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Estimation of Wake Vortex Advection and Decay Using Meteorological Sensors and Aircraft Data

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16. Abstract

The lift-generated wake vortices trailing behind an aircraft present a danger to aircraft following the same or nearby path. The degree of hazard to the following aircraft depends on the nature of the wake encountered in its flight path and on the ability of the aircraft to counter its effects. This report describes the current state of understanding of the factors that influence the motion and dissipation of wake vortices. The relationships of these factors to parameters that are measurable through meteorological sensors and from *a priori* knowledge of the vortex generating aircraft characteristics are discussed as an aid to structuring development plans for the creation of wake vortex advisory products by the Integrated Terminal Weather System (ITWS) and by special wake vortex sensors.

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ABSTRACT

The lift-generated wake vortices trailing behind an aircraft present a danger to aircraft following the same or a nearby path. The degree of hazard to the following aircraft depends on the nature of the wake encountered in its flight path and on the ability of the aircraft to counter its effects. This report describes the current state of understanding of the factors that influence the motion and dissipation of wake vortices. The relationships of these factors to parameters that are measurable through meteorological sensors and from a priori knowledge of the vortex generating aircraft characteristics are discussed as an aid to structuring development plans for the creation of wake vortex advisory products by the Integrated Terminal Weather System (ITWS) and by special wake vortex sensors.

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I am grateful to James Evans for suggesting this project and providing numerous helpful comments. Steven Campbell pointed me in the right direction and described existing and proposed terminal sensors, data collection, and communication systems. This study also benefitted from a discussion with Larry Cornman of NCAR on atmospheric turbulence measurements and a discussion with George Greene of NASA Langley on the current understanding of the physics of wake vortices.

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I. INTRODUCTION

The growth of commercial aviation and limitations on airport development provide a strong motivation to find ways to safely increase the air traffic capacity of existing runways. Current IFR separation standards require spacings of 3 to 6 nautical miles between leading and following aircraft, depending on their respective weight classes. These standards are driven by the need to avoid hazards associated with the lift-generated wake vortices trailing each aircraft, and could otherwise be reduced to spacings of 2.5 nm or less.

Shorter spacings successfully used under VFR conditions suggest that the spacings required by the IFR standards are overly conservative. Aircraft with widely varying wake vortex characteristics are combined into common classes, and atmospheric conditions which encourage rapid decay or advection of the vortices are not taken into account. An opportunity therefore exists to improve airport capacity by taking advantage of information from terminal weather information systems (in particular, the Integrated Terminal Weather System (ITWS)[1]) and aircraft, which can be combined with vortex and hazard models to predict when wake vortices are sufficiently diminished in strength or safely advected out of the path of following aircraft. Field tests, laboratory and numerical experiments, and analytical modelling over the last twenty years have provided insight into vortex development, movement, and decay for a wide variety of generating aircraft and meteorological conditions.

Initial studies of weather adaptive wake vortex advisory products have focussed on the measurement and prediction of vortex advection as the principal basis for an advisory service.[2] However, the conditions required for wake vortex hazard reduction by advection alone may not be present in circumstances where reduced separation is desired.[3] Thus, this short study has focussed in particular on conditions in which the vortex hazard will diminish in time rapidly enough to warrant reduced separation even if advection cannot totally eliminate the potential hazard.

Section II reviews basic features of wake vortex motion and evolution. In section III, we consider in some detail the effects of

(i) atmospheric stratification,
(ii) atmospheric turbulence,
(iii) cross-runway wind shear, and
(iv) ground effects.

Section IV suggests the airfield state of atmosphere parameters which should be measured and predicted to estimate wake vortex hazard.

II. WAKE VORTEX MOTION AND EVOLUTION

The strength of a wake vortex is often quantified by the average circulation,

$$\Gamma'(r) = (1/r)\int_0^r \Gamma(r')dr' \quad ,$$

with circulation $\Gamma(r)$ given by

$$\Gamma(r) = 2\pi r v(r) \quad .$$

The average circulation is a robust average over the data and is therefore relatively insensitive to velocity measurement errors. Wake vortices are frequently modelled as Rankine or Gaussian vortices, shown in Figure 1, with a core whose radius is defined by the location of maximum velocity.

To enable safe reduction of aircraft landing separations a wake vortex advisory system must be able to answer two questions: "Is there a wake vortex in the flight path?" and "If so, is it strong enough to be hazardous?" The answers to these questions requires knowledge and prediction of the movement of the wake vortex pair from the leading aircraft with respect to the following aircraft's flight path and an understanding of vortex decay mechanisms.

Horizontal Advection

Wake vortices are subject to advection by winds in the direction perpendicular to the runway. A hazard exists when vortices from one runway are blown onto an adjacent or parallel runway and when vortices travelling in the horizontal direction (as in ground effect) are blown back onto the same runway.

Sink Rate

Aircraft wake vortices are generated parallel to the ground with rotation such that the velocity between them is toward the ground (Figure 2). Through mutual induction, the first order effect of each vortex on the other is to cause the vortex pair to fall with constant velocity $\Gamma/2\pi b$, where b is the distance between them. If the rate of descent of the trailing vortices is known, the following aircraft can remain at a sufficiently high altitude to avoid them. This is a method currently used under VFR conditions, for which an accepted practice is to land a small aircraft at a position farther down the runway than the previous (larger) plane, thus avoiding the wake vortices by staying above them throughout the approach. Danger arises when ambient conditions result in a slower sink rate than predicted or in ascent of the vortices, leaving them in the path of an oncoming aircraft.

Decay Rate

Wake vortices dissipate on timescales on the order of several seconds to a few minutes. Simple diffusion of vortices occurs over a much longer timescale, and is almost never

