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Reduction of Uncertainties in Prediction of Wake-Vortex Locations

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Lift-generated vortex wakes of subsonic transport aircraft are known to pose a rolling-moment hazard to in-trail following aircraft. Hazardous wake encounters are now avoided by maintaining in-trail separation distances that are larger than needed for other operational considerations. To increase airport capacity, considerable effort has been devoted to the development of techniques and procedures by which vortex wakes can be accurately located as a function of time, so that following aircraft can avoid them with less in-trail spacings. To improve the accuracy with which vortex wakes can be located, a study of the uncertainties associated with the determination of the time-dependent location of vortex wakes and on ways to reduce the uncertainties are reported. It is found that it is beneficial to reduce the uncertainties as much as possible by application of technology currently available for aircraft guidance and for measurement of wind velocity along the flight corridor by aircraft. It appears, however, that the growth in, and spreading of, the size of the hazardous region surrounding wake vortices is so rapid that it currently prevents sizeable increases in the capacity of runways at airports as they now operate. Therefore, if airport capacity is to be significantly increased, it is concluded that it will be necessary to also introduce some other system of sequential flight corridors such as the ones illustrated here, for example, to provide more lateral and vertical distance between the flight paths of aircraft so that wake encounters are avoided.

Nomenclature

A	=	cross-sectional area, ft^2(m^2)
B	=	breadth, ft(m)
b	=	wing span, ft(m)
b'	=	distance between vortex centers, ft(m)
C_L	=	lift coefficient, L/qS
C_l	=	rolling-moment coefficient, M/qSb
c	=	wing chord, ft(m)
D	=	depth, ft(m)
d	=	diameter, ft(m)
L	=	lift, lb(kg)
M	=	rolling moment, ft $\cdot$ lb($m - N$)
P	=	probability
q	=	$\rho U_\infty^2/2$, lb/ft^2(N/m^2)
S	=	wing planform area, ft^2(m^2)
t	=	time, s
U	=	velocity of aircraft, ft/s(m/s)
V, W	=	time-averaged velocities in y and z directions, ft/s(m/s)
v, w	=	maximum variations in y and z velocities, ft/s(m/s)
Wt	=	weight of aircraft, lb(kg)
X	=	distance in flight direction, ft(m)
Y	=	distance in spanwise direction, ft(m)
Z	=	distance in vertical direction, ft(m)
Γ	=	circulation or vortex strength, ft^2/s(m^2/s)
δ_a	=	aileron deflection, deg
ρ	=	air density, slugs/ft^3(kg/m^3)

Subscripts

beg	=	beginning of approach corridor
enc	=	wake encounter
f	=	following aircraft
foll	=	flight corridor for following aircraft
g	=	wake-generating aircraft
hz	=	hazardous region of wake
m	=	maximum
o	=	centerline
ovrlp	=	overlap region of $A_{\rm foll}$ and $A_{\rm wnd}$
slf	=	self-induced
stn	=	wake station
td	=	touchdown
vr	=	vortex
wk	=	wake
∞	=	freesteam condition

Introduction

AIRCRAFT stay airborne by imparting downward momentum into the air surrounding their wings. Because the wingspans of aircraft are finite, the outboard edges of the downward moving air roll up into a pair of counter-rotating vortices. Because the weight of subsonic transport aircraft is usually over 100,000 lb, the volume and energy of the downward moving and rotating air masses can be considerable. These lift-generated vortices remain hazardous for several minutes before their energetic parts disperse enough so that they no longer pose a rolling-moment hazard. Of course, after some 2–5 min, depending on the turbulent state of the atmosphere, the energetic parts of the vortices disperse enough that their flowfields blend with the surrounding atmosphere. Airport safety and, therefore, capacity are affected after the vortex pairs are first generated and during the early part of the dispersion process. In fact, if a following aircraft encounters one of the two most energetic parts of a wake, its flight path may be considerably disturbed and perhaps disastrously compromised. The seriousness of possible in-trail wake encounters led to the development of in-trail spacing guidelines between aircraft during approach and departure from airports to make wake encounters unlikely. Even though the separation guidelines are effective, they slow the flow of air traffic, which lowers the capacity of airports. The purpose of the present study is to determine what specifications on the technology of air traffic management are

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required to remove the hazard posed by vortex wakes as the limiting factor on the capacity of airports. Throughout the paper, reference will occasionally be made to 1-min spacings between in-trail aircraft because, for a number of years, the 1-min figure served as a goal for the NASA wake-vortex program.[1,2]

As background information, one of the goals of the NASA/ Federal Aviation Administration (FAA) 1970s research program was to develop aerodynamic modifications to wake-generating aircraft that would reduce or alleviate to a tolerable level the rolling-moment hazard posed by vortex wakes, for example, see Wood[1] and Rossow.[2] These research efforts did provide several wing-design concepts that accelerate the dispersion of the intense parts of vortex wakes. Because the efficiency of the wake-generating aircraft is degraded by the required aircraft modifications, none of the concepts have so far been adopted as a solution.[2] It remains, therefore, that if airport capacity is to be increased, efficient and safe wake-vortex avoidance techniques need to be developed.

In addition to wake-alleviation studies, a parallel and much larger research effort was directed at the measurement of the persistence of lift-generated vortices shed by aircraft. Measurements were not only carried out at altitude,[3] but also on aircraft as they arrive at and depart from selected airports, for example, see Burnham and Hallock,[4] Rudis et al.,[5] Burnham,[6] Hallock and Burnham,[7] and Abramson and Burnham.[8] The information obtained by observation of vortex wakes, and from analysis, led to the development of techniques that suggested ways for aircraft to avoid vortex wakes in the airport environment, for example, see Wood,[1] Burnham and Hallock,[9] Spitzer et al.,[10] Wood,[11] Hallock,[12] Hinton,[13−15] Vicroy et al.,[16] Proctor,[17] and Posluns.[18] Most of the research efforts concentrated on methods that make only moderate changes in approach and departure procedures currently in use at airports and not necessarily in the instrumentation used to conduct the operations.

