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THE MOTION OF WAKE VORTICES IN THE TERMINAL ENVIRONMENT

J. N. Hallock, W. D. Wood and E. A. Spitzer

DOT/Transportation Systems Center
Cambridge, Massachusetts 02142

1. INTRODUCTION

The phenomenon of aircraft wake vortices has been known since the beginnings of powered flight. However, the potential danger of encountering wake vortices has only recently become apparent. Within a few years, a significant fraction of the civil air transport fleet will consist of wide-body jets in addition to the heavy B-707 and stretch DC-8 which generate vortices comparable in strength to the wide-body jets. Airport terminal areas, where light and heavy aircraft operate in close proximity and where the chance of a vortex/aircraft encounter is greatest, are of particular concern. To prevent aircraft/vortex encounters, the Federal Aviation Administration increased the separation standards behind heavy jets. But these increased separations decrease the capacity of the airport system and the present and predicted demands on airports cannot realistically be met by just constructing additional runways and airports.

The Transportation Systems Center (TSC) approach to the solution of the wake vortex problem is the design and development of a Wake Vortex Avoidance System (WVAS) which will be used in the terminal airspace to detect and/or predict the presence of vortices, to evaluate the threat, and to command the hazard avoidance action. A 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.

To learn more about how vortices move and die in the terminal environment, three test sites were instrumented to track vortices shed by landing aircraft and to correlate the motion with the recorded ambient meteorological conditions. The landing zone was monitored as this is potentially the most dangerous region as all aircraft must pass through essentially the same airspace to execute a landing. In a homogeneous quiet atmosphere the vortex pair will descend to an altitude of approximately half a wing span and then the pair will separate and move apart roughly parallel to the ground. But in the presence of winds, the vortices are convected by the wind; the induced motion near the ground added to the motion due to the wind can cancel each other resulting in a stalling of one vortex in the flight path of a following aircraft. Several effects modify the behavior of vortices near the ground. Wakes behave irregularly because of turbulence-stimulated distortion and instabilities. Often, one of the vortices is observed to rise; which vortex rises was found by Brashears and Hallock (1974) to correlate with the magnitude of the wind shear and the proximity of the ground. The magnitude of the total wind and the turbulence level both correlated with the life of a vortex (for example, when the winds were above 11 knots, CV-580 vortices were observed to disappear within 10 seconds).

During the summer and fall of 1973, TSC collected an extensive amount of data on the motion of aircraft wake vortices. Over 15,000 vortex tracks were recorded at the John F. Kennedy International Airport (JFK) in New York and the Stapleton International Airport (DEN) in Denver, Colorado, and the vortex motion was correlated with the ambient meteorological conditions. The JFK site (the approach end of runway 31R) is still in operation and the facility has been expanded to include tests of candidate vortex detection and tracking systems as well as continuing the collection of a statistical data base on the motion of vortices. In a cooperative venture with the British Civil Aviation Authority, Heathrow Airport has a runway approach zone equipped with vortex tracking and meteorological sensors which have been in operation since April 1974.

2. VORTEX DATA COLLECTION AND SENSOR EVALUATION

The major elements of a WVAS are the predictive model of vortex motion and decay and a realtime vortex tracking system. The emphasis of the test program activities are therefore directed toward the acquisition of the data required in the development of a vortex behavior model and in the selection of a vortex tracking technique. The method of approach followed at the test sites generally consists of:

- Deployment of vortex sensors and their use in tracking actual vortex motion.
- Deployment of a meteorological sensor network.
- Recording of vortex position data from the various vortex sensors and of the concurrent meteorological conditions.
- Reduction of the acquired data to evaluate the performance of vortex sensors, verification and refinement of the predictive models of vortex motion and decay, and the establishment of a large data base for use in the design of vortex avoidance systems.

2.1 Vortex Sensors

A number of approaches are being followed in the development of vortex detection and tracking sensors, their operation based on acoustics, optics or wind velocity sensing.

2.1.1 Pulsed Acoustic Vortex Sensing System

The operation of the bistatic Pulsed Acoustic Vortex Sensing System (PAVSS) is based on the refraction of a wavefront by the organized motion in the core of a vortex. Short pulses of acoustic energy are transmitted (2-4 ms at a 2 or 3 kHz frequency) in a direction perpendicular to the aircraft flight path. When there are no vortices within the sensitive volume, only that portion of the emitted pulse propagating along the ground is detected by a receiver located in the beamwidth of the transmitter. The detection of the ground pulse provides a time reference. A vortex in the sensitive volume will refract the wavefront to the receiver, resulting in the detection of an additional pulse. The time difference between the detected pulses defines the locus of an ellipse. Using two transmitters and one receiver or one transmitter and two receivers, two ellipses are defined, the intersection of which locates the position of the vortex.