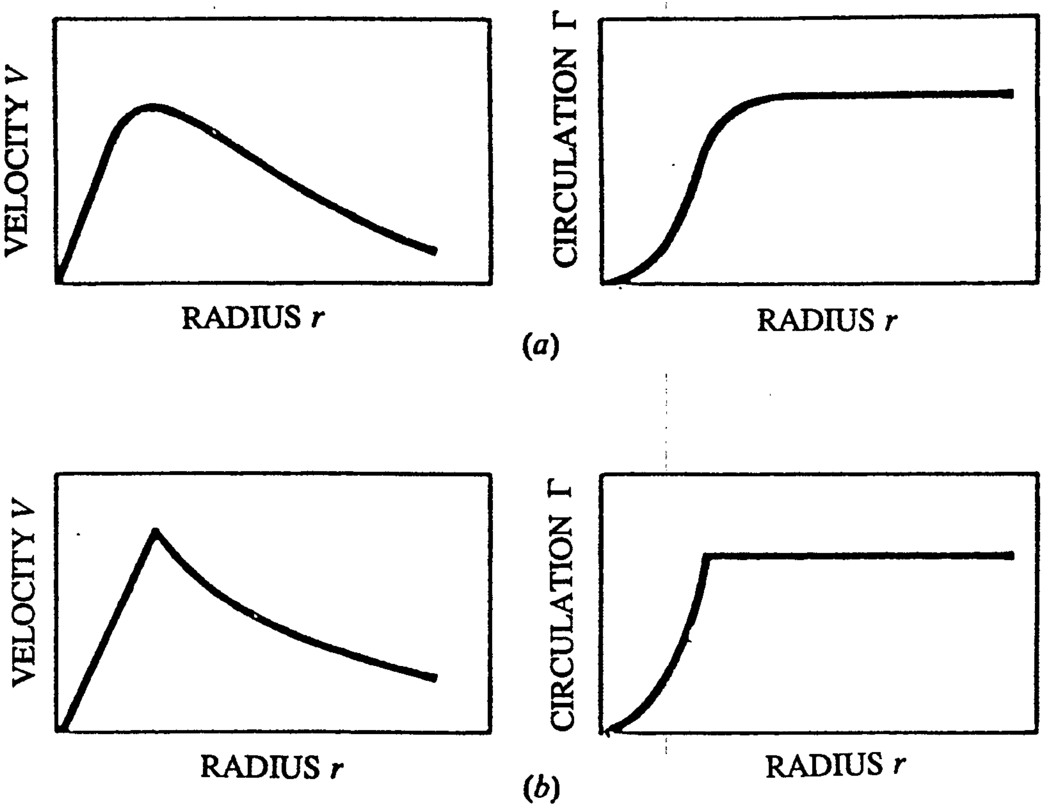


Figure 1. Vortex velocity and circulation as a function of radius for (*a*) a Gaussian vortex and (*b*) a Rankine vortex. The core radius is defined by the location of maximum velocity. From Barker and Crow, 1977.[27]

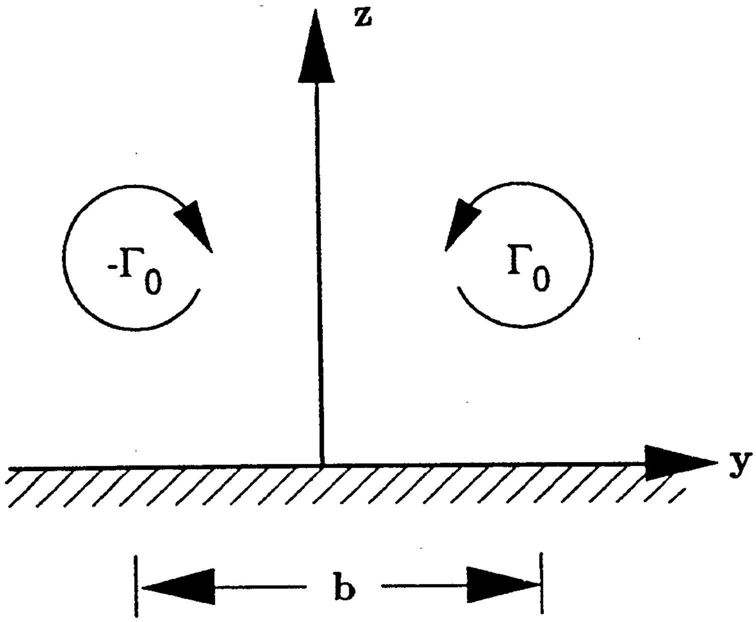


Figure 2. Coordinate system of descending wake vortex pair. From Zheng and Ash, 1991.[28]

observed in practice. Instead, two instability mechanisms, the Crow instability and vortex bursting, are found to be responsible for the decay of the vast majority of wake vortices. Current investigations suggest the effectiveness of a third decay mechanism, in which merging of several vortices shed by the wing results in a strong internal velocity field which rapidly disperses the wake vorticity.

A vortex pair marked by tracers such as condensed moisture or smoke is frequently observed to develop a wavy disturbance, which grows until the vortices connect at their points of minimum separation to form a train of vortex rings (Figure 3). Crow showed that this instability results from a combination of mutual interactions between the two sinusoidally deformed vortices and self-induced motion.[4] The geometry of the long wave disturbance predicted by this theory is shown in Figure 4. Its amplitude grows exponentially in time at a rate on the order of $(2\pi b^2/\Gamma)^{-1}$, the reciprocal of the time for the vortices to fall by a distance b, and its wavelength is on the order of 6-7 times the wingspan of the aircraft. This instability mechanism requires small vortex cores and high rotational velocities to be effective.

During vortex bursting, also known as vortex breakdown, the vortex suddenly increases in diameter in a localized region (Figure 5), accompanied by increases in turbulence and energy dissipation. This phenomenon is not yet well understood, although it is thought to be related to adverse axial pressure gradients in the core (pressure increasing in the direction of flow).[5,6] The bursting event has generally been considered to mark the demise of the vortex pair. However, recent studies by Delisi and coworkers[7,8] using entrained particles to track the evolution of wake vortices indicate that vorticity remaining after bursting may still be sufficiently organized to undergo the Crow instability and develop into ring vortices. Evidence from numerical studies supports the possibility that a hazard to the following aircraft continues after vortex bursting despite redistribution of the angular momentum in the core region.[9]

A third, highly effective, decay mechanism has been suggested by current research into the relationship of aircraft design to wake alleviation at NASA Ames Research Center. The injection of additional vortices into the aircraft wake by wing fins or flaps may result in the rapid disorganization of wake vorticity through large-scale self-induced velocity fluctuations, as demonstrated in wind tunnel experiments reported by Rossow.[9] Numerical studies by Bilanin et al.[10] show that the merging of nearby same sense vortices is particularly effective in producing turbulence followed by advection and diffusion of vorticity.

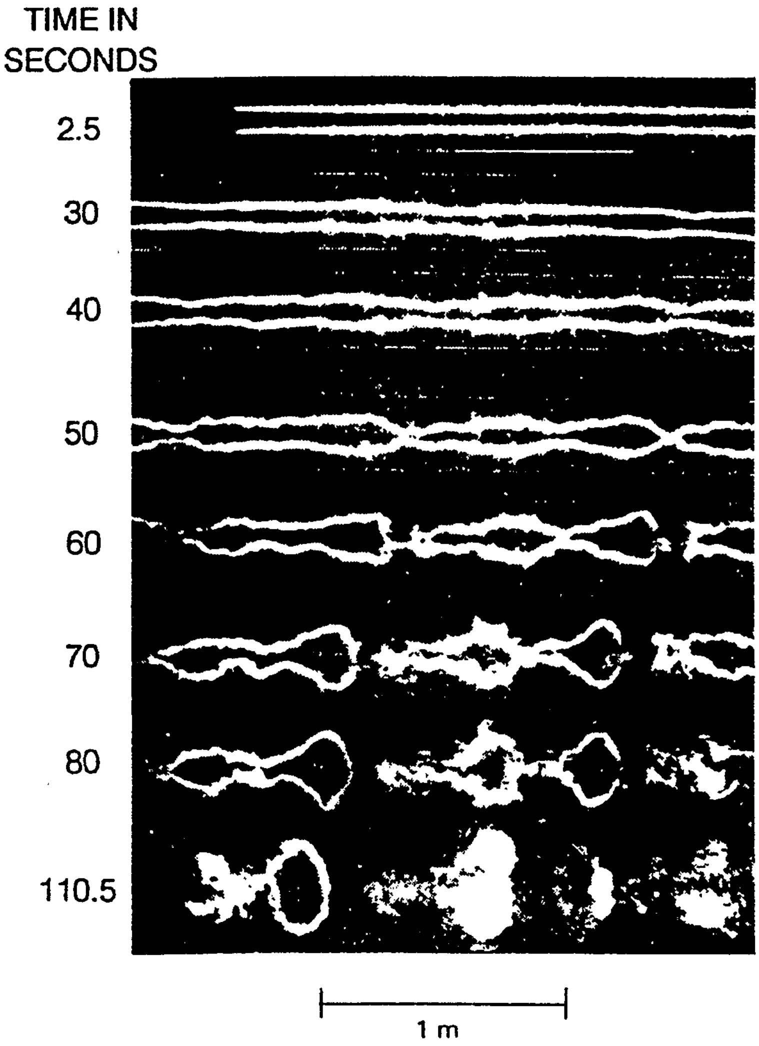


Figure 3. Development of a linking instability in a quiescent, neutrally stable environment. From Liu, 1991.[23]