The depth of the difficulty associated with avoidance of wake vortices is illustrated by an interesting avoidance technique developed by the Volpe Transportation Systems Center in Cambridge, Massachusetts in the 1970s, for example, see Spitzer et al.,[10] Wood,[1,11] and Hallock.[12] The method developed a wind ellipse that was based on a large database obtained at various airports. Whenever the wind magnitude in a given direction was such that a vector representation lay outside of the wind ellipse, it was predicted that in-trail separation distances could be safely reduced to 1 min. That is, the experimental data accumulated indicated that a wind of that magnitude and direction is sufficiently strong to either sweep away, or to disperse, vortex wakes in less than 1 min. The method was not adopted, however, because the required decision-making process increased the work load for air traffic controllers to an unacceptable level.

Another approach to the wake-vortex avoidance problem is currently being developed by NASA Langley Research Center. The method utilizes items such as long-term predictions of the state of the atmosphere, and any impact that atmospheric structure might have on the transport and decomposition of lift-generated vortex wakes in the airport environment.[13−15] Efforts of this kind throughout the world are described in the proceedings of a recent conference on the subject of wake-vortex avoidance.[18] Other explorations and recommendations for wake-vortex avoidance have been made to increase the safety and to simplify current operating procedures for landing.[2,19,20]

The goal of each of the foregoing programs is to develop safe and efficient wake-vortex avoidance techniques and procedures so that aircraft can proceed along approach flight corridors with in-trail separation distances that are constrained by factors other than a wake-vortex hazard. Any satisfactory system will no doubt require that the location of vortex wakes be accurately and reliably known so that assurance can be given to following aircraft that the flight corridor to be used does not contain a wake vortex.

The primary purpose of this study is to determine what specifications must be placed on the instrumentation onboard aircraft and on the technology used for air traffic management at airports to remove the hazard posed by vortex wakes as the limiting factor on airport capacity. At this time, it appears that the best way to accomplish such a goal is to have aircraft avoid vortex wakes. If avoidance is to be accomplished, a method must be developed that keeps accurate account of the region within which lift-generated vortex wakes are reliably known to be located. To better understand the avoidance process, a computer program was developed to indicate how various uncertainties affect the accuracy of the prediction of the location of vortex wakes as a function of time. The work reported in this paper extends previous work[19] by including a better representation[20] of the spreading and growth rate of the hazardous region posed by vortex wakes, and by indicating various corridor sequences that may lead improved wake-vortex avoidance capability.

Factors that Affect Wake Motion

The parameters that affect the motion of lift-generated vortex wakes shed by aircraft, and that are considered to have significant uncertainties, are 1) location of wake-generating aircraft because that is where vortex wakes begin their time history, 2) size and location of wake-hazardous region because that is what must be avoided, 3) self-induced descent velocity to monitor the downward movement of wakes, 4) wind velocity and its time variations because they convect and disperse vortex wakes, and 5) location of following aircraft, so that it can be directed along a flight path that does not intersect a wake-hazardous region.

Note that the uncertainty as to when a vortex wake is nonhazardous is not listed, even though considerable uncertainty exists. To bypass the uncertainty associated with wake decay or dispersion, it is simply assumed that the region surrounding the vortex pair is hazardous for 2–5 min after it was generated and then becomes harmless, as far as rolling-moment hazard is concerned. In addition, the relative sizes of the aircraft involved is not mentioned because the computer program is set up to analyze various situations with any set of aircraft combinations presently in the transport fleet.

Time is used rather than distance between in-trail aircraft because vortices are nearly stationary relative to the air in which they are embedded. As a consequence, vortex dispersion and motion depends mostly on time and not on distance between aircraft. To pose a tractable problem, the material in this paper was limited to those portions of a single approach flight corridor where vortex motions due to the ground plane are negligible. That is, only the motion of vortex wakes from the time that aircraft enter an approach flight corridor, until ground effect becomes important, are considered. After each of the foregoing uncertainties are discussed, suggestions are made as to how they might be reduced to a level two where high-capacity avoidance systems might be developed.

Method Used to Capture Uncertainties

The initial location of a vortex pair, and the hazardous region it generates, depends on the location of the wake-generating aircraft at the time a particular wake segment is deposited. Hence, any uncertainty in the location of the aircraft becomes an uncertainty in the initial and subsequent locations of the wake. The analysis method used here begins with the uncertainty in location of the centerline of the wake-generating aircraft within the finite, but often large, cross-sectional sizes of flight corridors used while on approach and departure from airports. All possible locations of vortex wakes are then assumed to be contained within the boundaries of a number of so-called wake stations along the flight corridor, as illustrated in Fig. 1. When the instrument landing system (ILS) is being simulated, the entire approach corridor is represented by a cone of square, or rectangular, cross section. Wake stations are then located at a number of places along the corridor (Fig. 1).

In the analysis, and in Fig. 1, the origin of the coordinate system being used is located at the touchdown point for the aircraft, with the positive x direction pointed along the runway from the touchdown point. The y coordinate extends to the left, or port direction of the touchdown point, and z is in the upward or vertical direction, to maintain proper vector orientation between axes. As a consequence of the coordinate system that was chosen, the flight corridor extends along the negative x axis from the touchdown point to the entry point for aircraft at the elevated open end of the cone that represents the approach corridor. The first wake station is located at the large open end of the flight corridor where aircraft enter, and wake stations

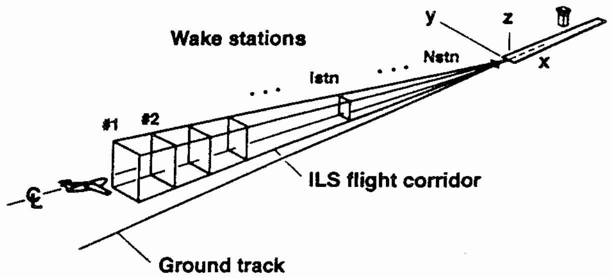


Fig. 1 Arrangement of aircraft, wake stations, and runway used to analyze uncertainties associated with vortex-wake locations; flight corridor for ILS.