A typical PAVSS sensor line consists of 6 or 8 transducers arrayed on a line perpendicular to the aircrafts flight path, yielding multiple time delay measurements which are then processed optimally to obtain the track of the two vortices. An engineering version of the PAVSS was developed by AVCO Inc. under contract to TSC. The system includes a minicomputer for real-time tracking and display and recording equipment. The system, consisting of 3 sensor lines of 8 sensors each is presently deployed at the JFK test site where it is undergoing evaluation.

2.1.2 Doppler Acoustic Vortex Sensing System

Another developed acoustic system utilizes the forward or back-scattering of acoustic energy due to temperature and velocity fluctuations in the atmosphere: the Doppler Acoustic Vortex Sensing System (DAVSS). The system consists of two broad beam transmitters and two 12-elevation beam receivers, one transmitter and receiver combination located on each side of the aircraft flight path on a line perpendicular to it. The transmitters can operate in a pulsed or CW mode; the sensors can be arrayed for operation as a bistatic forward scatter, bistatic backscatter, or monostatic system operation.

Usually, the DAVSS is operated in the pulsed backscatter mode. The system determines in which of the receiver beams the vortex is located through recognition of vortex-induced characteristic frequency shifts in the transmitted signals, and locates the vortex by the intersection of the respective receiver beams.

In the bistatic forward scattering mode of operation, the DAVSS operates partly as a PAVSS. The time delay between the received ground and refracted acoustic pulses in combination with the determination in which of the receiver beams the vortex signature is recognized is used to locate the position of the vortex in the sensitive volume.

Since at many airports there is a severe restriction on the availability of suitable real estate in the approach region to a runway, thus making the placement of sensor lines difficult, the evaluation of the DAVSS in the monostatic mode is of prime importance. One transmitter and receiver are colocated on the extended runway centerline. The system in this configuration operates in the pulsed backscatter mode; the received signal is due to back-scattering of the transmitted acoustic energy from temperature fluctuations in the atmosphere. Vortex location is determined by recognizing the doppler shifts caused by a vortex and then range gating to determine the distance from the receiver.

The DAVSS is being built by AVCO Inc. under contract to TSC and was delivered to the JFK test site in September 1974, where its various modes of operation are being evaluated.

2.1.3 Ground Wind Vortex Sensing System

The pressure and velocity fields associated with a low altitude vortex extend to the ground and can thus be detected by ground-based sensors. The Ground Wind Vortex Sensing System (GWVSS) utilizes an array of propeller anemometers to measure the component of wind perpendicular to the aircrafts flight path. Since most of the vortex wind field is in that direction, the passage of a vortex overhead will cause a large change (increase or decrease) in the ambient cross wind velocity. Only the lateral position of the vortex is measured by the GWVSS, not its height above ground.

Currently, Gill-type single axis propeller anemometers are used in the GWVSS, the anemometers arrayed on lines perpendicular to the runway centerline. A 50-foot spacing between anemometers is used up to 500 feet from the centerline, the spacing increasing to 100 feet beyond and extending to any desired length. The GWVSS has proven to be a very economical and reliable vortex sensing system, and is used extensively at all vortex test sites.

3.1.4 Laser Doppler Vortex Sensing System

The Laser Doppler Vortex Sensing System (LDVSS) is being developed by the NASA Marshall Space Flight Center. A CO_2 laser (10.6 microns) operating in the CW mode is used to scan a plane perpendicular to the aircraft flight path. The return signal is generated by the backscatter from atmospheric aerosols naturally suspended in the atmosphere. The received backscatter energy is mixed with a portion of the transmitted energy and, as in the DAVSS, the presence of a vortex determined by recognizing the characteristic shifts in the spectrum due to the velocity distribution of a vortex. Range resolution is obtained by scanning the focus of the optical system and accepting the major portion of the returned energy from the depth of field of the optics. Since the range resolution deteriorates with range, to preserve tracking accuracy, two systems are used and the position of the vortices determined from the intersection of the two beams scanning the vertical sensor plane.

2.2 Measurement of Meteorological Conditions

An essential output of the test program is the validation of techniques for long term forecasting of the behavior of a vortex wake. The predictive technique (see Brashears and Hallock (1974)) is an essential part of the wake vortex avoidance system (see Hallock and Wood (1974) and Wood, et. al. (1973)) and the predictive models must be fully validated before one can proceed with the system designs.

