, extending aft along the flight path. Vortex systems of large aircraft contain winds within and about these cylinders which can be hazardous to other aircraft encountering them in flight. Trailing vortices have been the cause of aircraft accidents. The greatest hazard potential exists in areas where aircraft of a wide range of classes are operating (e.g., utility/observation and heavy transport/bomber). Results of accident investigations, theoretical exercises, wind-tunnel experiments, and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence, including factors governing persistence. This information is then used to outline procedures for ready application by pilots, tower operators, and those concerned with the flow of traffic during tactical operations. Schemes under investigation to monitor remotely both the trailing vortex location and intensity in the airport area and to prohibit formation of high intensity vortices, through aircraft design, are discussed.

McGowan, W. A.,
"NASA AIRCRAFT TRAILING VORTEX RESEARCH,"
Symposium on Turbulence, FAA, Washington, DC, March 1971, p. 25.

A brief description is given of NASA's comprehensive program to study the aircraft trailing vortex problem. Wind tunnel experiments are used to develop the detailed processes of wing tip vortex formation and explore different means to either prevent trailing vortices from forming or induce early break-up. Flight tests provide information on trailing vortex system behavior behind large transport aircraft, both near the ground, as in the vicinity of the airport, and at cruise/holding pattern altitudes. Results from some flight tests are used to show how pilots might avoid dangerous areas when flying in the vicinity of large transport aircraft. Other flight tests will be made to verify and evaluate trailing vortex elimination schemes developed in the model tests. Laser Doppler velocimeters being developed for use in the research program and to locate and measure vortex winds in the airport area are discussed. Field tests have shown that the laser Doppler velocimeter measurements compare well with those from cup anemometers.

McGowan, W. A.,
"REMOTE DETECTION OF TURBULENCE IN CLEAR AIR,"
AIAA/FAA Air Transportation and Society Conference,
Key Biscayne, FL, June 1971.

Various concepts for remote detection of turbulence in the clear air were reviewed. It was concluded that there is no technique now available for operational use to remotely detect and measure turbulence in the clear air. Several techniques are under both study and development which seem to have good potential for future application; namely, the laser Doppler radar for airborne and ground-based use, and ground-based ultrasensitive microwave Doppler radars. Terminal area turbulence-sensing-techniques, having considerable potential to assist with the aircraft wake problem, include the laser Doppler and acoustic radars. The acoustic radar seems like a simple approach at this time. Further work is needed to see if the refinements in the system will result in a sophistication masking the original simplicity.

McGowan, W. A.,
"AIRCRAFT WAKE TURBULENCE AVOIDANCE,"
12th Anglo-American Aeronautical Conference, Paper No. 72/6,
Calgary, Canada, July 1971.

Results of analytical studies and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence. This information is then used to outline procedures for ready application by pilots, tower operator, and others concerned with the flow of traffic.

McGowan, W. A.,
"AIRCRAFT WAKE TURBULENCE AVOIDANCE,"
J. Aircraft, Vol. 9, No. 3, March 1972, pp. 197-198.

Aircraft trailing vortex systems are made up of two counter-rotating cylindrical air masses, about a wing span apart, extending aft along the flight path. Vortex systems of large aircraft contain winds which can be hazardous to other aircraft encountering them in flight. The greatest hazard potentials exist in areas where aircraft of a wide range of classes are operating (e.g., light utility/observation and heavy transport/bomber). Results of analytical studies and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence. This information is then used to outline procedures for ready application by pilots, tower operators, and others concerned with the flow of traffic. The procedures provide the necessary appreciation of the physical attributes of trailing vortices, the potential hazards involved when encountering them, and how best to avoid the dangerous portions of the wake during flight operations.

McGowan, W. A. and Charak, T.,
"AIRCRAFT WAKE TURBULENCE,"
16th Corporate Aircraft Safety Seminar, Flight Safety Foundation, April 1971, pp. 71-87.

The physical characteristics of aircraft wake turbulence, or trailing vortices, are described: their formation, persistence, and whereabouts after being spawned by the wing lift. Analytical and flight test data are used to establish the inflight hazards associated with trailing vortex encounters. Techniques are suggested on how pilots can best avoid the damaging manifestations of aircraft wake turbulence for various flight regimes. The comprehensive aircraft wake turbulence research program supported by the NASA is outlined. Flight and model tests, and instrument development for remote wind sensing are used to better understand the aircraft wake turbulence generated by heavy transport aircraft. Concurrently, other studies are hopeful of uncovering ways to either prevent the trailing vortices from forming or induce early dissipation of dangerous winds.

McMahon, T. A.,
"REVIEW OF THE VORTEX WAKE ROLL UP PROBLEM,"
ASRL-TR-145-1, June 1967,
Mass. Institute of Technology, Cambridge, MA.

The near wake problem behind an airfoil is reviewed in the context of some eighteen references, both theoretical and experimental. It is found that the body of theoretical literature makes an inconsistent approximation about the axial component of velocity in the flow. The techniques of self similar hydrodynamics, vortex system theory, and conservation of energy arguments as they apply to the roll-up problem are discussed. Some important experimental evidence seems to confirm that the near wake problem is basically three-dimensional and should be reexamined as such.

McMahon, T. A. and Widnall, S. E.,
"VORTEX WAKE ROLL-UP AND VORTICITY CONCENTRATION BEHIND AN AIRFOIL,"
ASRL TR 143-1, June 1967,
Mass. Institute of Technology, Cambridge, MA.

Some experimental evidence seems to confirm that the near wake problem is basically three-dimensional and should be reexamined as such. A concentration mechanism based on this three-dimensionality is proposed and found to predict a gradient of core circulation which is dimensionally correct and gives realistic answers when specific numerical cases are compared to published experiments. The correlation of experiment with theory involves a uniform translation of the theoretical points a specific distance upstream, implying that rotational fluid in the sheet requires a finite, uniform time to get to the core, no matter which downstream station is considered. A paradox in the role of viscosity in the concentrating mechanism is discussed.

McMillan, O. J., Schwind, R. G., Nielsen, J. N., and Dillenius, M. F. E.,
"ROLLING MOMENTS IN A TRAILING VORTEX FLOWFIELD,"
J. Aircraft, Vol. 15, No. 5, May 1978, pp. 280-286.

Pressure distributions are presented which were measured on a wing in close proximity to a tip vortex of known structure generated by a larger, upstream semispan wing. Overall loads calculated by integration of these pressures are checked by independent measurements made with an identical model mounted on a force balance. Several conventional methods of wing analysis are used to predict the loads on the following wing.

Strip theory is shown to give uniformly poor results for loading distribution, although predictions of overall lift and rolling moment are sometimes acceptable. Good results are obtained for overall coefficients and loading distribution by using linearized pressures in vortex-lattice theory in conjunction with a rectilinear vortex. The equivalent relation from reverse-flow theory that can be used to give economic predictions for overall loads is presented.

McWilliams, I. G.,
"HAZARD EXTENT ABOUT AIRCRAFT TRAILING WAKE VORTICES - ANALYTIC APPROACH,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 23-30.

The proposed Vortex Advisory System makes use of the fact that under certain wind conditions, vortices cannot be detected within a protected corridor after 80 seconds. The width of the corridor is dependent upon the hazard extent about vortices. Two methods for estimating the hazard extent are presented: a static calculation of the rolling moment on a generic aircraft as a function of distance from the vortex axis; and a dynamic simulation of a B-720 encountering vortices at varying distances. Both of these methods were found to be in substantial agreement and yielded a value of 30 meters as a conservative estimate for the hazard extent about vortices.

Melander, M. V., Zabusky, N. J. and McWilliams, J. C.,
"SYMMETRIC VORTEX MERGER IN TWO DIMENSIONS: CAUSES AND CONDITIONS,"
J. Fluid Mech., Vol. 195, Oct. 1988, pp. 303-340.

Two like-signed vorticity regions can pair or merge into one vortex. This phenomenon occurs if the original two vortices are sufficiently close together, that is, if the distance between the vorticity centroids is smaller than a certain critical merger distance, which depends on the initial shape of the vortex distributions. The conclusions are based on an analytical/numerical study, which presents the first quantitative description of the cause and mechanism behind the restricted process of symmetric vortex merger.

Meng, J. C. S.,
"THE PHYSICS OF VORTEX-RING EVOLUTION IN A STRATIFIED AND SHEARING ENVIRONMENT,"
J. Fluid Mech., Vol. 84, Part 3, 1978, pp. 455-469.

A semi-analytical numerical study was performed to simulate the development of a vortex ring in a stratified and/or shearing environment. Practical applications of the results of this study can be found in turbulence modelling and in studies of plumes and wakes. The objective is to follow exactly the evolution of a vortex ring so that the three-dimensional vortex-stretching mechanisms due to stratification and the shear effects, respectively, can be understood.

Meng, J. C. S. and Thomson, J. A. L.,
"LASER DOPPLER VELOCIMETER SYSTEM SIMULATION FOR SENSING AIRCRAFT WAKE VORTICES, PART II: PROCESSING AND ANALYSIS OF LDV DATA,"
PD-75-077, Feb. 1975,
Physical Dynamics Inc., Berkeley, CA.

A data analysis program has been constructed to assess the Scanning Laser Doppler Velocimeter system performance, to validate the simulation model, and to test various vortex location algorithms. The program takes either real or simulated Doppler spectra versus range and elevation, calculates the spatial distributions of various spectral moments (mean velocity, variance, skewness, kurtosis) or other spectral characteristics and presents these in a 3-D display. Each of the real or simulated scans can be processed by one of three different procedures: simple frequency or wavenumber filtering, matched filtering, and deconvolution filtering. Vortex tracks and system range resolutions are compared with theoretical predictions.

Meng, J. C. S. and Thomson, J. A. L.,
"SIMULATION AND DATA ANALYSIS OF A SCANNING LASER DOPPLER VELOCIMETER SYSTEM FOR SENSING AIRCRAFT WAKE VORTICES,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 94-105.

The objectives of this study are to simulate the response of a Scanning Laser Doppler Velocimeter System (SLDVS) in an aircraft wake environment and to display the expected spatial signatures. From analysis of these simulated signatures as well as flight data, optimal tactics for determining wake location and strength can be established.

Menkes, J. and Abernathy, F. H.,
"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION,"
P-514, May 1970,
Institute for Defense Analyses, Arlington, VA.

The use of suction devices in controlling the trailing vortex hazard for closely spaced parallel runways is examined. The feasibility of this proposal is examined by means of a computer simulation. It is established conclusively that the scheme has merit and that the power required to bring the hazard to acceptable levels is of the order of 2,000 hp per runway.

Menkes, J. and Abernathy, F. H.,
"AN ESTIMATE OF THE POWER REQUIRED TO ELIMINATE TRAILING VORTICES BY SUCTION,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 575-576.

A descending aircraft is affected by the interaction of its vortex system with the ground; if the ground effect could be modified, the vortex reaction would be affected. Such a modification is induced by suction. The conceptual scheme involves placing one or more ditches which house the suction blowers between the runways.

Merritt G. E.,
"WAKE GROWTH AND COLLAPSE IN STRATIFIED FLOW,"
AIAA Journal, Vol. 12, No. 7, July 1974, pp. 940-949.

The objective of this research was to obtain data that could be used to predict the effect of stratification on the development of a momentumless wake. Experiments were performed in which a grid was oscillated in a stably stratified flow to produce the steady-state counterpart of the momentumless wake of a self-propelled vehicle. A pH-sensitive indicator was used to produce a neutrally-buoyant tracer to visualize wake development and subsequent vertical collapse. Measured velocity profiles in the simulated wake indicated that it was nearly momentumless, and vertical temperature surveys revealed the degree of mixing in the wake. The wake growth before and after collapse and the distance to collapse were correlated by using power laws and a theoretical analysis of wake collapse. The scaling relations established for predicting stratified flow wake dimensions revealed that the important parameters were the Froude number and the ratio of the time after wake generation to the Brunt-Vaisala period.

Through the use of these parameters, two unique curves were obtained for estimating the horizontal width and vertical height of a wake in a stratified flow.

Merritt, G. E. and Russo, A. L.,
"THE EFFECT OF INITIAL CONDITIONS ON STRATIFIED FLOW WAKE COLLAPSE,"
AIAA Paper No. 75-118,
Pasadena, CA, Jan. 1975.

The effect of initial conditions on wake growth and collapse in a stratified flow has been studied experimentally and analytically. A turbulence generator was located in a flowing stream of thermally stratified water, and measurements were made with a laser Doppler velocimeter of turbulence intensity. The measured rate of turbulence intensity decay along the wake axis for different values of initial turbulence level was observed to agree well with an analysis based on the assumption that the turbulence is proportional to the measured rate of wake expansion in unstratified flow. Good agreement was noted between predictions based on a critical Richardson number from atmospheric data limiting vertical growth and measurements of wake growth and collapse for different ambient stratifications (Froude numbers) and wake turbulence levels. Measurements revealed the considerable effect that the initial wake intensity has on subsequent wake development.

Mertaugh, L. J. and Damania, R. B.,
"AN INVESTIGATION OF THE TRAILING VORTICITY BEHIND A STOL AIRCRAFT,"
AFFDL-TR-73-138, Dec. 1973,
Mississippi State University, Missippi State, MS.

This report presents the results of a test program to measure the near-field wake behind the wing of a test aircraft, out of the ground effect. The test aircraft was a high-lift L-19 aircraft incorporating a distributed-suction boundary layer control system. The wake measurement probe was supported from the fuselage of the test aircraft and was mounted on a trolley which moved along a boom structure. The velocity measurements were made with a six-element hot-film anemometer. The near field wake data were obtained in two measurement planes located 0.64 and 5.10 feet behind the wing. Data were obtained at zero and full-flap deflection and true speeds of 46, 66, and 85 mph. The data are presented as contours of constant nondimensional longitudinal velocity increment within the measurement planes.

Mertaugh, L. J., Damania, R. B. and Paillet, F. L.,
"AN INVESTIGATION OF THE NEAR-FIELD WAKE BEHIND A FULL-SCALE TEST AIRCRAFT,"
J. Aircraft, Vol. 14, No. 9, Sept. 1977, pp. 894-902.

Three-dimensional velocity field measurements were made on three transverse measurement planes located at 7.7, 33.3, and 61.2 inches behind the inboard-wing trailing edge of an aircraft in flight. The test aircraft as an L-19 modified to incorporate a distributed suction boundary-layer control system. Test data were obtained at various lift coefficients and with both zero and full flap deflections. Flowfield measurements were made with a total-vector hot-film probe mounted to a boom and traversing mechanism attached to the rear fuselage of the test aircraft.

Mertaugh, L. J. and Devarayalu, K.,
"FURTHER INVESTIGATIONS OF THE NEAR FIELD TRAILING VORTICITY BEHIND A STOL AIRCRAFT,"
AASE-75-142, Dec. 1975,
Miss. State Univ., Mississippi State, MS.

This report presents results of a test program to measure the velocity field in the near-wake behind the wing of a high-lift test aircraft. A direct measurement of the 3-component velocity vectors was made in several measurement planes located at various longitudinal positions behind the trailing edge of the aircraft wing. The test aircraft was a STOL L-19 equipped with a distributed suction boundary layer control system. Measurements were taken such that the velocity derivatives along all three coordinate axes could be computed. Thus, the three components of the vorticity vector could be determined at each point of the measurement matrix. It was found that, in general, velocity and vorticity vectors are not collateral. A design study was conducted to determine feasibility of a trailing probe support system which would allow detailed mapping of the wing wake velocity field at least 4 chord lengths behind the trailing edge of the generating wing. Such a system appears to be feasible and would provide a mechanism for further experimental study of the vortical flow at a point in the wake where roll-up is more developed.

Michanowsky, G.,
"ULTRAVIOLET RECONNAISSANCE AS A REMOTE DETECTOR AND TRACKER OF WAKE TURBULENCE,"
Final Report, Nov. 1972,
Amazonia Foundation Inc., New York, NY.

An ultraviolet reconnaissance technique was tested as a potential remote detector and tracker of wing tip vortices. The technique uses the jet engine exhaust particulates and other atmospheric impurities as tracers of the vortices.

Mironer, A.,
"ACCELERATED DIFFUSION OF WING TIP VORTICES BY HEATING,"
AIAA Paper No. 71-616,
Palo Alto, CA, 1971.

This paper describes the effects of heating on the vorticity diffusion rate in a gas vortex. The heating causes an outward radial convection and an increased kinematic viscosity which greatly enhances the overall rate of vorticity diffusion from the core. The coupled heat conduction and fluid dynamical equations which describe the vortex heating process have been solved on a digital computer using a finite difference technique. For an initial temperature ratio between the outside induced region of the vortex and core of 2:1, the vorticity diffusion rate is very nearly twice as fast as in a vortex with no heating present.

Mitchell, G. A.,
"PRELIMINARY INVESTIGATION OF INLET INGESTION OF A WING TIP VORTEX,"
NASA TM X-68225, April 1973,
NASA Lewis Research Center, Cleveland, OH.

An inlet-coldpipe assembly was placed in a Mach 0.4 stream to ingest the tip vortex of a forward mounted wing. The strongest vortex was produced by a wing angle of attack of 11 degrees. The vortex displayed a tangential velocity of 57 percent of local stream velocity prior to entering the inlet and a tangential velocity of 25 percent of local velocity at the simulated compressor-face. The total-pressure-profiles measured by standard compressor-face rakes were changed by the presence of the vortex only at the highest inlet mass-flow ratios.

Mitchell, G. A.
"EFFECT OF INLET INGESTION OF A WING TIP VORTEX ON COMPRESSOR FACE FLOW AND TURBOJET STALL MARGIN,"
NASA TM X-3246, July 1975,
NASA Lewis Research Center, Cleveland, OH.

A two-dimensional inlet was alternately mated to a coldpipe plug assembly and a J85-GE-13 turbojet engine, and placed in a Mach 0.4 stream so as to ingest the tip vortex of a forward mounted wing. Vortex properties were measured just forward of the inlet and at the compressor face. Results show that ingestion of a wing tip vortex by a turbojet engine can cause a large reduction in engine stall margin. The loss in stall compressor pressure ratio was primarily dependent on vortex location and rotational direction and not on total-pressure distortion.

Mitcheltree, R. A., Margason, R. J. and Hassan, H. A.,
"EULER EQUATIONS ANALYSIS OF THE INITIAL ROLL-UP OF AIRCRAFT WAKES,"
J. Aircraft, Vol. 23, No. 8, Aug. 1986, pp. 650-655.

A new approach has been developed to study the initial roll-up of aircraft wakes. This approach is based on the solution of the three-dimensional Euler equations subject to inflow and initial conditions predicted by a vortex-lattice method. Thus, solutions are limited to those flowfields generated by wings that are free of flow separation. Results are presented for four configurations: a rectangular wing with part span flap, a rectangular wing, a typical transport-type configuration, and a fighter configuration. In addition, an assessment of an "unsteady two-dimensional analogy" was undertaken using the two-dimensional time-accurate Euler equation solutions in cross-flow planes. In general, predictions from the two-dimensional unsteady analogy coincided with the three-dimensional results, which were found to be in good agreement with available experimental data.

Mokry, M. and Rainbird, W. J.,
"CALCULATION OF VORTEX SHEET ROLL-UP IN A RECTANGULAR WIND TUNNEL,"
J. Aircraft, Vol. 12, No. 9, Sept. 1975, pp. 750-752.

The note utilizes the concept of Green's functions to calculate the roll-up of a vortex sheet wake in a rectangular wind tunnel with solid walls. The computations are performed by the discretization of the continuous vortex sheet model by finite length elements which show more stable behavior than Westwater's array of point vortices. The results show that the vorticity distribution has essentially a stationary center of gravity, in marked contrast with the free air case where the center of gravity moves downwards.

Mook, D. T., Roy, S., Choksi, G. and Dong, B.,
"NUMERICAL SIMULATION OF THE UNSTEADY WAKE BEHIND AN AIRFOIL,"
J. Aircraft, Vol. 26, No. 6, June 1989, pp. 509-514.

The unsteady wake behind an airfoil is simulated numerically by a system of discrete vortex cores, also called point vortices. In common with previously developed procedures, at each time step a core is added to the wake at the trailing edge, and the cores already in the wake are convected at the local particle velocity. The innovation of the present method is that, as the cores begin to separate, more cores are added to the system and the circulations around the individual cores are reduced according to a linear interpolation routine. The spacing between cores is maintained approximately while the total circulation around the wake and airfoil is maintained exactly. In several examples, one finds qualitative agreement between computed wake shapes and flow visualization. The method shows promise as a means of simulating unsteady, closely coupled aerodynamic interference.

Moore, D. W.,
"THE DISCRETE VORTEX APPROXIMATION OF A FINITE VORTEX SHEET,"
AFOSR-TR-72-0034, Oct. 1971,
California Institute of Technology, Pasadena, CA.

It is shown by examination of a special case of aircraft trailing vortices that the approximation of replacing a finite vortex sheet by an array of line vortices can be unreliable regardless of how many vortices are used.

Moore, D. W.,
"FINITE AMPLITUDE WAVES ON AIRCRAFT TRAILING VORTICES,"
Aero. Quarterly, Vol. 23, Nov. 1972, pp. 307-314.

Numerical methods are used to study the growth of waves of finite amplitude on a pair of parallel infinite vortices. The vortices are treated as lines except in so far as the detailed structure of the core is needed to remove consistently the singularity in the line integrals for the velocities of the vortices. It is shown that the velocities eventually touch and the shape of the wake at this instant is calculated. The wave is quite distorted at this instant, but it is shown that its gross properties are given roughly by linear theory.

Moore, D. W.,
"A NUMERICAL STUDY OF THE ROLL-UP OF A FINITE VORTEX SHEET,"
J. Fluid Mech., Vol. 63, Part 2, April 1974, pp. 225-235.

A point-vortex representation is used to study numerically the evolution of an initially plane vortex sheet. By introducing a tip vortex to represent the tightly rolled portion of the vortex sheet, the chaotic motion which was a feature of some earlier studies is eliminated and the details of the outer portion of the spiral are calculated. The rate of rolling up is calculated and is shown to be governed by the analytically predicted similarity law of Kaden during the initial stages of the rolling up. The calculations are continued until 99% of the vorticity has been rolled up, at which stage the spiral displays a marked ellipticity.

Moore, D. W. and Saffman, P. G.,
"STRUCTURE OF A LINE VORTEX IN AN IMPOSED STRAIN,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 339-354

The velocity of a vortex line depends on its structure, i.e., the shape of the cross-section and the detailed vorticity distribution. As a first step towards an understanding of how the structure depends on the motion and the construction of a valid approximation for the motion of vortex lines in general flow fields, the structure of straight line vortices in a uniform two-dimensional straining field is considered. Two cases are considered in detail; irrotational strain and simple shear.

Moore, D. W. and Saffman, P. G.,
"THE MOTION OF A VORTEX FILAMENT WITH AXIAL FLOW,"
Phil. Trans. Royal Soc. London, Vol. 272, No. 1226, July 1972, pp. 403-429.

Infinitesimal waves on a uniform vortex flow is studied. The equation for the frequency of helical waves is obtained, and solved for the case of long waves which leave the internal structure almost unaltered. A method is developed to obtain results for vortices of non-uniform structure and for displacements which are not necessarily small compared with the core radius. The approach consists of balancing the

Kutta-Joukowski lift force, the momentum flux due to the axial motion, and the tension of the vortex line. A general equation for the motion of a vortex filament is obtained, valid for arbitrary shape and internal structure, and in the presence of an external irrotational velocity field. When the axial flow vanishes, the method is equivalent to using the Biot-Savart law for the self-induced velocity with a suitable cutoff.

Moore, D. W. and Saffman, P. G.,
"AXIAL FLOW IN LAMINAR TRAILING VORTICES;"
Proc. Royal Soc. London, Vol. 333, Series A, June 1973, pp. 491-508.

The structure of laminar trailing vortices behind a lifting wing is considered. The inviscid roll up of the trailing vortex sheet is examined, and the nature of the singularity at the center of the spiral is determined. It is shown that viscosity removes the singularity and the structure of the viscous core is obtained. The pressure in the viscous core is found and used to calculate the axial velocities produced by streamwise pressure gradients. It is found that the perturbation of axial velocity can be either away from the wing or towards the wing depending on the distribution of tip loading on the wing. For elliptic loading, the perturbation is towards the wing. The axial flow deficit in the core due to the boundary layers on the wing is also estimated. A comparison with experiment finds reasonable agreement.

Morris, D. J. and Holbrook, G. T.,
"BASIC RESEARCH IN WAKE VORTEX ALLEVIATION USING A VARIABLE TWIST WING,"
The 1980 Aircraft Safety and Operating Problem, Part 2, NASA Langley Research Center, March 1981, pp. 409-423.

The variable twist wing concept was used to investigate the relative effects of lift and turbulence distribution on the rolled up vortex wake. Several methods of reducing the vortex strength behind an aircraft were identified. These involve the redistribution of lift spanwise on the wing and drag distribution along the wing. Initial attempts to use the variable twist wing velocity data to validate the WAKE computer code have shown a strong correlation, although the vorticity levels were not exactly matched.

Morris, J. P.,
"EFFECT OF ADDING VORTEX ATTENUATING SYSTEMS ON THE DESIGN, PERFORMANCE, AND OPERATIONS OF A HEAVY COMMERCIAL JET TRANSPORT," Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 229-242.

Various trailing vortex attenuation concepts have been proposed for use on heavy jet transports. A preliminary investigation of the effects of several of these concepts on the design, performance and operations of a model 747-200 airplane has been conducted. Three of these concepts that have been judged to be potentially feasible have been selected for this presentation: retractable splines, modified approach flaps (30° inboard, 0° outboard), and flight spoiler deflection. The effectiveness of these devices in alleviating the wake vortices is not addressed; the discussion is limited to the impact on airplane design requirements and resulting performance characteristics.

Morton, B. R.,
"THE STRENGTH OF VORTEX AND SWIRLING CORE FLOW,"
J. Fluid Mech., Vol. 38, Part 2, Sept. 1969, pp. 315-333.

This note presents a discussion of the roles of axial momentum flux, flow force, angular momentum flux and circulation in determining the strength and hence characterizing the structure of such narrow rotating axisymmetric core flows as swirling jets, vortex jets, sink vcrtices and vortex wakes. The salient (though sometimes neglected) features of these core flows are that perturbation pressure plays an essential role both in the coupling of axial and aximuthal velocity fields and in the transmission of force along the core, and that flux of angular momentum is invariant only along cores with zero gross circulation. A number of existing solutions are brought into relationship by the discussion, including Long's similarity solution for draining vortices and Reynolds' dimensional treatment of swirling wakes.

Mosher, M. C.,
"A METHOD FOR COMPUTING THREE-DIMENSIONAL VORTEX FLOWS,"
Zeitschrift für Flugwissenschaften und Weltraumforschurg,
Vol. 9, May-June 1985, pp. 125-133.

A new vortex method is presented for computing incompressible, inviscid, three-dimensional fluid flows. It is pointed out that this method has the convenient numerical properties of the two-dimensional vortex method, and, for this reason, is ideally suited for computing fluid flows in many problems of aerodynamic and hydrodynamic interest. Thus, jets and concentrated wake vortices can be studied, taking into account wing-tip, strake, nose, and horseshoe vortices. The bookkeeping efforts involved in extending this method to a consideration of viscous effects are not very great, and the discussed procedure has, therefore, an advantage over the vortex filament method. Another advantage is related to the absence of requirements for the tracking of a finite difference grid. The considered method was successfully tested with respect to three problems.

Moulden, T. H. and Frost, W.,
"EFFECTS OF FOG DROPLETS ON WAKE VORTEX DECAY RATE,"
NASA CR-2758, Oct. 1976,
Univ. Tennessee Space Institute, Tullahoma, TN.

A simple model for the motion of particles in a laminar line vortex is discussed. The energy required to accelerate a set of these particles was determined and shown to be only a small fraction of the energy content of the vortex flow. It is shown that this energy transfer is unlikely to be sufficient to significantly modify the vortex decay rate. It is further argued that the effect of the particle on the viscous properties of the resulting two phase fluid leads to a slower decay rate than in single phase air flow. However, this conclusion may not necessarily follow for turbulence flows. Results show that the migration of particles to the outer flow results in a redistribution of the velocity profile in the vortex and in a non-uniform two phase viscosity across the core. It is suggested that these effects may accelerate vortex bursting.

Mowforth, E.,
"DETAILS OF MEASUREMENTS IN A TURBULENT TRAILING VORTEX,"
Aero. Quarterly, Vol. 10, May 1959, pp. 161-162.

The vortex was produced by an untwisted rectangular wing, which was mounted as a half-model in the middle of the wall of the low speed wind tunnel at Cambridge University. Measurements were made of total pressure, angle of upwash, and static pressure.

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Nagid, G.,
"WAKE TURBULENCE - THE INVISIBLE ENEMY,"
ICAO Bulletin, Vol. 43, April 1988, pp. 14-15.

Studies to reduce the danger of wake turbulence, especially to following aircraft, and guidelines for wake turbulence classification of aircraft are discussed. An ICAO conference created three categories of aircraft based on maximum certified take-off mass, with heavy craft being those over 136,000 kg, light craft being less than 7,000 kg and medium craft being those in between. The radar separation minima for light aircraft following medium aircraft has been increased from 7.4 km to 9.3 km. Further guidance material is being developed based on wake turbulence research.

Nakamura, Y. and Uchida, S.,
"BREAKDOWN CONDITION OF AN AXISYMMETRIC SWIRLING FLOW,"
AIAA Journal, Vol. 19, No. 8, Aug. 1981, pp. 1083-1085.

A method for prediction and explanation of vortex breakdown using a simple axial velocity profile is proposed. The principle underlying the method is to find solutions which approximately satisy the Navier-Stokes equations, thus leading to the critical condition of breakdown.

Narain, J. P. and Uberoi, M. S.,
"TRAILING VORTEX-PAIR INSTABILITY,"
Physics of Fluids, Vol. 16, No. 6, June 1973, pp. 761-768.

The instability of a vortex-pair to infinitesimal disturbances is studied in the inviscid and incompressible fluid approximations. The cores of the vortices contain uniform axial-velocity jets of fluid density different from that of the surrounding medium. In one model a nonrotating core with surrounding potential vortex is assumed, and in the other a uniformly rotating core. In the lowest order of a perturbation parameter, denoting the ratio of vortex core radius to the distance between the vortices, the long-wavelength symmetric amplification factor of a vortex-pair decreases with increasing jet axial-velocity in either model, with decreasing core density in a rotating core model, and with increasing core density in nonrotating core model. The vortex-pair is more unstable to negative mode of deformation than to the positive mode in the presence of an axial jet in both models considered. The surface tension has a destabilizing effect on the vortex pair in the long-wavelength approximations. The effect of core density and jet axial velocity on long-wavelength symmetric amplification factors of the vortex pair in higher orders of perturbation parameters have also been outlined.