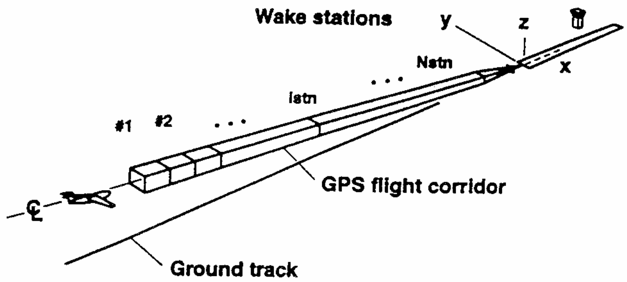


Fig. 2 Wake stations, etc., when flight corridor is based on GPSS.

are generated in sequence as the wake-generating aircraft passes through the flight corridor. The last station, N_{stn}, is located just before touchdown. Intermediate stations are labeled I_{stn}. The minimum spacing between wake stations is based on the time needed to obtain an accurate location of the wake-generating aircraft and to measure the velocity components of the winds in the region of that wake station[19] estimated at 1 s or more. Even though the time increment between stations may be constant, the distance along the corridor between the stations may not be equal because the aircraft velocity along the approach corridor may not be constant.

In the cases analyzed here, it is assumed that the centerline of the flight corridor is located along a line that begins at a distance from touchdown at $x_{beg} = -20$ n mile. The elevation of the centerline of the flight corridor is determined by the angle of the flight corridor relative to the horizontal and on the number of segments along its length. A distance of 20 n mile was chosen because, at that distance, a 3-deg glide slope produces a centerline height above the runway surface of $z_{beg} = 6400$ ft. If multiple-segment flight corridors are used, an even higher elevation is produced at the entry point to the flight corridor. In this way, should an aircraft encounter a vortex wake at or before the entry point and suffer a large change in flight orientation enough altitude should be available to recover safely.

The real-time analysis of wake location uses the boundaries of each wake station to enclose all possible locations of a vortex wake, including any uncertainties associated with its time history. That is, the flight corridor remains fixed in space, but the boundaries of the wake stations move with time so that the vortex wake of the wake-generating aircraft being considered is always known to be entirely within the region defined by the wake-station boundaries. It is not that the wake-station boundaries restrain the motion, but that the boundaries are moved with time so that the wake-station boundary always encompasses the entire region where any part of the vortices can reliably be found. The reason for designing such a wake station is that, if the interior of all of the wake stations is avoided by a following aircraft, the likelihood of a wake-vortex encounter is negligible. The following subsections describe how the wake-station boundaries are moved in the computations in response to various influences (and their uncertainties) that move and enlarge vortex wakes.

Uncertainty in Locating Wake-Generating Aircraft

During instrument flight rules at airports, aircraft are constrained to fly, in-trail style, within flight corridors while on approach to a runway for touchdown. A conically shaped corridor with square cross section, and vertex angles of 3 deg in both the vertical and horizontal directions, is used to represent the approach corridor defined by the ILS. As mentioned before, the apex of the square cone is located at the touchdown point, with the cone centerline elevated at 3 deg so that it coincides with the glide slope of aircraft on approach. As a consequence, the cross-sectional area of the approach corridor is small near touchdown, but far from the runway near the corridor entry station, the cross section of the approach corridor becomes very large (Fig. 1). Because aircraft can fly anywhere they wish inside an approach corridor, the location of an aircraft on approach, and the beginning location of its wake, have an uncertainty that is equal to the cross-sectional size of the corridor.

Two types of approach flight corridors are considered. The first one is representative of the ILS that is now in common use (Fig. 1). As discussed, the ILS flight corridor has the shape of a square cone with its apex at touchdown. Although the interior angles of the cone are somewhat arbitrary, the examples to follow use half-angles of 1.5 deg in both the vertical and the horizontal directions, and the centerline of the cone is taken as 3 deg above the horizontal, that is, a centerline glide slope of -3 deg.

The second approach flight corridor is based on a guidance system like the global positioning satellite system (GPS system, or GPSS) (Fig. 2). A GPS-based system allows the shape of the corridor to be arbitrary within wide limits. In principal, the flight corridor may be curved along its centerline, and/or the shape of its cross section may be irregular along the flight path. If the shape of a flight corridor is more complicated than simply straight, and rectangular in cross section, the analysis procedures are also more complex and error prone.

No matter which type of flight corridor is used, note that the centerline, and not necessarily the entire aircraft, is constrained within the flight corridor. Therefore, certain parts of the aircraft, and its vortex wake, may protrude outside of its flight corridor, especially when an aircraft is flying along side or near to a boundary of the corridor. To include those possibilities, when wake-encounter probability is calculated, the wake-station boundaries are adjusted outwardly so that the entire cross section of the hazardous region of the vortex wake, including uncertainties, are within the boundaries of each wake station.

Uncertainties in Wake-Hazardous Region

Because wake avoidance is the desired outcome of the study, it is necessary to define just what is to be avoided. As expected, the hazardous region associated with a lift-generated wake does not have sharp, definite boundaries, but fades in intensity as the distance from the vortex centers increases. In general, the boundaries of the region to be avoided during the early stages of wake decay are complicated by the vortices that can induce vertical and lateral loads that cause lifting, yawing, and pitching motions on an encountering aircraft throughout much of the active region of the wake. Each of these vortex-induced motions has its own set of regions that are hazardous under some circumstance. However, of these induced forces and moments, the most hazardous feature of the wake during in-trail flight procedures used during approach to an airport is an overpowering rolling moment near the center of a vortex. For this reason, the only hazardous region considered here is the one identified with wake-induced rolling moments.

Before Wake Instabilities Occur

An estimate of the initial size of the hazardous region posed by a vortex pair due to vortex-induced rolling moment has been determined experimentally and theoretically.[2] The experimental measurements were obtained with the large wind tunnels at NASA Ames Research Center, and the theoretical estimates were made with a modified strip theory, which agrees well with vortex-lattice theory.[2] Both indicate that during the early stages of wake decay, the wake-induced rolling moment on a following wing in the vicinity of a vortex wake is well represented by lines of constant rolling-moment coefficient as shown in Fig. 3 for the entire wake.[2,19] The center of the vortex wake, and not the center of the wake-generating aircraft, is located at the center or origin in Fig. 3. The computations are presented for a lift coefficient on the wake-generating aircraft of $C_{Lg} = 1.5$ and for a ratio of the span of the following