The forecasting technique is based on the measurement of the meteorological conditions to predict vortex behavior. One must be able to describe and predict the flow, stability and turbulence characteristics of the lower part of the earth's boundary layer with a forecasting period of 10 minutes or more to be of any practical value.

3. THE JFK VORTEX TEST SITE

The approach region to runway 31R at JFK was selected as the primary vortex test site because of the availability of the real estate necessary for the deployment of a large number of vortex sensing systems and a meteorological tower network, as well as the availability of a large and representative sample of aircraft. As shown in Fig. 1, the region between the runway threshold and 3500 feet from the threshold (the critical region for landings) is instrumented with 6 vortex sensing systems whose sensor planes are perpendicular to the extended runway centerline, thereby providing a detailed track of vortex position over the length of the vortex filament. The meteorological sensors are placed on an L-shaped tower array with a 140-foot tower located 3300 feet from the runway centerline, two 40-foot towers at 400 feet from the centerline and a 30-foot tower located closer to the threshold. To be added shortly is another 30-foot tower near the 31R threshold.

A monostatic acoustic sounder is used to probe the cross-section of the lower atmosphere yielding information on the heights of atmospheric structure fluctuations, yielding continuous information on inversion heights and the depth of the mixing region which influence vortex behavior.

Two of the GWVSS lines are extended to 3000 feet perpendicular to the runway centerline, their purpose is to measure and verify the predicted distances vortices travel in ground effect. This information is required for the assessment of the vortex hazard, if any, associated with closely spaced parallel runway operations.

Spaced along the extended GWVSS lines are 6 Monostatic Acoustic Vortex Sensing Systems (MAVSS). These are abbreviated versions of the DAVSS operating in the backscatter mode. Each unit consists of a single, narrow-beam transmitter and receiver. As a vortex passes through the beams the backscattered signal is received, recorded and analyzed to determine the vortex velocity distribution and hence its strength and potential hazard to an encountering aircraft. The string of