Narain, J. P. and Uberoi, M. S.,
"NONLINEAR STABILITY OF CYLINDRICAL VORTEX ENCLOSING A CENTRAL JET OF LIGHT OR DENSE FLUID,"
Physics of Fluids, Vol. 16, No. 9, Sept. 1973, pp. 1406-1417.

A nonlinear analysis of the inviscid stability of a cylindrical vortex enclosing a central jet of light or dense fluid is presented. A uniformly valid second-order expansion is obtained using the method of multiple time scales. For a stagnant core surrounded by a potential vortex, the axisymmetric mode remains stable to various scales of disturbances independent of core density. For asymmetric modes, the nonlinear effects make the stagnant core vortex sheet more unstable in second order for a given value of the core density. A central jet of any finite density always has a destabilizing effect on the jet-vortex system undergoing any mode of deformation. A jet of any velocity tends to increase the unstable growth rates with increasing order of perturbations. The surface tension has a stabilizing effect with increasing order of perturbations. The frequency of oscillation becomes amplitude dependent in various orders of perturbations. The cylindrical surface departs significantly from its initially perturbed sinusoidal form and assumes an asinusoidal form.

Nash, J. F.,
"SOME CALCULATIONS EXTENDING THE WILLIAMS' MODEL OF THE DECAY OF TRAILING VORTICES,"
LG73ER0191, Oct. 1973,
Lockheed-Georgia Company, Marietta, GA.

Part I gives the results of calculations presented for any given spanload distribution, relevant to the "second stage" of trailing-vortex decay (where roll-up is complete but before the interaction between the two vortices becomes dominant). The problem of relating equivalent wake "age" to distance downstream of the wing is addressed, for the case of a turbulent vortex. It is shown that a variable eddy viscosity is physically more realistic than a constant one, and the decay of the vortices with distance is calculated on this basis. Some exploratory calculations have been performed to investigate the influence on vortex decay of the displacement effect associated with core injection. It is shown that the main effect is to limit the maximum circumferential velocities, present in the vortex, during the early phases of decay. In Part II, the vorticity equations are solved for a semi-infinite rotationally-symmetric viscous vortex, in an incompressible, non-uniform axial flow. Input to the calculations consists of the vector vorticity profiles, at some initial axial station, together with the longitudinal variation of the far-field axial velocity. Output consists of the vector vorticity and velocity profiles at successive stations downstream.

Nelson, R. C.,
"THE DYNAMIC RESPONSE OF AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE,"
PhD Thesis, June 1974,
Penn. State Univ., University Park, PA.

This investigation deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A digital computer simulation was developed to study the response of an aircraft flying into a trailing vortex wake. The simulation includes the complete six degree of freedom equations of motion, a description of the vortex velocity field, unsteady aerodynamics, and pilot control input. The parameters, varied in this simulation, include the penetration angle, separation distance, aircraft size (for both the penetrating and generating aircraft), and pilot control input (single- or multi-axes). Predicted vortex induced motions are presented for a variety of probe aircraft. The probe aircraft selected are representative of general aviation, business, and light jet transport type aircraft. The aircraft used to generate the vortex wakes are representative of the commercial transport fleet. The computer predictions indicate that relatively large aircraft (light jet transport) can experience unacceptable vortex-induced roll excursions.

Nelson, R. C.,
"THE RESPONSE OF AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE,"
AFFDL-TR-74-29, June 1974,
Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH.

The investigation deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A digital computer simulation was developed to study the response of an aircraft flying into a trailing vortex wake. The simulation includes the compete six degrees of freedom equations of motion, a description of the vortex velocity field, unsteady aerodynamics, and pilot control input. The parameters varied in this simulation include the penetration angle, separation distance, aircraft size, and pilot control input.

Nelson, R. C.,
"DYNAMIC BEHAVIOR OF AN AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE,"
J. Aircraft, Vol. 13, No. 9, Sept. 1976, pp. 704-708.

This paper deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A digital computer simulation was developed to study the response of an aircraft flying into a trailing vortex wake. The simulation includes the complete six degree-of-freedom equations of motion, a description of the vortex velocity field, unsteady aerodynamics, and pilot control input. The parameters, varied in this simulation, include the penetration angle, separation distance, aircraft size (for both the penetrating and generating aircraft), and pilot control input (single or multi-axes). It was found that pilot control input could be momentarily out of phase with the vortex induced disturbance. Thus, in certain cases, the pilot's control input would tend to aggravate the vortex-induced upset.

Nelson, R. C. and McCormick, B. W.,
"AIRCRAFT-VORTEX PENETRATION,"
SAE Paper No. 730296,
Wichita, KS, 1973.

As a result of research programs, the hazard of wake turbulence to light aircraft has been well documented. In this paper it is emphasized that relatively large aircraft can also be susceptible to vortices generated by large jet transports. This conclusion is based upon a review of accident records and the results from a computer simulation of the aircraft-vortex interaction. The computer simulation consists of the equations of motion with six degrees of freedom as well as control input by the pilot.

Nelson, R. C. and McCormick, B. W.,
"THE DYNAMIC BEHAVIOR OF AN AIRCRAFT ENCOUNTERING AIRCRAFT WAKE TURBULENCE,"
AIAA Paper No. 74-774,
Anaheim, CA, 1974.

This paper deals with the dynamic behavior of an airplane encountering aircraft wake turbulence. A simplified analysis is presented in which the various factors influencing the vortex-induced rolling moment are examined. Based upon this simplified analysis, a method is developed which allows a rapid estimate of the vortex induced rolling moment to be made. Also, results from a digital computer simulation of the aircraft vortex penetration are presented. The computer predictions indicate that relatively large aircraft (80,000 lb. jet transport) can experience unacceptable vortex-induced roll excursions. Also the results from the simulation were found to compare favorably with flight test results. In addition to evaluating the vortex-induced responses, the effect of pilot control input was assessed. It was found that pilot control inputs were momentarily out of phase with the vortex-induced disturbance. Thus the pilot's control inputs tended to aggravate the vortex-induced upsets.

Neuhart, D. H., Greene, G. C., Satran, D. R. and Holbrook, G. T.,
"DENSITY STRATIFICATION EFFECTS ON WAKE VORTEX DECAY,"
J. Aircraft, Vol. 23, No. 11, Nov. 1986, pp. 820-824.

Results of an experimental study to determine the effects of density stratification on wake vortex decay are presented. The range of stratification commonly encountered in the atmosphere was simulated in the Vortex Research Facility at NASA Langley Research Center by variations in the vertical temperature gradient. Wake measurements were made for low and high aspect ratio, swept and unswept wings at chord Reynolds numbers of about 2×10^5 to 6×10^5. The results indicate that, in the absence of turbulence, density stratification can determine wake descent distance and lifetime. A comparison of laboratory and flight-test measurements with a vortex decay model suggests a significant Reynolds number effect on wake vortex decay.

Nevill, R. G.,
"DOPPLER SONAR IN DETECTION OF AIRCRAFT WAKES,"
AT-2027-098-ASA, Nov. 1974,
Univ. of Birmingham, Birmingham, England.

Doppler sonar remote velocity probes have been proposed as means of detecting and locating the hazardous wingtip vortices shed by heavy aircraft. A theoretical model is discussed in which the target strength is related to the energy dissipation in the vortex core and to the angle of scatter. This model includes a modification of existing scattering theory to account for the refraction expected in a real aircraft wake. An experiment designed to evaluate the acoustic target strength in a vortex core and assess the range of frequencies suitable for acoustic probing, is described. A brief trial of a doppler sonar equipment in conjunction with independent wake monitors at an airport is also reported.

Newman, B. G.,
"FLOW IN A VISCOUS TRAILING VORTEX,"
Aero. Quarterly, Vol. 10, May 1959, pp. 149-162.

The equations of motion for an isolated laminar viscous vortex at moderate to large Reynolds numbers are linearised, by assuming that both the rotational velocity and the deficit of longitudinal velocity are small compared with that in the free stream. The rotational motion and the longitudinal motion may then be superimposed and solutions are readily obtained for each. If the vortex is generated by a body with profile drag it is predicted that the deficit of longitudinal velocity will be positive, which is in agrement with experimental observation. Further details of the solution and its relation to the flow in real vortices are discussed; and the theory is compared with some measurements in a turbulent vortex.

Nielsen, J. N. and Schwind, R. G.,
"DECAY OF A VORTEX PAIR BEHIND AN AIRCRAFT,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 413-454.

A model of a trailing vortex pair behind an aircraft is presented which is thought to represent a case of extreme vortex persistency. Three stages are considered in the analysis: a rolling-up stage directly behind the aircraft, a second stage in which the vortices act independently as constant strength equilibrium turbulent vortices, and a third stage where the vortices physically interact and decay in strength. An overall theory is presented encompassing all three stages and aimed at obtaining equilibrium solutions. Calculative examples are presented for all stages.

Nielsen, J. N., Stahara, S. C. and Woolley, J. P.,
"INGESTION AND DISPERSION OF ENGINE EXHAUST PRODUCTS BY TRAILING VORTICES FOR SUPERSONIC FLIGHT IN THE STRATOSPHERE,"
AIAA Paper No. 74-42,
Washington, DC, 1974.

Detailed analysis has been made of the ingestion and dispersion of engine exhaust products into the trailing-vortex system of a supersonic aircraft flying in the stratosphere. The rate of mixing between the supersonic jet and the co-flowing supersonic stream was found to be an order of magnitude less than would be expected on the basis of subsonic eddy-viscosity results. Ingestion started at the end of the potential core and all hot gas from the engine was ingested into the trailing vortex within two core lengths. The temperature rise in the wake of the supersonic aircraft was found to be much greater than that for a subsonic transport since temperature rise varies directly as speed squared and inversely as aspect ratio.

Noonkester, V. R., Richter, J. H. and Jensen, D. R.,
"UNIQUE ECHOES OBSERVED BY FM-CW RADAR AT A JET AIRPORT,"
TN 2787, Sept. 1974,
Naval Electronics Lab. Center, San Diego, CA.

The capability of the recently developed FM-CW radar to detect detailed low-level small-scale humidity structure suggested the possibility that the radar may be capable of detecting wing-tip vortices. This report presents examples and describes statistical features of a unique echo observed by the FM-CW radar at the west end of runway 9-27 at the International Airport, Lindbergh Field, in San Diego. The data strongly indicate that the unique echo is created by departing aircraft. The source and nature of the echo is undetermined, however.

O

Offi, D. L., Lewis, W. and Lee, T.,
"DETECTION OF HAZARDOUS METEOROLOGICAL AND CLEAR-AIR PHENOMENA WITH AN AIR TRAFFIC CONTROL RADAR,"
Proceedings International Conf., Institution of Electrical Engineers, Oct, 1982, pp. 316-320.

An account is given of the modifications made in the Airport Surveillance Radar (ASR-8) test bed at the FAA Technical Center at Atlantic City Airport (N.J.). The modifications, arrived at by the FAA, the Wave Propagation Laboratory, and MIT's Lincoln Laboratory, were made in order to observe low-level wind shear and turbulence associated with both thunderstorms and aircraft trailing wake-vortices. The modifications, consisting of a second antenna system and a separate receiver and Doppler processing chain, used the standby channel of the radar for these measurements. The results obtained are summarized. In describing the system, it is noted that the 15-foot parabolic antenna is interconnected with the ASR-8, operating with a peak transmitter power of 1 MW, a frequency of 2.79 GHz, a pulse repetition rate of 1030/sec, and a pulse length of 0.6 microsec. The separate receiver and Doppler processing chain comprises inphase and quadrature detectors, analog/digital converters, and a minicomputer with associated peripherals.

Olsen, J. H.,
"RESULTS OF TRAILING VORTEX STUDIES IN A TOWING TANK,"
D1-82-1004, Sept. 1970,
Boeing Research Labs, Seattle, WA.

Flow visualization studies were performed in a towing tank using an electrochemically activated dye. Although test Reynolds numbers were far below flight Reynolds numbers (10 to the 4th versus 10 to the 7th power), the results were strikingly similar to flight test data. Two types of instability were observed in the tank. An instability associated with the axial flow within the core was observed to destroy the flow in the neighborhood of the core without destroying the motion far from the core. A second instability involving the mutual interaction of the two vortices was observed but somewhat masked by the first instability.

Olsen, J. H.,
"AIRCRAFT WAKE TURBULENCE - AN EXPANDING AREA OF LOW-SPEED AERODYNAMICS RESEARCH,"
Proceeding of the National Aerospace Electronics Conf., IEEE, Dayton, 1971, pp. 17-22.

A review of recent findings on the structure of a vortex wake and its interactions with following aircraft is given. Formation and disintegration processes are discussed including recently discovered instability mechanisms. Interactions between a wake and a following aircraft are shown to depend primarily on the circulation of the wake and the span of the following aircraft. Various methods suggested for reducing wake hazards are discussed. Finally, areas for further research are suggested.

Olsen, J. H.,
"CONFIGURATION EFFECTS ON WAKE STRUCTURE AND AIRCRAFT INTERACTION,"
Symposium on Turbulence, FAA, Washington, DC, March 1971, p. 24.

A survey of results of recent flight tests and laboratory experiments was presented with discussion of possible means for reducing the hazard of a wake. Wing modifications, engine placement, and instability mechanisms were discussed as means for increasing the vortex core diameter. The possibility of shortening the hazardous region of the wake by exciting a natural instability of the vortex pair was described.

Olsen, J. H.,
"RESULTS OF TRAILING VORTEX STUDIES IN A TOWING TANK,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 455-472.

Flow visualization studies were performed in a towing tank using an electrochemically activated dye. Although test Reynolds numbers were far below flight Reynolds numbers, the results were strikingly similar to flight test data. Two types of instability were observed in the tank. An instability associated with the axial flow within the core was observed to destroy the flow in the neighborhood of the core without destroying the motion far from the core. A second instability involving the mutual interaction of the two vortices was observed but somewhat masked by the first instability.

Olsen, J. H., Goldberg, A. and Rogers, M., editors,
Aircraft Wake Turbulence and Its Detection, 1st ed., Plenum Press, New York, 1971.

Proceedings of a Symposium on Aircraft Wake Turbulence held in Seattle, Washington, September 1-3, 1970. The volume covers the properties of wakes, including their formation, stability, and decay, and provides data on interactions between wakes and following aircraft as well as experimental methods of observing wake properties.

Oon, E. H.,
"DECAY OF TRAILING VORTICES,"
ARC-CP-1238, June 1971,
Bristol Univ., Bristol, England. (Also, ARC-33215).

Model wings of various planforms were plunged vertically into a water tank and the vortex patterns on the surface were studied. For each wing the wake drift rate was found to increase with incidence and to decrease with increasing core separation. The wake started off with discrete vortex cores which grew independently, maintained their initial separation, and had peak velocities which decayed as time to the minus one-half power. The edges of the cores ultimately came very close together and thereafter separation distance between the core centers increased with time, and the peak velocities tended to decay as the reciprocal of time.

Orloff, K. L.,
"TRAILING VORTEX WIND-TUNNEL DIAGNOSTICS WITH A LASER VELOCIMETER,"
J. Aircraft, Vol. 11, No. 8, Aug. 1974, pp. 477-482.

A two-dimensional laser velocimeter whose focal volume can be rapidly traversed through a flow-field has been used to overcome the problem introduced by excursions of the central vortex filament within a wind-tunnel test section. The operation of the instrument is reviewed and data are presented which accurately define the trailing vortex from a square-tipped rectangular wing. Measured axial and tangential velocity distributions are given, both with and without a vortex dissipator panel installed. From the experimental data, circulation and vorticity distributions are obtained and the effect of turbulence injection into the vortex structure is discussed.

Orloff, K. L.,
"SPANWISE LIFT DISTRIBUTION ON A WING FROM FLOWFIELD VELOCITY SURVEYS,"
J. Aircraft, Vol. 17, No. 12, Dec. 1980, pp. 875-882.

The application of the incompressible three-dimensional momentum integral equation to a finite wing is reviewed. The objective is to interpret the resulting equations in a way that suggests an alternate experimental method for determining the spanwise distribution of lift. Consideration is given to constraints that must be placed on the character of the vortex wake of the wing to provide the familiar relationship between lift and bound vorticity. A novel technique is then presented for obtaining, from behind the wing, the spanwise lift distribution from velocity surveys that are made over only a short distance above and below the wing trailing edge. The necessary formalism is developed to use these measured values to obtain the actual span loading by using an equivalent single-horseshoe vortex model to account for the unmeasured portion of the downward (or upward) momentum. The results of a numerical simulation are presented for a typical loading distribution. The technique is then verified experimentally using laser velocimeter data for the flowfield around a model wing.

Orloff, K. L. and Ciffone, D. L.,
"VORTEX MEASUREMENTS BEHIND A SWEPT WING TRANSPORT MODEL,"
J. Aircraft, Vol. 11, No. 6, June 1974, pp. 362-364.

A backscattering laser Doppler velocimeter (LDV) which simultaneously senses two components of the velocity (axial and tangential), has been used to traverse and measure the velocity distribution in the near wake of a swept wing semispan transport model in the NASA-Ames 7x10-foot wind tunnel. These measurements demonstrate the effect of flap deflection (flap-retracted and flaps deployed 27°) on the velocity profile.

Orloff, K. L., Ciffone, D. L. and Lorincz, D.,
"AIRFOIL WAKE VORTEX CHARACTERISTICS IN THE FAR FIELD,"
NASA TM X-62318, Nov. 1973,
NASA Ames Research Center, Moffett Field, CA.

Tangential and axial velocity profiles were measured in the far field wake vortices of several different airfoils. The results are summarized and discussed. A scanning laser velocimeter was used to obtain data up to 1000 chord lengths behind airfoils with rectangular, diamond-shaped, and swept wing planforms at several different angles of attack. The results show general agreement with wind tunnel measurements made in the near field. The results identify two separate flow regions for the dependence of vortex maximum tangential velocity on downstream distance: an inviscid region where the velocity remains constant after rollup to downstream distances of 200 chord lengths, and then a decay or viscous region that persisted to the limit of the test distance. The decay rates appear to be sensitive to both angle of attack and span loading. The maximum tangential velocity for downstream distances to 40 span lengths was reduced by a factor of 2 by changing from an elliptic (swept wing) or rectangular span loading to a triangular-like span loading (diamond-shaped planform wing). Measured axial velocity defects are shown to agree with those predicted by laminar theory.

Orloff, K. L. and Grant, G. R.,
"THE APPLICATION OF A SCANNING LASER DOPPLER VELOCIMETER TO TRAILING VORTEX DEFINITION AND ALLEVIATION,"
AIAA Paper No. 73-680,
Palm Springs, CA, 1973.

A two-dimensional laser Doppler velocimeter whose focal volume can be rapidly traversed through a flow field has been used to overcome the problem introduced by excursions of the central vortex filament within a wind-tunnel test section. The operation of the instrument is reviewed and data are presented which accurately define the trailing vortex from a square-tipped rectangular wing. Measured axial and tangential velocity distributions are given, both with and without a vortex dissipator panel installed. From the experimental data, circulation and vorticity distributions are obtained and the effect of turbulence injection into the vortex structure is discussed. The experimental velocity profiles are compared to the inviscid Betz theory (as presented by Rossow) and to the functional forms for the logarithmic and defect regions (given by Nielsen and Schwind).

Orman, J. C. and Hockaday, S. L. M.,
"CAPACITY PAYOFFS AT LARGE HUB AIRPORTS FROM ATC INITIATIVES,"
Proceedings Annual Assembly Meeting, RTCA,
Washington, DC, Nov. 1979, pp. 21-38.

The paper reviews the current status of system capacity and delay analysis with particular reference to ongoing FAA efforts in the E&D field. The main emphasis of the capacity element of existing E&D programs is on increasing system capacity through reductions in minimum IFR radar longitudinal separations between arrival aircraft. The biggest problem associated with achieving reduced longitudinal separation of any type is the ability to deal effectively with wake turbulence. Analysis at high-activity airports indicates that gains in system capacity and reductions in aircraft travel time may be achieved by methods other than reduction in minimum longitudinal separations. A summary of 14 of the more promising methods is presented, including examples of potential site-specific applications and benefits.

Ormsbee, A. I.,
"STUDY OF THE FEASIBILITY OF USING A SAILPLANE AS AN INSTRUMENT PLATFORM FOR THE STUDY OF WAKE VORTEX PHENOMENA,"
NASA CR-140603, Sept. 1974,
Illinois Univ., Urbana, IL.

The feasibility of utilizing instrumentation mounted on a sailplane wing is investigated to determine vortex wakes from a large aircraft. The instrumentation consisted of static and total pressure tubes and a rotating vane vorticity meter mounted in a pod on the glider wing tip. It was concluded that the study was not feasible.

Ormsbee, A. I., Bragg, M. B., Maughmer, M. D. and Jordan, Jr., F. L.,
"SCALING WAKE-PARTICLE INTERACTIONS FOR AERIAL APPLICATIONS RESEARCH,"
J. Aircraft, Vol. 18, No. 7, July 1981, pp. 592-596.

The differential equation for the trajectory of a spherical particle injected into an aircraft wake was developed and the proper scaling relations extracted. After some simplification, a convenient set of similarity parameters was established. Using these similarity parameters a scale-model test program was designed and performed in the NASA Langley Vortex Research Facility. The results of the tests demonstrated the validity of the similarity parameters in conducting scale model testing for aerial applications research.

Overcamp, T. J. and Fay, J. A.,
DISPERSION OF SST TRAILS IN THE STRATOSPHERE,"
AIAA Paper No. 72-650,
Boston, MA, June 1972.

A simple theory for the dispersion of the exhaust of a supersonic transport cruising in the stratosphere is presented. The model shows that far downstream of the aircraft, buoyancy dominates the growth of the wake. This growth is limited by the stable stratification of the atmosphere. Data on the visible width of the wake from scaled experiments in a towing tank and from studies on the growth of contrails of subsonic aircraft verify the growth of the wake in an unstratified atmosphere is predicted by the model. This growth is faster than would be predicted for the wake of an axisymmetric body with no buoyancy.

Owen, P. R.,
"THE DECAY OF A TURBULENT TRAILING VORTEX,"
ARC Report 25818, Apr. 1964,
Imperial College of Science and Technology, London, England.

The decay of a trailing vortex which contains turbulence in its core is examined according to the argument that the turbulence is partly sustained by and interacts with the irrotational flow through viscous diffusion of eddies across the core boundary. The region of interaction between the turbulence and the mean flow is a narrow one, separating the core from the outer irrotational flow, and expands with time as the square root of time characteristic of diffusion.

Owen, P. R.,
"THE DECAY OF A TURBULENT TRAILING VORTEX,"
Aero. Quarterly, Vol. 21, Feb. 1970, pp. 69-78.

The decay of a trailing vortex containing a turbulent core is examined according to the argument that turbulence is partly sustained by, and interacts with, the irrotational flow through viscous diffusion of eddies across the core boundary. The region separating the core from the outer irrotational flow, in which the interaction between the turbulence and the mean flow occurs, expands with time like $(\text{time})^{1/2}$, characteristic of viscous diffusion. The essential difference from Squire's solution found here is that the apparent viscosity is not simply proportional to the initial circulation about the vortex as he proposed, but depends on the Reynolds number defined with respect to the circulation.

P

Padakannaya, R.,
"EFFECT OF WING TIP CONFIGURATION ON THE STRENGTH AND POSITION OF A ROLLED-UP VORTEX,"
MS Thesis, March 1970,
Penn. State Univ., University Park, PA.

> This thesis studies the effects of different wing tip configuration on its rolled-up vortex. The spanwise load distribution on plain rectangular wings and on wings with dropped tips was calculated by vortex lattice theory, to determine the effects of the droop on the strength and the location of the vortex. The load distribution on wings with drooped tips shows that the stronger vortex moves from the tip of the wing to the hinge of the drooped tip as the droop angle increases. The experimental results confirmed the movement of the stronger vortex from the tip of the wing to the hinge of the drooped tip as the droop angle increases.

Paillet, F. L.,
"HYDRODYNAMIC STABILITY OF AN AXISYMMETRIC SWIRLING WAKE,"
PhD Thesis, June 1974,
Rochester University, Rochester, NY.

> The stability of a superimposed wake and vortex, designed to resemble the far field flow in an aircraft trailing vortex, is investigated through the use of linearized small perturbation theory. Inviscid and viscid stability are both considered. The mean velocity profiles used are the axisymmetric similarity wake for the axial component, and the asymptotic form of the convecting and diffusing vortex (the Lamb vortex) for the swirling component. Radial mean flow is neglected, and profiles are assumed constant over an axial distance much greater than the disturbance wavelength. Stability characteristics are calculated as a function of the ratio of maximum swirling velocity to maximum wake velocity defect for the lowest non-axisymmetric modes.

Paillet, F. L., editor,
"PROCEEDINGS OF THE AFFDL/NASA/FAA WAKE TURBULENCE WORK SHOP,"
AFFDL-TM-75-16-FGC, Sept. 1974,
Flight Dynamics Lab., Wright-Patterson Air Force Base, OH.

> Summaries of presentations given by ten authorities in the area of wake turbulence are included, along with conclusions

on how the present state of wake research relates to USAF operations. Specific attention is paid to wake formation and stability, accident statistics, wind tunnel tests of vortex theories, the simulation of vortex encounter, similarity theory, prediction of vortex encounter severity, and the testing of various vortex dissipation schemes by NASA.

Panton, R. L., Oberkampf, W. L. and Soskic, N.,
"FLIGHT MEASUREMENTS OF A WING TIP VORTEX,"
J. Aircraft, Vol. 17, No. 4, April 1980, pp. 250-259.

Detailed flight measurements of the wing tip vortex generated by a DeHavilland Beaver were made with instruments mounted on a sailplane, which was towed behind the aircraft. Data at three different downstream locations were obtained by using three different tow rope lengths. The measurement stations were 4, 8, and 16 span lengths behind the aircraft, and the vortex Reynolds number was slightly above 10^6. Results of the tests differed considerably from those of previous authors. Although the customary similarity variables for vortex decay were verified, the velocities were a factor of 2.5 higher than previous results. The vortex core radius and turbulence levels also proved to be substantially smaller than earlier measurements. These results indicate that the final similarity state of the vortex may depend strongly upon the initial tip shape, initial turbulence levels of the vortex, and/or the ambient turbulence levels.

Park, S. O., Kim, J. S. and Lee, B. I.,
"HOT-WIRE MEASUREMENTS OF NEAR WAKES BEHIND AN OSCILLATING AIRFOIL,"
AIAA J., Vol. 28, No. 1, Jan. 1990, pp. 22-28.

An experimental investigation was carried out to study the unsteady, near wakes behind an oscillating airfoil. The airfoil was given the harmonic pitching motion about the one-quarter chord axis at two reduced frequencies 0.1 and 0.2. The amplitude of oscillation was 7.4 deg. To assess the effect of mean incidence the mean incidence of oscillation was varied from 0-4 deg. When the mean incidence was 4 deg. the airfoil was found to undergo a deep stall. Streamwise velocity and turbulence intensity profiles were measured by hot-wire anemometry. The near-wake measurements made it possible to detect and characterize the emergence of unsteady separation. It was found that the unsteady boundary-layer separation occurred at a greater phase angle (i.e., separation was delayed) when the reduced frequency was greater. When the mean incidence of oscillation was larger, the unsteady separation occurred at a smaller phase angle (i.e., separation was promoted). Smoke-wire flow visualization was also effected to elucidate the link between some of the measured wake data and the various flow states around the airfoil. The phase lag of wake velocity profile relative to the motion of the trailing edge was estimated.

Parkinson, Jr., R. C. H. and Kelly, D. W.,
"A DYNAMIC ANALYSIS OF AEROPLANES ENCOUNTERING VORTEX WAKE TURBULENCE,"
ATN-7301, Jan. 1973,
University of Sidney, Sidney, Australia.

A six degree of freedom flight simulation model was developed for digital computers to investigate the response of aircraft to a pair of trailing vortices. The model was used to simulate the flight of a light, two-seat training aircraft and a twin-engined commercial transport into the vortices shed by medium weight and heavy weight aircraft.

Parks, P. C.,
"A NEW LOOK AT THE DYNAMICS OF VORTICES WITH FINITE CORES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 355-388.

The stability theory for wave-like disturbances in a pair of trailing line vortices developed by Crow has been modified to take account of finite core radii and appropriate distributions of vorticity within these cores. The essential features of Crow's theory are confirmed with small numerical changes. The effect of axial flow within the cores may be considered by wrapping the core in a sheath of vortex rings. This model leads to a new stability criterion for a single "jet-vortex". The theory, which assumes the vortices extend from infinity to infinity, cannot be used to calculate the growth of perturbations deliberately introduced at the wing of the aircraft, but a modified discretised theory amenable to digital computation has been developed to investigate initial growth of these excited waves.

Patterson, Jr., J. C.,
"A CONTROLLED METHOD TO OBTAIN A VISUAL HISTORY OF THE LIFT INDUCED WING TIP VORTEX,"
LWP-983, Aug. 1971,
NASA Langley Research Center, Hampton, VA.

Tests were performed in the towing tank facility of the Langley Loads Division. This method of flow visualization is particularly applicable to the study of lift-induced wing tip vortices and has made possible the ability to record the entire life span of the vortex. To accomplish this, a vertical screen of smoke is produced perpendicular to the flight path and allowed to become stationary. The wing panel is then passed through the screen of smoke producing the circular vortex motion which may be recorded by high-speed motion pictures.

Patterson, Jr., J. C.,
"LIFT-INDUCED WING-TIP VORTEX ATTENUATION,"
AIAA Paper No. 74-38,
Washington, DC, Jan. 1974.

It has been shown by a new static airflow visualization method that a drogue device properly positioned downstream of the wing tip causes vortex breakdown. This same result has been obtained by mounting a jet engine simulator at the wing tip and directing the high-energy jet blast downstream into the vortex. These configurations, among others, are now under intensive investigation in the new Langley Vortex Research Facility. In this facility a balance mounted vortex generating model is propelled along the 1800-foot track while a second model trailed at 160 feet (scale distance of 1 mile) measures the far-field rolling moment induced by the vortex of the generating model.

Patterson, Jr., J. C.,
"VORTEX ATTENUATION OBTAINED IN THE LANGLEY VORTEX RESEARCH FACILITY,"
J. Aircraft, Vol. 12, No. 9, Sept. 1975, pp. 745-749.

It has been shown by a new static airflow visualization method that a drogue device properly positioned downstream of the wing tip causes vortex breakdown. This same result has been obtained by mounting a jet engine simulator at the wing tip and directing the high-energy jet blast downstream into the vortex. These configurations, among others, are now under intensive investigation in the new Langley Vortex Research Facility. In this facility, a balance mounted vortex generating model is propelled along a 1800-foot track while a second model trailed at 160 feet (scale distance of 1 mile) measures the far-field rolling moment induced by the vortex of the generating model.