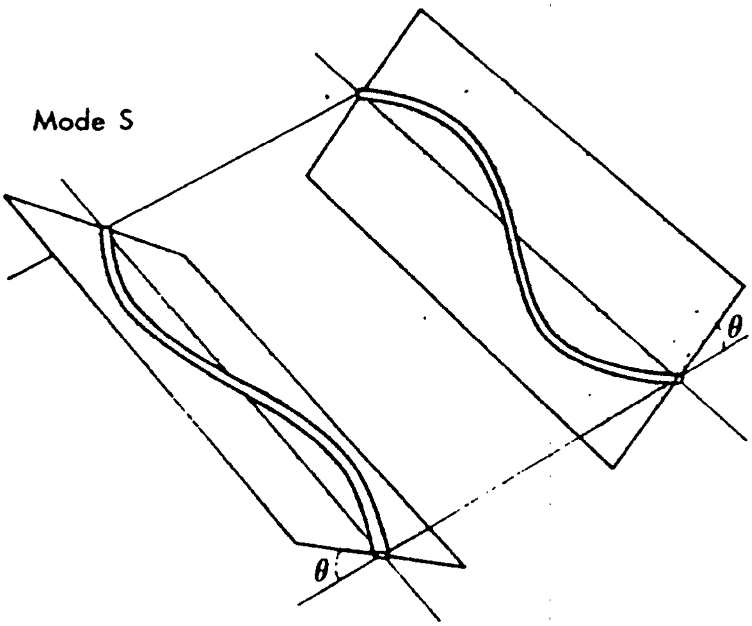


Figure 4. Mode shape of long-wavelength Crow instability. The perturbed vortices grow on planes inclined at an angle $\theta = 48°$ to the horizontal. From Crow, 1970.[4]

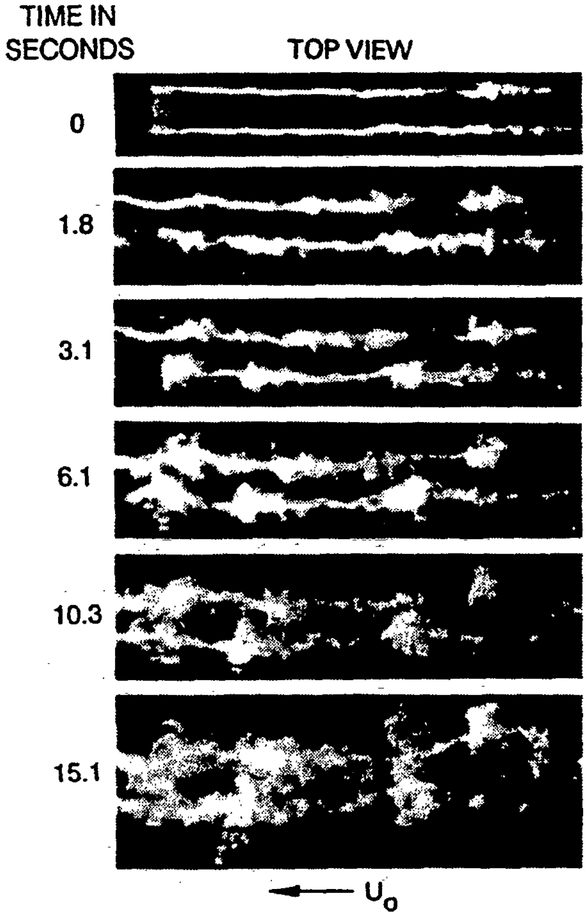


Figure 5. Development of vortex bursting in presence of stong ambient turbulence. From Liu, 1991.[23]

III. IMPORTANT FACTORS AFFECTING WAKE VORTEX ADVECTION AND DECAY

In the idealized case of a pair of two-dimensional inviscid line vortices of equal and opposite strength in a calm, neutrally stable environment far from boundaries, the vortices travel with constant velocity in the direction of the velocity along the centerline between them. In a real atmosphere, however, we must consider the effects of stratification, turbulence, wind and wind shear, and proximity to the ground. The effect of each of these factors is dependent on the strength, geometry, and internal turbulence of the initial vortices.

Properties of Initial Vortices

The properties of the initial vortex pair, including circulation, separation, and internal turbulence, are established by the aircraft wing design, its use of flaps, and its weight and airspeed. The generation of wingtip vortices is a direct consequence of the lift force.[11] Air flows around the end of the wings from the high-pressure region beneath to the low-pressure region above the wings, generating trailing vorticity with clockwise sense on the left wing and anti-clockwise sense on the right as observed from behind the aircraft.

A simplified model for predicting the properties of wake vortices from aircraft parameters was derived by Spreiter and Sacks.[12] According to this model, the vortex sheet behind an elliptically loaded wing of span s rolls up over a time $0.28(A_R/C_L)(s/V_0)$, where A_R is the aspect ratio of the wing, C_L is the lift coefficient, and V_0 is the aircraft speed. The circulation magnitude of the rolled-up vortices is $\Gamma_0 = (2/\pi)(sV_0)(C_L/A_R)$, their spacing is $b = s(\pi/4)$, and their core diameter is $c = 0.155s$.

More accurate models for deriving the structure of the wake vortices from the span-load distribution of a particular wing configuration, such as those incorporated into the UNIWAKE code developed for the Department of Transportation,[13] are based on a theory developed by Betz[14] and reintroduced by Donaldson.[15] The decay of wake vortices is strongly dependent on the positions of flaps and landing gear. Deployment of the landing gear on a B-747, for example, causes entrainment of low-velocity fluid into the vortices, preventing the growth of sinusoidal instabilities by increasing core size and decreasing vortex strength.[9] The merging of additional vortices from the flaps may considerably reduce the lifetime of wake vortices through large-scale disruption as discussed previously. Bilanin et al.[10] found the merging process to be quite sensitive to the locations and relative strengths of flap and wing vortices.

