P5.9 ACOUSTIC TECHNOLOGY FOR AIRCRAFT WAKE VORTEX DETECTION

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1. INTRODUCTION

Aircraft in flight generate a pair of counter-rotating vortices in their wake, one vortex forming near each wing tip. This vortex pair persists in the atmosphere for some time before dissipating, and may contain intense velocities that can cause following aircraft to roll, rapidly descend, or suffer structural damage. As a result, the Federal Aviation Administration (FAA) requires mandatory separation distances between all aircraft to avoid wake vortex encounters. These spacing standards are often over conservative, with wake vortices being dissipated to safe levels or advected out of harms way well before mandated separation standards have expired. These spacing standards limit airport capacity, and thus negatively impacting the airline industry. If aircraft spacing distances could be reduced by 25%, it could result in billions saved annually for the airline industry (Rubin et. al, 2000).

FAA separation standards are based on the estimated amount of time that trailing vortices pose a hazard to following aircraft. These vortices are affected by the local meteorological environment, particularly ambient turbulence and wind, which act to dissipate the vortices and advect them out of flight paths, respectively. The local meteorology plays a major role in the duration of hazard posed by a trailing vortex to following aircraft in the airport terminal area, and therefore has been a focal point of research aimed at reducing aircraft spacing distances.

National research efforts over the past two decades have focused on developing a wake vortex detection technology that could be deployed in an airport setting for real-time wake vortex hazard assessment. Recent research has proven a new acoustic method of wake vortex detection that has been successful in initial field trials at detecting the presence of wake vortex circulations (Rodenhiser, 2005). This paper discusses how this new technology can be utilized to determine the strength and location of wake vortices in the airport terminal area.

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1.1 *Background*

Prior research into wake vortex detection has utilized various technologies with varying degrees of success, but as of yet no system has met the stringent demands of an operational field system that can be utilized to reduce federal spacing standards. The most notable research effort has been NASA's Aircraft Vortex Spacing System (AVOSS), which incorporates wake vortex detection, numerical prediction, and terminal meteorological data to assess wake vortex hazard (Rutishauser et. al, 2003).

Vortex behavior in the wake of the generating aircraft has been well studied. The vortex pair induces a mutual downward velocity on each other, and vortices will sink and decay over time. However, the behavior of the vortex pair changes once it comes in proximity to the ground. A vortex whose distance to the surface is within $2b_o$, where b_o is its initial separation between vortices, is defined as *in ground effect,* IGE, (Proctor, Hamilton, and Han, 2000).

Vortices in ground effect will begin to separate laterally, due to induced velocity from their image vortices below the surface. Theory shows these vortices will not come any closer than ½ b_o to the surface. Observations from a 1994-95 data set collected at Kennedy Airport confirm this theory (Hallock, Sigona, and Burnham, 1998). Vortices IGE will also generate secondary areas of opposite sign vorticity near the surface, which have been observed to be approximately one third the strength of the primary vortex (Spalart, 1998). Without influence of local winds, the vortices will separate laterally to a maximum separation of 4 b_o.

This vortex pair is also greatly influenced by local surface meteorology, which makes predicting their movement and decay nearly impossible. Local winds will advect the vortices, ambient turbulence and the associated kinetic energy will dissipate the vortices, as will the increased shear stress found near the surface. Efforts have been made to utilize surface meteorological criteria to evaluate vortex decay and create new categories of spacing standards (Frech and Zinner, 2004).

In an effort to simplify the very complex nature of vortex behavior in the airport terminal area, we can consider the following ideas.

1) If successive aircraft are approaching a single runway utilizing the same glideslope, the mutually induced downward motion of the vortex pair causes it to sink out of the glideslope corridor, and therefore does not pose a hazard to following aircraft after a short period of time. At a point the vortices become IGE, this assumption does not hold true.

2) In the vicinity of an airport, the region in which wake vortices pose a hazard to other aircraft is deemed the safety corridor, which has been defined by previous studies as 45 meters of either side of the runway centerline; this standard applies for leading and following aircraft of any size (Hallock, Sigona, and Burnham, 1998).

If vortices are within this safety corridor and at a height less than 2 b_o then wake vortices are potentially hazardous to a following aircraft.