Patterson, Jr., J. C. and Flechner, S. C.,
"AN EXPLORATORY WIND TUNNEL INVESTIGATION OF THE WAKE EFFECT OF A PANEL TIP-MOUNTED FAN-JET ENGINE ON THE LIFT-INDUCED VORTEX,"
NASA TN D-5729, May 1970,
NASA Langley Research Center, Hampton, VA.

An investigation has been conducted in the Langley 8-foot transonic pressure tunnel to determine the effectiveness of a tip-mounted powered-model high-bypass fan-jet engine in reducing the tip vorticity of an unswept symmetrical panel. The effects of end plates, a body of revolution, and a flow-through nacelle on panel-tip vorticity were also determined for comparison.

Patterson, Jr., J. C., Hastings, Jr., E. C. and Jordon, Jr., F. L.,
"GROUND DEVELOPMENT AND FLIGHT CORRELATION OF THE VORTEX ATTENUATING SPLINE DEVICE,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, 1977, pp. 271-304.

The data presented in this report indicate that the wing-mounted spline is a effective vortex-attenuating device. A comparison of the vortex-induced rolling moment results at a separation scale distance of 0.70 km (0.38 n. mi.) obtained in the Langley Vortex Research Facility with those measured in full-scale flight indicate good agreement for the unattenuated vortex configuration. The comparison also indicates that the spline effectiveness in flight was greater than in the ground facility test. The results of an applications study show that, for the heavy commercial jet aircraft studied, use of the splines does result in some degradation of the climb gradient and rate of climb, but the aircraft should meet certification requirements.

Patterson, Jr., J. C. and Jordon, Jr., F. L.,
"A STATIC-AIR FLOW VISUALIZATION METHOD TO OBTAIN A TIME HISTORY OF THE LIFT-INDUCED VORTEX AND CIRCULATION,"
NASA TM X-72769, Sept. 1975,
NASA Langley Research Center, Hampton, VA.

An investigation of a recently proposed method of flow visualization has been conducted at Langley Research Center. This method of flow visualization is particularly applicable to the study of lift-induced wing tip vortices through which it is possible to record the entire life span of the vortex. To accomplish this, a vertical screen of smoke is produced perpendicular to the flight path and allowed to become stationary. A model is then driven through the screen of smoke producing the circular vortex motion made visible as the smoke is induced along the path taken by the flow and is recorded by high-speed motion pictures.

Patterson, Jr., J. C. and Jordon, Jr., F. L.,
"AN INVESTIGATION OF THE INCREASE IN VORTEX INDUCED ROLLING MOMENT ASSOCIATED WITH LANDING GEAR WAKE,"
NASA TM X-72786, Nov. 1975,
NASA Langley Research Center, Hampton, VA.

As part of a NASA-wide program now underway to attempt to reduce the hazard associated with the lift-induced vortex system of large aircraft, a flight test has been conducted at Flight Research Center to verify the results found in the ground base facilities of the effect of span load variation as well as the vortex attenuation of the high energy jet engine exhaust through proper thrust programming. During these flight tests a large increase in vortex strength was experienced as a result of extending the landing gear. Tests in the Langley Vortex Research Facility indicate that the wake produced by the landing gear may possibly form an aerodynamic endplate or reflection plane at the inboard edge of each inboard flap which increases the effective aspect ratio of the flap and thereby increases the strength of the flap outer edge vortex.

Patterson, Jr , J. C. and Jordon, Jr., F. L.,
"THRUST-AUGMENTED VORTEX ATTENUATION,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, 1977, pp. 251-270.

An experimental investigation has been conducted in the Langley Vortex Research Facility to determine the vortex attenuating effect of engine thrust. Tests were made using a 0.03-scale model of the Boeing 747 transport aircraft as a vortex-generating model. A Learjet-class probe model was used to measure the vortex-induced rolling moment at a scale separation distance of 1.63 km (0.88 n. mi.). These tests were conduced at a lift coefficient of 1.4 at a model velocity of 30.48 m/s. The data presented in this paper indicate that engine thrust is effective as a vortex attenuating device when the engines are operated at high thrust levels and are positioned to direct the high-energy engine wake into the core of the vortex. The greatest thrust vortex-attenuation is obtained by operating the inboard engine thrust reversers at one-quarter thrust and the outboard engines at maximum forward thrust.

Pauley, W. R. and Eaton, J. K.,
"EXPERIMENTAL STUDY OF THE DEVELOPMENT OF LONGITUDINAL VORTEX PAIRS EMBEDDED IN A TURBULENT BOUNDARY LAYER,"
AIAA J., Vol. 26, No. 7, July 1988, pp. 816-823

The mean streamwise development of pairs of longitudinal vortices and arrays of longitudinal vortices embedded in an otherwise two-dimensional turbulent boundary layer is studied. Planes of closely spaced measurements of the three components of mean velocity were obtained at several streamwise locations, and the vorticity and circulation were calculated. It was found that the rate of vorticity spreading in a vortex was greatly increased by close proximity of other vortices. Vortices remaining close to the wall produced significant levels of spanwise skin friction and, thus, a greater rate of streamwise circulation decrease.

Peace, A. J. and Riley, N.,
"A VISCOUS VORTEX PAIR IN GROUND EFFECT,"
J. Fluid Mech., Vol. 129, April 1983, pp. 409-426.

We calculate the flow induced by a vortex pair in a viscous fluid, which is otherwise at rest, in the presence of a plane boundary. This may be either a no-slip or a stress-free boundary. The phenomenon of rebound of the vortices from the boundary occurs for either type of boundary, and an explanation for this is offered in terms of voscous effects.

Petrie, S. L. and Emmer, D. S.,
"INVESTIGATIONS OF TRANSONIC TRAILING EDGE FLOWS,"
Proceedings of the Second Conf., Soc. for Computer Simulation, San Diego, CA, Jan. 1986, pp. 199-210.

An experimental study of several of the trailing edge and wake turbulence properties for a NACA 64A010 airfoil section was completed. The experiments were conducted at the Ohio State University Aeronautical and Astronautical Research Laboratory in the 6 inch x 22 inch transonic wind tunnel facility. The data were obtained at a free stream Mach number of 0.80 and a flow Reynolds number (based on chord length) of 5 million. The principal diagnostic tool was a dual-component laser Doppler velocimeter. The experimental data included surface static pressures, chordwise and vertical mean velocities, RMS turbulence intensities, local flow angles, and a determination of turbulence kinetic energy in the wake at chordwise locations between the transonic shock wave and the trailing edge, in the near wake just downstream of the trailing edge and in the far wake. At the two angles of attack tested (0 and 2 degrees), the turbulence intensities and turbulence kinetic energy were observed to decay in the streamwise direction. In the far wake, for the non-lifting case, the turbulence intensities were nearly isotropic. For the two degree case, the horizontal component of the turbulence intensity was observed to be substantially higher than the vertical component.

Piercy, N. A. V.,
"ON THE VORTEX PAIR QUICKLY FORMED BY SOME AEROFOILS,"
J. Royal Aeronautical Society, Vol. 27, No. 154, Oct. 1923,
pp. 488-500.

A study was made on the structure of a vortex in turbulent flow to determine the effect of eddies, if employed in aerofoil theory. This study was done because eddies were so commonly found in real flow pass other bodies.

Piggot, B. A. M. and Pask, J. A.,
"WAKE VORTEX INCIDENTS REPORTED IN THE UK 1972-1976,"
CAA Paper 77012, June 1977,
Civil Aviation Authority, London, England.

The CAA wake vortex incident reporting scheme was formally initiated in July 1972; reports had previously been collected on an informal basis and reasonably complete information is available on incidents occurring from January 1972 onwards. Pilots who believe their aircraft to have encountered a wake vortex are asked to complete a detailed questionnaire. Whenever possible, the reports are supplemented by spacing data supplied by the air traffic controllers and by meteorological data; this extra information is received as a matter of course when incidents are reported in the neighborhood of London Heathrow airport. In some cases it has been possible to examine flight data recordings from aircraft involved in reported incidents. An examination is made of the rate of occurrence of incidents before and after the change in separation standards introduced in March 1974.

Pinsker, W. J. G.,
"THE HAZARD OF VORTEX WAKE ENCOUNTERS IN THE CRUISE,"
TR 79063, June 1979,
Royal Aircraft Establishment, Farnborough, England.

Records are shown of encounters with vortex wakes of civil aircraft in en-route flight. These are of sufficient severity and frequency to constitute a potential airworthiness hazard. The principal concern is with airframe loads but one case is also documented of a major upset in roll.

Poisson-Quinton, P. and Werle, H.,
"WATER TUNNEL VISUALIZATION OF VORTEX FLOW,"
Astronautics and Aeronautics, Vol. 5, June 1967, pp. 64-66.

The complexities and subtleties of vortex flow about the wings, fins and fuselage of slender aircraft and missiles have been revealed elegantly by a small water-tunnel. Visualization of the vortices is obtained (1) by colored emissions that show the streamlines in the neighborhood of the model and (2) by air-bubbles showing the flow in a thin lighted section either normal or parallel to the flow.

Poppleton, E. D.,
"EFFECT OF AIR INJECTION INTO THE CORE OF A TRAILING VORTEX,"
J. Aircraft, Vol. 8, No. 8, Aug. 1971, pp. 672-673.

The radial distribution of axial velocity which occurs in the wake of any given aircraft depends on the manner in which the vortex is generated, and the overall axial-momentum balance for the fluid that ultimately constitutes the core of the vortex. The note describes preliminary experiments conducted in the McGill 30-inch blower tunnel to examine the possibility that if air is injected along the axis in the early stages of the formation of the vortex, its subsequent behavior may be modified by thus changing conditions in the nascent core. It was found that the effect of blowing through the jet is effectively to "age" the vortex prematurely.

Poppleton, E. D.,
"THE CONTROL OF WING-TIP VORTICES,"
Aero. Tech. Note 7102, Aug. 1971,
University of Sidney, Sidney, Australia.

A device is proposed for the control of the velocity distribution in the core of a trailing vortex. Preliminary calculations show that the required planform shape does not differ radically from that of a conventional wing, and that there is a considerable reduction in vortex drag.

Poppoff, I. G., Farlow, N. H. and Anderson, L. B.,
"STUDIES OF AIRCRAFT WAKE CHEMISTRY AND DISPERSION,"
Acta Astronautics, Vol. 1, Jan-Feb. 1974, pp. 157-178.

Use of aerospace technology to study aircraft wakes is reviewed. It is shown how aerospace vehicles can be used to provide data for increased understanding of the atmosphere and of aircraft exhaust trails where knowledge is inadequate to evaluate fully the potential impact of the engine emissions. Models of aircraft near-field exhaust wakes are characterized by jet, vortex, and dispersion regimes. Wake growth in the jet regime is self-determined and rapid, whereas further spreading is inhibited in the vortex regime because of circulating vortex motion. Wake diffusion in the dispersion regimes is initially influenced by aircraft induced turbulence but is dominated later by small-scale atmospheric turbulence. Computed fluid mechanical results show the importance of effects such as wake buoyancy, wind shear, turbulence, and traffic corridor exhaust buildup on dispersion of the wake. In the jet regime the exhaust characteristics and thermochemistry serve to illustrate initial chemical changes involving potential pollutant species.

Portnoy, H.,
"AERODYNAMIC EFFECTS OF VORTEX SUPPRESSORS,"
TAE-221, July 1974,
Technion-Israel Inst. of Technology, Haifa, Israel.

The effectiveness of various devices in accelerating the dissipation of wing-tip vortices has received considerable attention recently. These deices include jets blown into or near the vortex core, both in the upstream and downstream direction, small cruciform wings, both fixed and rotating, mounted close behind the wing near tip and angled fences or vortex generators mounted on the wing upper and lower surfaces so as to produce swirl opposite to that of the tip vortex. In this report are proposed mathematical models for representing some of these devices in order to calculate their effects on the wing aerodynamic properties.

Portnoy, H.,
"CALCULATION OF THE AERODYNAMIC EFFECTS OF CERTAIN VORTEX SUPPRESSING DEVICES,"
AFOSR-TR-75-0713, Dec. 1974,
Technion-Israel Inst. of Technology, Haifa, Israel.

There has been a recent increase of interest in devices for accelerating the dissipation of wing-tip trailing vortices. A number of experimental programs have been carried out to determine the effectiveness of various devices, such as tip-mounted jets, small windmills, suitably disposed vortex generators and so on, in increasing the rate of vortex decay. Only limited attention seems to have been paid to the effects of these devices on the wing aerodynamic properties and the work that has been done appears to be entirely experimental. It is the purpose of the present paper to propose three simple mathematical models which may be used to assess many of the current suppressors, from the viewpoint of wing property modification.

Portnoy, H.,
"THE INITIAL ROLL-UP OF A THICK, TWO-DIMENSIONAL WAKE BEHIND A WING OF FINITE SPAN,"
TAE-262, Nov. 1975,
Technion-Israel Inst. of Technology, Haifa, Israel.

This work is an attempt to remove the unrealistic features of earlier vortex wake models, namely zero wake thickness and vorticity concentrated on lines, by assuming that the wake vorticity is contained in a layer of finite thickness with some plausible cross-sectional shape. The wake flow is assumed to be two-dimensional and the rolling-up is studied via the time-dependent development of this model so that it deals with the slow rolling-up taking place far behind the wing. The mathematical model of the wake is described and examples of the initial roll-up phase have been calculated for three wakes of different thicknesses and elliptic cross-sections, subjected to uniform downwash (corresponding to elliptic spanwise loading).

Priest, A. J., Dobney, D. G. and Hill, R. P.,
"MEASUREMENTS IN THE NEAR-WAKE OF A TRANSPORT MODEL TO DETERMINE THE LIFT, DRAG AND DRAG COMPONENTS USING MASKELL'S ANALYSIS,"
RAE TR-81012, Feb. 1981,
Royal Aircraft Establishment, Farnborough, England.

Extensive measurements have been made on a plane normal to the wake of a swept-wing/fuselage model of airbus type, at C sub

L = 0.49 in incompressible flow, using a computer-controlled wake-traverse system incorporating a null-reading five-hole yawmeter probe. The results define the detailed distributions of total pressure defect, flow velocity, flow angles and streamwise vorticity in the viscous wake at that plane. The results have been analyzed within the basic theoretical framework set out by Maskell (1973), allowing the calculation of lift and drag from traverse data, and the resolution of the drag into provisionally-defined components C sub D sub I and C sub D sub II, respectively relating to the profile drag and vortex drag.

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Raat, J.,
"VORTEX DEVELOPMENT AND BREAKDOWN,"
AIAA Paper No. 75-881,
Hartford, CT, 1975.

A trailing vortex is assumed to consist of a thin axisymmetric viscous core embedded in an inviscid flow of uniform circulation and with axial velocity that may depend on the distance along the core. Self-similar solutions for axial velocity and circulation are presented for the special case of an external velocity inversely proportional to the core length. Integral solutions for uniform external flow fall into three different categories: (1) Wake-type vortex development, (2) Breakdown when the prescribed azimuthal energy conversion mechanism can no longer be satisfied, (3) Breakdown through core flow reversal. The effect of external pressure gradients on breakdown is exhibited.

Rader, L. G. and Kane, J. B.,
"INVESTIGATION OF FACTORS AFFECTING MINIMUM INTERVAL BETWEEN AIRCRAFT TAKEOFFS (MITO),"
TM 79-9.12/1, Sept. 1979,
Calspan Corp., Los Angeles, CA.

The factors that affect MITO fall into two basic categories: (1) the aerodynamic factors that contribute to vortex generation and to the control of following aircraft, and (2) the propulsion factors that contribute to the generation of exhaust turbulence and combustion by-products. A literature and data search failed to turn up any information related to the propulsion factors and only limited data related to the aerodynamic factors. The best current source of data are the DOT studies on landing and takeoff intervals of commercial aircraft. Although DOT's objectives in conducting these studies are significantly different from SAC's objectives for alert aircraft, it is possible that the DOT data will provide a good initial understanding of the takeoff interval problem.

Ragsdale, R. G.,
"APPLICABILITY OF MIXING LENGTH THEORY TO A TURBULENT VORTEX SYSTEM,"
NASA TN D-1051, Aug. 1961,
Lewis Research Center, Cleveland, OH.

Techniques of mixing length theory established for pipe flow are used to develop analogous expressions for turbulent vortex flow; the ability of these functions to correlate vortex data is then evaluated. Experimentally measured tangential velocity and static-pressure profiles are used to determine turbulent Reynolds numbers from Naiver-Stokes solutions for compressible flow in the annular region of a vortex with constant eddy viscosity assumed. Karman and Prandtl type mixing length expressions for vortex flow are given for various assumed boundary conditions. A modified Karman expression for eddy viscosity is derived and best correlates the data for the entire range of experimental conditions.

Raj, P. and Iversen, J. D.,
"COMPUTATIONAL STUDIES OF TURBULENT MERGER OF COROTATIONAL VORTICES,"
AIAA Paper No. 78-108,
Huntsville, AL, Jan. 1978.

A computational study has been conducted to gain a better understanding of the criteria governing the merger of corotating vortices. The zero-equation and one-equation turbulent-flow models are used to model the interaction of two rolled-up, corotational vortices. A model appropriate for the swirling flow under consideration has been proposed to prescribe the algebraic variation of mixing-length in the flow field. The unsteady, two-dimensional equations in a cross-plane are solved for primitive variables using an implicit finite-difference code. The computed downstream merging distances are in good agreement with available wind tunnel data.

Raj, P. and Iversen, J. D.,
"INVISCID INTERACTION OF TRAILING VORTEX SHEETS APPROXIMATED BY POINT VORTICES,"
J. Aircraft, Vol. 15, No. 12, Dec. 1978, pp. 857-859.

A computational study of the mutual interaction of vorticity sheets shed behind wings kept at a small distance apart has been made. The sheets are modeled by arrays of discrete point vortices and their inviscid motion is computed. The gross features exhibited by the results confirm the experimental observation that for a small initial separation distance, the trailing vorticity sheets roll up together.

Raj, P. and Iversen, J. D.,
"COMPUTATIONAL SIMULATION OF TURBULENT VORTEX MERGER AND DECAY,"
AIAA J., Vol. 18, No. 8, Aug. 1980, pp. 865-866.

In recent years, many theoretical and experimental studies have been conducted to gain a better understanding of corotational vortex merger in connection with the pairing of organized vortex structures observed in mixing layers and with the attenuation of wake-vortex hazard associated with wide-body aircraft. The latter is accomplished by modifying the wing such that two or more corotating vortices are shed from each half-span. The merger of these vortices can result in a redistribution of vorticity such that the hazard to trailing aircraft is considerably reduced compared to the conventional wing. In the present investigation, the interaction and merger of corotational vortices and the decay of a single vortex have been studied by employing zero-, one-, and two-equation turbulent flow models in an attempt to bridge the gap between the theoretical models and experimental observations. The zero- and one-equation formulations utilize a mixing-length model which incorporates the streamline curvature effect by prescribing a particular spatial variation. In the two-equation model, a turbulence kinetic energy equation and a rate of dissipation equation modified to include streamline curvature correction are solved. The computed results corresponding to the different flow models are compared with the available experimental data.

Ramirez, Jr., A., Rao, B. M. and Cronk, A. E.,
"LONGITUDINAL RESPONSE OF AN AIRCRAFT DUE TO A TRAILING VORTEX PAIR,"
J. Aircraft, Vol. 10, No. 10, Oct. 1973, pp. 638-639.

An approximate method to predict the response of a small aircraft in longitudinal motion when it is flying through a trailing vortex of a large aircraft was developed. The longitudinal stability equations of motion were linearized. The loads were computed assuming the wing and the horizontal tail as the lifting surfaces and neglecting the wing-body-tail interference effects. The results of the lift and moment coefficients variations with respect to the distance between the test aircraft, and time histories of the flight variables u, α, and θ were shown.

Ramsey, V. W.,
"ACOUSTIC SCATTERING FROM AN AIRCRAFT TRAILING VORTEX,"
PhD Thesis, May 1974,
Stanford Univ., Palo Alto, CA.

A detailed analysis is presented of acoustic scattering from the velocity field of an aircraft trailing vortex. A model of a turbulent vortex is obtained from the aerodynamic literature. Published vortex theories and experimental data are used to evaluate vortex flow compressibility, turbulence level versus that of the environment, the existence of an inertial subrange, and vortex turbulence scales. Much of this information then provides a basis for discussing refraction, multiple scattering, and the validity of the Born approximation in aircraft vortices.

Ramsey, V. W. and Peterson, A. M.,
"ACOUSTIC SCATTERING FROM A TURBULENT VORTEX,"
NASA CR-141186, Jan. 1974,
Stanford University Electronics Labs., Palo Alto, CA.

With the aid of the Born approximation, the time autocorrelation and power spectral density are calculated for the received acoustic signal scattered from velocity fluctuations in a turbulent aircraft trailing vortex. The turbulence is required to be globally stationary, but only locally homogeneous. The treatment includes the effects of spectral broadening due to convection of the scattering eddies by a spatially varying mean flow and by macroeddies. The 3 db bandwidth of the received signal is related to the scattering angle and the core Mach number of the vortex. A primary feature of the analysis is that it provides a method for inferring the radial intensity distribution of turbulence in a vortex. The analysis technique is also applicable to scattering from other turbulent flows where significant variations of turbulence level occur over distances on the order of the macroeddy size.

Randall, J. D. and Leibovich, S.,
"THE CRITICAL STATE - A TRAPPED WAVE MODEL OF VORTEX BREAKDOWN,"
J. Fluid Mech., Vol. 58, No. 3, May 1973, pp. 495-515.

A model of vortex breakdown is presented and its predictions compared with the experiments of Sarpkaya. The model is centered about a theory of long, weakly nonlinear waves propagating on critical flows in tubes of variable cross-section. Although the weakly nonlinear theory must be extended beyond its domain of formal validity, many of the experimentally observed features of vortex breakdown are reproduced by the model. The description of the time evolution of the flow field that is presented requires numerical calculations that are not simple, but some important conclusions may be determined by easy computations. In particular, the axial position of a breakdown may be found from a very simple equation.

Reed, Jr., R. E.,
"PROPERTIES OF THE LATERAL RANDOM OSCILLATIONS OF TRAILING VORTICES OBSERVED IN WIND-TUNNEL TESTS,"
NEAR TR-47, Jan. 1973,
Nielsen Eng. and Research Inc., Mountain View, CA.

The characteristics and causes of the lateral oscillations of trailing vortices observed during tests in the 40- by 80-foot and 7- by 10-Foot Wind Tunnels at Ames Research Center are studied. Various statistical properties of the oscillations are computed from movie camera data. A comparison of these data with a derived analytical expression indicates that the vortex oscillation is caused by the tunnel turbulence and the rms amplitude is independent of the properties of the vortex for the range of parameters considered.

Reeder, J. P., Taylor, R. T. and Walsh, T. M.,
"NEW DESIGN AND OPERATING TECHNIQUES FOR IMPROVED TERMINAL AREA COMPATIBILITY,"
SAE Paper No. 740454,
Dallas, TX, 1974.

Current aircraft operating problems that must be alleviated for future high-density terminal areas are safety, dependence on weather, congestion, energy conservation, noise, and atmospheric pollution. The microwave landing system (MLS) under development by FAA provides increased capabilities over the current ILS. It is however, necessary and urgent to develop the airborne system's capability to take maximum advantage of the MLS capabilities in order to solve the terminal area problems previously mentioned. A major limiting factor in longitudinal spacing for capacity increase is the trailing vortex hazard. Promising methods for causing early dissipation of the vortices are being explored. Also, flight procedures for avoiding the hazard will be explored.

Reeder, J. P. and Wetmore, J. W.,
"AIRCRAFT VORTEX WAKES IN RELATION TO TERMINAL OPERATIONS,"
NASA TM X-51683, Nov. 1962,
NASA Langley Research Center, Langley Station, VA.

The purpose of this paper is to examine the problems associated with trailing vortices, particularly in the airport terminal area where separation of aircraft must be kept to a safe minimum for efficient traffic handling and where the low flight speeds result in more intense vortices. A brief discussion is given of the formation of trailing vortices from lifting surfaces and of the effects of such major factors as aircraft weight, wingspan, and speed on intensity and extent of the resulting airflow disturbance. The decay of vortex intensity with time is considered in the light of available experimental results and theory. Effects on aircraft encountering trailing vortices including structural loads, upset, and settling are considered together with the influencing factors. Finally, the theoretically determined timewise settling and spreading of the trailing vortices from an airplane in typical takeoff and landing are described and discussed in relation to safe procedures for following airplanes. Airplanes considered as examples in the discussion include a heavy jet transport of 300,000 lb gross weight, a 35,000 lb light turboprop transport and a 2,000 lb light personal airplane.

Rehback, C.,
"NUMERICAL STUDY OF THE INFLUENCE OF THE WING TIP SHAPE ON THE VORTEX ROLL UP,"
NASA-TT-F-14538, Aug. 1972,
Scientific Translation Service, Santa Barbara, CA.

A computer program to analyze the wing tip vortex distribution as a function of wing tip shape is presented. The wing and the sheet are replaced by a vortex surface. The continuous vortex distribution over the surface is replaced by a discrete vortex distribution, which is a horseshoe distribution of finite magnitude and is placed over the wing only. The shear appears in the form of a series of vortex threads which emanate at moderate incidence angles from the leading edge to the wing tip. Starting with the given initial position, the threads evolve during the course of an iteration calculation and assume equilibrium positions parallel to the average velocity over the sheet.

Reich, P. G.,
"INFLUENCE ON LAND AND AIRSPACE DEMANDS OF TECHNIQUES IN CURRENT USE,"
Air Traffic, Navigation and the Community, Royal Aeronautical Society and Institute of Navigation, Symposium on Air Traffic in the 1980's, London, May 1970.

Study of the limitations of techniques already commonly applied, and of the more promising points of application for new technology in navigation, surveillance, and traffic control. In seeking the latter, some of the current trends in other fields, particularly aircraft design, are taken into account. Considerable emphasis is placed on the efficient use of land at airports, in view of the strength of feelings aroused in communities by questions of apportionment and exploitation of land resources. The incidence of much stronger wing tip vortices associated with heavy CTOL aircraft is likely to make increases in land productivity difficult, if not impossible, to achieve.

Rinehart, S. A., Balcerak, J. C. and White, Jr., R. P.,
"AN EXPERIMENTAL STUDY OF TIP VORTEX MODIFICATIONS BY MASS FLOW INJECTION,"
RASA-71-01, Jan. 1971,
Rochester Applied Science Assoc., Rochester, NY.

An experimental program was conducted to investigate the modifications of a tip vortex which could be obtained by injecting the core of a tip vortex with a stream of air. Wind tunnel tests of an airfoil model were conducted. The results obtained from flow-visualization studies, balance data and vortex-meter measurements show how the strength of the tip vortex can be reduced significantly by the injection of a linear mass flow of air into the core of the tip vortex.

Roberts, L.,
"ON WAKE VORTEX ALLEVIATION,"
The Future of Aeronautics, Kansas Univ., 1974, pp. 139-167.

Research within NASA relating to the nature of lift-induced vortex wakes behind large aircraft and the means whereby the hazard they represent to smaller aircraft can be alleviated is reviewed. The research, carried out in ground based facilities and in flight shows that more rapid dispersion of the wake can be effected by several means and that the modification of span-loading by appropriate flap deflection holds promise of early practical application.

Robins, R. E. and Delisi, D. P.,
"THE POTENTIAL HAZARD OF AIRCRAFT WAKE VORTICES IN GROUND EFFECT AND CROSSWIND,"
AIAA Paper No. 89-3400,
Boston, MA, Aug. 1989.

Aircraft trailing vortices, evolving close to the ground in a crosswind, are a potential hazard to aircraft landing or taking off on the same or parallel runways. The objective of our work has been to study, by means of numerical simulation, the effect of aerodynamic and environmental conditions on the generation and transport of such vortices. Our approach has been to use a computer code, which solves the 2D, time-dependent, incompressible Navier-Stokes equations, to study trailing vortices in ground effect and crosswind. The code permits the specification of arbitrary atmospheric stability and wind profiles. A mixed no-slip/free-slip lower boundary condition has been invoked to model the interaction of the vortices with the ground. We have validated our numerical model by comparing its results with laboratory and field data. Our simulation results have shown that, even after evolution times and cross-runway transport distances on the order of three minutes and five hundred meters, vortices generated by large aircraft close to the ground in a crosswind can carry sufficient average circulation to be a potential hazard to smaller aircraft.

Robins, R. E. and Delisi, D. P.,
"NUMERICAL STUDY OF VERTICAL SHEAR AND STRATIFICATION EFFECTS ON THE EVOLUTION OF A VORTEX PAIR,"
AIAA J., Vol. 28, No. 4, April 1990, pp. 661-669.

The objective of this study is to investigate with a numerical model how coexisting vertical shear and stratification affect the evolution of a vortex pair. Our results show that the Richardson number (the ratio of stratification forces to shear forces) is an important parameter in the evolution. When the Richardson number is large, the vortex pair evolves more or less symmetrically, the left and right vortex decaying equally, or nearly equally, rapidly. In this case, the effect of the shear is small, and stratification dominates the evolution. When the Richardson number is sufficiently small, however, the evolution is dramatically different. Under these conditions, the vortices evolve asymmetrically, and the vortex with rotational sense opposite to that of the mean shear decays while the vortex with the same rotational sense as the mean shear survives. This "solitary vortex" then decays slowly with time. The transition from solitary to nonsolitary vortex evolution occurs over Richardson numbers between 0.5 and 4 for the Froude number range 0.5 to 4.0.

Robinson, G. H. and Larson, R. R.,
"A FLIGHT EVALUATION OF METHODS FOR PREDICTING VORTEX WAKE EFFECTS ON TRAILING AIRCRAFT,"
NASA TN D-6904, Nov. 1972,
NASA Flight Research Center, Edwards, CA.

The results of four current analytical methods for predicting wing vortex strength and decay rate are compared with the results of a flight investigation of the wake characteristics of several large jet transport aircraft. An empirical expression defining the strength and decay rate of wake vortices is developed that best represents most of the flight-test data. However, the expression is not applicable to small aircraft that would be immersed in the vortex wake of large aircraft.

Rodoni, C. A.,
"AN INVESTIGATION OF THE FLOW PARAMETERS OF A CONFINED TURBULENT VORTEX,"
MS Thesis, Sept. 1969,
Mass. Inst. of Technology, Cambridge, MA.