Atmospheric Stratification

As wake vortices descend through the atmosphere, the air entrained in the wake (usually modelled as an oval enclosing both vortices) is compressed adiabatically due to the increasing ambient pressure. If the lapse rate of the atmosphere is adiabatic, then the density of the air inside and outside the wake will be the same. If the lapse rate is not adiabatic, then the difference in density will result in a buoyant force on the wake. The static stability of the atmosphere is measured by the Brunt-Väisälä frequency, the oscillation frequency of a hypothetical displaced parcel of air,

$$N = \left[\frac{g}{\theta}\frac{d\theta}{dz}\right]^{1/2} \quad ,$$

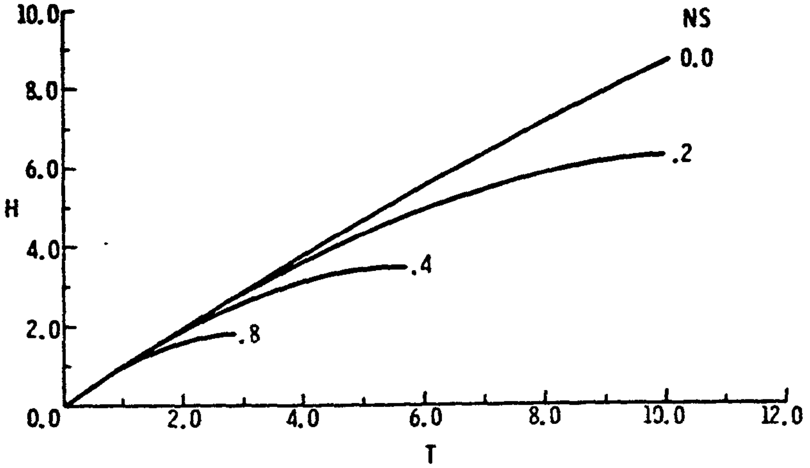
where θ is the potential temperature and g is acceleration due to gravity. For $N^2 > 0$, with a smaller temperature decrease with height than that of the adiabatic lapse rate (or a temperature inversion), the atmosphere is stable. For $N^2 < 0$, the atmosphere is unstable, and convective overturning is expected.

According to the above argument, an increase in atmospheric stability should cause the wake vortex pair to slow its rate of descent. However, disagreements about the proper assumptions to be used in theoretical and numerical models of this problem have resulted in conflicting predictions. An assumption that the rate of change of the impulse of a vortex pair is balanced by the buoyancy force led Scorer and Davenport[16] to conclude that the pair is accelerated downward and drawn closer together, with eventual detrainment of the accompanying fluid. Saffman[17] assumed constant separation between the vortices and constant shape of the volume containing the fluid moving with the pair. In this case, the vortex pair was found to slow down and then oscillate between two levels. The modelling of the surface of the entrained fluid by a vortex sheet was found by Hill[18] to result in initial slowing of the vortex pair followed by acceleration and detrainment, with the vortex separation decreasing throughout.

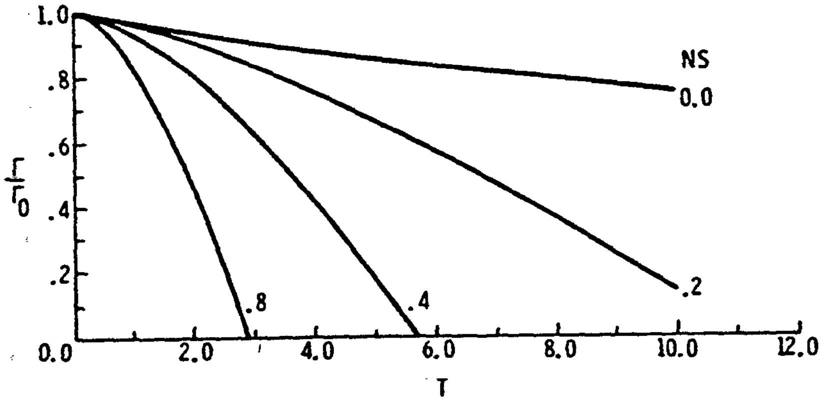
In contrast to the controversy among the analytical models, field and laboratory experiments clearly indicate that strong stratification slows the rate of descent of a vortex pair and shortens its lifespan through core bursting and the generation of countersign vorticity.[19] Good agreement with stratification experiments under low-turbulence conditions was obtained by a simple model proposed by Greene,[20] in which the rate of change of impulse per unit length is equated to the sum of viscous, buoyancy, and turbulence-generated viscous forces. The vortices are assumed to maintain a constant spacing, as observed in experiment, and the volume of fluid with oval cross-section entrained by the vortex pair is assumed to descend with velocity directly proportional to the circulation. According to this model the circulation is reduced to zero when the descent velocity of the wake has slowed to a stop. Greene argues that this point marks the demise of the wake vortices, since internal forces arising from a subsequent rise of the buoyant vortex pair would cause rapid expansion and disruption of the core. The wake descent and circulation decay predicted by this model are reproduced in Figure 6 for the case of no atmospheric turbulence. Greene observes that a change in lapse rate of only 1°C/100 m is sufficient to double the predicted wake lifetime from 2 to 4 minutes for a heavy jet.

Atmospheric Turbulence

Atmospheric turbulence strongly enhances vortex decay through transport of vorticity across streamlines and forcing of the Crow instability. Greene's semi-empirical model,[20] introduced in the previous section, shows that even light atmospheric turbulence causes rapid initial decay of circulation, accompanied by reduction of the descent rate of the vortex



a) Wake descent.



b) Circulation decay.

Figure 6. Effect of density stratification on wake motion and decay predicted in a quiescent atmosphere by Greene's semi-empirical model. The vertical axes are H, the distance of the wake downward from its initial position nondimensionalized by the vortex spacing b, and Γ/Γ_0, the circulation normalized by its initial value. The horizontal time axis, T, is nondimensionalized by b/V_0, where $V_0 = \Gamma_0/2\pi b$ is the initial wake descent speed. The parameter NS describes the stability of the atmosphere, with NS=0 representing neutral stability and NS=0.8 representing a strong inversion. For a heavy jet, NS=0.4 corresponds to a slight temperature increase with height of 0.25°/100m and NS=0.8 to about +4°/100m. From Greene, 1986.[19]

pair (Figure 7). An estimate of the time to vortex pair linking due to the Crow instability argues that this decay mechanism should dominate for higher turbulence intensities.

A series of flight experiments were carried out by Tombach[21] using a light aircraft under a variety of atmospheric stability and turbulence conditions. The lifespan of the vortex pair, as defined by the time to linking for the Crow instability or the time to a clear space in the smoke trail for vortex bursting, was strongly dependent on the turbulence level. Data points fell between the lines defined by $t = 15/\epsilon^{1/3}$ and $t = 70/\epsilon^{1/3}$, where ϵ is the turbulent energy dissipation rate. Bursting was the dominant mode of decay in these experiments, especially at low levels of turbulence, but the vortex lifetime was insensitive to whether decay was due to bursting or linking. Tombach found that the descent speed slowed as the vortex pair descended, in qualitative agreement with Greene.

Consensus has not yet been reached on the proper parameterization of the turbulent atmosphere. Crow and Bate[22] determined $\eta = (\epsilon b)^{1/3}/(\Gamma/2\pi b)$ to be an appropriate dimensionless measure of turbulence intensity, in agreement with the effects studied by Tombach. However, numerical studies by Bilanin et al.[10,23] suggest that the decay rate depends on the turbulent macroscale length Λ as well (Figure 8). The turbulent length scales were shown by Liu[24] to influence the dominant mechanism of vortex decay. In towing tank experiments with turbulence generated by grids of various size, the small grid (integral scales small compared with vortex separation) was found to promote vortex bursting over linking, with vortex lifespans in weak turbulence smaller by as much as a factor of four than those for which turbulence was generated by larger grids. Contrary to Tombach's results, Liu found linking to dominate at low levels of turbulence and bursting at high levels.