This paper discusses vortex hazard only in the immediate airport terminal area, which is most critical in determining whether airport capacity can be increased. Of course, other regions of hazard exist, such as aircraft crossing another aircraft's path at a lower altitude such as to encounter the sinking vortex pair. Other methods of wake vortex avoidance can be utilized above the surface, such as the use of individual flight corridors, as discussed by Rossow (2003).

2. TECHNOLOGY

A new ground-based wake vortex detection sensor that indicates the presence or absence of wake vortices has been developed and tested. This technology detects circulation by measuring the transmission time of acoustic pulses propagating in a closed path around the vortex circulation. Since propagation speeds of acoustic pulses are affected by the velocity of the medium in which they travel, this measurement senses the in-line velocity component for the entire perimeter of the designated path. The net circulation contained within a closed path is directly related to the in-line velocity component around the perimeter of the path. By setting up an acoustic path that encloses an aircraft wake vortex, the magnitude and direction of the wake vortex can be calculated from these travel times.

The theory behind this technology has been presented previously by Johari and Durgin (1998), and has been patented as a means for wake vortex detection (Johari and Durgin, 2000). It was demonstrated to effectively measure the wake turbulence in a wind tunnel setting of a NACA half wing (Desabrais and Johari, 2000). The first ever full scale prototype was developed, and field measurements using the prototype system showed it can accurately detect the magnitude and direction of wake circulations of a Piper PA-28 aircraft in a convectively stable atmosphere and no wind (Rodenhiser, 2005).

A schematic of the prototype system used for the field trials is shown in Figure 1. Other path geometries are possible, and some are described in Johari and Durgin (2000). Acoustic transducers transmit a 57 kHz signal burst around the closed path, designated by the white dashed line, in both directions. The signal is detected at the beginning and end of its travel around the path by microphones placed in the acoustic path. Signal processing techniques, described in Rodenhiser (2005), are used to determine the travel time of the acoustic pulse around the path in both direction. Equation 1, developed in Johari and Durgin (1998) and Rodenhiser (2005), shows the relationship between the measured acoustic propagation times and the enclosed net circulation within the acoustic path.

$$\Gamma = 2(\Delta t)\left(\frac{L}{\sum t}\right)^2 \tag{1}$$

The system is placed next to the runway, with the cross-sectional measurement area perpendicular to the runway. Thus, the three dimensional vortex line produced by an aircraft landing or departing will enter the observational area, oriented such that the axis of circulation is perpendicular to the measurement area, and measurements of circulation strength and direction can be made.

This technology boasts many advantages, such as low cost, simplicity of equipment operation, and no interference with other critical airport systems. Future testing is planned to evaluate the ability to operate in all weather conditions.

3. OPERATIONAL USE

The operational use of this new ultrasonic technology is considered for the region defined previously, which includes the safety corridor of the runway, with a vertical extent of 2 b_o. The use of this system can be considered during two types of wind conditions, times of little or no wind, and times of crosswind, with the threshold being 1 m/s. Operational setup would consist of one measurement system placed on either side of the runway, near the edge of the safety corridor.

Figure 2 depicts a schematic of anticipated system setup and the safety region being monitored.

During periods of no wind, the vortices will separate due to proximity to the ground to a maximum distance of $4b_o$. For most large aircraft, this indicates the vortices could travel to the edge of the safety corridor or beyond. (A B-747 creates vortices with an initial separation of ~ 40m, and thus a max lateral separation due to ground effect of 160m.) Winds less than 1 m/s will likely advect the downwind vortex off the runway more quickly, and keep the upwind vortex stationary on the runway. Observational studies by Hallock, Sigona, and Burnham (1998), show that the typical crosswind leading to a vortex stalling on the runway for at least 80 seconds is 0.5 m/s.

Light winds result in low atmospheric turbulence levels, which correspond to slow vortex decay. The likelihood is that the vortex on the runway will be at a hazardous intensity until the separation standard has expired. However, if the downwind vortex is observed by the measurement system to leave the safety corridor, its circulation strength will be measured at that time. It can be assumed that the decay of the two vortices is equivalent, as has been observed in data gathered from Hallock, Whitney, and Burnham (1999). Therefore, the vortex leaving the safety corridor can be evaluated, and if its circulation is at a non-hazardous level, it can be assumed the vortex, stalled on the runway, has an equivalent circulation level.