The object of this paper is to find out to what extent laminar vortex models can be adjusted by means of empirically derived "effective eddy viscosity" terms to describe turbulent vortices; and to look directly for empirical correlations for the characteristic flow parameters. A literature search was conducted to obtain the empirical data, and a computer program was written to determine its dependence on the appropriate dimensionless parameters. Although the observed vortex flow patterns are shown to agree with theory, it is found that the "eddy viscosity" approach to predicting the angular momentum dissipation is not very satisfactory.

Rogers, M.,
"A REVIEW OF AFOSR EFFORTS IN WAKE TURBULENCE,"
Proceedings AFFDL/NASA/FAA Wake Turbulence Work Shop, AFFDL-TM-75-16-FGC, edited by F. Paillet, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, 1974, p. 71.

A brief summary is given of the wake turbulence topics which have interested the Air Force Office of Scientific Research. These topics included vortex formation and decay and the manner in which they affect Air Force operations, the effect of viscosity on vortex aerodynamics, and the relationship between span loading and vortex characteristics. Possible future applications of the basic vortex understanding gained were suggested: improved control and performance through the use of vortex technology (use of canard surfaces to control separation over a swept wing), use of helicopter wakes to disperse fog or pollutants, effect of fatigue failure, and the possible coupling of aircraft wakes in the generation of gravity waves.

Rohne, E.,
"EXPERIMENTELLE UNTERSUCHUNGEN ÜBER DIE AUFSPULLANGE DER INSTABILEN UNSTETIGKEITSFLACHE HINTER EINEM TRAGFLUGEL VON ENDLICHER SPANNWEITE,"
Zeitschrift für Flugwiss, Vol. 5, No. 12, Dec. 1957, pp. 365-370.

The length over which the trailing vortex sheet is rolled up into two vortex cores and the distance between the rolled-up vortices have been investigated experimentally for a rectangular and a trapezoidal wing with GP-387 aerofoil sections, each with the wing tips sharp and rounded off.

Rom, J., Portnoy, H. and Zorea, C.,
"INVESTIGATION INTO THE FORMATION OF WING-TIP VORTICES,"
TAE-199, Feb. 1974,
Technion-Israel Inst. of Technology, Haifa, Israel.

A resume of the program of theoretical investigations into wing-tip vortex formation which is now in process in the Department of Aeronautical Engineering at the Techion, Haifa is given. The work is proceeding along two separate paths which it is hoped eventually to amalgamate. The first investigation consists of numerical work on the rolling up of the wing trailing vortex system when it is represented by discrete vortices according to a series of models of increasing complexity starting from the two-dimensional elliptic distribution as originally treated by Westwater and proceeding by stages through various lifting-line and lifting surface models, including some exhibiting non-linear lift characteristics.

Rom, J., Portnoy, H. and Zorea, C.,
"INVESTIGATIONS OF THE ROLLING-UP OF THE VORTEX WAKE AND CALCULATION OF NON-LINEAR AERODYNAMIC CHARACTERISTICS OF WINGS,"
AFOSR-TR-76-1146, June 1976,
Technion-Israel Inst. of Technology, Haifa, Israel.

This report investigates the rolling-up of vortices over and behind wings of low and high aspect ratios, and simultaneously the evaluation of the aerodynamic characteristics including the spanwise and chordwise pressure distributions on the wings. The present method is based on the extension of the Vortex Lattice concepts also to low aspect ratio wings and the rolled-up vortex which is established over as well as behind the wings. The computer program, which was developed, is capable of reproducing the results of the Vortex Lattice Method (VLM) for linear aerodynamic coefficients for high aspect ratio wings. The wake effect is included in the modified VLM program. This wake calculation showed that the center of the tip vortex is very near the wings' tip for the high aspect ratios wings. The non-linear aerodynamic characteristics are evaluated when the vortices are shed over the wing and begin the rolling-up process from the leading edges. This effect is particularly important for wings of low aspect ratios.

Rom, J. and Zorea, C.,
"THE CALCULATION OF THE LIFT DISTRIBUTION AND THE NEAR VORTEX WAKE BEHIND HIGH AND LOW ASPECT RATIO WINGS IN SUBSONIC FLOW,"
TA-168, Jan. 1973,
Technion-Israel Inst. of Technology, Haifa, Israel.

A method is presented for the combined calculation of the lift and lift distribution on a wing and also of the trailing vortex flow behind the wing. It is assumed that the lift of a wing is generated by a system of vortices distributed over the complete wing planform and shed away from each elemental area on the planform. Using the concepts of the vortex lattice method, it is assumed in the linear lift variation case, that the vortices are aligned on the wing planform and are shed away from the trailing edges. Vortex line interaction calculations for the trajectories of the vortex lines are programmed. As a result, the leading edge lift vortices which are obtained on slender wings can now be handled. This report contains a description of the numerical method.

Rom, J., Zorea, C. and Gordon, R.,
"ON THE CALCULATION OF NON-LINEAR AERODYNAMIC CHARACTERISTICS AND THE NEAR VORTEX WAKE,"
International Council of the Aeronautical Sciences Paper 74-27, Haifa, Israel, 1974.

Methods for the calculation of the distribution of vortices on the wing planform and on the trailing vortex wake by an iterative procedure based on the application of the vortex lattice method concept are described. In the case when the trailing vortices are taken to leave the wing at the trailing edge only, the calculation results in determining the linear aerodynamic characteristics and the shape of a rolled wake. The present investigation considers the case when the vortices for each cell are allowed to leave the wing planform at a fixed angle, and the case when the vortex shedding can be limited to the planform edge only.

Roper, A. T.,
"DEVELOPMENT OF AIRCRAFT VORTEX WAKES IN TURBULENT FLOW,"
J. Aircraft, Vol. 6, No. 1, Jan-Feb. 1969, pp. 65-66.

This paper presents a method for predicting the time dependence of vortex size, strength, and peak tangential velocity in turbulent flow. The existence of a similar solution is assumed for large times and the turbulent shearing stresses are represented in general functional form without recourse to mixing length or eddy viscosity assumptions.

Rorke, J. B. and Moffitt, R. C.,
"WIND TUNNEL SIMULATION OF FULL SCALE VORTICES,"
NASA CR-2180, March 1973,
Sikorsky Aircraft, Stratford, CT.

An experimental investigation has been conducted to determine the important scaling parameters for the flow in the core region of a vortex generated by a rectangular wing tip. The effect of an unconventional planform, the ogee tip, on the tip vortex is also determined. For rectangular planform wings, the measured vortex core diameter to chord ratios, peak tangential velocity ratios, and axial velocity ratios are shown to be functions only of wing lift coefficient and elapsed time from vortex formation, and appear to be independent of both Mach number and Reynolds number. The peak tangential velocities in the diffuse vortex generated by the ogee tip are only 25 percent of those in the vortex generated by the rectangular wing.

Rose, R. and Dee, F. W.,
"AIRCRAFT VORTEX WAKES AND THEIR EFFECTS ON AIRCRAFT,"
ARC Report CP-795, Dec. 1963,
Royal Aircraft Establishment, Farnborough, England. (Also, Tech. No. Aero. 2934 and ARC-25419).

Tests have been made using a Venom traversing aircraft to determine the strength and decay, away from the ground, of vortex wakes behind Comet and Vulcan aircraft. The present tests show that the effects of an intersection at right angles to the wake reduce to a low level (less than 8 ft/sec equivalent gust) after 2 minutes. This result is unlikely to be any more severe for a transport aircraft.

Rossow, V. J.,
"THEORETICAL STUDY OF LIFT-GENERATED VORTEX SHEETS DESIGNED TO AVOID ROLL-UP"
NASA TM X-62,304, Sept. 1973,
NASA Ames Research Center, Moffett Field, CA.

The random motions of the vortex elements behind a wing that sheds a disturbed translating array of vortices are analyzed. The analysis indicates that the wake would diffuse and decay rapidly when viscosity is present and would produce small rolling moments on encountering aircraft. It was found that comparable results could also be achieved with an array consisting of vortices that are equal in magnitude but which alternate in sign. This observation indicates that random motion can probably be achieved with a variety of stepped loadings.

Rossow, V. J.,
"ON THE INVISCID ROLLED-UP STRUCTURE OF LIFT-GENERATED VORTICES,"
J. Aircraft, Vol. 10, No. 11, Nov. 1973, pp. 647-650.

A simple form is presented of the relationships derived by Betz for inviscid, fully developed structure of lift-generated vortices behind aircraft. An extension is then made to arbitrary span-load distributions by inferring guidelines for the selection of rollup centers for the vortex sheet. These techniques are easier to use and yield more realistic estimates of the rolled-up structure of vortices than the original form of Betz' theory when the span loading differs appreciably from elliptic loading.

Rossow, V. J.,
"SURVEY OF COMPUTATIONAL METHODS FOR LIFT-GENERATED WAKES,"
Aerodynamic Analyses Requiring Advanced Computers, Part I,
NASA SP-347, 1975, pp. 897-923.

The persistence and strength of vortices that trial behind heavy aircraft have recently caused attention to be focused on the potential hazard they present to smaller aircraft that might encounter them. A survey is made here of some computational methods that are used to predict the structure and duration of these lift-generated vortices and to explore mechanisms that might significantly reduce their lifetime and hazard potential.

Rossow, V. J.,
"THEORETICAL STUDY OF LIFT-GENERATED VORTEX WAKES DESIGNED TO AVOID ROLLUP,"
AIAA Journal, Vol. 13, No. 4, April 1975, pp. 476-484.

Two hypothetical vortex wakes are introduced and studied theoretically to explore whether the rollup of lift-generated vortex sheets can be suppressed. The circulation distribution across each wake is specified such that one rotates and the other translates as a unit due to their self-induced velocities. Several span loadings are constructed from these solutions and the resulting inviscid wake structure is computed for several span lengths behind the generating wing by use of the discrete vortex method wherein the vortex wake is represented by an array of vortices. The final distribution of vortices is then used to estimate the rolling moment on an encountering wing. It is found that, even though the initial specified motions are not sustained, substantial reductions in rolling moment are predicted for certain ranges of the ratio of the span of the generating wing to the following wing.

Rossow, V. J.,
"PREDICTION OF SPAN LOADING FROM MEASURED WAKE-VORTEX STRUCTURE - AN INVERSE BETZ METHOD,"
J. Aircraft, Vol. 12, No. 7, July 1975, pp. 626-628.

The Betz theory is based on the conservation equations for inviscid, two-dimensional vortices and predicts the circulation in the fully-developed vortex from the span loading on the generating wing. The relationship between span loading and vortex structure is extended here by introducing a so-called inverse rollup method that predicts the span loading on the generating wing when the radial distribution of circumferential velocity in the vortex is given. Several examples are presented wherein measured circumferential velocities in several vortices are used with the inverse method to infer the span loading that produced the vortices. These span loadings are compared with those predicted by vortex-lattice theory for the generating wing. The technique yields a fairly accurate representation of the span loading on the generating wing when turbulence effects are not large.

Rossow, V. J.,
"INVISCID MODELING OF AIRCRAFT TRAILING VORTICES,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, 1977, pp. 9-60.

A survey is presented of inviscid theoretical methods that have proven useful in the study of lift-generated vortices. Concepts derived using these inviscid theories are then presented which have helped to guide research directed at alleviating the velocities and rolling moments imposed on aircraft entering these wakes.

Rossow, V. J.,
"CONVECTIVE MERGING OF VORTEX CORES IN LIFT-GENERATED WAKES,"
J. Aircraft, Vol. 14, No. 3, March 1977, pp. 283-290.

The several wake vortices that originate from aircraft wingtips, flap edges, engine pylons, etc. usually merge, in the far field to form a single pair whose structure determines the hazard posed to encountering aircraft. In order to gain an understanding of the process whereby vortices merge and disperse, a numerical study was made of the interaction of two-dimensional, time-dependent, invisid vortical regions. It was found that discrete boundaries, which depend on the structure and spacing of the vortices, distinguish merging from nonmerging situations. Furthermore, certain arrays of finite vortex cores that alternate in sign were found to undergo division and merging that may be useful in alleviating the hazard posed by aircraft wakes.

Rossow, V. J.,
"ALLEVIATION OF LIFT-GENERATED WAKES BY VORTEX INTERACTIONS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 150-160.

The requirements for wake alleviation by inviscid convective interaction of vortices are reviewed. It is concluded that these wake structures will disperse and merge to alleviate the wake hazard, but unacceptably large aerodynamic penalties occur when the required loadings are generated by use of trailing-edge flap deflections. It is suggested, therefore, that the vortex pairs of opposite sign be generated above or below the wing with devices such as fins, fences, engine thrust, etc. Guidelines for the effective disposition and strength of these extra or auxiliary vortices are derived and numerical examples are presented for various configurations. Results of some preliminary wind-tunnel experiments confirmed that vortex injection into a wake by fins provides alleviation and warrants further study to optimize the various design parameters.

Rossow, V. J.,
"EFFECT OF WING FINS ON LIFT-GENERATED WAKES,"
J. Aircraft, Vol. 15, No. 3, March 1978, pp. 160-167.

A theoretical and experimental study has been made of the effect of wing-mounted fins on the vortex wakes of subsonic aircraft. The lateral lift on the fins injects vortices into the wake and redistributes the lift on the wing. The revised wake vorticity then interacts convectively to form a new configuration with low rotational velocities. Wind-tunnel tests were used to evaluate the alleviation achievable and to find the optimum values for the various fin parameters. It was found that vertical fins mounted on the upper surface of a wing could lower the wake-induced rolling moments on an encountering wing by a factor of 3 or more.

Rossow, V. J.,
"EXPERIMENTAL INVESTIGATION OF WING FIN CONFIGURATIONS FOR ALLEVIATION OF VORTEX WAKES OF AIRCRAFT,"
NASA TM-78520, Nov. 1978,
NASA Ames Research Center, Moffett Field, CA.

A variety of fin configurations were tested on a model of the Boeing B747 in the 40- by 80-Foot Wind Tunnel at Ames Research Center and in the Ship Model Basin at Hydronautics, Inc., near Laurel, Maryland. The test results confirmed that a reduction in wake rolling moment is brought about by the vortex shed by the fins so that a wide range of designs can be used to achieve wake alleviation. It was also found that the reduction in wake-induced rolling moments is especially sensitive to the location of the smaller fins on the wing and that the penalties in lift and drag can probably be made negligible by proper fin design.

Rossow, V. J.,
"WAKE HAZARD ALLEVIATION ASSOCIATED WITH ROLL OSCILLATIONS OF WAKE-GENERATING AIRCRAFT,"
J. Aircraft, Vol. 23, No. 6, June 1986, pp. 484-491.

An explanation is provided for the difference in wake vortex alleviation achieved by roll oscillations during flight tests with B-747 and L-1011 transport aircraft. Both aircraft had their landing flaps extended and several spoilers deployed. Numerical analysis shows that the growth in amplitude of the initial waves in the vortex filaments is brought about by inviscid vortex interactions. In the case of the B-747, growth is enhanced by a vortex whose strength is about the same as the tip vortex that is shed near the fuselage by the inboard end of the flaps. Conversely, the L-1011 is estimated to shed a negligible fuselage vortex and to have a relatively strong wing tip vortex. These characteristics bring about a rotation and a large amplification of the initial waves in the vortex filaments in the wake of the B-747, but not in the L-1011 vortex wake. An aircraft following the B-747 would then experience only intermittent encounters with the intense parts of the wake vortices, such that the time-averaged wake-induced rolling moment is substantially reduced.

Rossow, V. J.,
"PROSPECTS FOR DESTRUCTIVE SELF-INDUCED INTERACTIONS IN A VORTEX PAIR,"
J. Aircraft, Vol. 24, No. 7, July 1987, pp. 433-440.

The vortex wakes of large transport aircraft can pose a hazard to smaller following aircraft in the vicinity of airports during landing and takeoff operations if certain separation guidelines are not observed. In order to reduce the hazard potential, and thereby the separation distances, efforts are being made to find more rapid wake-dissipation mechanisms. In this paper, numerical simulations are made of the three-dimensional time-dependent instabilities that might be initiated in a vortex pair by sinusoidal displacements of the filaments. The objective of the study is to find those displacements and phase angles that produce the most rapid destruction of the vortices. It is concluded that, of the wave patterns tried on the one pair of wake filaments, the only instability made that leads to destructive interactions of the vortices is the Scorer-Crow process.

Rossow, V. J.,
"SPUR-TYPE INSTABILITY OBSERVED ON NUMERICALLY SIMULATED VORTEX FILAMENTS,"
J. Aircraft, Vol. 25, No. 9, Sept. 1988, pp. 835-841.

An instability observed on vortex filaments during numerical simulations of the three-dimensional, time-dependent dynamics of vortex wakes is studied to determine when and why it occurs. It is concluded that the observed instability is a consequence of the use of straight-line vortex segments of finite length to model continuously curving vortex filaments.

The instability appears to occur only when the link length is a sizeable fraction of the vortex span and, therefore, is not expected in an experiment. Guidelines are then given that help avoid numerical instabilities when vortex filaments are used in flow simulations.

Rossow, V. J., Corsiglia, V. R. and Phillippe, J. J.,
"MEASUREMENTS OF THE VORTEX WAKES OF A SUBSONIC- AND A SUPERSONIC-TRANSPORT MODEL IN THE 40- BY 80-FOOT WIND TUNNEL,"
NASA TM X-62,391, Sept. 1974,
NASA Ames Research Center, Moffett Field, CA.

The rolling moment induced on aircraft models in the wake of a model of a subsonic transport and of a supersonic transport was measured as a function of angle of attack for several configurations. A description of the tests and a presentation and analysis of the data is given.

Rossow, V. J., Corsiglia, V. R., Schwind, R. G., Frick, J. K. D. and Lemmer, O. J.,
"VELOCITY AND ROLLING-MOMENT MEASUREMENTS IN THE WAKE OF A SWEPT-WING MODEL IN THE 40- BY 80-FOOT WIND TUNNEL,"
NASA TM X-62414, April 1975,
NASA AMES Research Center, Moffett Field, CA.

Measurements were made in the wake of a swept-wing model to study the structure of lift-generated vortex wakes shed by conventional span loadings and by several span loadings designed to reduce wake velocities. Variations in the span loading on the swept-wing generator were obtained by deflecting seven flap segments on each side by amounts determined by vortex-lattice theory to approximate the desired span loadings. The resulting wakes were probed with a three-component, hot-wire probe to measure velocity, and with a wing to measure the rolling moment that would be induced on a following aircraft. The experiments are described, and the measured velocity and rolling moments are presented, along with some comparisons with the applicable theories.

Rossow, V. J. and Tinling, B. E.,
"RESEARCH ON AIRCRAFT/VORTEX-WAKE INTERACTIONS TO DETERMINE ACCEPTABLE LEVEL OF WAKE INTENSITY,"
J. Aircraft, Vol. 25, No. 6, June 1988, pp. 481-492.

An evaluation of the literature on large aircraft wake-vortex encounters in flight and in flight simulators has furnished an estimate of the level to which the vortex-induced rolling moments must be reduced in order to be perceived as nonhazardous at a 2-n.mi. separation distance. The criteria are based on the ratio of the vortex-induced acceleration in roll to the aileron-induced roll acceleratior. A wake is acceptably alleviated if the ratio of vortex-to-aileron rolling moments is less than about 0.5. When a satisfactory alleviation scheme is identified, the alleviated vortex structure should be inserted into a simulator to ascertain whether the maximum bank angles induced are within tolerable limits.

Rotta, N. R.,
"THE STABILITY OF A VORTEX PAIR IN THE PRESENCE OF A GROUND PLANE,"
Report 71-81A, June 1971,
Oceanics Inc., Plainview, NY.

The configuration stability of a vortex pair in the presence of a ground plane is examined. First the motion of a vortex in three dimensions is examined by the solution of matched asymptotic expansions in which the solution of the Navier-Stokes equations are constructed asymptotically. The explicit dependence of the stability on the perturbation wavelength is discussed and illustrated. Comparison of the present analysis in the limit of zero ground effect with photographs of vortices undergoing a configuration instability is made. The viscosity necessary for agreement is found to be on the order of the eddy viscosity for the turbulent line vortex, indicating the existence of turbulence in the vortex core.

Rotta, N. R. and Goodman, T. R.,
"THE VORTEX WAKE HAZARD OF LARGE TRANSPORTS IN TAKEOFF AND LANDING,"
Proceedings of the National Aerospace Electronics Conf., IEEE, Dayton, 1971, pp. 41-46.

The configuration stability of a vortex pair in ground effect is examined for the trailing vortex wake of a large high weight aircraft. In ground effect, the large scale motion of the vortices is adequately represented by the equations of potential theory which shows the vortex pair to descend to lower altitudes with increased separation. The stability theory indicates the vortex pair to be unstable, with the instability and time estimated for break-up shown to depend on the altitude at which the vortex pair was generated. The results of the study of the landing of a 747 shows good agreement with FAA full-scale flight tests for the behavior of the vortex wake at low altitudes.

Rudland, R. S.,
"AVOIDANCE OF TRAILING VORTEX HAZARD BY AIRPORT WARNING SYSTEM."
The 1972 NASA-ASEE Summer Faculty Fellowship Program Research Reports, NASA and American Society of Engineering Education, Sept. 1972, pp. 507-532. (Also, NASA CR-61396).

In an effort to improve airport traffic operation near jumbo jets, an airport trailing vortex warning system (ATVWS) was developed to predict trailing vortex turbulence. The ATVWS consists of a computer simulator which is compatible with a vortex sensor such as a laser Doppler velocimeter or an acoustic radar. A study of the traffic in one of the ten busiest airports, Atlanta Municipal Airport, provided information on traffic patterns of a statistical nature. With this information, airport traffic patterns can be studied and hazard statistics developed. Based on a careful study of this simulation model, requirements for the development and testing of an ATVWS can be accurately specified.

Rudland, R. S.,
"USE OF SIMULATION IN EVALUATING AN EARLY WARNING SYSTEM FOR AVOIDANCE OF JUMBO JET TRAILING VORTEX TURBULENCE IN AIRPORTS,"
Proceedings of Eighth Annual Pittsburgh Conf., Volume 8 - Modeling and Simulation, Inst. Soc. of America, Pittsburgh, PA, April 1977, pp. 393-396.

Wake turbulence from large aircraft has created a safety hazard for smaller aircraft that land soon after a Jumbo-Jet. A laser detection system was developed to monitor wake turbulence in the airport and to provide early warning to the air traffic controller. Since each part of the system has been developed separately, proper integration of this system depends on simulation of realistic landing patterns with wake turbulence to see if the detection system and the warning system can provide the controller with the right information at the right time. A description of the simulation model is developed to be able to provide random landing patterns to create realistic aircraft sequencing. With this simulation model controller performance can be evaluated.

Rudolph, J. F.,
"AIRCRAFT WAKE TURBULENCE,"
Economics of Air Safety and Long-Range Safety Research and Development, Proceedings of the 26-th Annual International Air Safety Seminar, Flight Safety Foundation, Nov. 1973, pp. 31-47.

Discussion of an FAA R&D program aimed at coping with current wake vortice problems which are significant in large transport aircraft. The program is planned to increase aircraft safety in terms of vortex hazard and allow a large increase in airport capacities by reducing the takeoff and landing spacing. The major points of the program include aircraft design modifications for wake vortex elimination, vortex dissipation methods, and automatic wake vortex avoidance systems.

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Saffman, P. G.,
"THE VELOCITY OF VISCOUS VORTEX RINGS,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 9-10

The motion of vortex rings of small cross section is considered. A formula is given for the velocity of a ring in an ideal fluid with an arbitrary distribution of vorticity in the core and an arbitrary circumferential velocity. A definition of velocity is given for the unsteady diffusing ring in a viscous fluid, and the speed is found by the method used for rings in ideal fluids.

Saffman, P. G.,
"THE MOTION OF A VORTEX PAIR IN A STRATIFIED ATMOSPHERE,"
Studies in Appl. Math., June 1972, Vol. 51, No. 2, pp. 107-119.

The movement of a horizontal vortex pair through an inhomogeneous fluid is considered. The problem is formulated first for the case when the ambient fluid is uniform, the fluid moving with the vortex pair has a different density, and the motion is supposed laminar and inviscid. An approximate solution is obtained, which predicts that the distance between the vortices stays constant and the vortices accelerate at a constant rate. This solution is then applied to motion in a stratified atmosphere and it is found that the vortices oscillate vertically with a frequency and amplitude depending on the initial conditions and the stratification. Finally, approximate equations are constructed to describe the effects of turbulent entrainment into the fluid moving with the vortex pair, and an estimate of the damping is obtained.

Saffman, P. G.,
"THE STRUCTURE OF TURBULENT LINE VORTICES,"
AFOSR-72-2283, Oct. 1972,
California Institute of Technology, Pasadena, CA.

A theory is given to explain the observed dependence on Reynolds number of the decay of turbulent line vortices. The discussion considers first the self-similar vortex, in which all quantities are assumed to depend only on the circulation at infinity, the Reynolds number, and the time from a virtual origin. It is argued that the turbulent line vortex has a triple structure: an outer vortex of given radius, an inner vortex, and a viscous core. The axial velocity in the core, produced by growth of a trailing vortex, is shown to be Reynolds number dependent.

Saffman, P. G.,
"STRUCTURE OF TURBULENT LINE VORTICES,"
Physics of Fluids, Vol. 16, No. 8, Aug. 1973, pp. 1181-1188.

A theory is given to explain the observed dependence on Reynolds number of the decay of turbulent line vortices. It is argued that the turbulent vortex has a triple structure; an outer region with a logarithmic distribution of circulation; and an inner region and viscous core in both of which the motion is close to solid body rotation. The development of an overshoot of circulation in the outer region is discussed, and the axial velocities produced by growth of a trailing vortex are calculated.

Saffman, P. G.,
"A MODEL OF VORTEX RECONNECTION,"
J. Fluid Mech., Vol. 212, March 1990, pp. 395-402.

A model is proposed to describe the breaking and rejoining of vortex lines which occurs when vortex filaments of equal and opposite strengths touch. It is based on the idea that viscosity cancels the vorticity where the filaments first touch. The weakening of the centrifugal force in the vortex core then leads to a local increase in the pressure which accelerates the fluid in the cores in the axial direction and convects the vorticity away from the initial contact and produces an apparent rejoining.

Sammonds, R. I. and Stinnett, Jr., G. W.,
"HAZARD CRITERIA FOR WAKE VORTEX ENCOUNTERS,"
NASA TM X-62473, Aug. 1975,
NASA Ames Research Center, Moffett Field, CA.

A piloted, motion-base simulation was conducted to evaluate the ability to produce realistic vortex encounters and to develop criteria to define hazardous encounters. A boundary for encounter hazard based on subjective pilot opinion was identified in terms of maximum bank angle. For encounters from 200 to 500 feet, tentative hazard criteria established for visual conditions indicated that the acceptable upset magnitude increased nearly linearly with increasing altitude.

Sammonds, R. I., Stinnett, Jr., G. W. and Larsen, W. E.,
"WAKE VORTEX ENCOUNTER HAZARDS CRITERIA FOR TWO AIRCRAFT CLASSES,"
FAA-RD-75-206, June 1976,
NASA Ames Research Center, Moffett Field, CA.

An investigation was conducted using a piloted, motion-base simulator to determine wake vortex hazard criteria for two classes of jet transport aircraft. A light business jet and a large multiengine jet transport were represented respectively. The hazard boundaries were determined in terms of the maximum bank angle due to the vortex encounter. Upsets as small as 7 deg in bank angle were considered to be hazardous at breakout altitude (200 ft (61.0 m)) for Instrument Flight Rule (IFR) and at 50 ft (15.2 m) for Visual Flight Rule (VFR) for both aircraft classes. Proximity to the ground was the primary reason for a hazardous rating. This was reflected in the reduction in the maximum bank angle at the hazard boundary and in more consistent ratings as altitude was decreased.

Sammonds, R. I., Stinnett, Jr., G. W. and Larsen, W. E.,
"CRITERIA RELATING WAKE VORTEX ENCOUNTER HAZARD TO AIRCRAFT RESPONSE,"
J. Aircraft, Vol. 14, No. 10, Oct. 1977, pp. 981-987.

Piloted six-degree-of-freedom motion simulator investigations were conducted at the NASA Ames Research Center to determine criteria relating the hazard posed by a wake vortex encounter to the response of the encountering airplane. These investigations demonstrated that wake vortex encounters can be reproduced realistically on a simulator, established that the maximum bank angle due to the encounter provides the best correlation with the pilot's subjective assessment of the hazard, and determined hazard boundaries in terms of maximum bank angle for two classes of jet transport aircraft.

Sarpkaya, T.,
"ON STATIONARY AND TRAVELLING VORTEX BREAKDOWNS,"
J. Fluid Mech., Vol. 45, No. 3, Feb. 1971, pp. 545-559.

This paper describes some experiments in swirling flows in a diverging cylindrical tube in which various types of vortex breakdowns were observed. In one set of experiments, the position of the breakdown, axial component of the velocity of the vortex core, swirl angle distribution ahead of the breakdown, and the pressure distribution along the tube were determined for various flow rates for various values of circulation imparted to the fluid (water). Basically, three types of vortex breakdown were observed, viz. mild (double helix) breakdown, spiral breakdown (followed by turbulent mixing), and axisymmetric breakdown (followed by a thicker vortex core, then a spiral breakdown, and finally turbulent mixing). The type and the location of the stationary breakdowns were found to be dependent, for the particular vortex tube used, upon the Reynolds and circulation numbers of the flow. In a spiral breakdown, the vortex core filament maintained the same sense of rotation as the upstream fluid elements. In an axisymmetric breakdown, the bubble included an inclined vortex-ring axis gyrated about the axis of the tube.

Sarpkaya, T.,
"VORTEX BREAKDOWN IS SWIRLING CONICAL FLOWS,"
AIAA Journal, Vol. 9, No. 9, Sept. 1971, pp. 1792-1799.

This paper describes some experiments in swirling flows in a mildly diverging cylindrical tube in which three types of vortex breakdown were observed: double-helix and spiral forms (followed by turbulent mixing), and axisymmetric form (often followed by a spiral breakdown, then by turbulent mixing). The type and location of the breakdowns were found to be dependent upon the Reynolds and circulation numbers of the flow. The observations reported and the evidence presented herein revealed that the axisymmetric breakdown is basically a finite transition between two separate states of flow, from a uniform state of swirling flow (supercritical) to one (subcritical) featuring a series of standing waves of finite amplitude. The double-helix and spiral forms, which occur in a region well defined by Reynolds and circulation numbers, appear to be a consequence of the instability of the vortical viscous flow to spiral disturbances.

Sarpkaya, T.,
"EFFECT OF THE ADVERSE PRESSURE GRADIENT ON VORTEX BREAKDOWN,"
AIAA Journal, Vol. 12, No. 5, May 1974, pp. 602-607.