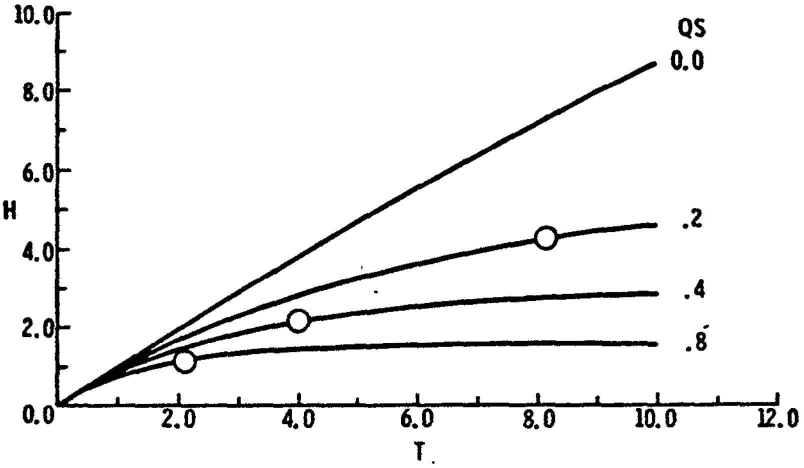
Cross-runway Wind Shear

The presence of wind shear, or a change in wind velocity with height ($\partial V/\partial z$), in the cross-runway direction significantly alters the behavior of the vortices. The vortex whose rotation is in the opposite sense as the wind shear is torn apart, as illustrated in Figure 9.[25] As this vortex loses strength, the greater circulation of its mate causes the plane of the vortex pair to tilt. Eventually the first vortex is destroyed, leaving as the survivor the vortex with rotation in the same sense as the shear. The lifetime of this solitary vortex may be considerable due to the lack of a mate to induce the Crow instability.

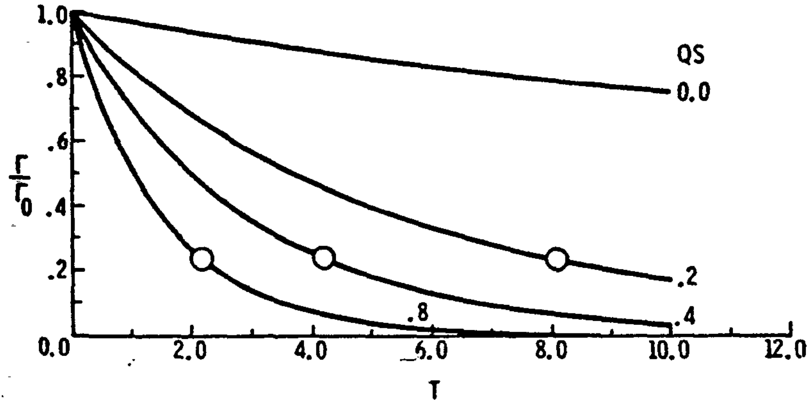
The long lives of such solitary vortices were noted in field experiments by MacCready[26] and Tombach[21], who reported lifetimes of 6-7 minutes and over 3 minutes respectively. Tombach also reported frequent rolling of the plane of the vortices, strong enough in some cases to rotate the vortex plane to vertical or beyond.

Using a numerical model which allows for the generation of turbulence, Bilanin et al.[23] show that the rolling moment induced on a following aircraft by the solitary vortex resulting from a cross shear may be considerably below that induced by a vortex pair in a calm atmosphere. They speculate, however, that this result may not hold under conditions when stable stratification suppresses turbulence.

The development of vortex pairs in the presence of shear has not been sufficiently studied to determine the sensitivity of behavior with the magnitude of the shear. Strong



a) Wake descent.



b) Circulation decay.

Figure 7. Effect of turbulence on wake motion and decay predicted in a neutrally stable atmosphere by Greene's model. Axes are the same as in Figure 6. The parameter QS measures the level of atmospheric turbulence. For light-to-moderate turbulence, QS∼0.4 for a heavy jet and ∼0.8 for a light aircraft. The effect of a given level of turbulence is greater on the weaker vortices generated by a light aircraft. From Greene, 1986.[19]

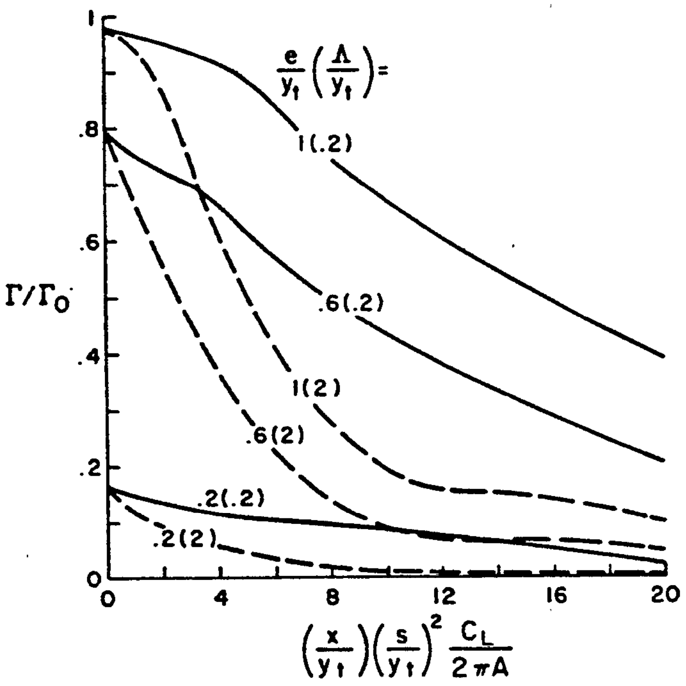


Figure 8. Decay of circulation for a turbulent atmosphere with fixed dissipation rate $\epsilon^{1/3}$. Note the sensitivity of decay with background turbulent macroscale length Λ (in parentheses) for the same values of e, the size of the contour box about which circulation is measured. The vertical axis is circulation Γ normalized by the initial halfplane circulation Γ_0, and the horizontal axis is distance from the aircraft along the streamwise x direction. Spatial variables are scaled by y_t, the distance from the wing centerline to the wingtip vortex. Other parameters in this plot are s, the wing semispan, C_L, the lift coefficient, and A, the aspect ratio. From Bilanin, Teske and Williamson, 1977.[9]

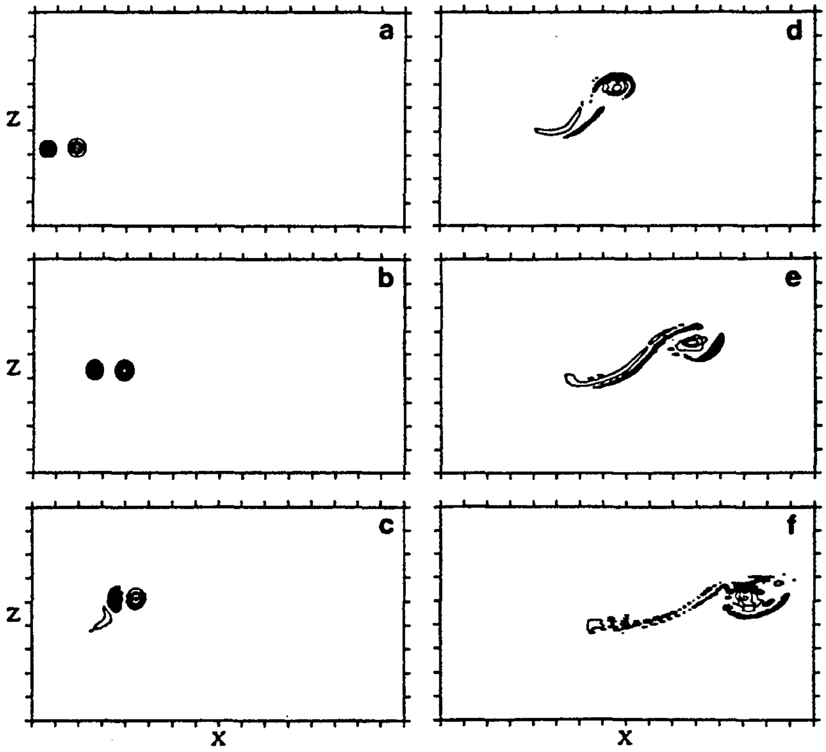


Figure 9. Contours of perturbation vorticity for a vortex pair evolving in the presence of high shear. The vortex that rotates in the opposite sense of the shear (on the left) is destroyed; the same-sense vortex survives as a solitary vortex. Note that the rotations of these vortices are in the opposite sense to actual wake vortices and cause the pair to rise rather than descend. From Robins and Delisi, 1990.[24]