In crosswind conditions greater than 1 m/s, the vortex pair will be blown off the runway. Both vortices should be detected by the measurement equipment at the edge of the safety corridor, and once they are detected the runway is assumed safe for the next aircraft. Crosswinds also act to create ambient circulations within the planetary boundary layer, and this generates a greater level of ambient circulations that are detected by the measurement system.

There is a threshold for cross-wind speed above which the system will not be able to discern a hazardous strength vortex from the ambient circulation levels. This threshold is dependent upon exact system configuration, and will most likely be between 14 and 18 m/s. Most aircraft are not able to land in crosswinds of this magnitude, so the chance of ambient turbulence prohibiting system operation is very unlikely.

In addition to considering the operational capability of the system in various cross wind conditions, the capability can also vary based on airport configuration. In a single runway airport, or an airport where runways are sufficiently spaced such that vortices from one runway could never contaminate another, then the use of this technology is simply to determine when the vortex has left the runway's safety corridor.

For parallel runways, this technology can be useful in determining when vortices have left the safety corridor of one runway, and when they may enter the safety corridor of the parallel runway. With a detection system placed at the edge of the safety corridor for each runway, the system can not only detect when a vortex is leaving or entering a given safety corridor, but it can also measure the strength of the vortex. Therefore, vortices drifting onto a parallel runway can be tracked for location, and also evaluated to determine if they are of a hazardous circulation level.

For intersecting runways, this technology is also of greater use, as systems can be positioned to track the lateral and longitudinal motion of the vortices, and determine whether vortices from one runway are contaminating a second runway. The FAA institutes greater restrictions on aircraft spacing in such conditions, and therefore the opportunity to reduce the spacing standards is greater.

Table 1 summarizes the expected operational capability of the system in the two wind categories discussed, and its usefulness in various runway configurations.

4. EXAMPLE AIRPORT CONFIGURATION

Future field trials are scheduled to assess this operational system at a large airport with large aircraft. Figure 2 depicts what the expected full operational setup of equipment would look like on an airfield.

Computers at the base of each tower would be used to control the transducers and log the signal transmission time data. These computers on the airfield would be wirelessly networked with a control computer setup indoors. Real-time display of the circulation data gathered at each local system site on the airfield would be displayed on the control computer.

Anemometers would be placed atop each tower, to measure the ambient wind speed and direction at each site. This would enable a calculation of actual cross-wind speed, and thus determine the type of system use. In addition, knowing the ambient cross-wind speed will allow for calculations of ambient circulation contained within the measurement area due to wind shear, which is vital in understanding the measured circulation levels.

5. SUMMARY

A new acoustic technology is discussed as a practical, robust, and inexpensive means to detect wake vortices in the airport terminal area. The ground based system has been proven effective in accurate measurement of the strength and direction of circulation produced from a small Piper aircraft in field trials.

This technology acts to detect the presence or absence of vortices within a designated measurement area. Positioning multiple systems at the edge of a runway safety zone can determine if a vortex has left the safety corridor or not. Vortices leaving the safety corridor indicate the runway is safe for additional air traffic. The ultimate goal of the operational system is to allow reduced separation standards and increase airport capacity.

Specific anticipated application of this technology to various surface wind conditions and runway configurations is presented. Field testing is planned to confirm the capability of the technology for application at a large airfield with large aircraft.