The present work examines in detail the effect of the degree of divergence on the type and location of the vortex breakdown in swirling flows in tubes of various angles of divergence, compares the results with those predicted through the use of the analytical models proposed by Randall and Leibovich and by Mager, and illustrates the role played by the flow separation and reversal on the tube wall.

Sarpkaya, T.,
"TRAILING VORTICES IN HOMOGENEOUS AND DENSITY-STRATIFIED MEDIA,"
J. Fluid Mech., Vol. 136, Nov. 1983, pp. 85-109.

Experiments were conducted with three delta wings and two rectangular wings to investigate the evolution of trailing vortices in stratified and unstratified water. The vortex trajectories were determined as a function of the normalized time Vt/b, stratification parameter Nb/V and an effective vortex-core size r/b. The results have shown that the vortices rise only to a finite height as they decay gradually at first and rapidly thereafter under the influence of turbulence, sinusoidal instability, and core bursting. The effect of stratification is to reduce the lifespan of vortices and the maximum height attained by them.

Sarpkaya, T. and Daly, J. J.,
"EFFECT OF AMBIENT TURBULENCE ON TRAILING VORTICES,"
J. Aircraft, Vol. 24, No. 6, June 1987, pp. 399-404.

The effects of ambient turbulence (generated by a biplanar grid) on the migration and lifespan of trailing vortices are investigated in a towing tank through the use of two NACA-0012 foils moving at a constant angle of attack. The results show that the rise and demise of the vortices are controlled primarily by the rate of dissipation of the background turbulence. The integral scale of turbulence plays only a minor role. In both a quiescent or weakly-turbulent fluid the sinusoidal instability and in a fluid with stronger turbulence, the vortex bursting precedes the subsequent instability events which brings about the eventual destruction of the vortices. Both forms of the large scale instability are often accompanied by the roll of the vortex pair onto its side. Shear is not necessary for the roll but may enhance it under atmospheric conditions.

Scheiman, J. and Shivers, J. P.,
"EXPLORATORY INVESTIGATION OF THE STRUCTURE OF THE TIP VORTEX OF A SEMISPAN WING FOR SEVERAL WING-TIP MODIFICATIONS,"
NASA TN D-6101, Feb. 1971,
NASA Langley Research Center, Hampton, VA.

Wind-tunnel tests were performed on a semispan wing with rather radical wing-tip modifications. These modifications were chosen in an attempt to deform, displace, or modify the cross-sectional characteristics of the trailing tip vortex. The wing-tip modifications test did not grossly affect the spanwise lift distribution and did not produce a noticeable change in the position of the downstream tip vortex. Tip-vortex cross-sectional variations were obtained such that the outer flow field was no longer potential flow.

Scheiman, J., Shivers, J. P. and Megrail, J. L.,
"EXPLORATORY INVESTIGATION OF FACTORS AFFECTING THE WING TIP VORTEX,"
NASA TM X-2516, April 1972,
NASA Langley Research Center, Hampton, VA.

An investigation was conducted in the Langley full-scale tunnel to study some factors affecting the tip vortex of a wing. It was found that there was a pronounced effect of Reynolds number on the tip-vortex core size. An attempt was made to determine what aerodynamic parameters - such as lift, drag, or induced drag - influence the size of the vortex core, but no particular function of the parameters was found to be superior to all others. Various spoilers placed on the upper and lower surfaces of the wing to increase the boundary-layer thickness resulted in a reduction in the vorticity as determined from the tuft grid. Various solid objects placed in the vortex core downstream of the wing tip seemed to decrease the vorticity within the vortex core.

Schooley, A. H.,
"WAKE COLLAPSE IN A STRATIFIED FLUID,"
Science, Vol. 157, No. 3787, July 1967, pp. 421-423.

A two-dimensional model is used to obtain quantitative data on characteristics of turbulently mixed wakes of bodies submerged in stratified fluids. The time between turbulent mixing and maximum expansion of the wake before vertical collapse starts is 0.44T, where T is the local Vaisala-Brunt period. Time after mixing for maximum rate of horizontal spreading is about 2.0T. Qualitative observations of aircraft vapor trails tend to confirm that the phenomenon does occur at full scale.

Schweiger, R. N.,
"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME I: HARDWARE DESIGN,"
FAA-RD-74-19.1, June 1977,
Avco, Wilmington, MA.

An engineered Pulsed Acoustic Vortex Sensing System (PAVSS) was developed. This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing

vortices. This volume of the report presents hardware design aspects of the system. The design of the acoustic antenna and transducer is described. System control, computer hardware, and system/subsystem hardware interfaces are discussed.

Schweiger, R. N.,
"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME II: STUDIES OF IMPROVED PAVSS PROCESSING TECHNIQUES,"
FAA-RD-74-19.2, June 1977,
Avco, Wilmington, MA.

AVCO Corporation's System Division designed and developed an engineered Pulsed Acoustic Vortex Sensing System (PAVSS). This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report presents the results of two subcontractor studies directed toward development of improved vortex tracking software techniques for the PAVSS. The volume recommends the incorporation of several improvements in the software.

Schweiger, R. N.,
"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME III: PAVSS OPERATION AND SOFTWARE DOCUMENTATION,"
FAA-RD-74-19.3, June 1977,
Avco, Wilmington, MA.

AVCO Corporation's System Division designed and developed an engineered Pulsed Acoustic Vortex Sensing System (PAVSS). This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report presents the operation of the pulsed acoustic vortex sensing system and the computer software documentation.

Schweiger, R. N.,
"PULSED ACOUSTIC VORTEX SENSING SYSTEM, VOLUME IV: PAVSS PROGRAM SUMMARY AND RECOMMENDATIONS,"
FAA-RD-74-19.4, June 1977,
Avco, Wilmington, MA.

An engineered Pulsed Acoustic Vortex Sensing System (PAVSS) was developed. This system is capable of real-time detection, tracking, recording, and graphic display of aircraft trailing vortices. This volume of the report summarizes the background and accomplishments of the PAVSS program carried out by Avco,

and presents Avco's recommendation that further work on the PAVSS would not be economically sound.

Scorer, R. S. and Davenport, L. J.,
"CONTRAILS AND AIRCRAFT DOWNWASH,"
J. Fluid Mech., Vol. 43, Part 3, Sept. 1970, pp. 451-464.

Aircraft downwash consists initially of a vortex pair descending with its accompanying fluid through the atmosphere. Condensation trails are formed in exhaust emitted into the accompanying fluid and the shapes of them and their evolution depend on the positions of the engines in relation to the wing tip vortices. The atmosphere is stably stratified and so the descending accompanying fluid acquires upward buoyancy. Consequently vorticity is generated at the outside of the accompanying fluid and the flow pattern in the vortex pair is altered so as to produce detrainment of its exterior part. So long as any air which is a mixture of accompanying fluid and exterior air is detrained, the vortices remain stable, but the width of the pair decreases and its downward velocity increases with time as a result of the buoyancy. Eventually the upper stagnation point in the motion relative to the vortices begins to move upwards relative to the vortices so that some mixed fluid is entrained into the circulation and the vortices immediately become unstable, mixing occurs, the pressure in the core rises, and any vortex core trails that may exist appear to burst. The motion produces downward-thrust blobs in trails from centrally placed engines, which correspond to the holes sometimes seen in cloud when distrails are formed.

Scott, G. A.
"NEW HORIZONS IN AIR TRAFFIC CONTROL,"
AIAA Paper No. 75-569,
Boston, MA, 1975.

According to the FAA's latest air traffic forecasts, aviation in the United States will continue to grow into the indefinite future. To meet the demands of this continuing growth, the existing air traffic control (ATC) system must be improved. The goals of the future upgraded ATC system are: maintain or improve safety, constrain or reduce costs, and increase and improve performance. These goals will be met in part by the following new ATC features - Airport Surface Traffic Control System (ASTC), Discrete Address Beacon System (DABS), Air Traffic Control Automation, Intermittent Positive Control (IPC), Area Navigation (RNAV), Microwave Landing System (MLS), and Wake Vortex Avoidance System (WVAS).

Scruggs, R. M. and Theisen, J. G.,
"TRANSONIC BUFFET RESPONSE TESTING AND VORTEX CONTROL,"
Proceedings of Symposium on Unsteady Aerodynamics,
U.S. Air Force Office of Scientific Research and Univ. of Arizona,
Vol. I, 1975, pp. 337-357.

The basic theory of vortex stabilization by means of corewise blowing is presented as a vortex-lattice, source-induction (VLSI) computer simulation. An extension of Polhamus' leading-edge suction analogy to high aspect-ratio wing is derived, showing the effect of aspect ratio on near wake vortex burst.

Sforza, P. M.,
"AIRCRAFT VORTICES: BENIGN OR BALEFUL?,"
Space/Aeronautics, April 1970, pp. 42-48.

Vortices in aerodynamics are discussed with particular application to aircraft. The use of vortex lattice calculation techniques are described as are the effect of leading edge vortices on the lift of low aspect ratio wings. Fuselage and wing tip vortices are shown to have a strong effect on stability and control of the generating aircraft as well as other aircraft operating in its wake.

Sheftel, D. J.,
"OVERVIEW OF POTENTIAL ATC DEVELOPMENTS,"
Proceedings 22nd Annual Meeting, Air Traffic Control Assoc.,
Las Vegas, Oct. 1977, pp. 252-257.

The paper presents a broad overview of developments in air traffic control. Projects related to improved aircraft safety are noted including the beacon collision avoidance system, the minimum safe altitude warning concept, and studies of wind shear. Improvements in controller productivity have been suggested in terms of the electronic tabular display subsystem, the discrete address beacon system, and the automation of flight service stations. Increases in capacity are discussed with reference to the wake vortex avoidance system, the microwave landing system, and airport surface traffic control. Energy conservation is considered and developments in the area of fuel conservation are proposed including flow control. Future air traffic control procedures are identified such as automated en route traffic control, automated terminal service, advanced computer systems, and the incorporation of satellite technology.

Sheldon, D. B.,
"VORTEX MOTION PROGRAM,"
STC-DOT-TSC-297-71-828, June 1971,
Service Technology Corp., Cambridge, MA.

The report is the accompanying documentation for a computer program and plotting routine which describes the motion in three dimensions of an aircraft's trailing vortices immediately prior to landing.

Sheng, C. and Zhang, F.,
"THE EXPERIMENTAL INVESTIGATION ON THE FORMATION AND DECAY OF VORTEX UNDER INTERACTION OF A JET WITH A CROSSFLOW,"
Acta Aerodynamica Sinica, Vol. 6, March 1988, pp. 104-109.

Three different vortex systems exist in the flow field for the interaction of a jet with a crossflow: bound vortex, wake vortex, and shear vortex. In this paper, the mechanism of vortex formation is suggested, and interference among vortices is investigated on the basis of observation and measurement by the fluorescent-filament method and seven-hole probes. Finally, the major factors which influence the development and decay of streamwise vortices are also analyzed and discussed.

Shields, W. L.,
"AIRCRAFT WAKES: A NEW LOOK AT A CLASSICAL PROBLEM,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 1-8.

The paper presents a frame of reference for the Wake Turbulence Symposium, first by elucidating some historical aspects of the aircraft wake problem, then by recounting the genesis of the AFOSR wake turbulence research program and finally by commenting on some of the challenging research opportunities contained within the wake problem.

Short, B. J. and Jacobsen, R. A.,
"EVALUATION OF A WAKE VORTEX UPSET MODEL BASED ON SIMULTANEOUS MEASUREMENTS OF WAKE VELOCITIES AND PROBE-AIRCRAFT ACCELERATIONS,"
NASA TM-78561, March 1979,
NASA Ames Research Center, Moffett Field, CA.

Simultaneous measurements were made of the upset responses experienced and the wake velocities encountered by an instrumented Learjet probe aircraft behind a Boeing 747 vortex-generating aircraft. The vortex-induced angular accelerations experienced could be predicted within 30% by a mathematical upset response model when the characteristics of the wake were well represented by the vortex model. The vortex model used in the present study adequately represented the wake flow field when the vortices dissipated symmetrically and only one vortex pair existed in the wake.

Silverman, P.,
"VORTEX CASES - AT A TURBULENT CROSSROADS,"
J. Air Law and Commerce, Vol. 39, Summer 1973, pp. 325-342.

Discussion of some of the legal aspects of the problem of wake turbulence, a phenomenon to which a substantial number of air crashes has been attributed in recent years. The duty of air traffic controllers to warn of possible wake turbulence and the nature of this warning are examined. A number of court cases is reviewed to show how the courts look at wake turbulence, and some controversial cases are analyzed. During 1968-1970, more than $3,000,000 have been paid by the United States Government in indemnities where air traffic controllers were judged to have been negligent in helping prevent air crashes that had been caused by wake turbulence. It is felt that wake turbulence accidents cannot be expected to cease to happen, but the trend against the Government may ease sufficiently to permit a greater sharing of responsibility by pilots, the flying schools, and air taxi operators that employ them.

Simpson, T. R.,
"PRELIMINARY ANALYSIS OF CIVIL AVIATION ACCIDENTS, JANUARY 1964 - DECEMBER 1972,"
FAA-AVP-75-2, April 1975,
Mitre Corp., McLean, VA.

This document presents a preliminary analysis of all civil aviation accidents which occurred within the United States and its territories and possessions during the nine year period from January 1964 to December 1972. An overview is first presented which identifies the distribution of these accidents by user class, by aircraft type, and by phase of flight. Due to earlier detailed studies of midair collisions and the small number of fatalities that occurred in accidents when the aircraft were on the ground, the category of single aircraft airborne accidents was selected for further examination. Accidents that occurred during landing and accidents involving encounters with wake vortices were given special emphasis.

Sinha, A. N.,
"USE OF MULTIPLE GLIDE SLOPE ANGLES,"
WP-79W00278, May 1979,
Mitre Corp., McLean, VA.

There has been renewed interest in the use of multiple glide slopes for vortex avoidance with the development of microwave landing systems. Three concepts of multiple glide slope use are proposed and analyzed from navigation error, vortex safety and capacity benefit aspects. The results of this analysis are to be considered as preliminary findings. The primary purpose of this report is to consolidate some of the recent work in this area and present a unified talking paper as a base for further discussion and research. As a result, the paper draws heavily on the work of others - the major ones being reproduced as appendices fcr ready reference.

Smith, B. E. and Ross, J. C.,
"APPLICATION OF PANEL METHOD TO WAKE VORTEX/WING INTERACTION AND COMPARISON WITH EXPERIMENT,"
AIAA Paper 84-2182,
Seattle, WA, Aug. 1984.

The ability of a low-order panel method to calculate the aerodynamic loads on wings caused by interaction with wake vortices was studied. The loads were calculated for various positions of a downstream following wing relative to an upstream vortex-generating wing. Calculated vortex-induced span loads and rolling-moment coefficients on the following wing were compared with experimental data. A good agreement with experiment was obtained when the following wing was located more than one following-wing chord length from the tip vortex. The predictions deteriorated as the following wing was placed closer to the vortex. At large downstream distances (approximately 10 generating-wing chord lengths), induced rolling-moment coefficients on the following wing were consistently overestimated. Despite the strong interaction between the wake-vortex filaments and surface doublet panels, the accuracy of the calculations was in most cases independent of the panel distribution and density. A good agreement between theoretical and experimental loads was obtained with a minimum of experimentation with panel arrangements.

Smith, B. E. and Ross, J. C.,
"APPLICATION OF PANEL METHOD TO WAKE VORTEX/WING INTERACTION AND COMPARISON WITH EXPERIMENTAL DATA,"
NASA TM-88337, Sept. 1987,
NASA Ames Research Center, Moffett Field, CA.

The ability of the Vortex Separation AEROdynamics (VSAERO) program to calculate aerodynamic loads on wings due to interaction with free vortices was studied. The loads were calculated for various positions of a downstream following wing relative to an upstream vortex-generating wing. Calculated vortex-induced span loads, rolling-moment coefficients, and lift coefficients on the following wing were compared with experimental results of McMillan et al. and El-Ramly et al. Comparisons of calculated and experimental vortex tangential velocities were also made.

Smith, H. C.,
"METHOD FOR REDUCING THE TANGENTIAL VELOCITIES IN AIRCRAFT TRAILING VORTICES,"
J. Aircraft, Vol. 17, No. 12, Dec. 1980, pp. 861-866.

A method is presented to reduce the tangential velocities in the trailing vortex system shed from an airplane wing. The device employed is a porous section of the wing at the tip which essentially tends to equalize the pressure on the upper and lower surfaces. Experiments were conducted on a full-scale aircraft in flight and vorticity measured by probes devised specifically for this purpose. Results showed significant reduction in tangential velocities close behind the wing and to a lesser degree far downstream. Controllable porosity is suggested as a means of reducing the vortex tangential velocities and subsequent potential induced rolling moment imposed on a following aircraft.

Smith, H. J.,
"A FLIGHT TEST INVESTIGATION OF THE ROLLING MOMENTS INDUCED ON A T-37B AIRPLANE IN THE WAKE OF A B-747 AIRPLANE,"
NASA TM X-56031, April 1975,
NASA Flight Research Center, Edwards, CA.

A flight test investigation of the B-747 vortex wake characteristics was conducted using a T-37B as a probe aircraft. The primary purpose of the program was the validation of the results of B-747 model test which predicted significant alleviation of the vortex strength when only the inboard flaps were deflected. Measurements of the vortex-induced rolling moments of the probe aircraft showed that the

predicted alleviation did occur. Unfortunately, this alleviation could not be fully realized for realistic operations: the effects of landing gear extension, increased lift coefficient, idle thrust, and side-slip were investigated, and all had an adverse effect on the alleviated condition as evidenced by increased induced rolling moments of the T-37B probe aircraft. Idle thrust also increased the strength of the B-747 wake vortexes with both inboard and outboard flaps extended.

Smith, T. B. and MacCready, Jr., P. B.,
"AIRCRAFT WAKES AND DIFFUSION ENHANCEMENT,"
MRI63-FR-71, May 1963,
Meteorology Research Inc., Altadena, CA.

Studies have been made of the effect of an aircraft wake on the size and growth characteristics of a cloud of material disseminated from the aircraft. Smoke released from a Cessna 180 has been measured on a number of occasions to determine the dimensions of the wake at various distances behind the aircraft. Results indicate that the wake descends for a short time at a rate which approximates the calculated downwash velocity but soon slows appreciably to a much smaller descent rate. This effect limits the usefulness of the aircraft wake in downward propagation of material under light turbulence conditions.

Smith, W. G. and Lazzeroni, F. A.,
"EXPERIMENTAL AND THEORETICAL STUDY OF A RECTANGULAR WING IN A VORTICAL WAKE AT LOW SPEED,"
NASA TN-339, Oct. 1960,
NASA Ames Research Center, Moffett Field, CA.

A systematic study has been made, experimentally and theoretically, of the effects of a vortical wake on the aerodynamic characteristics of a rectangular wing at subsonic speed. The vortex-induced lift was calculated by several theoretical methods including strip theory, reverse-flow theory, and reverse-flow theory including a finite vortex core. In addition, the Prandtl-lifting-line theory and the Weissinger theory were used to calculate the spanwise distribution of vortex-induced loads.

Smith, Jr., W. J. and King, C. J.,
"EFFECT ON WING TIP VORTICES AND SONIC SHOCK ON ARMY AIRCRAFT IN FLIGHT,"
Evaluation Report, Jan. 1957,
Beech Aircraft Corp., Wichita, KS.

The report is a preliminary study of the oscillograph records obtained during the United States Army Aviation Board tests conducted in conjunction with the Air Force at Eglin AFB, Florida. In a limited number of flights involving QL-17, F-100, B-47, and L-19 aircraft, the following items were tentatively established: negative load factors higher than the minimum ultimate design requirements for normal category personal aircraft can reasonably be expected at higher cruise speed; every change in attitude of the QL-17 resulting from vortex penetrations would have been more severe for a piloted Navion than for the QL-17 controlled by the autopilot; and separations greater than 30 seconds would be required by light aircraft following a B-47.

Snedeker, R. S.,
"EFFECT OF AIR INJECTION ON THE TORQUE PRODUCED BY A TRAILING VORTEX,"
J. Aircraft, Vol. 9, No. 9, Sept. 1972, pp. 682-684.

An experiment was performed to determine the effect of air injection on the torque produced by a trailing vortex. The results of this experiment was limited to measurement at a single axial station. It was shown that the torque induced by the vortex on a typical wing changes very little in the near field.

Snedeker, R. S.,
"A COMPARISON OF THE TRAILING VORTEX MEASUREMENTS OF POPPLETON WITH INVARIANT MODELING COMPUTATIONS,"
ARAP Tech. Memo 72-5, Nov. 1972,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

The trailing vortex measurements made in a wind tunnel by Poppleton were used as a basis for comparison with computations made by application of the invariant modeling method. The measured profiles of mean and turbulent velocity at a point downstream of the vortex generator were used as initial conditions for the computation. A comparison was then made between the measured and computed profiles at a point further downstream. The comparison revealed that the computation, which was based on a two-dimensional form of the theory, gave poor agreement with the measured data, except in the case of the mean tangential velocity. It was concluded that the lack of agreement was primarily a result of the strong axial or three-dimensional effects which were evident throughout most of the range of the measurements. It was suggested that a form of the theory in which axial effects are included, and which is now under development at A.R.A.P., would be more appropriate for application to flows of the type studied by Poppleton.

Snedeker, R. S. and Bilanin, A. J.,
"ANALYSIS OF THE VORTEX WAKES OF THE BOEING 727, LOCKHEED L1011, MCDONNELL DOUGLAS DC-10, AND BOEING 747 AIRCRAFT,"
ARAP Report 245, July 1975,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A study has been made of the vortex wakes behind B-727, L1011, DC-10, and B-747 aircraft in several flight conditions. An analytical method is developed for the computation of the wake vortex patterns and their velocity profiles for these aircraft. The method, which is based on an extension of the Betz method for an inviscid wake, is further modified to include the effects of distributed wing drag and the computation of axial velocity profiles. Comparisons are made between wake vortex swirl velocity profiles computed for these aircraft and corresponding measurements made by the FAA in full-scale flyby tests. The results indicate that the inviscid calculation works well for simple wakes containing one predominant pair of vortices, such as those shed with the aircraft in its cruise or holding configuration. With flaps deployed for takeoff or landing, these aircraft, became of the segmented design of their flaps, produce complex wakes, which may contain as many as five pairs of vortices. It is concluded that the effects of drag on the inviscid structure of the vortices are small.

Snow, W. L., Burner, A. W. and Goad, W. K.,
"PHOTOGRAMMETRIC TECHNIQUE USING ENTRAINED BALLOONS FOR IN-FLIGHT RANGING OF TRAILING VORTICES,"
NASA TM-4129, Oct. 1989,
NASA Langley Research Center, Hampton, VA.

A novel method for experimentally determining the radial distance of a probe aircraft from a trailing vortex is described. The method relies on photogrammetric triangulation of targets entrained in the vortex core. The report describes the theory and preliminary testing using laboratory mock-ups.

Snyder, Jr., M. H.,
"EFFECTS OF A WINGTIP-MOUNTED PROPELLER ON WING LIFT, INDUCED DRAG, AND SHED VORTEX PATTERN,"
PhD Thesis, May 1967,
Oklahoma State University, Stillwater, OK.

Experimental investigations of the use of end-plates to control and to vary the wing lift distribution and induced drag are reviewed. An experimental investigation of a reflection-plane wing with a nacelle and propeller mounted at the wingtip is reported. Use of a rotor turning in the direction opposite to that of the wing's trailing vortex shifts the core of the trailing vortex outboard and downward. Use of a pro-vortex rotating rotor moves the core inboard. A counter-vortex turning propeller decreased drag; a vortex-turning propeller increases drag.

Sonnenschein, C. M., DiMarzio, C. A. and Clippinger, D. H.,
"DATA ANALYSIS STUDY AND PERFORMANCE EVALUATION OF THE SCANNING LASER DOPPLER SYSTEM,"
Interim Report NAS-8-30795, Dec. 1974,
Raytheon Company, Sudbury, MA.

This report describes the data analysis performed on the laser Doppler system data to evaluate system performance, develop vortex location algorithms, and obtain vortex transport data during testing at Marshall Space Flight Center and early operations at JFK International Airport.

Sonnenschein, C. M., DiMarzio, C. A., Clippinger, D. H. and Toomey, D. W.,
"AVIATION SAFETY RESEARCH AND TECHNOLOGY/HAZARD AVOIDANCE AND ELIMINATION,"
Interim Report NAS-8-30795, Oct. 1975,
Raytheon Company, Sudbury, MA.

This report describes the data analysis performed on the data from the Scanning Laser Doppler System during tests at Marshall Space Flight Center and at JFK International Airport through May 1975. Vortex tracks and flow fields are considered with several hundred tracks analyzed to determine data quality and average parameters of vortex tracks from different aircraft in different wind conditions.

Sonnenschein, C. M., DiMarzio, C. A., Clippinger, D. H. and Toomey, D. W.,
"AVIATION SAFETY RESEARCH AND TRANSPORTATION/HAZARD AVOIDANCE AND ELIMINATION,"
ER 76-4220, Aug. 1976,
Raytheon Company, Sudbury, MA.

Data collected by the Scanning Laser Doppler Velocimeter System (SLDVS) was analyzed to determine the feasibility of the SLDVS for monitoring aircraft wake vortices in an airport environment. Data were collected on atmospheric vortices and analyzed. Over 1600 landings were monitored at Kennedy International Airport and by the end of the test period 95 percent of the runs with large aircraft were producing usable results in real time. The transport was determined in real time and post analysis using algorithms which performed centroids on the highest amplitude in the thresholded spectrum. Making use of other parameters of the spectrum, vortex flow fields were studied along with the time histories of peak velocities and amplitudes. The post analysis of the data was accomplished with a CDC-6700 computer using several programs developed for LDV data analysis.

Sonnenschein, C. M., Jelalian, A. V., Keene, W. H. and Campbell, R. B.,
"DEVELOPMENT STUDY OF A THREE DIMENSIONAL LASER DOPPLER SYSTEM FOR THE MEASUREMENT OF ATMOSPHERIC WIND VELOCITY AND AIRCRAFT TRAILING VORTICES,"
NAS-8-26800, Jan. 1972,
Raytheon Company, Sudbury, MA.

The results of studies to determine required system parameters for atmospheric wind measurements are presented. Several system configurations are considered. Simulation programs were used to determine that the designed system could meet the accuracy requirements for vortex flow field measurements.

Sonnenschein, C. M., Jelalian, A. V., Keene, W. H., Harris, C. E. and Miller, C. R.,
"REMOTE DETECTION OF TRAILING VORTICES,"
NAS-8-30512, Feb. 1970,
Raytheon Company, Sudbury, MA.

This report summarizes the results of the first successful remote detection of vortices with a CO_2 laser system. Sample signal spectra of vortices were obtained and results were compared with smoke visualizations of the vortex.

Spahr, J. R.,
"THEORETICAL PREDICTION OF THE EFFECTS OF VORTEX FLOWS ON THE LOADING, FORCES, AND MOMENTS OF SLENDER AIRCRAFT,"
NASA TR R-101, 1961,
NASA Ames Research Center, Moffett Field, CA.

A general calculative method based on slender-body theory is developed for predicting the paths of vortices in the presence of wing-body combinations at subsonic, transonic, and supersonic speeds, and the influence of the vortices on the loading forces and moments acting on the combinations. The method is applied to wing-body combinations to study the effects of vortex strength and initial position, combined angles of pitch and roll and wing aspect ratio on the vortex paths and induced loads. The results indicate that these effects were significant because of the dependence of the vortex paths and induced loads on the vortex strengths and on the proximity of the vortices to the surface of a wing-body combination. Comparison of theoretical and experimental results indicated that the vortex paths and vortex-induced force and moments for slender-wing-body combinations were closely predicted by the slender-body method but for nonslender combinations these characteristics were only approximated.

Spangler, S. B., Dillenius, M. F. E., Schwind, R. G. and Nielsen, J. N.,
"ASSESSMENT OF A WAKE VORTEX FLIGHT TEST,"
NEAR-TR-48, July 1974,
Nielsen Eng. and Research Inc., Mountain View, CA.

A proposed flight test program to measure the characteristics of wake vortices behind a T-33 aircraft was investigated. A number of facets of the flight tests were examined to define the parameters to be measured, the anticipated vortex characteristics, the mutual interference between the probe aircraft and the wake, the response of certain instruments to be used in obtaining measurements, the effect of condensation on the wake vortices, and methods of data reduction. Recommendations made as a result of the investigation are presented.

Spitzer, E. A.,
"OPERATIONAL SYSTEM GUIDELINES FOR VORTEX ADVISORY SYSTEM,"
FAA-RD-79-20, April 1979,
DOT Transportation Systems Center, Cambridge, MA.

The phenomenon of wake vortices has introduced a major operational constraint on airport operations, resulting in a reduction of runway capacities. Increased knowledge about the behavior of wake vortices has resulted in the development of a model of vortex behavior as a function of meteorological conditions. Based on this vortex behavior model, a Vortex Advisory System (VAS) has been designed and built. The VAS measures the primary meteorological parameter (wind) which affects vortex behavior and indicates to controllers via displays when conditions are such that more efficient runway use is possible. A detailed description of the VAS and guidelines for an operational system are given.

Spitzer, E. A., Hallock, J. N. and Wood, W. D.,
"STATUS OF THE VORTEX ADVISORY SYSTEM,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 326-334.

A Vortex Advisory System is currently undergoing tests at the Chicago O'Hare International Airport. By measuring the wind magnitude and direction with respect to a runway heading, the VAS indicates via a display when aircraft separations could be safely reduced to three nautical miles for all landing aircraft. The paper presents the rationale for the system, the concept, the system design, how data are being acquired to check the operation of the system, and the test results to date.

Spreiter, J. R. and Sacks, A. H.,
"THE ROLLING UP OF THE TRAILING VORTEX SHEET AND ITS EFFECT ON THE DOWNWASH BEHIND WINGS,"
J. Aeronautical Sciences, Vol. 18, No. 1, Jan. 1951, pp. 21-32.

The motion of the trailing vortices associated with a lifting wing is investigated by theoretical and visual-flow methods for the purpose of determining the proper vortex distribution to be used for downwash calculations. This involves the study of the rolling up and displacement of the trailing vortex sheet and the development of the cores of the rolled-up vortices. Both subsonic and supersonic speeds are considered in the analysis.

Squire, H. B.,
"THE GROWTH OF A VORTEX IN TURBULENT FLOW,"
ARC-16666, March 1954,
Imperial College, London, England.

The growth of a line vortex with time and the spread of a trailing vortex behind a wing due to turbulence are considered. It is shown that the eddy viscosity for this type of motion may be taken to be proportional to the circulation round the vortex and the solution is then similar to the solution for the growth of a vortex in laminar flow. The method is applied to calculate the distance behind a wing for which the trailing vortices will touch one another.