effects have been observed for shear of magnitude $\beta = (\partial V/\partial z)(2\pi d^2/\Gamma_0) = 0.5$, where $d = b/2$ is the half spacing between vortices.[23] Note that the shear is scaled by one-quarter of the time for the vortices to descend by a distance equal to their spacing.

Ground Effects

As a descending vortex pair approaches the ground, the trajectories of the individual vortices are radically changed. In the inviscid limit, the vortices are predicted to follow hyperbolic paths, descending until they approach a distance of half their initial spacing ($b/2$) from the ground and then moving away from each other with speed equal to their sink rate far from boundaries. Observations show, however, that a vortex pair interacting with the ground plane rises after sinking to a point of closest approach (Figure 10).[24] This rebound phenomenon is explained by the generation of a weak secondary pair of vortices below and outside of the wake vortex pair as it approaches the ground, due to the viscous no-slip boundary condition (Figure 11).[27,23] The motion induced by these secondary vortices causes the wake vortex pair to separate and rise.

This explanation of rebound is well accepted over the alternate theory proposed by Barker and Crow,[28] in which rebound is attributed to the finite size of the vortex cores.

The movement of vortices away from each other in ground effect is important to the assessment of the effects of advective wind, since a cross wind equal to the speed of separation could cause a vortex to stall on the runway.[29] Figure 12 shows the vortex trajectory, its vertical and lateral position with time, and circulation decay predicted by Zheng and Ash using a numerical model.[30] The velocity of a vortex in ground effect can be estimated from these plots.

The viscous interaction of wake vortices with the ground was found by Bilanin et al.[23] to result in a large reduction of the rolling moment induced on a following aircraft through scrubbing, in which increased vortex separation and spread of vorticity reduces the vortex strength. Zheng and Ash found stable stratification to be particularly effective at confining and destroying vortices near the ground.

Cross-runway Advective Winds

The wind velocity in the cross-runway direction may advect a wake vortex into the path of another aircraft landing on the same or nearby runway. Knowledge of the cross-runway winds must be added to an understanding of the natural horizontal motions of the vortices (separating in ground effect, for example) to predict the location of each vortex with respect to air traffic.

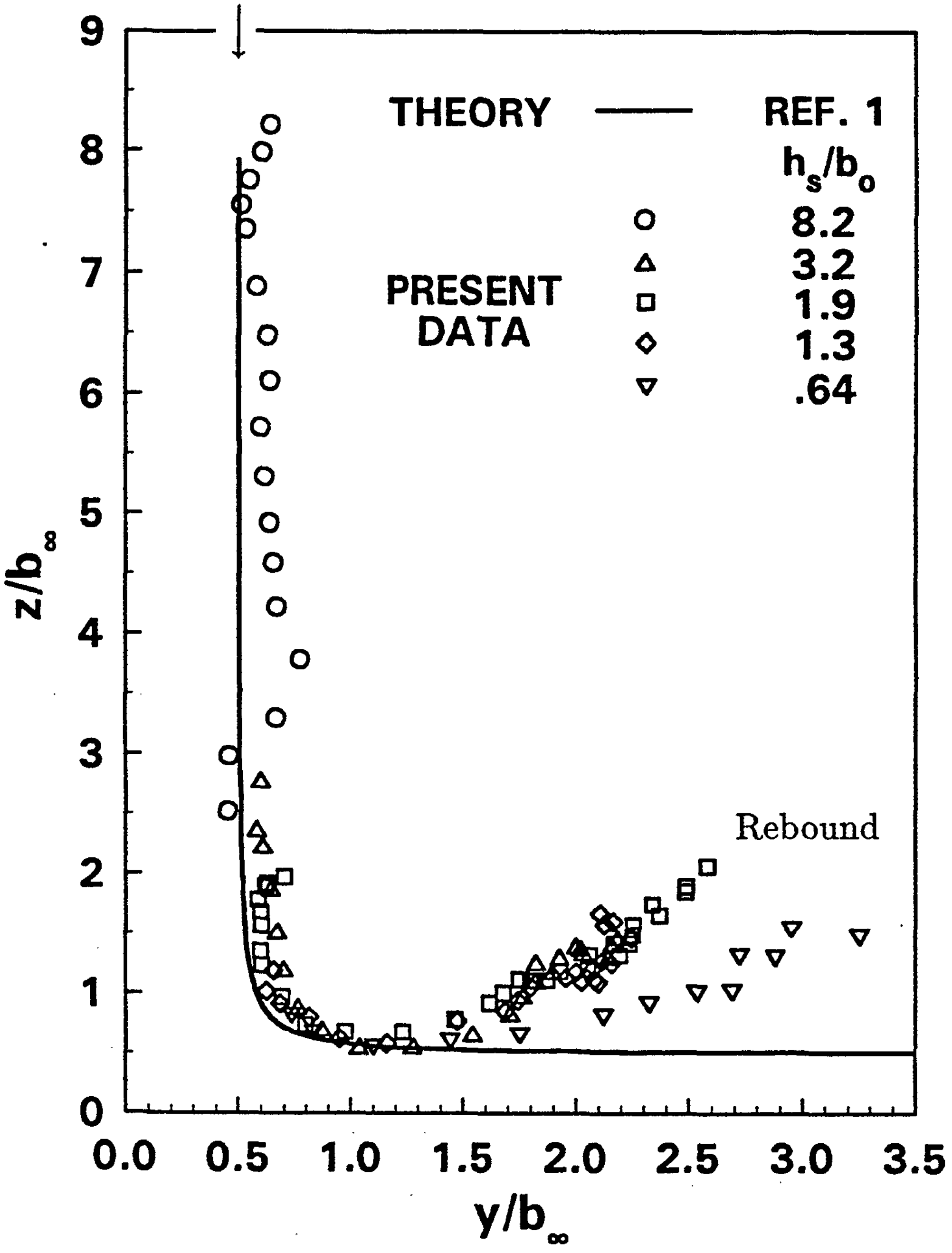


Figure 10. Trajectory of a vortex pair approaching the ground plane. Vertical axis is the distance from the ground and horizontal axis is the distance from the centerline between vortices, both normalized by b_∞, the asymptotic vortex spacing as $z \to \infty$. The vortices follow mirror image paths in the absence of other effects. The solid line is the hyperbolic trajectory predicted by the classical inviscid model. Data points show the rebound of vortex pairs in laboratory experiments. From Liu, 1991.[23]