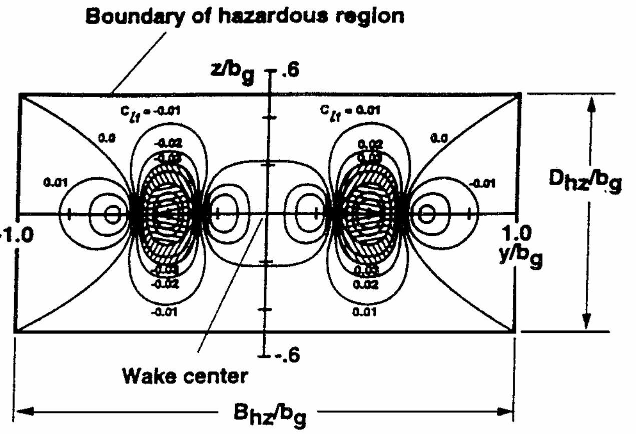


Fig. 3 Contours of constant wake-induced rolling-moment coefficient[19] to define boundary of hazardous region outside of which $|C_{lf}| < 0.01$, $C_{Lg} = 1.5$, and $b_f/b_g = 0.29$; vortex-induced overpowering rolling moments occur when centerline of following aircraft is in cross-hatched region.

wing to that of the generating wing of $b_f/b_g = 0.29$; For example, a wake-generating aircraft with a wing span of about 200 ft and a following aircraft with a wing span of about 60 ft. Each point on the various contours represents the location of the centerline of the following or encountering aircraft relative to the centerline of the vortex wake. The wake at this stage of its history is primarily composed of a vortex pair that is symmetrical above and below the vortex centers (located at $y/b_g = 0.4$, $z/b_g = 0.0$) and antisymmetrical port and starboard.

The contour lines presented in Fig. 3 define the hazardous boundary as two spanlengths in width and one in height. The choice of such a boundary begins with the observation that the maximum aileron-induced rolling moment is typically $|C_{l\delta am}| \approx 0.06$ for subsonic transports.[2] Inside the cross-hatched regions around the vortex centers in Fig. 3, the wake-induced rolling moments exceed the aileron-induced capability of the encountering aircraft. Therefore, if a following aircraft should encounter a cross-hatched region for a significant period of time, for example, several seconds, it would be unable to cope with the encounter. However, outside of the rectangular region defined as the wake-hazardous region, it is estimated that the encountering aircraft has enough roll control power for the ailerons to cope with, and to recover from, any vortex-induced roll excursion. To be conservative, a rectangular boundary was placed around, and well outside of, all of the 0.01 contours of wake-induced rolling moment. The rectangular box is drawn so that, if the centerline of a following aircraft is always outside of the box, the presence of the vortex wake inside the box would be barely perceptible. Throughout the study, it is assumed that the initial size of the hazardous region is two wingspans in breadth, and one wingspan in depth, for all sizes of wake-generating aircraft, and independent of the size of the following aircraft.

Note that an encounter with the hazardous region does not necessarily mean that overpowering rolling moments will be experienced. Rather, the encounter must be with one of the two small cross-hatched regions inside the hazardous region near the vortex centers, where intense, vortex-induced overpowering rolling moments are predicted. Based on the ratio of the entire area of the hazardous region to that where intense rolling moments are induced by a vortex (Fig. 3), an encounter with a vortex core is estimated to be about 0.08 times as likely as the probability of an encounter with any part of the hazardous region.

During and After Wake Instabilities

As vortex wakes age, shortwave (a fraction of a wing span) and longwave (several wing spans or more) instabilities occur that spread and disorganize the coherent structure of the vortex pair.[21–26] These instabilities are regularly observed in condensation trails shed by aircraft at cruise altitudes[20] because, during cruise, aircraft are in a low drag configuration, which encourages the instabilities. In support of the observed connection between the shortwave instability, and the fluid dynamics and wake spreading that follows, are some observations and computations made by Thomas and Auerbach,[21] Crouch,[22] Leweke and Williamson,[23] Laporte et al.,[24] and Holzaepfel et al.[25] that appear to simulate the circumferential striations observed in the condensation wakes of aircraft at cruise altitudes.[20] It is, therefore, surmised that vortices are first dispersed by a shortwave or elliptic instability, as described by Thomas and Auerbach[21] and Leweke and Williamson.[23] The shortwave instability appears to cause the outer parts of vortices to spread rapidly during the early stages of wake decay, but it is not certain what effect it has on the overall dispersion of the hazard posed by a vortex pair.[20]

Destructive mixing of the coherent structure of the vortex pair appears not to take place until the large-scale (or Crow[26]) instability occurs. The ultimate formation of irregularly shaped vortex loops brings about spreading of the wake over at least several wingspans both vertically and laterally to the flight direction. The resulting redistribution of the energetic parts of the wake very effectively reduces the rolling-moment hazard to a negligible level.[20] Thereafter, the wake appears to be benign for in-trail penetrations, and continues to spread. It must be remembered, however, that even though the wake no longer poses a coherent rolling-moment hazard during in-trail wake penetrations, it does continue to pose a vertical loads hazard if across-trail penetrations are made.[20]

Another mechanism for wake spreading comes about when they are near the ground. Fluid dynamic friction of the vortex flowfield with the ground and any atmospheric eddys from thermal activity and the wind increase the rate of dispersion of vortex wakes when they are in the lower parts of approach corridors. Because the foregoing sources vary considerably with time of day, altitude, wind conditions, etc., wake mixing cannot be relied on in wake-vortex avoidance procedures. The large uncertainties in wake-mixing processes indicate that more statistical observations are needed to model satisfactorily or predict wake dynamics and dispersion due to the presence of the ground plane.

For the foregoing reasons, the rectangular hazardous region ($= 2b_g x b_g$) described in Fig. 3 applies only to the early stages of the life of lift-generated wakes. To account for the cross-sectional area added to the hazardous region by the sinuous motion of the vortex cores and the instabilities, the region to be avoided is enlarged by amounts suggested in Fig. 4. In the absence of corresponding data for wakes shed in approach corridors, it is assumed that the spreading rate of vortex wakes with time is approximately the same in approach corridors as observed in condensation wakes behind aircraft at cruise altitudes.[20] Data obtained at cruise altitude are also approximate, because, in the data taking process, it was not possible to identify clearly whether wake growth with time was uniform in all directions, or greater in any one direction, for example, in the direction of the longwave, or Crow,[26] instability, which is mostly downward. Therefore, the enlargement of the wake cross section with time will be approximated as the same amount in the lateral and vertical directions and proportional to $t^{1/2}$, as indicated in Fig. 4.