Squire, H. B.,
"THE GROWTH OF A VORTEX IN TURBULENT FLOW,"
Aero. Quarterly, Vol. 16, Aug. 1965, pp. 302-306.

The growth of a line vortex with time and the spread of a trailing vortex behind a wing due to turbulence are considered. It is shown that the eddy viscosity for this type of motion may be taken to be proportional to the circulation around the vortex and the solution is then similar to the solution for the growth of a vortex in laminar flow. The method is applied to calculate the distance behind a wing for which the trailing vortices will touch one another.

Srinivasan, G. R., McCroskey, W. J., Baeder, J. D. and Edwards, T. A.,
"NUMERICAL SIMULATION OF TIP VORTICES OF WINGS IN SUBSONIC AND TRANSONIC FLOWS,"
AIAA J., Vol. 26, No. 10, Oct. 1988, pp. 1153-1162.

A multiblock zonal algorithm is used to solve numerically the thin-layer Navier-Stokes and the Euler equations for simulating the flowfields of isolated wings, with particular emphasis on understanding the formation and roll-up of tip vortices in subsonic and transonic flows. Four test cases consisting of wings of different planforms have been considered to examine the influence of the tip-cap shape, tip planform, and freestream Mach number. Comparison of the numerical results with the available experimental data shows good agreement for the surface pressures in the regions where the flow is attached or mildly separated. However, discrepancies exist in regions of massive shock-induced separation in transonic flow and in the immediate vicinity of the wing tip in subsonic flow. In general, a fairly good definition of the formation and roll-up of the tip vortex is demonstrated for all of the cases considered here, subject to the coarseness of the grid in the far field. Finally, the calculated lift, drag, and pitching-moment coefficients agree well with the experimentally determined values, where available.

St. John, O. B.,
"COLLECTION OF OPERATIONAL DATA ON WAKE VORTEX INCIDENTS IN THE UK,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 6-10.

Data relating to pilots' reports of a total of over 300 incidents have been collated and analyzed covering a 5-year period.

Starr, J. W., Sernas, V. and Fletcher, L. S.,
"AIRCRAFT VORTEX DETECTION USING DUAL LASER BEAMS,"
J. Aircraft, Vol. 12, No. 2, Feb. 1975, pp. 123-124.

The note reports laboratory experiments on a dual laser beam vortex detection system which in practice could be relatively simple, insensitive to heating effects, and wouldn't interfere with visibility or normal airport functions. The laser beams are directed along the length of the runway and are used in pairs to detect the difference in the deflection of the beams. The optical vortex detection system works on the same principal as a schlieren system in which the individual laser beams act as schlieren system beams which are cut off by their own knife edge.

Staufenbiel, R. W.,
"STRUCTURE OF LIFT-GENERATED ROLLED-UP VORTICES,"
J. Aircraft, Vol. 21, No. 10, Oct. 1984, pp. 737-744.

Widely used analytical models describing the structure of lift-generated vortices behind aircraft wings (e.g., models of Betz or Lamb) are generally not in acceptable agreement with experiments. The lack in conservation of vortical dispersion and rotational energy, which is connected with the induced drag of the generating wing, is considered as a reason for this discrepancy. The model of Lamb is modified in a simple way to account for the conservation laws. These modifications yield a reduction in the core radius and a remarkable increase in the maximum tangential speed. A comparison with experiments is made and reasonable agreement is found. For the modification of the vorticity distribution in the Lamb model, the Kirchhoff-Routh function is used. This function is proportional to the rotational energy for a continuously spaced array of point vortices having the proper vorticity. The proposed model can be adapted to arbitrary vorticity distributions and, hence, wing loadings.

Steger, J. L. and Kutler, P.,
"IMPLICIT FINITE-DIFFERENCE PROCEDURES FOR THE COMPUTATION OF VORTEX WAKES,"
AIAA J., Vol. 15, No. 4, April 1977, pp. 581-590.

Implicit finite-difference procedures for the primitive form of the incompressible Naiver-Stokes and the compressible Euler equations are used to compute vortex wake flows. The partial differential equations in strong conservation-law form are transformed to cluster grid points in regions with large changes in vorticity. In addition to clustering, fourth-order accurate, spatial difference operators are used to help resolve the flowfield gradients. The use of implicit time-differencing permits large time steps to be taken since temporal variations are typically small. Computational efficiency is achieved by approximate factorization. Both two-dimensional and preliminary three-dimensional calculations are described.

Stewartson, K. and Hall, M. G.,
"THE INNER VISCOUS SOLUTION FOR THE CORE OF A LEADING-EDGE VORTEX,"
J. Fluid Mech., Vol. 15, Part 2, Feb. 1963, pp. 306-318.

Hall proposed a simplified model for the vortex core formed over a slender delta wing at incidence by the rolling-up of the shear layer that separates from a leading edge. This model enabled an outer inviscid solution and an inner viscous solution for the core to be obtained from the equations of motion. However the procedure used for the inner solution led to a number of defects: in particular, the matching of the inner and outer solutions seemed unsatisfactory. In the present paper the defects are avoided by using a different procedure. The first approximation, in the sense of boundary-layer theory, is sought. A solution, in special variables, is obtained which is in the form of an asymptotic expansion containing inverse powers of the logarithm of a Reynolds number. The leading terms of the expansion are computed, and the results confirm that the inner and outer solutions are properly matched.

Stickle, J. W. and Kelly, M. W.,
"GROUND-BASED FACILITIES FOR EVALUATING VORTEX MINIMIZATION CONCEPTS,"
Proceedings Wake Vortex Minimization Symposium, SP-409, NASA, 1977, pp. 129-156.

To determine the feasibility of altering the formation and decay of aircraft trailing vortexes through aerodynamic means, NASA used the test capabilities of two wind tunnels and two towing basins. This paper describes the facilities, common models, and measurement techniques that were employed in the evaluation of vortex minimization concepts.

Stoffers, G.,
"WAKE VORTICES AND THEIR AERODYNAMIC ALLEVIATION: A REVIEW OF THE LITERATURE,"
DFVLR-MITT-83-07, April 1983,
DFVLR, Braunschweig, Germany.

Wake vortex minimization and remedial measures to be taken at the vortex generating aircraft were investigated. Boeing 747, DC 10 and L 1011 aircraft were equipped with spoilers, winglets, ogee tips or splines, and flight tests, wind tunnel and water channel tests were performed. Best results are obtained with spoilers. It is concluded that the additional equipment gives rise to higher engine power delivery at ground approach/take off hence higher noise level and increased fuel consumption.

Stuber, K. and Gharib, M.,
"EXPERIMENTS ON THE FORCED WAKE OF AN AIRFOIL,"
AIAA Paper No. 88-3840,
Cincinnati, OH, July 1988.

An experimental effort has been made to understand the nature of an airfoil wake whose oscillation frequency is controlled by the introduction of an external perturbation. The waves are introduced into the airfoil top and bottom surfaces' boundary layers by strip heaters; attention to the linear and nonlinear interactions of these wake waves has resulted in observation of three modes of interaction: (1) frequency locking, in which the vortex-shedding frequency is the same as the forcing frequency; (2) quasiperiodic vortex interaction, in which periodic clusters of vortices are observed in the wake; and (3) chaotic vortex interaction, in which the wake vortices exhibit a three-dimensional random structure.

Suciu, E. O.,
"A FINITE ELEMENT ANALYSIS OF THE EXACT NONLINEAR FORMULATION OF A LIFTING SURFACE IN STEADY INCOMPRESSIBLE FLOW, WITH THE EVALUATION OF THE CORRECT WAKE GEOMETRY,"
MS Thesis, Dec. 1975,
Boston University, Boston, MA.

The problem of steady incompressible flow around wings with wake roll-up is considered. This problem requires the solution of an integral equation relating the values of the potential on the lifting surface and its wakes to the values of the normal derivative of the potential which are known from the boundary conditions. An iteration procedure is used to obtain the wake geometry; the velocities at the corner points of the wake elements are calculated and the (originally straight) wake streamlines are aligned to be parallel to the velocity vector. The procedure is repeated until convergence is attained.

Sullivan, J. P., Widnall, S. E. and Ezekiel, S.,
"A STUDY OF VORTEX RINGS USING A LASER DOPPLER VELOCIMETER,"
AIAA Paper No. 73-105,
Washington, DC, Jan. 1973.

Measurements of the axial and radial velocity distributions in vortex rings were made using a two-component laser Doppler velocimeter. The rings were generated by pulsing air through a sharp edged orifice using a loudspeaker: the strength and vortex core size could be controlled somewhat by the duration and amplitude of the pulse. From detailed surveys of the velocity field, both the circulation and vorticity distribution were found for two different rings: one with a relatively thick core, the other with a thin core. The vorticity was found to be rather concentrated for both rings. Streamlines were also calculated and compared with observations. Vortex rings were found to be unstable to azimuthal perturbations; the observed mode number and growth rate are in reasonable agreement with theory.

Sullivan, R. D.,
"A PROGRAM TO COMPUTE THE BEHAVIOR OF A THREE-DIMENSIONAL TURBULENT VORTEX,"
ARL-TR-74-009 and ARAP No. 200, Feb. 1974,
Aeronautical Research Assoc. of Princeton, Princeton, NJ.

A program to compute the downstream behavior of a turbulent vortex has been prepared for Aerospace Research Laboratories. The mathematical basis and the numerical technique of the

program are set forth. Subsidiary calculations are described. Finally, the structure of the program is explained and information needed to run it is given.

Sullivan, T. E. and Burnham, D. C.,
"GROUND-WIND VORTEX SENSING SYSTEM CALIBRATION TESTS,"
FAA-RD-80-13, Feb. 1980,
DOT Transportation Systems Center, Cambridge, MA.

This report describes the collection of data related to the calibration of two systems for detecting and tracking aircraft wake vortices. The systems tested were the propeller anemometer Ground Wind Vortex Sensing System and the Pulsed Acoustic Vortex Sensing System. The data were analyzed and the location of the vortices as determined with these systems were compared with the vortex location as determined photographically.

Sullivan, T. E., Burnham, D. C. and Kodis, R. D.,
"VORTEX SENSING TESTS AT LOGAN AND KENNEDY AIRPORTS,"
FAA-RD-72-141, Dec. 1972,
DOT Transportation Systems Center, Cambridge, MA.

This report describes a series of tests of wake vortex sensing systems at Logan and Kennedy Airports. Two systems, a pulsed acoustic radar (acdar) and an array of ground level pressure sensors, were tested. Site restrictions limited the Logan work to preliminary evaluation. The tests at Kennedy Airport established the general operating characteristics of both tracking systems. It was found that the acoustic sensor can detect and track the vortices of all commonly used commercial aircraft, though with varying degrees of sensitivity. The pressure sensors generally behaved best during conditions of low to moderate winds when the vortices could often be tracked laterally up to several hundred feet from the aircraft flight path.

Sullivan, T. E., Hallock, J. N. and Winston, B. P.,
"ANALYSIS OF GROUND-WIND VORTEX SENSING SYSTEM DATA FROM O'HARE INTERNATIONAL AIRPORT,"
FAA-RD-80-133, Sept. 1980,
DOT Transportation Systems Center, Cambridge, MA.

From July 1976 through September 1977, aircraft wake vortex data were collected on the approach to runways 14R, 27R, and 32L at O'Hare International Airport. The vortices from over

21,000 aircraft were tracked using the propeller anemometer Ground-Wind Vortex Sensing System, and the vortex behavior as correlated with the associated ambient meteorological conditions. The primary purpose of the tests was the evaluation of the Vortex Advisory System (VAS) concept. The elliptical wind criterion used in the VAS was verified using the vortex data.

Sullivan, T. E., Hallock, J. N., Winston, B. P., McWilliams, I. G. and Burnham, D. C.,
"AIRCRAFT WAKE VORTEX TAKEOFF TESTS AT TORONTO INTERNATIONAL AIRPORT,"
FAA-RD-78-143, Feb. 1979,
DOT Transportation Systems Center, Cambridge, MA.

This report describes the collection and analysis of data related to the behavior of the wake vortices of departing aircraft. The test site was located on the departure end of Runway 23L at Toronto International Airport, Toronto, Ontario, Canada. Three arrays of Ground Wind Vortex Sensing Systems and one Monostotic Acoustic Vortex Sensing System were used to detect, track and measure the strength of the vortices. The data were analyzed to determine vortex lifetimes, transport characteristics and decay mechanism. The results of the data analysis were used to generate an elliptical wind rose criterion similar to that used in the Vortex Advisory System for reduction in interarrival aircraft spacings.

Swedish, W. J.,
"EVALUATION OF THE POTENTIAL FOR REDUCED LONGITUDINAL SPACING ON FINAL APPROACH,"
FAA-EM-79-7, Aug. 1977,
Mitre Corp., McLean, VA.

Reducing the separations between aircraft can improve airport capacity and decrease delays. This report addresses the feasibility of reduced IFR separation standards on final approach, and identifies the characteristics of the ATC system which affect or are affected by the separation standards. This study has been limited to conditions during which wake turbulence is not a factor. Given this assumption, separation reduction will be most limited by the need to avoid simultaneous runway occupancy by successive arrivals. As the interval between landings decreases, so must the time spent on the runway, if dual runway occupancy is to be avoided. For acceptable performance, the average runway occupancy time must be no more than 50 seconds for a 2.5 nmi minimum separation standard or 37 seconds for a 2.0 nmi standard, with the

current ATC system. Various technical improvements now under development may make it possible to operate a 2.0 nmi minimum with average runway occupancies as great as 45-50 seconds. Adequate communications and surveillance for the controller, and enforcement of current ATC procedures are also required for operations with reduced separations. An alternative solution to the runway occupancy problem is to use a pair of close-spaced, dependent (dual-lane) runways and alternate arrivals between them. Reduced separation on approach to a single runway cannot be realized until the wake vortex problem is resolved.

Swedish, W. J.,
"THE REQUIREMENTS FOR REDUCED IFR SEPARATIONS ON FINAL APPROACH,"
Proceedings 25th Conf., Air Traffic Control Assoc.,
Arlington, VA, Oct. 1980, pp. 39-43.

This paper examines the factors which affect the feasibility of reducing IFR standards from a minimum of 3.0 nmi to 2.5 or 2.0 nmi. For those aircraft pairs which are not restricted by wake vortices, separation reduction is likely to be limited by the rate at which aircraft must go around to avoid simultaneous runway occupancy. The runway occupancy performance required to avoid an unacceptable increase in the go-around rate is determined. The impacts of ATC improvements such as metering and spacing on the runway occupancy requirements and on the controller's decision-making workload are then presented. Alternating arrivals to close-spaced parallel runways are discussed as one means to avoid the constraints of runway occupancy and, possibly, wake vortices. Lastly, it is proposed that further research on reduced separations should address a single specific airport, in order to narrow the range of variables and thereby facilitate the identification of problems and solutions.

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Tam, K. K.,
"A NOTE ON THE FLOW IN A TRAILING VORTEX,"
J. Engineering Mathematics, Vol. 7, Jan. 1973, pp. 1-6.

It is shown that if the equations governing the fluid motion in a trailing vortex are linearized more than one solution can be constructed. Within the framework of the linear theory, there is no criterion to determine which solution is to be used. To clarify the situation, the Navier-Stokes equations are formulated in parabolic coordinates, and asymptotic solutions are sought which are valid for downstream. It is found that the axial velocity defect decays algebraically.

Tank, W. G. and Stinson, W. E.,
"THE DISSIPATIVE EFFECTS OF JET AIRCRAFT WAKES ON FOG,"
Bull. American Meteorological Society, Vol. 53, No. 11, Nov. 1972, p. 115.

An investigation was made of the imprint in fog of the landing approach of a Boeing 747 aircraft wake. It was found that the individual vortices increase in size downstream until they meet at the vertical plane of symmetry, at which point they interact, with annihilation gradually taking place. A typical observed lifetime of the visible wake is 2-5 min.

Tartaglione, J. J.
"AN ANALYSIS OF THE AIRCRAFT TRAILING VORTEX SYSTEM,"
AIAA Paper No. 78-312,
Washington, DC, Feb. 1978.

A review of the aircraft trailing vortex system is presented. Particularly the transport and decay of the vortex systems and its potential hazard to other aircraft is discussed. In addition an analysis of trailing vortex decay data is presented. Although various theories have been proposed for predicting the decay of a vortex system, most of them have failed when compared with flight test data. Recently J. D. Iversen proposed a method for correlating trailing vortex data based upon a variable eddy viscosity vortex decay model. His model was applied to previously uncorrelated flight test data. The data used, which was obtained by the National Aviation Facilities Experimental Center (NAFEC), includes measurements of the vortex structure behind nearly all the large commercial jet transports. The correlation technique was found to successfully collapse the trailing vortex data to a single curve. Thus, Iversen's assumption of variable eddy viscosity is the key factor that enables a universal collapse of both the model and flight test data.

Taylor, L. W. and McLaughlin, M. D.,
"A MODIFIED NEWTON-RAPHSON ANALYSIS OF FLIGHT MEASUREMENTS OF THE TRAILING VORTICES OF A HEAVY JET TRANSPORT,"
NASA TN D-7404, Aug. 1974,
NASA Langley Research Center, Langley Station, VA.

A modified Newton-Raphson method has been used to determine the parameters in equations describing the vortex flow to obtain a best match with flight measurements of the flow behind the C-5A airplane. The flight measurements were made using a specially instrumented T-33 airplane which passed as closely as possible to the centers of the trailing vortices at several distances behind the C-5A airplane. The flight measurements were transformed to flow velocity relative to an inertial frame of reference. The assumed form of the flow consisted of the superposition of two counterrotating, finite core vortices. The positions of the vortex centers, their total circulation, the effective eddy viscosity and measurement bias were the parameters adjusted. Previous analyses of the experimental data have used graphical techniques to determine vortex-flow parameters. The modified Newton-Raphson method of analysis eliminates considerable manual labor and yields more consistent vortex-flow parameters.

Teske, M. E.,
"COMPUTER PROGRAM FOR PREDICTION OF THE DEPOSITION OF MATERIAL RELEASED FROM FIXED AND ROTARY WING AIRCRAFT,"
NASA CR-3780, March 1984,
Continuum Dynamics, Princeton, NJ.

This is a user manual for the computer code 'AGDISP' (AGricultural DISPersal) which has been developed to predict the deposition of material released from fixed and rotary wing aircraft in a single-pass, computationally efficient manner. The formulation of the code is novel in that the mean particle trajectory and the variance about the mean resulting from turbulent fluid fluctuations are simultaneously predicted. The code presently includes the capability of assessing the influence of neutral atmospheric conditions, inviscid wake vortices, particle evaporation, plant canopy and terrain on the deposition pattern.

Theisen, J. G.,
"VORTEX FLOWS IN WAKES,"
Proceedings of Boundary Layer Symposium, ER-8290,
Lockheed-Georgia Research Lab., 1965, pp. 151-178.

A steady solution of the viscous Navier-Stokes equations for a vortex flow field has been obtained. A perturbation form of the circulatory terms leads to a nonlinear, total differential equation having a solution characterized by spatially periodic waveforms, including nonlinear harmonics as multiples of the fundamental. The existence of aperiodic spatial waveforms is shown to be dependent upon an hypothesized form of the axial streamfunction used in a variable-separable solution. The perturbation transformation and the omission of explicit time-dependency result in a formulation which is not useful for evaluating the magnitudes of the circulation and streamfunction. Rather, they permit a study of quasi-periodic waveforms in the streamfunction for a vortex flow.

Theisen, J. G.,
"VORTEX PERIODICITY IN WAKES,"
AIAA Paper No. 67-34,
New York, NY, Jan. 1967.

An analytic solution is presented for the Navier-Stokes equations associated with vortex flows, including nonlinear, viscous terms. Appropriate consideration of three-dimensional disturbances, recently observed experimentally in wakes has enabled reduction of these equations to tractable form using perturbation analysis. Both stable and unstable, peripherally periodic modes for a vortex with large swirl (small Rossby number) are determined for radial and tangential velocities as functions of the radial inflow Reynolds number and the Rossby number.

Theisen, J. G.,
"V/STOL STABILITY AND CONTROL IN TURBULENCE,"
Proceedings of the National Aerospace Meteorology Conference, AMS/AIAA, 1968, pp. 505-514.

The six-degree-of-freedom equations of motion employed in early simulations of wake penetration dynamics are described. Both digital and analog computers were employed with a fixed base simulator, useful for basic stability and trend studies.

Theisen, J. G. and Scruggs, R. M.,
"VISCID EFFECTS ON WAKE TURBULENCE PERSISTENCE AND STABILITY,"
Proceedings Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorological Society, El Paso, 1974, pp. 370-377.

A mathematical analysis is given which describes the basic features of the process of the generation of an axial periodicity in vortices which are being fed non-conservatively by the shear layers of an external flow in a non-axisymmetric manner. The existence of atmospheric wind-shear mechanisms provide a broad-band, periodic feeding of vorticity along the axis of a vortex contrail, so that the source of energy to amplify a resonant excitation such as vortex burst is apparent. Also, differential flap motion could excite the non-axis-symmetric modes observed.

Theisen, J. G. and Scruggs, R. M.,
"AIRCRAFT WAKE VORTEX DYNAMIC STABILITY SUBJECTED TO REAL ATMOSPHERIC EFFECTS,"
LG75-ER0125, June 1975,
Lockheed-Georgia, Marietta, GA.

Three-dimensional turbulence theory is used with a vortex filament model of aircraft contrails to predict the probability that the theoretical core-wise wavelengths can be amplified to cause a "breakdown" of the primary axisymmetric vortex. Such a cascading of energy is ideally sought as a possible solution of the vortex wake hazard problem.

Theisen, J. G., Scruggs, R. M. and Dixon, C. J.,
"VORTEX WAKE OPERATING PROBLEMS, ANALYSIS AND TESTING,"
LG73-ER-0021, Aug. 1973,
Lockheed-Georgia Company, Marietta, GA.

A mathematical analysis is given which describes the features of the process of the generation of an axial periodicity in vortices which are being fed non-conservatively by the shear layers of an external flow in a non-axisymmetric manner. A vortex-lattice computer simulation is described of a tip-mounted nacelle with power effects on the wing vortex wake. Canted end-plates were also simulated, and the effects on span-lift distribution were similar, to first order, compared with the nacelle mounted cases.

Thomas, D. D.,
"TURBULENCE RELATED ACCIDENTS, WORLDWIDE SYNOPSIS,"
Symposium on Turbulence, FAA, Washington, DC, March 1971, p. 22.

Wake turbulence accidents are rare in air carrier operations, but clear air turbulence accidents are reaching the frequency of cloud associated accidents. One-half of all the turbulence accidents in general aviation are fatal, and one out of four of the total turbulence accidents involves wake vortex turbulence while clear air turbulence accidents are infrequent.

Thompson, D. H.,
"A PRELIMINARY TOWING TANK STUDY OF THE TRAILING VORTEX GENERATED BY A RECTANGULAR WING, INCLUDING THE EFFECTS OF SEVERAL TIP MODIFICATIONS,"
ARL/A-Note-342, Sept. 1973,
Aeronautical Research Labs., Melbourne, Australia.

The structure of the trailing vortex generated by a rectangular wing in a small towing tank has been studied using the hydrogen bubble flow visualization technique. The effects on the vortex of starting and stopping the towing carriage and of passing a body through the vortex core have been examined. A total of fourteen modifications to the basic wing have been tested for the effect of each on the trailing vortex.

Thompson, D. H.,
"EXPERIMENTAL STUDY OF AXIAL FLOW IN WING TIP VORTICES,"
J. Aircraft, Vol. 12, No. 11, Nov. 1975, pp. 910-911.

This note describes a qualitative towing tank study of some of the factors which control the axial flowfield in a trailing vortex and attempts an explanation of the differing results of previous axial velocity measurements. The towing tank tests showed that the axial velocity distribution in a wing tip vortex can take the form of a centerline velocity excess, a centerline velocity deficit, or a centerline velocity combined with a core edge velocity excess. The velocity distribution at any station behind the wing depends on the wing section, tip shape, Reynolds number, wing incidence and distance of the station from the wing.

Thompson, J. F., Shanks, S. P. and Wu, J. C.,
"NUMERIC SOLUTION OF THREE-DIMENSIONAL NAVIER-STOKES EQUATIONS SHOWING TRAILING TIP VORTICES,"
AIAA Journal, Vol. 12, No. 6, June 1974, pp. 787-794.

Numerical solution of the incompressible Navier-Stokes equations in integro-differential form is applied to time-dependent flow about a rectangular slab at an angle of attack. With this formulation the solution is obtained in the entire unbounded flowfield, but with actual computation required only in regions of significant vorticity. This allows considerable reduction in computer storage, since only points in regions of significant vorticity need be stored at any particular time. The computational field thus expands in time. (This method is not to be confused with "vortex methods" using discrete vortices and images.) The finite numerical calculation field in the integro-differential formulation is, in effect, infinite, and the necessity of locating "infinity" at a finite distance is avoided. Although it is not necessary in this numerical method to calculate the velocity at points outside the region of nonzero vorticity, the velocity at these points and, in fact, to infinity, is determined by the solution via an integral over the vorticity distribution. The method requires two orders of magnitude less computer storage than do methods based on the differential formulation. Results have been obtained for the development of trailing tip vortices and the force coefficients.

Thomson, J. A. L. and Meng, J. C. S.,
"LASER DOPPLER VELOCIMETER SYSTEM SIMULATION FOR SENSING AIRCRAFT WAKE VORTICES, PART I: SIMULATION MODEL,"
PD-74-058, Dec. 1974,
Physical Dynamics Inc., Berkeley, CA.

A hydrodynamic model of aircraft vortex wakes moving in a turbulent wind shear field near the ground is developed and used as a basis for modeling the characteristics of a laser Doppler detection and vortex location system. The trailing vortex sheet and the wind shear are represented by discrete free vortices distributed over a two-dimensional grid. The time dependent hydrodynamic equations are solved by direct numerical integration. The effects of buoyant exhaust and atmospheric stratifications are incorporated in the Boussinesq approximation. The ground boundary is simulated by images, and fast Fourier Transform techniques are used to evaluate the vorticity stream function. The response of a simulated laser Doppler velocimeter is analyzed by simulating the signal return from the flow field as sensed by a simulation of the optical/electronic system.

Thomson, J. A. L. and Meng, J. C. S.,
"SCANNING LASER DOPPLER VELOCIMETER SYSTEM SIMULATION FOR SENSING **AIRCRAFT WAKE** VORTICES,"
J. Aircraft, Vol. 13, No. 8, Aug. 1976, pp. 605-613.

The objectives of this study are to simulate the responses of the Scanning Laser Doppler Velocimeter System in a vortex wake environment and to display the spatial signatures. From analysis of these signatures and future parallel processing of flight data and simulated data, optimal detection tactics can be established. A hydrodynamic model is developed that represents the trailing vortex sheet and wind shear as discrete free vortices distributed over a two-dimensional grid. The effects of buoyant exhaust and atmospheric stratifications can be incorporated in the Boussinesq approximation; the atmospheric turbulence can be simulated by constructing specific realization.

Thomson, J. A. L. and Meng, J. C. S.,
"SIMULATION AND DATA ANALYSIS OF A SCANNING LASER DOPPLER **VELOCIMETER,"**
Proceedings Minnesota Symposium on Laser Anemometry, Univ. **Minnesota,** Minneapolis, 1976, pp. 231-276.

The paper discusses the spectral signal characteristics of coaxial *scanning* laser Doppler velocimeter systems which are relevant to the modeling of the response of such systems to simulated and actual aircraft vortex wakes transported through the atmosphere. Some examples of the analysis of the measurements on real and simulated wakes are presented.

Tilmann, P.,
"PROPAGATION OF SOUND RADIATION THROUGH VORTICES: A CONTRIBUTION TO THE THEORY OF FLOW MEASUREMENT WITH ULTRASOUND,"
Report 6/1972, 1972,
Max Planck Institut für Stromungsforschung, Gottingen, Germany.

The circulation and core diameter of vortices are determined from the frequency distribution of the phase deviations (phase spectra) of an ultrasonic wave propagation through a wake. Theoretical principles are developed which make use of the geometrical acoustic approximation. An exact solution of the canonical equations for the development of acoustic radiation in the potential vortex is presented in integral form, and a closed solution for the corresponding problem in the rigidly rotating vortex core is indicated. A simplified application of these solutions leads to a method for the approximate size of the vortex core diameter from the phase spectra.

Timm, G. K.,
"SURVEY OF EXPERIMENTAL VELOCITY DISTRIBUTIONS IN VORTEX FLOWS WITH BIBLIOGRAPHY,"
Report D-82-0683, Nov. 1967,
Boeing Scientific Research Labs, Seattle, WA.

Vortex flow is basic to and of great importance throughout fluid dynamics. Experimental data on circumferential velocities in real vortices was determined mostly for vortex flows generated by straight wings and delta wings. A literature search was conducted to collect pertinent data and to present a unified picture of present experimental knowledge. Circumferential velocity distributions in using vortices determined in four investigations are set forth in which there was an acceptable degree of confidence in the instrumentation techniques and data analysis. A bibliography on vortex flows is also prescribed.

Ting, L.,
"STUDIES IN THE MOTION AND DECAY OF VORTICES,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 11-39.

Solutions of Navier-Stokes equations are constructed as an asymptotic expansion in terms of a small parameter related to the Reynolds number of the vortex. A general scheme is presented for the matching of the inner viscous core of the vortex to the outer inviscid solution. The singularities in the inviscid theory are removed and the condition of regularity in the flow field defines the velocity of the vortex line. This general scheme is applied to study vortices in two dimensional, axially symmetric and in three dimensional flow fields. Results for the outer solution which do or do not require the solution in the viscous core are obtained separately.

Ting, L. and Tung, C.,
"ON THE MOTION AND DECAY OF A VORTEX IN A NON-UNIFORM STREAM,"
PIBAL-851, Aug. 1964,
Polytechnic Institute of Brooklyn, Brooklyn, NY.

A systematic procedure is presented for the study of the motion of a vortex in a two-dimensional, incompressible, nonuniform stream as a solution of the Navier-Stokes equations by the introduction of a small parameter e, which is inversely proportional to the square root of the Reynolds number of the vortex. Two different sets of length and time scales are introduced. The set with longer length and time scales is identified with the typical scales of the outer nonuniform flow. The ratio of the two length scales and that of the time scales are powers of the small parameter e. By the expansion of the solutions in the power of e with appropriate time and length scales, it is shown that the outer solution of the Navier-Stokes equations will be the same as the invisid solution, and the leading term in the inner solution agrees with that of a decaying axially symmetric vortex. The singularity associated with an inviscid vortex is removed.