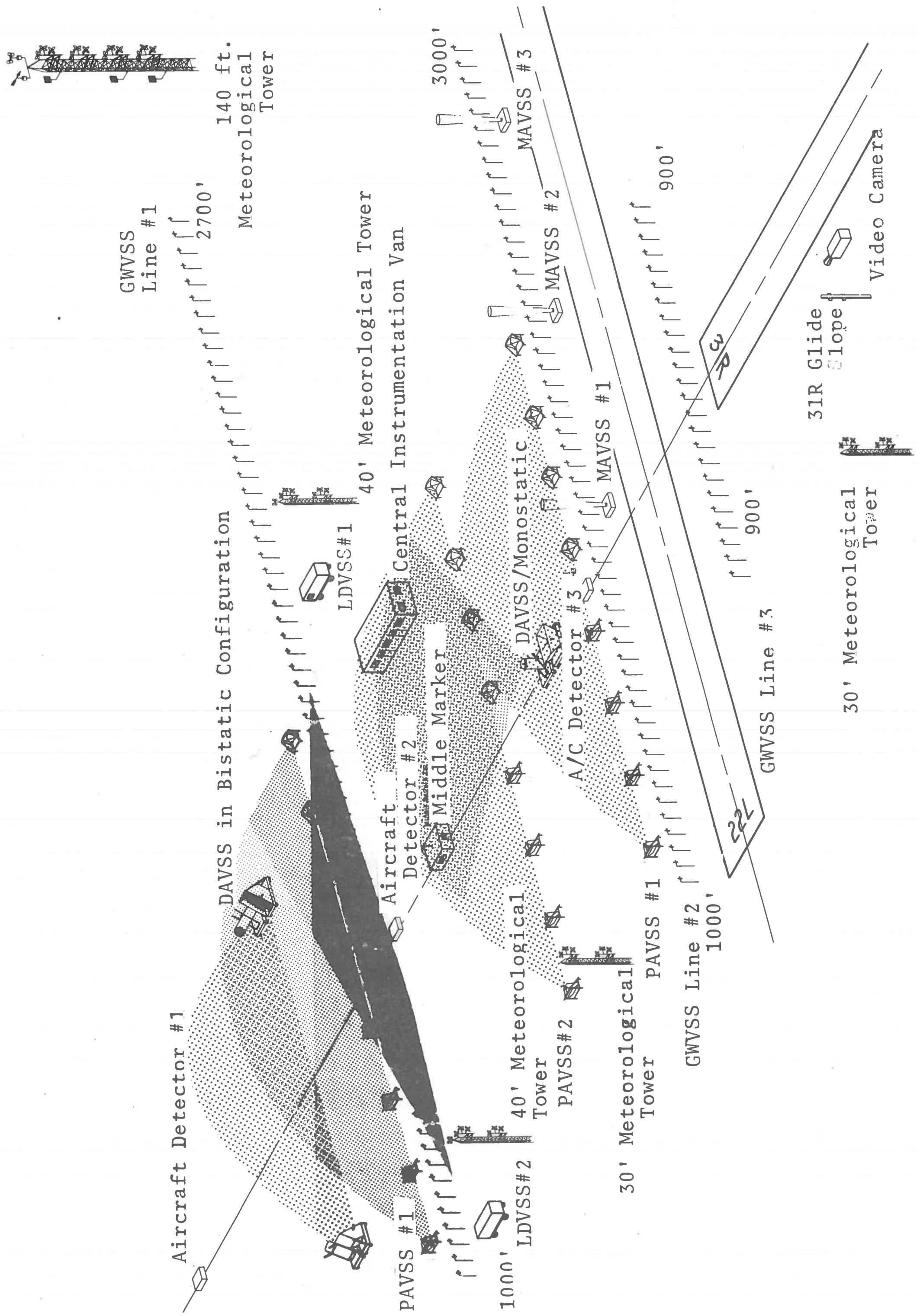


FIGURE 1: JFK TEST SITE

MAVSS thus provide a means to measure vortex circulation as a function of time, required in the verification of the vortex decay models.

Pressure transducers located along the runway centerline are used to detect the passage of aircraft by the pressure wave the aircraft generates. All control monitoring and recording equipment is housed centrally in a large instrumentation van.

Operation of the site is automatic. An operator visually identifies the type of aircraft approaching for a landing and depresses a correspondingly marked key. As the aircraft passes over the first pressure transducer, data processing and recording is started. The type of aircraft is recorded, arrival time, velocity, separation from previous aircraft, the time history of its vortices in each of the sensor planes, vortex velocity distribution and the concurrent meteorological conditions.

4.0 WAKE VORTEX AVOIDANCE SYSTEM DEVELOPMENT

Ultimately, the results of the theoretical studies, test and simulation activities presently underway will result in the development of a Wake Vortex Avoidance System (WVAS). An analysis of the WVAS user needs indicates that one of the primary requirements is for the WVAS to be designed on a modular concept, where the capability and the associated complexity of the system can be tailored to meet the individual requirements of the various classes of airports. Hence, a number of WVAS concepts were developed ranging from a very simple meteorological system to a complex, fully-automated system, each stage of the system readily upgraded to a higher level as required to meet the growing demands of an airport.

4.1 Meteorological Advisory System

Based on the large amount of data gathered to date on vortex behavior as a function of meteorological conditions, a wind rose type of criterion could be used as a vortex conditions indicator. The wind magnitude and direction with respect to the runway would determine whether a 3/4/5 mile spacing is required, or a 3 mile spacing for all aircraft could be used.

This result allows the mechanization of a very simple and economical system, which utilizes only measurements of wind velocity in the operating corridors to provide the controllers with a two-light display indicating which aircraft separation criterion to apply. A review of the NOAA airport meteorological data shows that, given freedom in the selection of runway usage, aircraft separation reductions could be achieved 50% - 70% of the time by this wind-rose criterion, a significant improvement.

4.2 Vortex Advisory System

Upon full verification of the predictive models for vortex behavior, wherein all meteorological factors affecting vortex behavior are taken into account, such as wind magnitude and direction, turbulence, stability, humidity, etc.; a predictive system can be mechanized using the measurements from meteorological sensors placed near the operating corridors as inputs to a minicomputer. The minicomputer processes the measurements using a predictive algorithm to display for the controller separation requirements by aircraft type with the predictions valid for a minimum of 10 to 15 minutes in advance. The meteorological advisory system can readily be upgraded to a vortex advisory system through the addition of sensors and added computer capability.