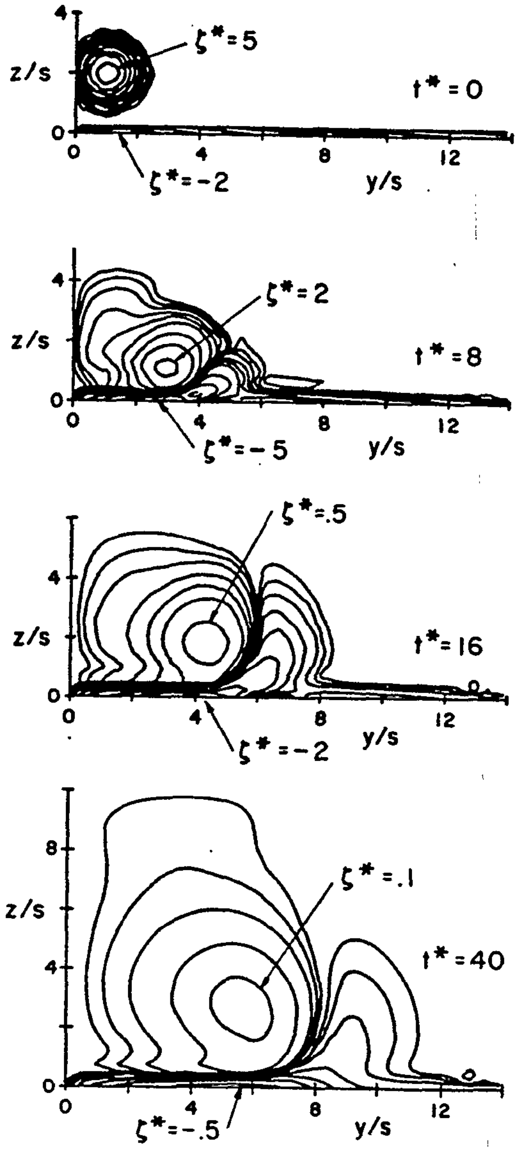


Figure 11. Vorticity contours for a vortex pair approaching the ground ($z/s = 0$). A secondary vortex of opposite sign generated below and outside the descending vortex induces an upward and outward motion on it, causing the rebound phenomenon. Note the spreading of vorticity (scrubbing) which greatly reduces the rolling moment hazard to the following aircraft. In this plot, z and y are normalized by s, half the vortex separation. From Bilanin, Teske and Hirsh, 1978.[22]

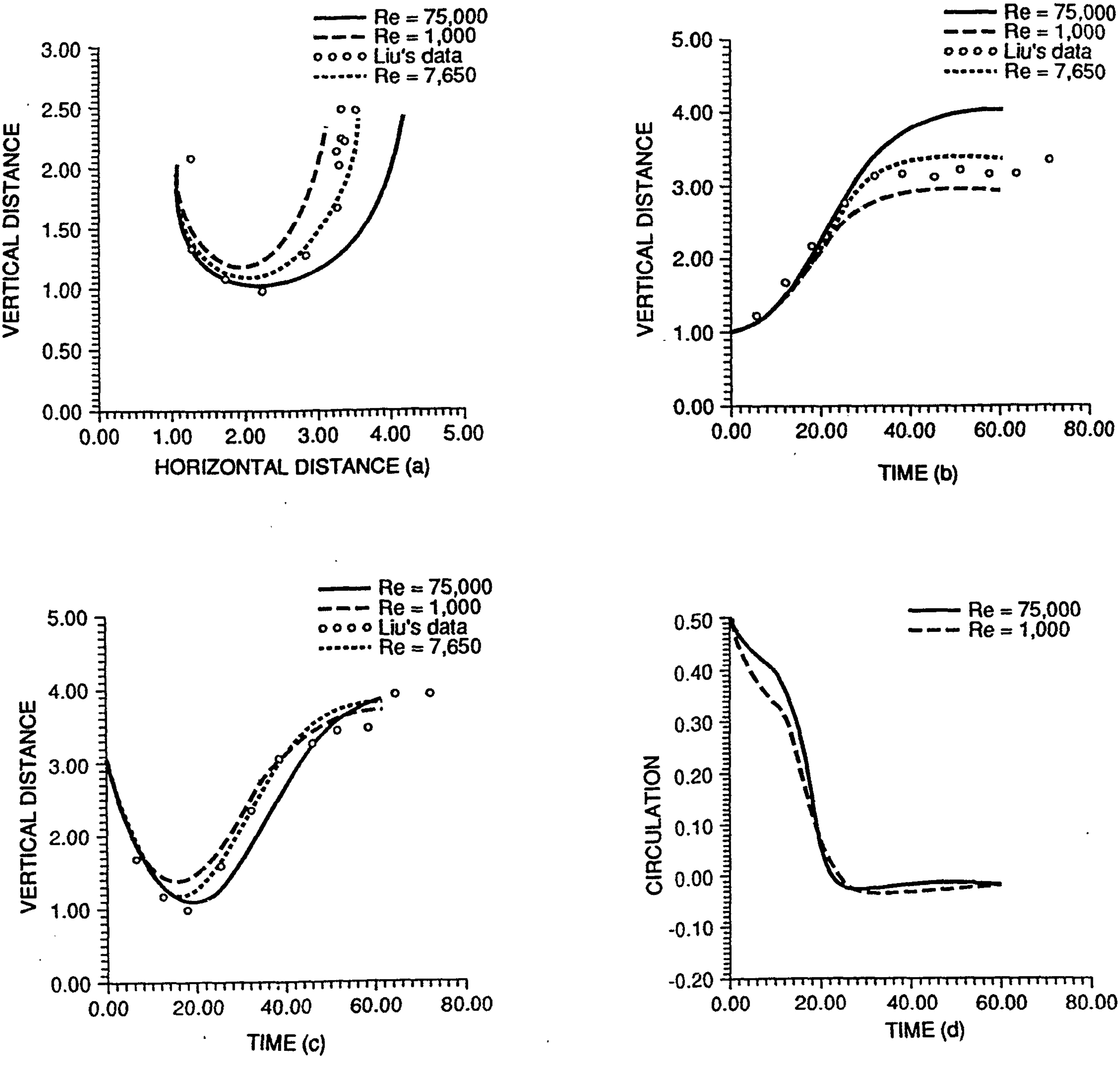


Figure 12. Computed behavior of a vortex pair in ground effect: (*a*) vortex trajectories (z vs. y), (*b*) lateral vortex position history (y vs. t), (*c*) vertical vortex position history (z vs. t), and (*d*) circulation decay (Γ vs. t). Distances are normalized by the initial vortex semispacing $d = b/2$, circulation by initial vortex circulation Γ_0, and time by d^2/Γ_0. The circulation is obtained by integrating vorticity over the half area used in the calculation, and the Reynolds number is $Re = \Gamma_0/\nu$, where ν is the kinematic viscosity. In the first three plots, numerical results are compared to laboratory experiments by Liu (circles identify data points). From Zheng and Ash, 1991.[28]

IV. AIRFIELD DATA SOURCES

Advances in the understanding of aircraft wakes over the last twenty years have clarified the measurements that would be most helpful in tracking and predicting their behavior. The most important information for a wake vortex prediction advisory product includes the following:

- Aircraft parameters to define the properties of the initial wake vortex pair, including initial vortex strength, location, separation, and internal turbulence.
- Temperature and humidity profile with height for determination of atmospheric stability.
- Velocity measurements to determine the speed and direction of the mean (advective) winds, the wind shear, and the atmospheric turbulence level and scale.