Ting, L. and Tung, C.,
"MOTION AND DECAY OF A VORTEX IN A NONUNIFORM STREAM,"
Physics of Fluids, Vol. 8, No. 6, June 1965, pp. 1039-1051.

The motion of a vortex in a two-dimensional incompressible nonuniform stream is studied by including the viscous effects in the inner core of the vortex. A systematic procedure is presented by the introduction of two different sets of length and time scales with the larger scales identified with the typical scales of the outer nonuniform flow. The ratios of the scales are powers of the small parameter e which is inversely proportional to the square root of the Reynolds number of the vortex. It is shown that the leading term of the solution to the Navier-Stokes equations is composed of the classical inviscid solution matched with the solution of a decaying axially symmetric vortex. Thus the singularity in the center of the vortex associated with the classical inviscid theory is removed. The next-order solution shows that the time average of the velocity of the center of the vortex over a period of the order of the larger time scale should agree at least to the order of e^2 with the local space mean of the velocity or the outer inviscid flow which has been assumed to be the velocity of the center of the vortex in the classical inviscid theory of vortex motion.

Tinling, B. E.,
"ESTIMATION OF VORTEX-INDUCED ROLL EXCURSIONS BASED ON FLIGHT AND SIMULATION RESULTS,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 11-22.

The results of flight measurements at altitude were combined with an analytical procedure to estimate the wake vortex roll excursions for aircraft ranging in size from small business jets to jumbo jets. The roll excursion estimates were compared with a bank-angle boundary developed from piloted simulation. The estimates indicate that if the vortex from a jet transport of medium size or larger should be encountered out of ground effect at current separation distance standards, the resulting maximum bank angle exceeds the boundary for all following aircraft except the large heavy transports. The possible bank-angle excursion for small aircraft, even though their separation distances are greater, exceeds the boundary by a large amount. In view of this apparent hazard, it is reasoned that the current extremely low accident rate exists because the specified separation allows sufficient time for the vortices to be removed from the path of following aircraft by winds and by their mutual induction, and because the vortex strength is dissipated at low altitudes by ground effect.

Tinling, B. E.,
"ESTIMATES OF THE EFFECTIVENESS OF AUTOMATIC CONTROL IN ALLEVIATING WAKE VORTEX INDUCED ROLL EXCURSIONS,"
NASA TM X-73267, Aug. 1977,
NASA Ames Research Center, Moffett Field, CA.

Estimates of the effectiveness of a model following type control system in reducing the roll excursion due to a wake vortex encounter were obtained from single degree of freedom computations with inputs derived from the results of wind tunnel, flight, and simulation experiments. The analysis indicates that the control power commanded by the automatic system must be roughly equal to the vortex induced roll acceleration if effective limiting of the maximum bank angle is to be achieved.

Titcher, I. M. and Taylor-Russell, A. J.,
"EXPERIMENTS ON THE GROWTH OF VORTICES IN TURBULENT FLOW,"
ARC Report CP-316, March 1956,
Imperial College, London, England.

Measurements of the flow in turbulent line vortices along the center of a pipe have been made to determine the growth of trailing vortices in the wake of an aeroplane. It is found that the rate of growth is small and of the same order as for a laminar line vortex.

Tombach, I. H.,
"TRANSPORT OF A VORTEX WAKE IN A STABLY STRATIFIED ATMOSPHERE,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, 1971, pp. 41-56.

Atmospheric stratification affects the downward motion of an aircraft vortex wake and influences the persistence and stability of the vortex pair configuration. Observations of actual wakes have shown significant variation in the distance to which they descend and in their lifetimes under different degrees of atmospheric stability. This behavior has been modeled analytically as a pair of infinite vortices in an inviscid, compressible, stably stratified atmosphere with entrainment characterized by a single parameter which is related to the difference between the density in a particular region of the wake and that external to the wake. It has been found that the motion of such a vortex system is governed by a parameter Q which depends on the initial circulation and vortex spacing, on the atmospheric stability, and on the entrainment parameter.

Tombach, I. H.,
"TRANSPORT AND STABILITY OF A VORTEX WAKE,"
MRI 72 FR-1010, April 1972,
Meteorology Research Inc., Altadena, CA.

The influence of the atmospheric environment on the transport and decay of a trailing vortex wake has been studied. An analytic model describing the descending motion of an entraining wake in a stably stratified atmosphere has been developed. This model was compared with several other recent theoretical analyses and with limited experimental observations in order to determine the validity.

Tombach, I. H.,
"OBSERVATIONS OF ATMOSPHERIC EFFECTS ON VORTEX WAKE BEHAVIOR,"
J. Aircraft, Vol. 10, No. 11, Nov. 1973, pp. 641-647.

Smoke-marked trailing vortices were generated by a light aircraft under a hierarchy of measured atmospheric stability and turbulence levels and their motion and decay was recorded photographically. Decay from both sinuous vortex interaction and core bursting type instabilities occurred, with bursting being the dominant mode. Turbulence had a strong effect on wake life, with time-to-breakup for both modes varying as $\epsilon^{1/3}$, where ϵ is the turbulent dissipation rate. Observed lifetimes ranged from 6 sec in light-to-moderate turbulence to more than

80 sec in calm, stable air. One exceptionally long-lived solitary vortex was observed for more than 3 min. Atmospheric stratification had a weak influence on wake life and its effect on wake descent could not be determined, since descent was often stopped by a rolling of the plane of the vortices. The observed data correlates well with a new theory for time-to-breakup.

Tombach, I. H.,
"THE EFFECTS OF ATMOSPHERIC STABILITY, TURBULENCE AND WIND SHEAR ON AIRCRAFT WAKE BEHAVIOR,"
Proceedings of the Sixth Conference on Aerospace and Aeronautical Meteorology, American Meteorology Society, El Paso, 1974, pp. 405-411.

The properties of a smoke-marked wake from a light, twin-engine aircraft were measured experimentally. Correlations were made between wake motion and size and the atmospheric factors of wind, stability, turbulence, and wind shear.

Tombach, I. H.,
"INFLUENCE OF METEOROLOGICAL FACTORS ON THE VORTEX WAKE OF A LIGHT, TWIN-ENGINE AIRCRAFT,"
AFOSR-74-1507, March 1974,
AeroVironment Inc., Pasadena, CA.

The smoke-marked trailing vortex wake generated by a light, twin-engine aircraft (Aero Commander 560F) was probed by another instrumented aircraft and the velocity and temperature fields in the wake were measured. Cround-based cameras recorded overall wake motion and decay due to instabilities. It was determined that wakes descending in a stably stratified atmosphere acquire buoyancy and then subsequently begin to lose it before they break up. The speed of descent of the wakes decreases with time, and the vortex spacing and the size of the buoyant oval both increase very slightly as the wake descends. A clear correlation between wake tilting and wind shear has been established, and it was determined that shear is one factor which causes the sometimes-observed single persistent vortex.

Tombach, I. H.,
"MEASUREMENTS OF THE BEHAVIOR OF VORTEX WAKES OF AIR FORCE TACTICAL AIRCRAFT,"
AV FR 654, June 1976,
AeroVironment Inc., Pasadena, CA.

The velocity fields induced by the trailing vortices generated by T-38, F-4, and A-7 aircraft flying over a 4-meter high anemometer array were recorded. A total of 163 tests were flown, which encompassed both normal approach and holding configurations of the aircraft. Meteorological conditions were measured simultaneously for correlation with the velocity measurements.

Tombach, I. H. and Bate, Jr., E. R.,
"STUDY OF THE MOTION AND PROPERTIES OF THE VORTEX WAKE OF A LIGHT TWIN-ENGINE AIRCRAFT,"
AV FR-351, Sept. 1973,
AeroVironment Inc., Pasadena, CA.

The smoke-marked trailing vortex wake generated by a light twin-engine aircraft (Aero Commander 560F) was probed by another instrumented aircraft and the velocity and temperature fields in the wake were measured. Ground-based cameras recorded overall wake motion and decay due to instabilities. It was determined that wakes descending in a stably stratified atmosphere acquire buoyancy and then subsequently begin to lose it. The speed of descent of the wakes decreases slightly, and the vortex spacing and the size of the buoyant oval both increase as the wake descends. The tangential velocity around the vortices also decreases slightly as the wake ages. From the various observations it is concluded that representation of wake behavior in terms of an inviscid stage, an entraining stage, and a decaying stage is valid and useful. An experiment was performed to evaluate the effect of the motion of a wing-mounted drag-flap on vortex instabilities. The flap was found to affect vortex-behavior, but a complete assessment of its effectiveness will require further tests.

Tombach, I. H., Bate, Jr., E. R. and MacCready, Jr., P. B.,
"INVESTIGATION OF THE MOTION AND DECAY OF THE VORTEX WAKE OF A LIGHT TWIN-ENGINE AIRCRAFT,"
AV-FR-439, Oct. 1974,
AeroVironment Inc., Pasadena, CA.

The properties of the smoke-marked trailing vortex wake generated by a light, twin-engine aircraft (Aerocommander 560F) were investigated experimentally. Velocity and

temperature fields in the wake were measured by another instrumented probe aircraft. Ground-based and airborne cameras recorded the motion and decay of the smoke-marked vortices. A clear correlation between wake tilting and wind shear transverse to the wake was observed. The measured descent speed of wakes decreased with time in a stable atmosphere, and the spacing between the vortex pair and the size of the buoyant wake oval both increased slightly as the wake descended. Termination of the organized motion in the wakes was always brought about by vortex instabilities, with vortex breakdown (bursting) predominating for the aircraft scale and flight conditions investigated.

Tombach, I. H., Crow, S. C. and Bate, Jr., E. R.,
"INVESTIGATION OF VORTEX WAKE STABILITY NEAR THE GROUND,"
AFOSR TR-75-1501, July 1975,
AeroVironment Inc., Pasadena, CA.

The sinuous mutual induction instability of a vortex pair has been investigated theoretically and experimentally in atmospheric conditions which prevail near the aground. Two theoretical models were developed - one for a vortex pair in the constant stress layer of the atmospheric boundary layer, and the second for a vortex interacting with its image when in ground effect. The theoretical results show that the proximity of the ground shortens wake lifetime by up tc 10% compared to the results aloft. The experimental data agrees satisfactorily with the theoretical predictions.

Tombach, I. H., Lissaman, P. B. S. and Mullen, J. B.,
"AIRCRAFT VORTEX WAKE BEHAVIOR AND DECAY NEAR THE GROUND,"
Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 297-309.

One of the apparent modes of decay of aircraft wake vortices has been variously described as vortex breakdown or vortex bursting, the latter because of the visual appearance of this decay mode when the vortices are marked with smoke. A multi-faceted experimental and analytical research program was carried out to explore the details of vortex breakdown under conditions representative of those which would prevail at low altitudes in the vicinity of airports. Three separate approaches were taken simultaneously. Flight tests with Lockheed L-18 Lodestar and Boeing 747 aircraft flying over an array of ground-based cameras and instrumentation provided data on overall vortex behavior, on the vortex ages at the time of onset of instabilities, and on the changes in the vortex velocity fields which resulted from vortex breakdowns. Analytical work on stability theories identified conditions under which vortices could undergo unstable decay. Experimental tests in a water tank looked at the internal instability of vortices, and also shed light on vortex motion near the ground. Finally, a heuristic modeling approach consolidated the results of these programs into a simple representation of the relationship between the times of vortex breakdowns and the ambient turbulence levels.

Tombach, I. H., Lissaman, P. B. S., Mullen, J. B. and Barker, S. J.,
"AIRCRAFT VORTEX WAKE DECAY NEAR THE GROUND,"
FAA-RD-77-46, May 1977,
AeroVironment Inc., Pasadena, CA.

A multi-faceted experimental and analytical research program was carried out to explore the details of aircraft wake vortex breakdown under conditions representative of those which would prevail at low altitudes in the vicinity of airports. Three separate approaches were taken simultaneously. Flight tests with Lockheed L-18 Lodestar and Boeing 747 aircraft flying over ground-based instrumentation provided data on overall vortex behavior, on the vortex ages at the time of onset of instabilities and on the changes in the vortex velocity fields which resulted from vortex breakdowns. Analytical work on stability theories identified conditions under which vortices could undergo unstable decay. Experimental tests in a water tank looked at the internal instability of vortices, and also shed light on vortex motion near the ground. Finally, a heuristic modeling approach resulted in a simple representation of the relationship between the times of vortex breakdowns and the ambient turbulence levels.

Tracy, P. W. and Berger, J. H.,
"THE EFFECTS OF INSTALLING VORTEX ATTENUATING DEVICES ON THE DESIGN, PERFORMANCE, AND OPERATIONS OF A HEAVY COMMERCIAL JET TRANSPORT,"
D6-34174, Oct. 1975,
Boeing Commercial Airplane Company, Seattle, WA.

The effect of two trailing vortex attenuation concepts on the design, performance, and operations of an existing heavy jet transport have been investigated. The two concepts studied are the trailing-edge spline and high thrust on the outboard engines. Losses in takeoff, landing, and mission performance, along with potential operational problems, have been identified and feasibility recommendations have been made.

Traugott, S. C.,
"VISCOUS DECAY OF A TWO-DIMENSIONAL INTERACTING VORTEX PAIR,"
Bull. Am. Physical Society, Vol. 20, No. 11, Nov. 1975, p. 1428.

The far downstream stage of decay of a stable vortex wake behind an aircraft is simulated by a rectilinear counter-rotating vortex pair. A numerical finite difference calculation is used to follow the evolution of an initially prescribed vorticity distribution under the action of viscosity. The initial vorticity distribution is not concentrated in cores but is continuously distributed according to an analytical steady inviscid solution which represents the two-dimensional analog of Hill's spherical vortex. There is initially no jump in vorticity at the boundary between inner and outer flow, and the numerical results then describe distortion and decay as the vortices annihilate each other.

Troncoso, F. M. and Feldman, A. B.,
"WAKE TURBULENCE AND THE JUMBO JETS - WHOSE RESPONSIBILITY, PILOT OR CONTROLLER,"
Annals of Air and Space Law, Vol. 3, 1978, pp. 269-285.

Case law regarding the wake turbulence danger for small aircraft operating near jumbo jets is reviewed. One of the questions arising in the cases studied is whether the controller has a duty to provide wake turbulence warnings, or whether it is the pilot's duty to avoid the vortices. A finding of wake turbulence does not necessarily mean that the Government bears responsibility for negligence; the determination of duty and proximate cause is essential to the resolution of the cases.

Tucker, H. G.,
"DIRECTIONAL ANEMOMETER FOR NEAR-GROUND AIRCRAFT VORTEX WAKE DETECTION,"
National Research Council Canada Bulletin, Vol. 8, No. 2, July 1976.

The Control Systems and Human Engineering Laboratory in the Division of Mechanical Engineering is currently developing a specialized anemometer which is based on the deflection of a turbulent air jet and is capable of simultaneously measuring the direction and mean magnitude of the horizontal wind velocity component as well as the fluctuations of the vertical wind velocity component. This instrument has potential application in increasing the utilization rate of airfield landing strips by detecting and monitoring vortex wakes generated during landings and take-offs. In particular, the instrument may be readily designed to exceed the reliability, sensitivity and dynamic response requirements while being cost effective relative to other anemometers of at least comparable performance.

Tulin, M. P. and Schwartz, J.,
"THE MOTION OF TURBULENT VORTEX-PAIRS IN HOMOGENEOUS AND DENSITY STRATIFIED MEDIA,"
TR-231-15, April 1971,
Hydronautics Inc., Laurel, MD.

A theory for the motion of two-dimensional turbulent vortex pairs in homogeneous media has been developed based on separate velocity scaling of the internal and external flow fields involved in the motion and taking into account variations in volume, circulation, momentum, and energy. Based on the results obtained from this theory a simplified theory is derived to deal with the rising motion of turbulent vortex pairs in stratified media. The theoretical results are compared with systematic experimental observations.

Tymczyszyn, J. J.,
"SUMMARY OF PANEL STATEMENT REGARDING WAKE TURBULENCE,"
Symposium on Turbulence, FAA, Washington, DC, March 1971, p. 21.

The highlights of the Wake Turbulence Program at Edwards Air Force Base, Seattle, and Idaho Falls was presented. The principal results included: that flap extension on the generating airplane always resulted in a reduction of apparent vortex strength and persistence, the influence of span ratios of the following aircraft was dominant, and that general aviation airplanes sometimes experienced violent vertical acceleration at distances greater than that which would produce uncontrollable roll.

Tymczyszyn, J. J. and Barber, M. R.,
"RECENT WAKE TURBULENCE FLIGHT TEST PROGRAMS,"
Soc. Exp. Test Pilots 1974 Report to the Aerospace Profession, Eighteenth Symposium Proceedings, Vol. 12, No. 2, 1974, pp. 52-67.

The introduction of wide-bodied jumbo jet transports into commercial and military service in the last 5 years has prompted four major wake vortex flight tests which involved having various instrumented probe aircraft fly behind jumbo jets. The early test programs, which were conducted by NASA/FAA/USAF/industry/airline teams, were intended primarily to determine separation distance requirements. More recently they have also been made to demonstrate the potential of wake vortex alleviation configurations. These tests were made using the B-747 airplane.

Tymczyszyn, J. J. and Barber, M. R., "TECHNIQUES FOR EARLY DEMISE OF VORTICES - A PILOT'S VIEW," Proceedings of the Aircraft Wake Vortices Conf., FAA-RD-77-68, edited by J. Hallock, DOT Transportation Systems Center, Cambridge, June 1977, pp. 247-263.

The emphasis on full-scale airborne flight testing of wake vortex turbulence has naturally phased into a systematic evaluation of methods for attenuating vortex strength rather than concentrating primarily on the basic consideration of determining separation distances required for safe control of the following aircraft. A brief review of several techniques is provided with emphasis on the most successful configuration explored to date. This configuration change has been the extension of the two most outboard spoiler segments during the landing approach of the B-747. Similar configurations have been successfully tested in wind tunnels by NASA-LRC for the DC-10 and L-1011 and flight tests of the L-1011 are scheduled for the immediate future. An attempt is made to predict the operational environmental and certification problems which would have to be considered if reduced spacing is dictated by the need to improve airport capacity and general arguments are presented in favor of wake vortex alleviation.

U

Uberoi, M. S.,
"MECHANISMS OF DECAY OF LAMINAR AND TURBULENT VORTICES,"
J. Fluid Mech., Vol. 90, Part 2, 1979, pp. 241-256.

The dynamics of an infinitely long one-dimensional vortex and a swirl are compared with the dynamics of a semi-infinitely long trailing vortex and trailing swirl. With increasing distance, the change in the axial velocity difference between the core of the trailing vortex and the surrounding region causes radial convection and some associated axial convection of angular momentum. In laminar or turbulent trailing vortices, we show that under most conditions of interest this is the dominant mechanism for the decrease in the velocities of swirl in the core and corresponding growth of the core. On the basis of theoretical considerations and experimental observations, we show that the axial velocity difference between the core of the trailing vortex and the surrounding region is necessary for the sustenance of turbulence in the vortex core. A theory of the turbulent trailing vortex is developed on the basis of these mechanisms and the results are compared with our experimental observations.

Ulken, R.,
"INVESTIGATION OF WAKE VORTICES OF LANDING AIRCRAFT AT FRANKFURT AIRPORT,"
DFVLR MITT-88-15, May 1988,
DFVLR, Braunschweig, Germany.

At Frankfurt Airport investigations of wake vortices were carried out. It should be discovered whether and under which meteorological conditions landing aircraft could be endangered by wake vortices generated by leading large transport aircraft on a parallel glide path. The crosswind shows an evident influence on the horizontal motion of a vortex. But its velocity during 56% of the time of the main air traffic is so slow that a vortex cannot reach the parallel glide path with dangerous intensity due to its limited life-span. Within the remaining time the danger to a following aircraft depends very strongly on the meteorological conditions of the vicinity.

V

van der Laan, J. M.,
"EXPERIMENTELE VORTEX ANALYSATOR,"
NLR MP 82006 U, Jan. 1982,
National Aerospace Laboratory, Amsterdam, The Netherlands.

A measuring system is described for detection and analyses of aircraft wake vortices in the approach zone of a runway. This system consists of propeller anemometers, a data-acquisition unit, a quick-look monitor and a NOVA minicomputer with a real-time vortex detection program. A short description of aircraft wake vortices is also given. Some results of the measuring program are discussed.

van der Laan, J. M., van den Dam, R. F., van der Weijden, H., and Aardoom, W.,
"RESULTS FROM THE RLD/NLR AIRCRAFT WAKE VORTEX MEASUREMENT PROGRAM (DATA COLLECTION PERIOD APRIL - OCTOBER 1980),"
NLR TR 81067 L, June 1981,
National Aerospace Laboratory, Amsterdam, The Netherlands.

The results are given of an aircraft wake vortex measurement program. A Vortex Detection System is used, based on propeller anemometers. This system as well as the vortex detection software is described. Several observed weather and vortex phenomena are discussed. Cumulative distributions of vortex residence time are given, for several combinations of aircraft and windspeeds. Some aspects of the feasibility of a Vortex Advisory System, based on a wind criterion, are discussed.

Verstynen, Jr., H. A.,
"NASA FLIGHT RESEARCH ON AIRCRAFT WAKE VORTICES AND MINIMIZATION CONCEPTS,"
AIAA Paper No. 74-953,
Los Angeles, CA, 1974.

A summary of NACA and NASA wake vortex flight research is presented with selected data from some tests. A brief review of current NASA wake vortex programs is given and a preview of potential future flight tests in the wake vortex area.

Verstynen, Jr., H. A. and Dunham, Jr., E. R.,
"A FLIGHT INVESTIGATION OF THE TRAILING VORTICES GENERATED BY A JUMBO JET TRANSPORT,"
NASA TN D-7172, April 1973,
NASA Langley Research Center, Hampton, VA.

A flight investigation has been conducted to study the velocity and persistence characteristics of the trailing vortices generated by a jumbo jet transport. The investigation showed that the tangential velocities were initially higher for vortices generated with the flaps up and that they persisted for longer distances behind the aircraft than those generated with the flaps down. The core radii with flaps down appeared to be generally larger than those with flaps up.

Verstynen, H. A. and Patterson, Jr., J. C.,
"PRELIMINARY FLIGHT TEST INVESTIGATION OF AN AIRBORNE WAKE VORTEX DETECTION CONCEPT,"
AIAA Paper No. 90-1282,
Ontario, CA, May 1990.

One means to help reduce vortex-limited minimum in-trail separations might be to provide pilots with onboard sensors capable of detecting impending vortex encounters and provide warnings and recommended avoidance maneuvers. Preliminary results of a flight test indicate that measured maximum detection distances using wingtip-mounted flow angularity vanes are slightly lower than predicted.

Vickers, T. K.,
"LIVING WITH VORTICES,"
The Controller, Vol. 4, Jan. 1965, pp. 6-13.

Summary of the most important facts which have been learned about the generation and behavior of trailing vortices. Large aircraft generate turbulent wakes which can be hazardous to small aircraft encountering them. Factors affecting vortex intensity are weight of the aircraft, the load factor, wingspan, air speed, and air density. Vortex rotation, wake movement, helicopter vortices, and vortex dissipation are discussed. Factors involved when an aircraft penetrates a vortex are examined, and various ways of avoiding vortices are presented.

Vickers, T. K.,
"ATC IMPLICATIONS OF THE 747 SP,"
Journal of Air Traffic Control, Vol. 16, Sept.-Oct. 1974, pp. 9-11.

This year Boeing is shrinking the 747 design to create a more compact, lighter, long-range wide-body transport, the 747 SP. The reduced size combined with the same engines as used in the standard 747 will result in some spectacular increases in performance for the new aircraft. Most of these increases will directly benefit the ATC system. On flights up to 3000 miles in length the SP will lift off in only 25 seconds. Other improvements include a shorter takeoff runway length, a higher climb rate, and a higher cruising altitude. The advantages of these improvements are discussed along with the effects the design changes could have on the alleviation of the trailing vortex problem.

W

Walsh, Jr., R. G.,
"LEADING-EDGE PRESSURE MEASUREMENTS OF AIRFOIL VORTEX INTERACTION,"
NASA CR-112129, Jan. 1970.
Mass. Inst. of Technology, Cambridge, MA. (Also, ASRL-TR-153-1).

Experimental pressure-differential measurements made at 10% chord of an airfoil-vortex interaction are presented. A line vortex was oscillated over an airfoil perpendicular to the span and parallel to the chord. The pressure time history was recorded in order to show the sharp pressure pulses resulting from the bursting of the vortex core as it impinges upon the airfoil. Results for various vortex sizes and free stream velocities were obtained. Measurements were also made when the airfoil was yawed to the line vortex. Maximum pressure differences were observed to occur in phase across the blade even with yaw, and were directly proportional to the square of the free stream velocity. The maximum dynamic pressure coefficients obtained were as high as 1.0 when vortex bursting occurred.

Weaver, E. A., Bilbro, J. W., Dunkin, J. A. and Jeffreys, H. B.,
"LASER DOPPLER TECHNOLOGY APPLIED TO ATMOSPHERIC ENVIRONMENTAL OPERATING PROBLEMS,"
Proceedings Aircraft Safety and Operating Problems,
NASA, Washington, DC, 1976, pp. 287-302.

Carbon dioxide laser Doppler ground wind data were very favorably compared with data from standard anemometers. As a result of these measurements, two breadboard systems were developed for taking research data: a continuous wave velocimeter and a pulsed Doppler system. The scanning continuous wave laser Doppler velocimeter developed for detecting, tracking and measuring aircraft wake vortices was successfully tested at an airport where it located vortices to an accuracy of 3 meters at a range of 150 meters. The airborne pulsed laser Doppler system was developed to detect and measure clear air turbulence (CAT). This system was tested aboard an aircraft, but jet stream CAT was not encountered. However, low altitude turbulence in cumulus clouds near a mountain range was detected by the system and encountered by the aircraft at the predicted time.

Weber, F.,
"WAKE VORTEX TURBULENCE AND ITS EFFECT ON THE FLIGHT OPERATIONS - POSSIBILITIES FOR ITS EXPLORATION AND PREDICTION,"
Ortung und Navigation, No. 3, 1977, pp. 77-85.

It has been found that turbulence effects produced in the wake of a large aircraft can constitute a serious danger for other aircraft which are passing through the turbulent region. The danger is particularly great during takeoff and landing operations. A description is presented of the results of investigations which have been conducted in the U.S. and England to obtain information regarding the origin and the characteristics of wake turbulence. It was found that wake vortices are generated at the wing tip in the form of a pair of vortices which consist of masses of air rotating in the opposite direction. The behavior of the wake vortices after their generation is discussed. Predicted and photographically observed vortex paths are shown in a graph. The nature of the hazards represented by the trailing vortices is examined and a description is provided of vortex tracking systems. Attention is also given to the time periods during which trailing vortices remain in a certain 'security zone' of the London-Heathrow Airport.

Weber, O. and Ulken, R.,
"A THEORETICAL STUDY OF THE IMPACT OF AIRCRAFT WAKE VORTICES ON ROOFS IN THE FINAL APPROACH AREA OF DUSSELDORF AIRPORT,"
DFVLR-MITT-82-01, Dec. 1981,
DFVLR, Braunschweig, Germany.

Damage to buildings caused by the impact of trailing wake vortices shed from widebodied aircraft in the final approach area of Dusseldorf Airport was studied. Forty-two occurrences of roof damage were analyzed, using a simplified model for the strength, transport, and decay of wake vortices. The model is interpreted with reference to the results of a vortex alleviation program carried out in the U.S. Wake vortex characteristics, maximum tangential velocity and vortex decay are discussed. Measurement of vortex far field reduction is considered. Other investigations of roof damage in the approach areas of Hamburg, Berlin (Tempelhof), and London (Heathrow) airports are summarized. The value of potential aircraft modifications and precautions on the ground are assessed, suggesting supplementary measurements on board aircraft and in buildings.

Wentz, Jr., W. H., Ostowari, C. and Seetharam, H. C.,
"EFFECTS OF DESIGN VARIABLES ON SPOILER CONTROL EFFECTIVENESS, HINGE MOMENTS, AND WAKE TURBULENCE,"
AIAA Paper No. 81-0072,
St. Louis, MO, Jan. 1981.

Wind tunnel tests have been conducted to determine effects of certain design variables on spoiler performance and spoiler flow field characteristics. Measurements include forces and surface pressures, oil flow surveys on a vertical splitter plate, wake pressures, and wake velocity and turbulence measurements using a dual split-film anemometer system. Results include the effects of spoiler design variables, such as: spoiler slope for constant projection height, hingeline gap, lower surface venting and deflector, spoiler trailing edge notching and spoiler porosity. Hingeline gap, porosity, lower surface venting and lower surface deflector can be designed to reduce control dead-band tendency. Wake turbulence studies show that certain modifications can be utilized to diminish peak frequencies in the wake.

Werner, C.,
"FAST SECTOR SCAN AND PATTERN RECOGNITION FOR A CW LASER DOPPLER ANEMOMETER,"
Applied Optics, Vol. 24, Nov. 1985, pp. 3557-3564.

A fast data system was developed for a CW laser Doppler anemometer. Using a digital differentiation technique, it allows multiple peak values in a Doppler spectrum to be recorded at 50-msec intervals. Computer programs for sine wave fitting of the data for a velocity-azimuth-display (VAD) scan pattern or a reduced sector VAD scan are used to reduce the errors in the wind field determination in unfavorable weather conditions. The sector scan is necessary if the field of view is limited by buildings etc., and the time consumption for a sector scan is much less than the full VAD scan. For atmospheric inhomogeneities such as wake vortex signatures, a special pattern recognition procedure was developed. This procedure identifies inhomogeneities in the stored velocity information, and the result can be used to draw the wake vortex distribution in time or range.

Westwater, F. L.,
"ROLLING UP OF THE SURFACE OF DISCONTINUITY BEHIND AN AEROFOIL OF **FINITE SPAN,"**
R&M 1692, Aug. 1935,
Aeronautical Research Council, Great Britain.

The existence of a surface of discontinuity or vortex sheet behind an aerofoil of finite span is well known. In aerodynamic problems it is necessary to calculate the interference flow due to the vortices of this sheet. The vortex sheet is unstable and rolls up, the rolling up beginning at the edges. The paper discusses the rolling up process in detail.

Wetmore, J. W.,
"AIRCRAFT TRAILING VORTICES - A HAZARD TO OPERATIONS,"
Aeronautics and Astronautics, Vol. 2, No. 12, Dec. 1964, pp. 44-51.

It is shown how a thorough understanding of the phenomenon of aircraft trailing vortices, coupled with air-traffic procedures emphasizing appropriate sequencing and flight-path control, can help prevent an increase in incidents as the volume of air traffic grows. The characteristics of vortices are reviewed and expected load factors which could develop on aircraft which inadvertently penetrate a vortex are shown.