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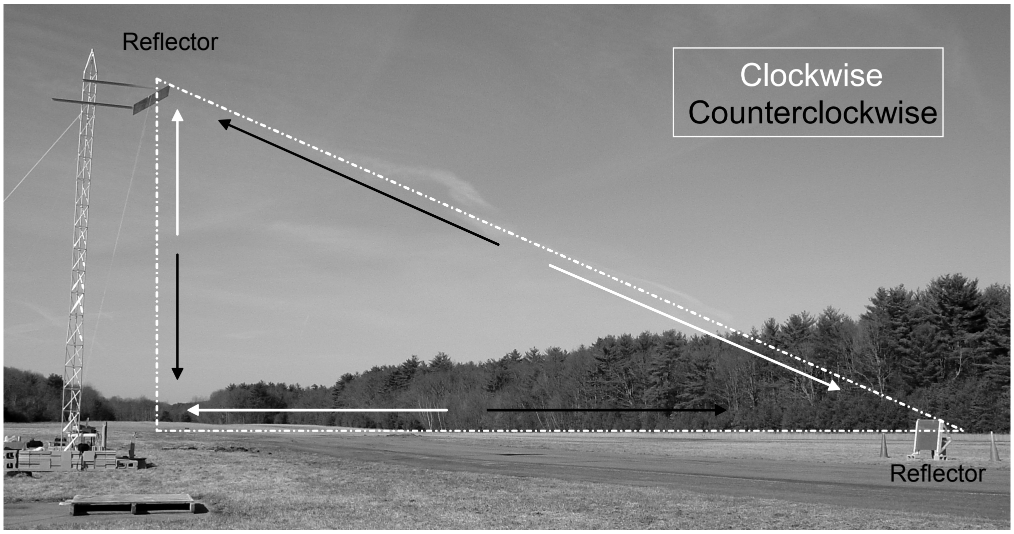

Figure 1 - Block diagram of acoustic measurement system

Crosswind Speed	< 1m/s	> 1m/s
Description	Vortices will have a long residence time in safety corridor, and possibly vortex stalling on the runway	Vortices will be blown out of the safety corridor by crosswind, and detected by the measurement system.
Single Runway	If no vortices are observed by measurement system, then current spacing standards are used. If one vortex is detected, its strength is assessed to determine hazard. If below hazardous level, it can be assumed other vortex has similar strength, and spacing can be reduced.	Once both vortices are observed leaving the safety corridor, the runway is safe for traffic. Continuous monitoring will occur to ensure vortices are not blown back in safety corridor by wind direction changes.
Parallel Runways	Vortices should not affect parallel runways because lateral movement will not be significant. Benefits will be the same as in the single runway scenario.	In addition to benefits noted in the single runway scenario, system can also detect when vortices from one runway enters safety corridor of a neighboring runway. Entering vortex is measured, and determination made whether it is hazardous to parallel runway.
Intersecting Runways	In addition to the benefits noted in the single runway scenario, system can also monitor the location and strength of the vortex line contaminating an intersecting runway, and determine when it has dissipated to a safe level.	In addition to the benefits noted in the single runway scenario, the system can also monitor the location and strength of the vortex line contaminating an intersecting runway, and determine when it has dissipated to a safe level.

Table 1 - Description of System Application for Various Runway Configurations

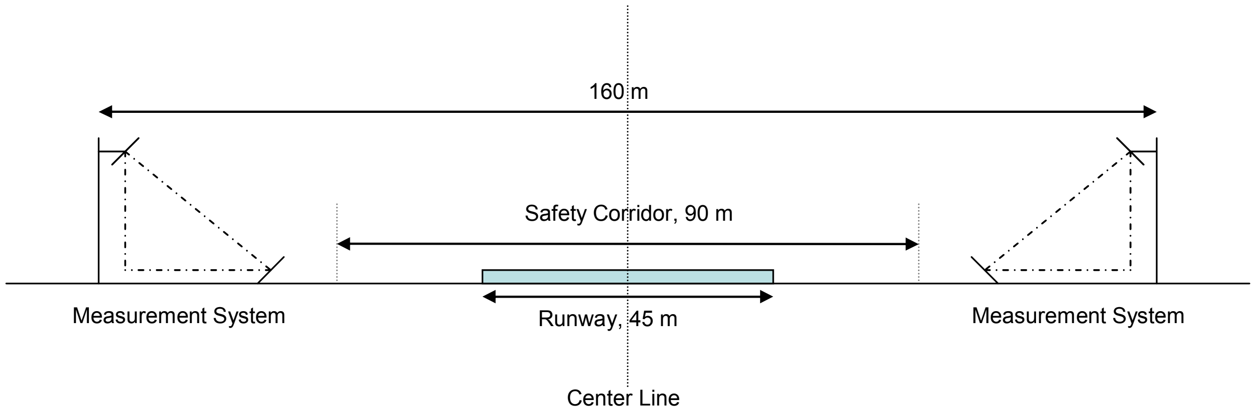

Figure 2 – Expected operational setup at a runway of measurement system