A vortex measurement and tracking capability to check the wake vortex model and provide data for its refinement will be necessary for initial product development and may be useful for safety monitoring.

The aircraft that have been collected into each of the three weight classes used in the IFR separation standards have widely varying wake vortex characteristics. Some aircraft tend to generate long-lived coherent vortices; others trail vortices with significant turbulence in their cores, which reduces their lifetimes considerably. The positions of flaps and landing gear also influence vortex lifetimes. The wingspan of the aircraft determines the vortex separation, and aircraft design and speed determine their strength (circulation). The flight path fixes the initial location of the vortices, including the proximity to the ground for determination of ground effects. Identification of aircraft type and other flight operation data, including altitude and speed, is obtainable from terminal air traffic control systems (such as the ARTS computer or the Center Traffic Automation System[31]). For maximum benefit in developing aircraft-specific vortex spacings, information available to the wake vortex advisory system model regarding each type of aircraft should include characteristics of the wake vortices generated under the appropriate flight conditions (e.g. in final approach).

The atmospheric stability was seen to be very important in the overall vortex dynamics and dissipation. Vertical temperature profiles should be measured carefully, given the sensitivity of vortex lifetime to a change in lapse rate as small as $1^\circ\mathrm{C}/100\,\mathrm{m}$ as reported by Greene (see Atmospheric Stratification in section III). The spatial resolution and maximum altitude required is unclear and depends on local gradients during operationally significant conditions and the maximum altitude at which vortex advisory service is required. A review of the literature on sounding profiles for various scientific experiments, including past wake vortex studies, is required. Temperature profiles can be obtained operationally by using data from a variety of sources, e.g.,

(i) surface sensors
(ii) aircraft measurements (e.g., ACARS data)
(iii) radio acoustical sounders (RASS)

Tall instrumented towers could be used at special test sites, although obstruction clearance criteria may significantly reduce the practicality of towers at major airports.

The average wind velocity as a function of height can be determined using the same sensors as used for temperature sensing and by use of Doppler weather radars (e.g. the Terminal Doppler Weather Radar (TDWR). Of particular interest is the component of wind in the cross-runway direction, which advects the vortices and causes shear effects, including the potential development of a long-lived solitary vortex. Here again, the vertical spatial resolution required will be dictated by the spatial scales of the vertical structure during operationally significant weather situations. Data from Doppler weather radar experiments (and high resolution experimental soundings by other approaches) should be analyzed to determine the required vertical resolution.

The characterization of atmospheric turbulence near the airfield is the most difficult measurement task. The decay rate and mechanism for wake vortex pairs has been found to be related not only to the turbulent eddy dissipation rate, ϵ, but also to the integral scale Λ. It is possible to relate ϵ to either the spatial spectra or the spectrum width of the velocity field measured by Doppler radar[32,33] in cases where the turbulence is well approximated by the classic Kolmogorov theory. However, the conditions for achieving this may not be met in many cases near the airport surface. The presence of debris from previous wake vortices and of other large-scale flow structures, such as those generated by nearby buildings, may clutter the airfield region in such a way that traditional assumptions of turbulence do not hold.

Determining the turbulent velocity scale q or turbulent spatial scale Λ is even more problematical due to our incomplete understanding of the nature of atmospheric turbulence. It may well be easier to determine conditions under which wake vortices will be long-lived than to predict the actual decay rate of vortices in the presence of atmospheric turbulence.

The focussing capabilities of the laser Doppler radar, such as discussed by Heinrichs et al.,[34] enable the acquisition and tracking of vortex cores. This would allow determination of vortex strength and location, including the distance of the vortex from the ground. The accumulation of aircraft wake vortex data over a long time period using a laser radar with wake vortex detection, tracking, and characterization capability would enable verification of the predictive model as it is developed and implemented. A major benefit of this proposed system would be to determine other primary influences on vortex behavior that have not been adequately studied; for example, the effects of rain, fog, and other weather conditions.

The growth of sinusoidal disturbances along the length of a vortex pair due to the Crow instability needs to be taken into account during vortex tracking. Ideally, the laser Doppler radar used for tracking will not only monitor the vortex pair as it passes overhead, but will also characterize the vortices along their length by scanning at selected angles. This procedure would avoid misinterpretation of vortex location and movement, provide knowledge of the decay mechanism under various conditions, and support predictions of vortex lifetime. Lateral and vertical excursions along each vortex before linking will be on the order of $b/2$ with a wavelength of about 6-7 wingspans. The amplitude of the Crow instability is a current topic of research at the NASA Langley Research Center.[35]

V. DISCUSSION

Field and laboratory experiments, theoretical analysis, and numerical models over the last twenty years have established that the behavior of aircraft wake vortices is strongly affected by several factors, including the attributes of the initial vortex as determined by the aircraft in flight, atmospheric stability and turbulence, advective and shear winds, and proximity to the ground. These major influences are summarized in Table 1, which also lists their primary effects and the airfield measurements that would enable their quantization.

In order to provide a useful tool for increasing throughput on runways, wake vortex strength and advection will need to be predicted over a time horizon of 15-30 minutes. This will give air traffic controllers sufficient time to space aircraft appropriately on final approach. Short-term weather forecasting at airports should have the capability of predicting winds, turbulence, and stratification over the necessary time frame in order to estimate wake vortex behavior from the models. The forecasting tool must also be able to judge conditions under which the short-term prediction is unreliable.

No single wake vortex model yet includes all factors contributing to their advection and disruption, although several models consider the combined effects of two or more factors. Atmospheric stratification and turbulence are included in the semi-empirical model of Greene.[20] Robins and Delisi[25] determine the evolution of a vortex pair as a function of the Richardson number, the ratio of stratification forces to shear forces. The effects of atmospheric stability and turbulence on the behavior of wake vortices near the ground plane has been studied by Zheng and Ash.[30] Brashears et al.[36] showed that the effect of wind shear on vortices in ground effect depends on magnitude, with weak shear causing higher rebound of the downwind vortex and strong shear higher rebound of the upwind vortex. Collection of further data on aircraft-generated wake vortices will improve our understanding of the interaction of multiple influences on wake vortex behavior.

This preliminary study does not address the relationship between wake vortex properties and the hazard experienced by following aircraft. There is some controversy over whether the lifetime of wake vortices is properly marked by linking and bursting events or whether sufficient coherent vorticity remains to constitute a hazard. This issue must be resolved in the development of a useful advisory tool for aircraft spacing.

Table 1. Summary of major influences on wake vortex behavior (LDWR = Laser Doppler Weather Radar)

Wake vortex factor	**How measured**	**Effect**
Aircraft Parameters		Initial vortex attributes
Type (wingspan, C_D, vortex characteristics)	Beacon, aircraft data	Initial strength, separation, core turbulence
Weight	Beacon	Initial strength
Speed	Beacon	Initial strength
Position	Beacon	Initial position
Flaps and landing gear		Core turbulence
Stratification (Lapse rate)	Temperature and humidity sensors	Decreased sink rate Increased decay rate
Turbulence	LDWR and anemometers for $\epsilon^{1/3}$ and Λ	Decreased sink rate Increased decay rate
Vertical Wind Shear	LDWR and anemometers	Solitary long-lived vortex
Ground effect	LDWR for vortex altitude	Rebound Travel along ground Increased decay rate
Advective winds	LDWR and anemometers	Travel along ground

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