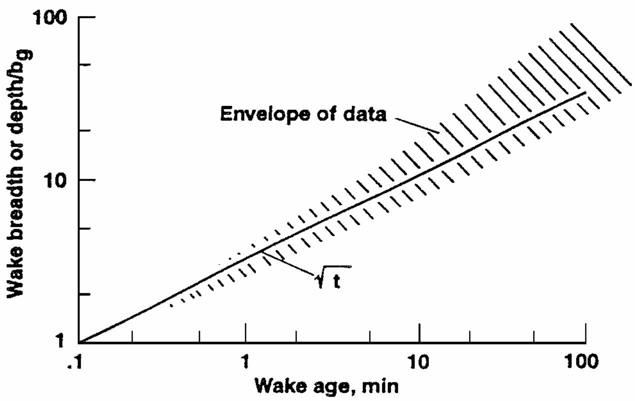


Fig. 4 Approximate breadth and depth dimensions of condensation wakes as a function of time as measured behind aircraft at cruise altitudes.[20]

The long-term spread of the wake can then be written in equation form as

$$d_{\mathrm{wk}}/b_g = C_{\mathrm{inst}}(\Delta t)^{\frac{1}{2}} \tag{1}$$

where d_{wk} is the effective diameter of the wake and C_{inst} is the proportionality factor that converts time into wake spreading. Based on Fig. 4, the time-averaged value for wake spreading during the first minute of existence is three wingspans per minute, and the maximum spreading rate is about four wingspans per minute. Because a conservative value is preferred and, when time is converted from minutes to seconds, the proportionality constant becomes

$$C_{\mathrm{inst}} = 4.0\big/\sqrt{60} \approx 0.5 \tag{2}$$

As the various elements of the wake disperse with time, the energy in the wake is redistributed, causing the velocity magnitudes to diminish.

To prevent an underestimate of wake size, the cross-sectional dimensions of the hazardous region will be taken as the larger of the two quantities given by two wingspans wide by one wingspan deep, or by Eqs. (1) and (2). Therefore, in the evaluation of probability of wake encounter, the area of the hazardous region is defined as a region two spans in breadth and one in depth,

$$A_{\mathrm{hz}} = 2b_g^2 \text{ ft}^2, \qquad \Delta t \le \sqrt{\pi/8} \text{ s} \tag{3a}$$

or, if the age of the wake exceeds $\sqrt{(\pi/8)}$ s, the area of the hazardous region is given by

$$A_{\mathrm{hz}} = (\pi/8)b_g^2\Delta t, \qquad \Delta t \ge \sqrt{\pi/8} \text{ s} \tag{3b}$$

Self-Induced Downward Motion of Vortex Pair

The self-induced downward velocity of a vortex pair depends on the spanwise distribution of the loading on the wake-generating wing and on the total lift of the wing. The downward or descent velocity of the vortex centers (and, consequently, their hazardous regions) for a specific aircraft depends on its flight velocity, altitude, weight, and slat and flap arrangement for the span loading. Because in steady flight the lift on the wing equals the weight of the aircraft, the circulation in the vortex is estimated as

$$\Gamma/b_g U_\infty = \tfrac{1}{2}(b_g/b'_g)(C_{Lg}/AR_g) \tag{4}$$

The time-averaged downward velocity of the vortex pair is then given by $W_{\mathrm{slf}} = -\Gamma/2\pi b'_g$, where Γ is the centerline circulation on the wing of the wake-generating aircraft and b'_g is the spanwise distance between the vortex centers. Combination of these equations yields

$$W_{\mathrm{slf}}/U_\infty = -(1/4\pi)(b_g/b'_g)^2(C_{Lg}/AR_g) \tag{5}$$

where W_{slf} is the self-induced velocity of the vortex pair, which will be negative when the lift is positive.

It is found that size and weight differences in subsonic transports cause the downward velocities of their trailing vortex wakes to range from several feet per second for commuter-type aircraft, up to about 10 ft/s for larger aircraft. In fact, the weight of a given airplane changes throughout its flight from a maximum at takeoff to a minimum at landing. To provide a conservative and yet realistic estimate of the self-induced downward velocity, a value is calculated for each aircraft based on both the empty and maximum landing weights. The time-averaged value W_{slf} is then determined as the average of the two quantities and the uncertainty as one-half of their difference, $w_{\mathrm{slf}} = \Delta W_{\mathrm{slf}}/2$. Upper case letters are used to denote time-averaged values and lower case to denote uncertainty values. Such an estimate is certainly conservative, but because the descent velocities are small, any overstatement of value does not significantly change the conclusions presented here.

The side boundaries of the wake station need not move because the self-induced wake motion is only downward, as long as the wake is not near the ground. The uncertainty in the self-induced velocity is taken as upward on the upper boundary and as negative on the lower boundary of a wake station (Fig. 5). In this way, the uncertainty in downward velocity reduces the downward velocity of the upper boundary and increases the velocity of the lower boundary, causing the vertical extent of the wake station to increase with time.

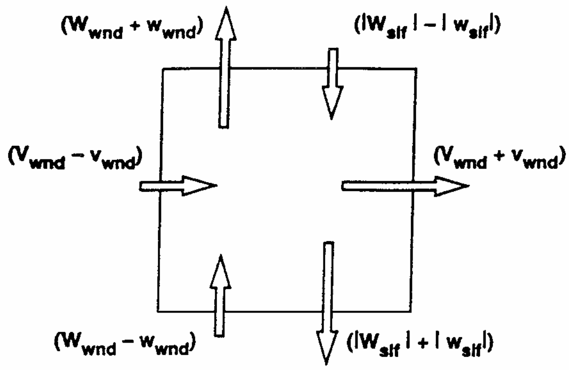


Fig. 5 Method used to move boundaries of wake stations as a function of time due to various inputs and their uncertainties.