4.3 Vortex Warning System

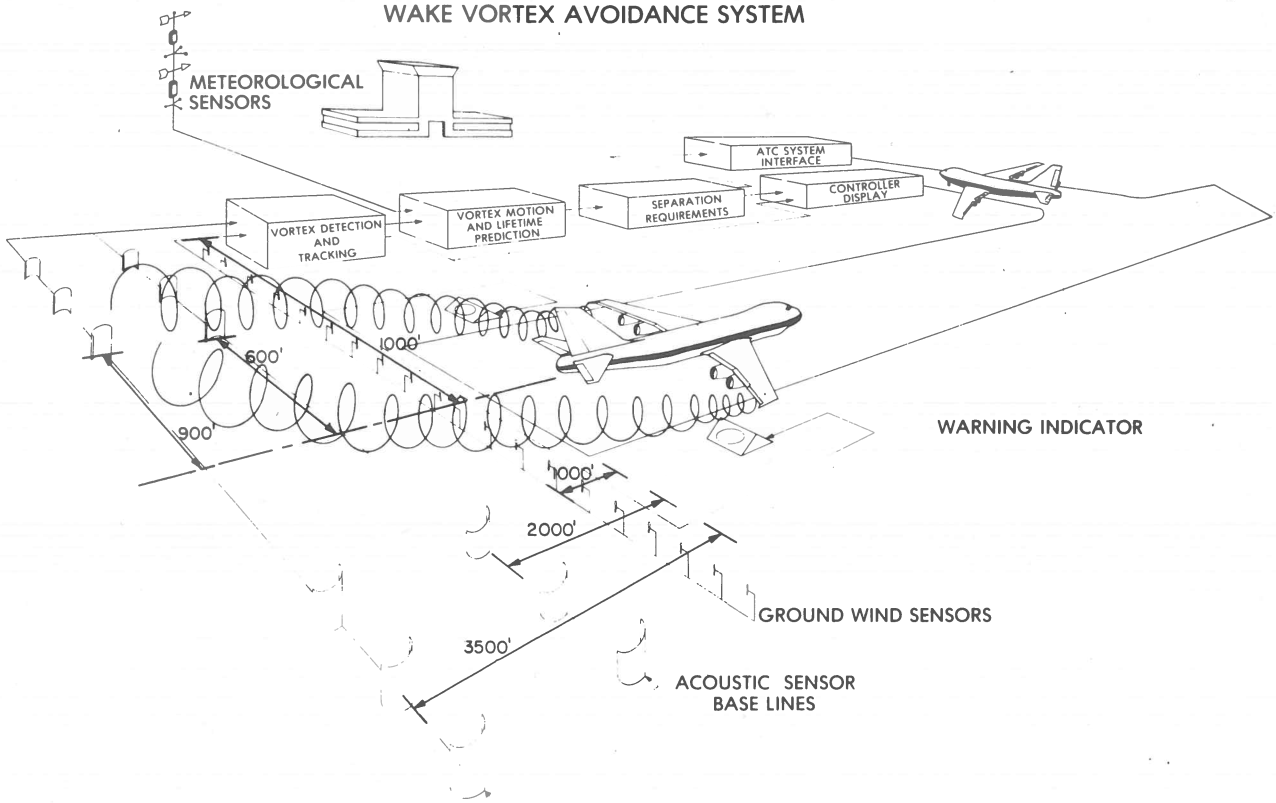
Under IFR conditions aircraft separation standards are strictly adhered to, since the aircraft position is constantly monitored by the controllers. Under VFR conditions, however, responsibility for maintaining separation on approach is the pilots. Where absolute safety on landing is required at high density airports with a large mix of aircraft, a system can be designed which utilizes one of the vortex detection and tracking systems to monitor the approach corridor, and, if a vortex is present, to generate a signal, such as by an array of intense lights at the runway threshold to warn the pilot of a potential hazard. If the signal is still present when the aircraft is at some decision height, such as 250 feet in altitude, the pilot executes a go-around in order to avoid a possibly hazardous encounter with a vortex.

4.4 Vortex Avoidance System

The previously described system concepts can be combined into a fully automated system, consisting of the meteorological sensors, vortex detection and tracking systems, computer, and controller and pilot displays. (See Figure 2.) Availability of realtime vortex tracking information allows for monitoring and updating of the predictive algorithm, increasing the prediction accuracy, and hence allowing reduced separations continuously optimized to the existing meteorological conditions. The separation requirements are input to an automated landing system which uses these to optimize the traffic flow, the

FIGURE 2

WAKE VORTEX AVOIDANCE SYSTEM



entire operation in a sense transparent to the controllers, who could not cope with the changing separation requirements. The system contains a large measure of safety, since in the event of a failure of any of the subsystems, it will degrade to a warning or an advisory mode of operation.

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