Wetmore, J. W. and Reeder, J. P.,
"AIRCRAFT VORTEX WAKES IN RELATION TO TERMINAL OPERATIONS,"
NASA TN D-1777, April 1963,
NASA Langley Research Center, Hampton, VA.

An analysis has been made, on the basis of present understanding of trailing vortex characteristics, to provide an indication of the possible effects on aircraft encountering these vortices, the circumstances under which encounters might occur in terminal-area operations, and some means of dealing with the vortex problem in operations planning and traffic control.

White, Jr., R. P., Gangwani, S. T. and Janakiram, D. S.,
"A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF VORTEX FLOW CONTROL FOR HIGH LIFT GENERATION,"
RASA/SRL-14-78-1, March 1978,
Systems Research Labs., Newport News, VA.

An experimental and theoretical program of research was conducted to determine the effect of the main wing wake on the effectiveness of the horizontal tail surface and to further refine and expand the predictive theory initiated during the previous years' effort. Experimentally, it was determined that while the vortex flows developed large pitching moments on the wing, the horizontal tail surface, regardless of its geometrical location with respect to the wing MAC, was able to counter the pitching moment and trim the configuration. The experimental data also indicated that, while large changes in the pitch angle of the horizontal tail were required to obtain configuration trim when the concentrated wing vortex wake was in the vicinity of the horizontal tail surface, the aerodynamic angle of attack remained relatively small and the tail effectiveness did not change by more than 25%. The refined and expanded theoretical prediction method provided greater insight in the aerodynamic characteristics on the upper and lower surface and, in general, predicted the vortex flow effects more accurately. The results suggest that with the proper program streamlining and documentation the predictive program can be used successfully as a design tool.

Wickens, R. M.,
"THE VORTEX WAKE AND AERODYNAMIC LOAD DISTRIBUTION OF SLENDER RECTANGULAR WINGS,"
Canadian Aeronautics and Space Journal, Vol. 13, June 1967, pp. 247-260.

An experimental investigation has been made of the aerodynamic characteristics of two slender rectangular plates or wings having an aspect ratio of 1/4. One of the plates was flat, the other had a midcord deflection of 20°. The flow on the upper surface of both plates was characterized by a pair of rolled up vortex sheets, which spring from the streamwise edge and are similar to those shed from slender, sharp-edged delta wings. The secondary vortices, which are frequently seen on deltas, however, were not observed (for zero yaw) at any incidence.

Wickens, R. M.,
"THE TRAILING VORTEX WAKE DOWNWIND OF AN EXTERNAL FLOW JET FLAP,"
Canadian Aero. and Space Journal, Vol. 18, No. 3, March 1972, pp. 67-68.

A five-hole probe was used to map out the flow behind a wing containing both propulsive and vortical components. The rolled-up vortices which characterize the trailing jet sheet were observed by smoke flow visualization, but strong vorticity was evident in the relative orientation of the side-wash and downwash contours.

Wickens, R. M.,
"A TECHNIQUE FOR SIMULATING THE MOTION AND GROUND EFFECT OF AIRCRAFT WAKE VORTICES,"
Canadian Aero. and Space J., Vol. 26, 1980, pp. 129-133.

An experimental technique is described which is intended to simulate the motion and induced flows of a vortex pair in ground effect without the use of a wind tunnel or lifting surface. The basic principle of the simulation is that the trailing vortex flows which occur in planes downwind of the aircraft, relative to an observer fixed on the ground, are similar in most respects to the vortex pair in two-dimensional flows. The production of lift and the shedding of trailing vortices result from a large number of short impulsive flows which disturb the ambient fluid and merge into a continuous streamwise effect. The sudden appearance of the vortices and their subsequent downward motion is meant to represent the passage of an aircraft above an observer on the ground.

Widnall, S. E.,
"THE STABILITY OF A HELICAL VORTEX FILAMENT,"
J. Fluid Mech., Vol. 54, Part 4, March 1972, pp. 641-663.

The stability of a helical vortex filament of finite core and infinite extent to small sinusoidal displacements of its center-line is considered. The influence of the entire perturbed filament on the self-induced motion of each element is taken into account. The effect of the details of the vorticity distribution within the finite vortex core on the self-induced motion due to the bending of its axis is calculated using the results obtained previously by Widnall, Bliss & Zalay. In this previous work, an application of the method of matched asymptotic expansions resulted in a general solution for the self-induced motion resulting from the bending of a slender vortex filament with an arbitrary distribution of vorticity and axial velocity within the core.

The results of the stability calculations presented in this paper show that the helical vortex filament has three modes of instability; a very short-wave instability which probably exists on all curved filaments, a long-wave mode which is also found to be unstable by the local-induction model and a mutual-inductance mode which appears as the pitch of the helix decreases and the neighboring turns of the filament begin to interact strongly. Increasing the vortex core size is found to reduce the amplification rate of the long-wave instability, to increase the amplification rate of the mutual-inductance instability and to decrease the wavenumber of the short-wave instability.

Widnall, S. E.,
"THE STRUCTURE AND DYNAMICS OF VORTEX FILAMENTS,"
Annual Review of Fluid Mechanics, Vol. 7, Annual Reviews Inc., Palo Alto, CA, 1975, pp. 141-165.

A review is given of the fluid mechanics of trailing vortices and vortex rings as well as in the more general problem of the structure, motion, and stability of free vortices: compact regions of concentrated vorticity in free motion in a surrounding fluid that is either homogeneous and at rest or with weak background vorticity or stratification.

Widnall, S. E. and Bliss, D. B.,
"SLENDER-BODY ANALYSIS OF THE MOTION AND STABILITY OF A VORTEX CONTAINING AN AXIAL FLOW,"
J. Fluid Mech., Vol. 50, Part 2, Nov. 1971, pp. 335-353.

Previous results concerning the effects of axial velocity on the motion of vortex filaments are reviewed. These results suggest that slender-body force balance between the Kutta-Joukowski lift on the vortex cross-section and the momentum flux within the curved filament will give some insight into the behaviour of the filament. These simple ideas are exploited for both a single vortex filament and a vortex pair, both containing axial flow. The stability of a straight vortex filament containing an axial flow to long wave sinusodial displacements of its center-line is investigated and the stability boundary obtained. The effect of axial flow on the stability of a vortex pair is explored. It is shown that to lowest order (in the ratio of vortex core radius to distance between the vortices) the effect of axial flow is to reduce the self-induced rotation of a single filament and that this effect can be considered as a change in effective core radius. To the next order, travelling waves appear in the instability, the instability mode for the vortex pair becomes non-planar but the amplification rate of the instability is not affected.

Widnall, S. E., Bliss, D. B. and Tsai, C. Y.,
"THE INSTABILITY OF SHORT WAVES ON A VORTEX RING,"
J. Fluid Mech., Vol. 66, Part 1, 1974, pp. 35-47.

A simple model for the experimentally observed instability of the vortex ring to azimuthal bending waves of wavelength comparable with the core size is presented. Short-wave instabilities are discussed for both the vortex ring and the vortex pair. Instability for both the ring and the pair is predicted to occur whenever the self-induced rotation of waves on the filament passes through zero. Although this does not occur for the first radial bending mode of a vortex filament, it is shown to be possible for bending modes with a more complex radial structure with at least one node at some radius within the core.

Widnall, S. E., Bliss, D. B. and Zalay, A. D.,
"THEORETICAL AND EXPERIMENTAL STUDY OF THE STABILITY OF A VORTEX PAIR,"
Aircraft Wake Turbulence and Its Detection, edited by J. Olsen, A. Goldberg and M. Rogers, Plenum Press, New York, pp. 305-338.

The linear stability of the trailing vortex pair from an aircraft is discussed. The method of matched asymptotic expansions is used to obtain a general solution for the flow field within and near a curved vortex filament with an arbitrary distribution of swirl and axial velocities. The velocity field induced in the neighborhood of the vortex core by distant portions of the vortex line is calculated for a sinusoidally perturbed vortex filament and for a vortex ring. General expressions for the self-induced motion are given for these two cases. It is shown that the details of the vorticity and axial velocity distributions affect the self-induced motion only through the kinetic energy of the swirl and the axial momentum flux. The presence of axial velocity in the core reduces both the angular velocity of the sinusoidal vortex filament and the speed of the ring. Experimental results for the distortion and breakup of a perturbed vortex pair are presented.

Wilk, L. S.,
"BACKSCATTER DATA ANALYSIS,"
MIT-MSL-RE-88, Aug. 1973,
MIT Measurement Systems Lab., Cambridge, MA.

> This report presents the results of data analysis performed on data acquired from a previous test operation. That operation undertaken in September, October, and November 1972 at the Vortex Test Facility at the National Aviation Experimental Center, Pleasantville, N.J., involved the design, operation and data acquisition of a monostatic acoustic backscatter vortex detection sensor. This report briefly reviews the previous effort, describes the technique used to reduce the data, and draws conclusions from the analysis. The end results of the data processing - various types of acoustograms - are contained under separate cover and have not been reproduced. Those acoustograms from an integral part of this report. The conclusion drawn from this study is that it is possible to build a monostatic, acoustic backscatter vortex sensor, and that the next phase of development can be undertaken with a considerable degree of confidence that the technical feasibility of a backscatter sensor can be demonstrated.

Williams, G. M.,
"TRAILING VORTEX WAKE SYSTEMS,"
LR-24275, Jan. 1971,
Lockheed-California Company, Burbank, CA.

> The report is a general review of the aircraft wake turbulence problem. More emphasis is given to the aerodynamic aspects of the problem than is devoted to related areas such as operational avoidance procedures. The fundamental properties of vortices are discussed, and mathematical models of vortex formation and decay are developed.

Williams, G. M.,
"A TWO-DIMENSIONAL WAKE MODEL FOR THE VISCOUS TRAILING VORTEX PAIR FORMED DOWNSTREAM OF A LIFTING WING,"
LR-25070, Feb. 1972,
Lockheed-California Company, Burbank, CA.

> The trailing vortex wake system downstream of a lifting, finite wing is modeled with a pair of two-dimensional, laminar, viscous vortex models of the multi-vortex type. The initial, or "embryonic" form of this viscous wake model is matched to the inviscid Betz model of the trailing vortex pair formed by the roll-up of the trailing-edge vortex sheet.

Downstream profiles derived from the viscous wake model appear to agree well with limited results from published experimental data. The proposed wake model predicts that the wing span load distribution will have a strong influence on the character and aging processes of the downstream flow; some of these predictions have been qualitatively observed in published reports of flight test investigations.

Williams, G. M.,
"VISCOUS MODELING OF WING-GENERATED TRAILING VORTICES,"
Aero. Quarterly, Vol. 25, May 1974, pp. 143-154.

The trailing vortex wake system generated by a lifting wing of finite span is modeled with a pair of laminar, viscous vortex models of a new type. This embryonic form of the viscous wake model is matched, at several interior collocation points, to the viscous Betz model of the wake convolution process that transforms the wing trailing-edge vortex sheet into a pair of axisymmetric trailing vortices. The present laminar theory appears to offer a useful basis for developing an engineering prediction method of aeroplane wake characteristics.

Williamson, G. G., Snedeker, R. S. and Donaldson, C. duP.,
"ON THE OPERATION OF AIRCRAFT IN THE WAKES OF OTHER AIRCRAFT,"
Proceedings of the Aircraft Wake Vortices Conf., DOT Transportation Systems Center, FAA-RD-77-68, June 1977, pp. 136-149.

The study explores the possible benefits of the operation of one aircraft in the wake of another through utilization of the energy contained in the wake vortices.

Wilson, D. J., Brashears, M. R., Carter, E. A. and Shrider, K. R.,
"WAKE VORTEX AVOIDANCE SYSTEM,"
FAA-RD-72-108, Dec. 1972,
Lockheed Missiles & Space Company, Huntsville, AL.

This report provides a conceptual design for a predictive-detective system to: (a) predict the movement and decay of aircraft-generated vortices in air corridors near the air terminal using forecast meteorological conditions; (b) periodically update the prediction by monitoring vortex movements; (c) provide a forecast of separation requirements for optimum aircraft spacing according to prevailing vortex conditions, and (d) provide a waveoff (or hold) capability for rare cases when vortices stray unpredictably into a "hazard"

zone. In addition, the report discusses the predictive system computer model including the meteorological input data and the fluid mechanics used to develop the vortex prediction. Fluid mechanic discussions include wind, wind shear and buoyancy effects upon vortex transport and decay. Computer runs are presented to demonstrate vortex transport under numerous meteorological conditions at example airports. Finally, a test for proof of the predictive system concept is discussed.

Wilson, D. J., Brashears, M. R., Carter, E. A., Shrider, K. R., Hallock, J. N. and Szymkowicz, J. S.,
"WAKE VORTEX AVOIDANCE SYSTEM,"
Proceedings of the Accident Prevention Forum on Aircraft Approaches and Landings, NTSB, Oct. 1972, pp. 1-15.

Four options exist for wake vortex avoidance systems: a predictive concept in which the aircraft spacings are set based upon predicted meteorological conditions; a surface sensor concept in which surface winds are used to determine whether crosswinds are above a predetermined threshold which in turn indicates that minimum spacings may be used; a scanning sensor concept in which active sensors are employed to track the vortices and a waveoff is called for if the vortices are still within an approach corridor when a following aircraft arrives; and a predictive-detective concept in which vortex movement is monitored and used to update predictions of what separations may be safety employed.

Wilson, D. J., Krause, M. C., Coffey, E. W., Huang, C. C., Edwards, B. B., Shrider, K. R., Jetton, J. L. and Morrison, L. K.,
"DEVELOPMENT AND TESTING OF LASER DOPPLER SYSTEM COMPONENTS FOR WAKE VORTEX MONITORING. VOL. 1: SCANNER DEVELOPMENT, LABORATORY AND FIELD TESTING AND SYSTEM MODELING,"
NASA CR-120466, Aug. 1974,
Lockheed Missiles & Space Company, Huntsville, AL.

Three elevation and range scanners were developed for the NASA LDV systems. The elevation scanners provide a capability to manually point the LDV telescope at operator selected angles from 3.2 to 89.6 degrees within 0.2 degrees or to automatically scan the units between operator chosen limits at operator chosen rates of 0.1 to 0.5 Hz. Likewise, the range scanners provide a capability to manually adjust the focal point of the system from a range of 32 meters to 896 m; range and elevation scanner controls are designed to allow simultaneous range and elevation scanning so as to provide finger scan patterns, arc scan patterns and vertical line scan patterns.

Wilson, D. J., Krause, M. C., Craven, C. E., Edwards, B. B., Coffey, E. W., Huang, C. C., Jetton, J. L. and Morrison, L. K., "CONDUCT OVERALL TEST OPERATIONS AND EVALUATE TWO DOPPLER SYSTEMS TO DETECT, TRACK AND MEASURE VELOCITIES IN AIRCRAFT WAKE VORTICES," NASA CR-120600, Dec. 1974,
Lockheed Missiles & Space Company, Huntsville, AL.

The report discuses a program plan, a critical path review of events necessary to check out the laser Doppler systems, and the results of the tests. The tests included noise and wind tests, large blower flowfield tests, single unit (1-D) flyby tests. The scanning laser Doppler systems were found to be capable of accurately tracking aircraft wake vortices from small aircraft or large aircraft and in almost any type of weather.

Wilson, D. J., Shrider, K. R. and Lawrence, T. R.,
"FEASIBILITY OF WAKE VORTEX MONITORING SYSTEMS FOR AIR TERMINALS,"
HREC 6668-1, Aug. 1972,
Lockheed Missiles & Space Company, Huntsville, AL.

Wake vortex monitoring systems, especially those using laser Doppler sensors, were investigated under this contract. The initial phases of the effort involved talking with potential users (air traffic controllers, pilots, etc.) of a wake vortex monitoring system to determine system requirements from the user's viewpoint. These discussions involved the volumes of airspace to be monitored for vortices, and potential methods of using the monitored vortex data once the data are available. A subsequent task led to determining a suitable mathematical model of the vortex phenomena and developing a mathematical model of the laser Doppler sensor for monitoring the vortex flow field. The mathematical models were used in combination to help evaluate the capability of laser Doppler instrumentation in monitoring vortex flow fields both in the near vicinity of the sensor (within 1 km) and at long ranges (10 km).

Wilson, D. J., Zalay, A. D., Brashears, M. R., Craven, C. E., Shrider, K. R. and Jordan, A. J.,
"FULL-SCALE WAKE FLOW MEASUREMENTS WITH A MOBILE LASER DOPPLER VELOCIMETER,"
J. Aircraft, Vol. 16, No. 3, March 1979, pp. 155-161.

Wake flow measurements were conducted with a mobile Laser Doppler Velocimeter (LDV). The measurements included surveys of aircraft wake vortices behind a B-747 aircraft, aircraft carrier wake measurements from aboard the U.S.S. Nimitz, and

tower wake measurements for a 100-kW wind turbine. Results of these tests demonstrated that a mobile ground-based LDV is a versatile and useful tool for the measurement of full-scale three-dimensional wake flows. The potential is demonstrated for utilization of this system to study complex wakes for a variety of applications.

Wilson, J. D. and Loth, J. L.,
"REAL TIME DEVELOPMENT OF THE WAKE OF A FINITE WING,"
MS Thesis, Feb. 1974,
West Virginia Univ., Morgantown, WV.

A real time, three-dimensional method is presented to monitor the development of the wake generated by a finite wing, which suddenly begins to produce lift in an irrotational, incompressible fluid. The wake is represented by equal strength vortex filaments which are bounded by a lifting line at the wing position and a starting vortex which washes downstream with the free stream velocity. The geometric angle of attack of the wing was changed with time so that only one starting vortex was shed and the circulation of the bound vortex remains constant. The computational time was significantly reduced by neglecting the component of induced velocity in the free-stream direction. The Biot-Savart law was needed to calculate the wake deformation of an Army 0-1 aircraft, for which experimental results have been reported by B. W. McCormick. Experimental and theoretical values for circulation at contours in the wake showed agreement although the experimental results, which consisted of contours of constant vorticity, were limited to a region near the wing tips and within a chord length of the wing trailing edge.

Wood, W. D., editor,
"FAA/NASA PROCEEDINGS WORKSHOP ON WAKE VORTEX ALLEVIATION AND AVOIDANCE,"
FAA-RD-79-105, Oct. 1979,
DOT Transportation Systems Center, Cambridge, MA.

This document is a record of the joint FAA/NASA Workshop on Wake Vortex Alleviation and Avoidance conducted at the DOT Transportation Systems Center, November 28-29, 1978. The workshop was sponsored by the Federal Aviation Administration to apprise the appropriate specialists of the state of the art and to formulate program recommendations for wake vortex alleviation at the source, for wake avoidance systems, and for operations, and safety regulations.

Wood, W. D., Hallock, J. N. and Spitzer, E. A.,
"WAKE VORTEX PROGRAM,"
IEEE Northeast Electronics Research and Engineering Meeting,
Boston, MA, 1973.

The objective of the DOT/TSC wake vortex program is the increase in airport capacity without compromising the safety of operations. The paper shows how vortex dynamics and sensors coupled with user requirements lead to the description of three basic vortex avoidance systems: a warning system, an advisory system, and an Air Traffic Control integrated system which satisfies both the safety and the capacity aspects.

Wood, W. D. and McWilliams, I. G.,
"WAKE TURBULENCE DETECTION AND ECONOMIC IMPACT OF PROPOSED IMPROVEMENTS,"
SAE Paper 77-0583,
Wasnington, DC, May 1977.

Increased separations of aircraft following heavy jets, which have been mandated because of the threat posed by aircraft trailing wake vortices, have aggravated the problem of air traffic delays at some of the busier airports. An extensive vortex measurement program at three major airports has provided the data base for the design of a Vortex Advisory System which will permit reduction of the vortex imposed separations under certain measurable wind conditions. This system which promises to effect an appreciable reduction in traffic delay is currently undergoing testing at Chicago's O'Hare International Airport.

Wu, J. M. and Gilliam, Jr., F. T.,
"A FLOW VISUALIZATION STUDY OF THE EFFECT OF WING-TIP JETS ON WAKE VORTEX DEVELOPMENT,"
in Flow Visualization III, Proceedings of the Third International Symposium, Ann Arbor, MI, Sept. 1983,
Hemisphere Publishing Corp., 1985, pp. 387-391.

The use of discrete wing-tip jets to improve the wing performance and to modify the tip vortex roll up has been investigated. A complicated three-dimensional vortex interaction in the vicinity of the wing tip flow field becomes more clear through the flow visualization study in a water tunnel. The existence of many induced secondary vortices was discovered. This finding leads to a theoretical model for analyzing the interacting vortices flow field. Flow visualization also helped in pointing out the direction for future study.

Wu, J. M., Vakili, A. D. and Gilliam, Jr., F. T.,
"AERODYNAMIC INTERACTIONS OF WINGTIP FLOW WITH DISCRETE WINGTIP JETS,"
AIAA Paper 84-2206,
Seattle, WA, Aug. 1984.

Wind and water tunnel data and calculations of the effects on wing aerodynamic performance by the presence of discrete wing tip jets are reported. A NACA 0012-64 airfoil equipped for interchangeable tips that provided various blowing configurations was used in the tests. Data were gathered on forces and moments at three spanwise locations and dye injection provided flow visualization. A relatively small jet had a large effect on the spanwise pressure distribution. Three separate types of boundary vortices were produced by the tip jets: spin-off vortices extending into the potential flow region, auxiliary vortices parallel to the main flow, and entrained vortices in the jet and wingtip vortices. Wake vortices were dispersed while total circulation increased, thereby effectively enhancing the aspect ratio and overall wing performance.

Wurzbach, R.,
"DAS GESHWINDIGKEITSFELD HINTER EINER AUFTRIEB ERZCUGENDEN TRAGFLACHE VON ENDLICHER SPANNWEITE,"
Zeitschrift für Flugwiss, Vol. 5, No. 12, Dec. 1957, pp. 360-365.

When calculating the velocities induced by a wing of finite span, the process of rolling-up the vortex sheet formed behind the wing, and its displacement are considerably simplified. For estimating the field of induced velocities a method is given which takes into account the rolling-up and the displacement of the vortex sheet.

Y

Yates, J. E.,
"CALCULATION OF INITIAL VORTEX ROLL-UP IN AIRCRAFT WAKES,"
J. Aircraft, Vol. 11, No. 7, July 1974, pp. 397-400.

The initial in-plane acceleration of a vortex sheet in two-dimensional incompressible flow is calculated. The theory is used to estimate the strength and location of the discrete vortices that roll-up behind an aircraft wing. Numerical results are presented for a C-141 takeoff and a DC-9 landing configuration. The results verify a hypothesis of Donaldson for estimating the strength and location of the discrete vortices that is required in a Betz-type roll-up calculation. The present theory also provides an estimate of the relative rates of vortex roll up.

Yen, K. T.,
"THE AERODYNAMICS OF A JET IN A CROSSFLOW,"
NADC-78291-6, Dec. 1978,
Naval Air Development Center, Warminster, PA.

The aerodynamics of a jet in a crossflow considered as the key problem in transition aerodynamics for VSTOL aircraft has been reviewed. Experimental results on the flow structure of the jet, the contrarotating vortices, the jet entrainment phenomenon, and the surface pressure distributions have been analyzed. The influences on these characteristics by the jet parameters such as the velocity ratio, injection angle and jet orifice shape have been considered based on available measurements. In the theoretical area, particular attention has been directed to the methods of prediction and analysis, and the fundamental physical bases of these methods. Current developments in transition aerodynamics, and some recent work on the formation of contrarotating vortices and the wake flow are described.

Yuan, S. W.,
"VORTEX POLLUTION-WING-TIP VORTICES: THE HAZARD AND THE REMEDY,"
Aeronautical Soc. of India Journal, Vol. 23, May 1971, pp. 67-70.

A device has been developed for controlling wing tip vortices, and its effectiveness has been verified by wind-tunnel testing. Multiple apertures (or a continuous slot) extending along the chordwise direction of the wing tip are used for blowing tangential jets of gas at preselected locations. Rows of vortices are thus produced to counterbalance the undesirable wing-tip vortices. The small amount of gas required can be bled off from the jet engine through a conduit, or it can be generated locally. The system improves lift efficiency and increases the volume of airport landing and takeoff operations by shortening the separation requirements dictated by vortex hazards.

Yuan, S. W. and Bloom, A. M.,
"EXPERIMENTAL INVESTIGATION OF WING-TIP VORTEX ABATEMENT,"
International Council of the Aeronautical Sciences, Paper 74-35,
Haifa, Israel, 1974.

Detailed measurements of aerodynamic forces and downstream velocity distributions of a model airplane with and without vortex abatement device have been made. Time-mean-average velocity components were measured, using an triple-sensor hot film probe, at 1/2-chord and 5-chord distances behind the trailing edge of the wing. The results of these tests clearly indicate that not only does the vortex abatement device reduce greatly the size of the wing-tip vortex but also the strength of the vortex core. The effect of the vortex abatement device also results in a considerable increase in lift and decrease in drag.

Yuen, H. C.,
"WAVES ON VORTEX FILAMENTS,"
PhD Thesis, May 1973,
California Institute of Technology, Pasadena, CA.

Various problems concerning waves on vortex filaments are considered. The local force balance method introduced by Moore and Saffman for the calculation of the induced velocity at a point of a vortex filament with arbitrary structure and shape is used to examine the effect of axial flow on the stability of trailing vortices and vortex rings. It is found that the effect is small in both cases.

Z

Zalay, A. D.,
"EXPERIMENTAL INVESTIGATION OF THE DECAY OF A VORTEX PAIR,"
MS Thesis, June 1970,
Mass. Inst. of Technology, Cambridge, MA.

Simulation, visualization, and qualitative measurements of the decay process of a pair of trailing vortices is outlined in this report. The vortex pair is generated in the laboratory by a tank piston arrangement. A titrated iodine starch solution and electrically pulsed plates are used to create a dark dye locally which is caught up in the vortex core and permits visualization of the decay process. Actual measurements of core size and velocity distribution are made by means of constant temperature hot wire probes and motion pictures. Experimentally measured wave lengths and wave amplitude growth rates for the vortex pair are compared against a linearized model of mutual and self induction.

Zalay, A. D.,
"HOT-WIRE AND VORTICITY METER WAKE VORTEX SURVEYS,"
AIAA Journal, Vol. 14, May 1976, pp. 694-696.

The vorticity meter used in the experiments consists of a paddle-wheel sensor mounted on a rotating shaft and fitted with a jeweled bearing. Vorticity data for a trailing vortex obtained with the vorticity meter are presented in a graph, taking into account an injected and a basic vortex. The tangential and axial velocity profile of a trailing vortex, as determined with the aid of a three-component hot-wire anemometer system, is shown, and a comparison is conducted regarding the vortex circulation strength calculated from vorticity meter and hot-wire measurements.

Zalay, A. D., White, Jr., R. P. and Balcerak, J. C.,
"INVESTIGATION OF VISCOUS LINE VORTICES WITH AND WITHOUT THE INJECTION OF CORE TURBULENCE,"
RASA Report 74-01, Feb. 1974,
Rochester Applied Science Associates, Rochester, NY.

An experimental research program was conducted to investigate the general characteristics of a line vortex trailed from a three-dimensional lifting surface, and to determine how its general velocity distribution, turbulence level, turbulent frequency content, and dissipation rates are affected by the injection of a jet of turbulent air and by a fixed turbulence generator. Three component hot-wire surveys indicated that injection of the vortex core reduced the peak tangential velocity, established a strong axial flow component, increased the core diameter, altered the turbulence spectrum, and enhanced the turbulence level in the viscous core.

Zalovcik, J. A. and Dunham, Jr., R. E.,
"VORTEX WAKE RESEARCH,"
Flight Mechanics Symposium on Flight in Turbulence,
AGARD, CP-140, 1973, pp. 13-1 to 13-14.

Recent NASA investigations of aircraft trailing vortices are 2reviewed. Some results obtained in flight on vortex characteristics, such as decay of maximum velocity and vortex drift, are presented for distances behind a generating C-5A airplane from 0.6 to 13.0 nautical miles. The lateral control activity of a CV-990 airplane probing the vortices generated by a C-5A airplane is illustrated and the effect of the C-5A aircraft configuration on this activity is indicated. The roll response at various distances behind a generating aircraft and the separation distance for limit controllability of small and medium size aircraft (Cessna 210, Learjet, DC-9, and CV-990) are related to the initial circulation of the generating aircraft. Some results are presented from near-field and far-field studies on accelerated vortex dissipation through the use of various devices such as mass ejection, spoilers, vortex generators, trailing drag devices, and so forth.

Zorea, C. and Rom, J.,
"VORTEX ROLLUP OVER AND BEHIND WINGS RELATED TO NONLINEAR AERODYNAMIC CHARACTERISTICS,"
J. Aircraft, Vol. 15, No. 4, April 1978, pp. 193-194.

The present paper describes the investigation of the rolling up of vortices over and behind wings of rectangular and delta planforms. The present method can also be used to evaluate the loading of these wings. The method is based on the representation of the vortex distribution over the planform by a vortex lattice system incorporating in this calculation the influence of the vortices shed from these cells into the flowfield. The evaluation of the diameter of the vortices far downstream of the wing, the spanwise position of the center of this vortex, and the appearance of the secondary vortices, which are some of the results obtained in this investigation, all are in reasonable agreement with available experimental results.

Zwieback, E. L.,
"TRAILING VORTICES OF JET TRANSPORT AIRCRAFT DURING TAKEOFF AND LANDING,"
FAA-RD-64-3, Jan. 1964,
Douglas Aircraft, Long Beach, CA.

The effect of ground plane and ambient winds on movement and strength decay was investigated. The results are compared with a modified potential flow theory. The position of the trailing vortices near the ground is extremely sensitive to low level ambient winds and vertical gradients of the wind. The measured positions of the trailing vortices indicate probable correlation with the potential flow theory with noted exceptions to the assumptions used. Measured vortex velocity decay rates are comparable to a modified theoretical free vortex viscous decay. Distinct vortex velocity fields were observed near the ground using a smoke generator technique for periods up to 65 seconds after aircraft passage. No differences in the trailing vortex system of two rolled-up vortices were observed for both the takeoff and landing configurations of the DC-8 aircraft.

Zwieback, E. L.,
"TRAILING VORTICES OF JET TRANSPORT AIRCRAFT DURING TAKEOFF AND LANDING,"
J. Aircraft, Vol. 1, No. 5, Sept.-Oct. 1964, pp. 308-310.

A test program with a DC-8 determined that wing trailing vortex positions were extremely sensitive to low-level wind conditions, including vertical velocity gradients, and that the existing theories can predict the approximate behavior of the vortices near the ground. It is concluded from the test results that the location of trailing vortices near the ground cannot be accurately predicted on the basis of routine wind data furnished by the control towers.

AUTHOR INDEX

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