Wind Velocity and Atmospheric Turbulence

It is assumed that measurements of the three velocity components of the wind and their variations, for example, variance and turbulence components, are obtained along the flight path of wake-generating aircraft with onboard instrumentation.[19] Any uncertainties in these measurements (variance, or maximum deviation from the steady-state value) cause the wake-station boundaries to enlarge with time by a corresponding amount. Because the measurements are made only along the flight paths of aircraft during approach, vortex wakes may move to locations not precisely covered by the data. It is assumed that the locations where the wind velocities were measured by the wake-generating aircraft also move with the wind and, therefore, remain with the fluid occupied by the wake so that the velocities of convection are unchanged throughout the time that wake motion is being monitored. Any mutually induced or random velocities caused by proximity of filament segments of the same or other nearby vortices and wake instabilities are assumed to be represented by the measured velocities and the spreading rate predicted by Eqs. (1) and (2). Furthermore, any effect of viscosity or small-scale, for example, boundary layer on the wing, turbulence in the wake and local atmosphere on the decay, dispersion, and motion of the vortices is either negligible or also represented by one of the foregoing lumped parameters.

Probability of Wake Encounter

Calculation of the probability of wake encounter begins with a determination of the initial locations of the wake stations and their boundaries along the flight corridor for each succeeding wake-generating aircraft. An adjustment is made in the wake-station boundaries to cover the possibility that wake-generating aircraft may fly with their centerline at or near the boundaries of the approach flight corridor. Because as much as half of the wake may protrude outside of the flight corridor, the sides of the wake-station boundary must be moved outward by half the size of the hazardous region in the lateral, Δy, and vertical, Δz, directions (Fig. 6), as predicted by Eq. (3).

When the next wake-generating aircraft arrives at the entry of the flight corridor, it is first treated as a following aircraft. In this way, a determination can be made as to whether the flight corridor (which has a cross-sectional size given by A_{foll}) that is being used overlaps with the time-adjusted locations of the boundaries of the wake stations B_{stn}, D_{stn}, or A_{stn}, of preceding aircraft (Fig. 6). The overlap region is designated as A_{ovrlp}. If no overlap is predicted, which makes A_{ovrlp} zero, the analysis indicates that the probability of a wake encounter is negligible. If, however, overlap does occur, the cross-sectional areas of the wind-enlarged wake station, the flight corridor, and the hazardous region are used to estimate the

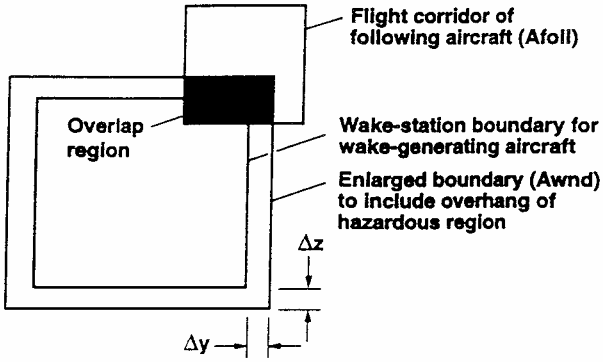


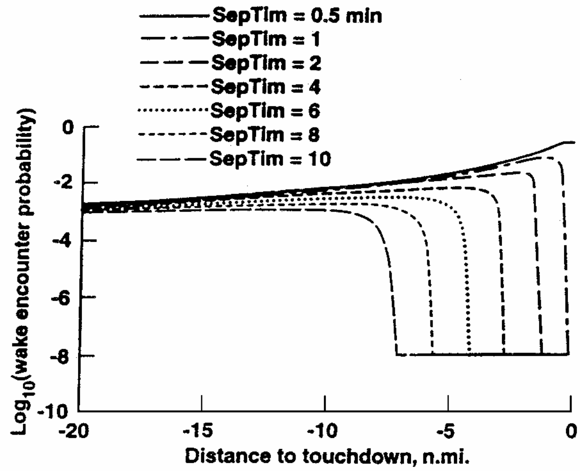
Fig. 6 Enlargement of wake station to include portion of hazardous region that extends outside of wake station when centerline of wake-generating aircraft is at or near perimeter; relationship to overlap region.

probability of encounter. In the evaluation, it is assumed that the location of the wake-hazardous region A_{hz} is equally likely throughout the uncertainty region defined by A_{stn}. Similarly, it is assumed that the location of the following aircraft is equally likely throughout the cross section of the flight corridor at that station, which is defined as A_{foll}. The various probabilities are then defined as 1) (A_{hx}/A_{stn}) is the probability that hazardous region is at any given place in the entire wake station and 2) (A_{ovrlp}/A_{foll}) is the probability that following aircraft is in overlap region of flight corridor. The product of these two definitions leads to a value for the probability of an encounter of a following aircraft with a wake-hazardous region as

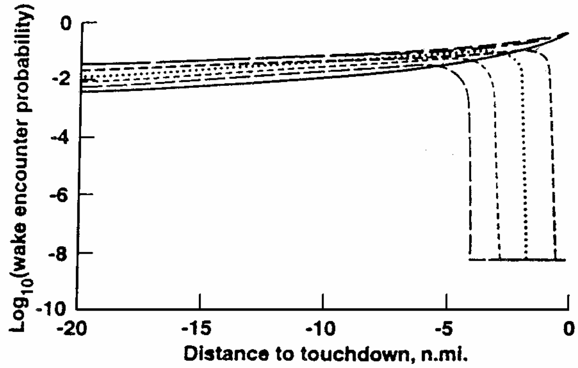
$$P_{enc} = (A_{hx}/A_{stn})(A_{ovrlp}/A_{foll})$$

As a reminder, and as pointed out in a preceding section, the probability P_{vr} that the following aircraft will encounter the intense parts of the hazardous region where the vortex-induced rolling moments are overpowering, that is, near the vortex centers, is given by

$$P_{vr} = 0.08 \times P_{enc}$$



a) Wake hazardous region held constant at initial size



b) Wake hazardous region based on cruise altitude data

Fig. 7 Wake encounter probability as a function of distance along flight corridor for range of arrival times by aircraft behind one in heavy category when using a 3-deg ILS approach corridor; no wind.

Illustrations of Encounter Probability

Graphical results are now presented to illustrate how the probability of wake encounter with any part of a wake-hazardous region is affected by various magnitudes of uncertainties. Results are first presented for ILS and GPSS flight corridors, both when the wake cross-sectional size is fixed and when it spreads with time according to Eq. (1). The effect of a side wind is then considered. Because wakes can pose a hazard throughout the entire length of the flight corridor, wake-encounter probabilities are determined all along the corridor by the computer program. A safe situation is assumed to exist if no part of the wake-hazardous region overlaps with the flight corridor of the following aircraft. The calculated probability is then zero. Because the scale used for probability is logarithmic, the zero value is represented in the figures as being at 10^{-8}.

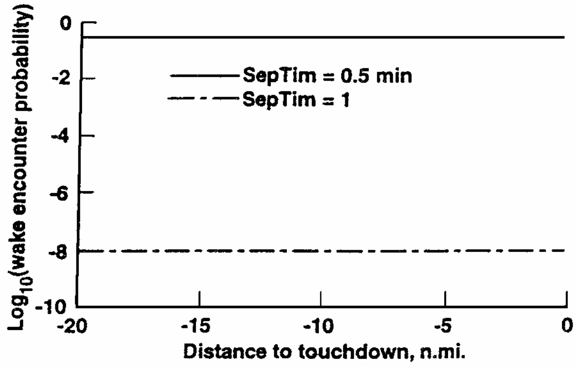
ILS Flight Corridors

The uncertainty in the initial location of both the wake-generating and following aircraft is determined by the cross-sectional size of their approach corridors. These uncertainties are important because the initial location of the wake-generating aircraft governs the starting location of each wake element and, therefore, contributes to the uncertainty in vortex wake. Similarly, the initial and time-dependent location of the following aircraft is important because its flight path must be directed around the hazardous region generated by the wakes of preceding aircraft. The effect of the shape and cross-sectional size of the flight corridor used by a wake-generating and following aircraft on the probability of encounter is now illustrated. For ILS flight corridors, the uncertainty in location of the generator aircraft is largest at entry and vanishes at touchdown. If the size of the wake-hazardous region remains the same as its original size and does not grow, and the wind along with all other uncertainties is negligible, only the self-induced downward motion of the vortices moves the wake-station boundaries. Under those circumstances, the probability of encounter for a sequence of aircraft following a heavy wake-generating aircraft, such as the B-747, at different time intervals is estimated as indicated in Fig. 7a. Note that, according to the criteria being used in this analysis, the encounter probability throughout most of the flight corridor does not become negligible even after 10 min. At a 1-min spacing, the encounter probability does drop to zero (indicated by a probability of 10^{-8}) over the region where the corridor cross section is very small near touchdown, indicating the need for flight corridors of small cross section.

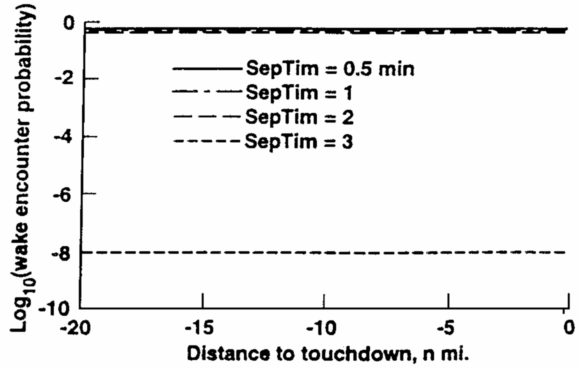
The results in Fig. 7a are not surprising because the conically tapered shape of the ILS flight corridor causes the cross-sectional size of the flight corridor to decrease as the aircraft proceeds to touchdown. When the cross-sectional area of the flight corridor becomes small enough, the self-induced downward velocity of the vortex pair is able to convect the hazardous region out of the flight corridor quickly. As the cross section of the flight corridor increases with distance from touchdown, more and more time is required for the wake to be convected out of the flight corridor. At the greater distances from touchdown, wakes will decay to a harmless level before they are convected out of the corridor. If the ILS corridor is assumed to have 1-deg angles at its vertex in both the vertical and horizontal directions, vortex wakes exit the corridor in roughly one-third of the time that it takes to exit a 3-deg ILS flight corridor, as expected. However, when a more realistic growth rate is used for the size of the hazardous region of vortex wakes (Fig. 7b), the larger wake diameters increase the time required for them to vacate both 1- and 3-deg ILS flight corridors.

GPSS Flight Corridors

Confirmation of the foregoing observation about flight corridors of small cross section is obtained when it is assumed that the



a) Wake hazardous region held constant at initial size



b) Wake hazardous region based on cruise altitude data.

Fig. 8 Wake encounter probability as a function of distance along flight corridor for range of arrival times by aircraft behind one in heavy category when using an 80 × 80 ft approach corridor based on GPSS; no wind.

approach flight corridor is defined by GPSS technology. For example, assume that the flight corridor has a constant cross-sectional size of 80 × 80 ft (Fig. 2) and that the wake-hazardous region does not grow with time above its initial $2b_g \times b_g$ dimension. In that case, the computational method estimates that, for a GPSS flight corridor, the probability of a wake encounter by the following aircraft is negligible throughout the length of the flight corridor even at a 1-min in-trail spacing (Fig. 8a). Also note that the probabilities are all constant along the flight corridor because both the flight corridor and the in-trail spacing between aircraft are taken as constant. These results also indicate the need for refinements in the guidance used for aircraft on approach to an airport to constrain the aircraft to corridors of small cross sections.[19]

If the wake is allowed to spread as a function of time, as observed in condensation wakes, Eq. (1), much more time is required for wakes to clear the flight corridor (Fig. 8b). A safe separation time between aircraft then increases to something under 3 min. The advantages of flight corridors with small cross sections are still apparent, but their benefit is not enough to counter the influence of wake spreading. Also note that the results presented in Figs. 7 and 8 again worsen if the self-induced downward velocity of the pair has any uncertainty above that assumed in the computations. The greater uncertainty also forces longer separation times between aircraft if the probability of wake encounter is to be negligible. When smaller aircraft are used in the numerical experiment, the results are quite similar to those shown in Figs. 7 and 8 because the smaller self-induced downward velocity of the wake is approximately offset by the smaller cross-sectional size of the hazardous region.

Uncertainty in Side Winds

Because the time required for a lift-generated wake to vacate a flight corridor is directly proportional to the size of the flight corridor and inversely proportional to the wind velocity, it is obvious that the corridor size should be as small as possible and that any wind should be utilized. It is again assumed here that all three components of the

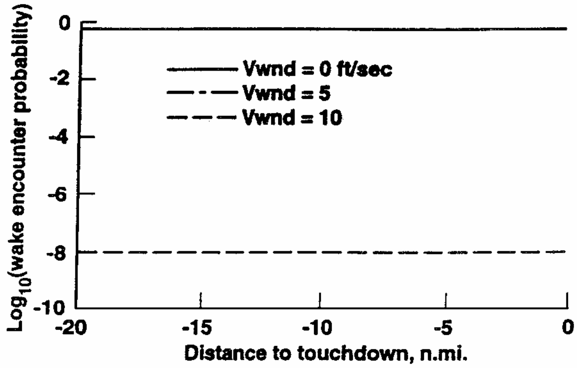


Fig. 9 Effect of side wind on encounter probability as a function of distance along flight corridor when arrival time of following aircraft is 1 min behind wake-generating aircraft in heavy category; 80 × 80 ft GPSS approach corridor.

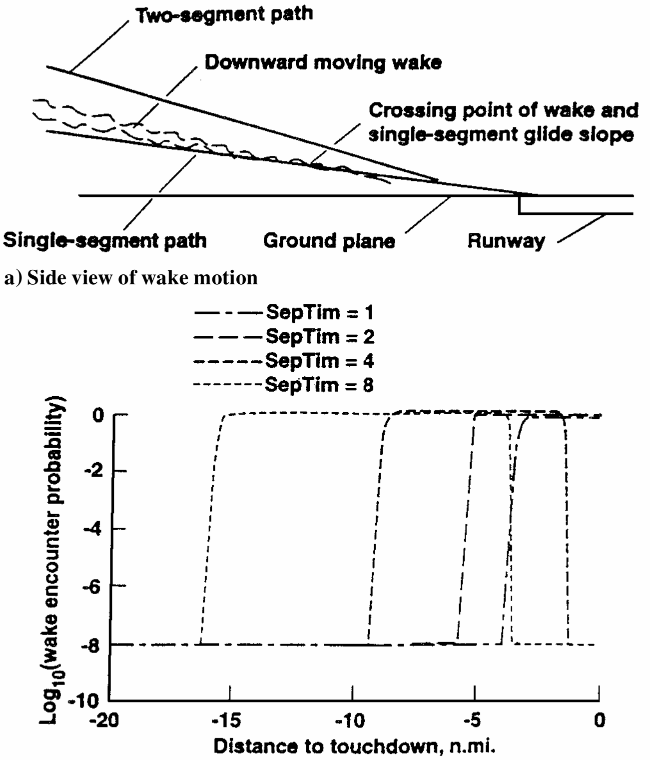
wind are measured by aircraft as they pass through the flight corridor to touchdown by means of a technique similar to that used in the AVOSS program.[27]

Because a side-wind component has a prolonged time in which to convect a vortex wake out of a corridor, its magnitude need not be large for corridors of small width. For example, assume that the time-averaged side wind is 10 ft/s. It then takes less than 1 min for the entire vortex wake to be blown clear of a small, for example, 80 × 80 ft, flight corridor (Fig. 9). However, if the wind velocity can only be measured to within ±10 ft/s, the uncertainty is equal to the time-averaged velocity. In such a case, the uncertainty in velocity completely offsets its time-averaged value, so that the benefits of a side wind vanish. As an experimental reference, note that some ground-based measurements by Hallock and Whitney[28] also indicate that a side wind of 10 kn or more is sufficient to remove a wake from departure corridors within 40 s. The wind ellipse developed for the vortex advisory system,[10–12] discussed in the Introduction, indicates that side winds greater than 8 kn (13.5 ft/s) are more than adequate to clear an approach corridor of vortex wakes in less than 1 min.

Similar requirements are necessary for the vertical and along-trail components of wind velocity. That is, upwardly directed winds offset the self-induced downward motion of the vortex pair, which can move the wake-hazardous region into the path of following aircraft. Of course, downwardly directed winds promote the exit of vortex wakes out of the flight corridor. Similarly, tailwinds tend to move vortex wakes largely along the flight path so that wakes appear to rise from the viewpoint of following aircraft. Headwinds are beneficial because they tend to give vortex wakes an apparent downward motion, which accelerates their departure from a flight corridor. The wind ellipse developed for the vortex advisory system indicates that a head or tail wind of 14 kn (24 ft/s) is necessary for safe approach through a flight corridor when in-trail spacings between aircraft are 1 min. In this latter case, the mechanism that leads to safety is believed to be increased atmospheric turbulence that rapidly disperses vortex wakes and not the result of wake convection.[10–12]

Two-Segment Flight Corridors

One way to alter approach corridors for noise abatement over inhabited areas under flight patterns is to maintain higher altitudes on approach. Descent to touchdown is then accomplished by use of steeper glide slopes. Because some aircraft are able to safely execute glide slopes between −3 and −6 deg during the first part of their approach path, whereas others may not have such a capability, a mixture of glide slopes is needed to accommodate the capabilities of all aircraft. A flight corridor that uses two glide slopes along its flight corridor is referred to as a two-segment approach. The junction of the two glide slopes can be executed fairly close to touchdown. If different glide slopes are used for the outer segment of the approach path, the probability of wake-vortex encounters is increased over a large part of the approach path (Fig. 10a). As indicated, the hazard



a) Side view of wake motion

b) Wake encounter probability

Fig. 10 Increase in wake encounter probability when an aircraft on a single, − 3-deg glide slope follows an aircraft in heavy category that is using a two-segment (− 6 deg/− 3 deg) approach path; segments join at − 1 n mile, no wind, 80 × 80 ft GPSS approach corridors.

comes about because, as time progresses, the wake from the upper aircraft on a two-segment approach descends down through the flight corridor being used by the lower aircraft, which is on a single-segment approach path. The intersection region moves away from the runway with time and increases in size with time as the wake cross-section enlarges. (The probability curves in Fig. 10b have been given a small vertical offset to better indicate the connection between the various parts of the curves.) Because the wake intersects the lower flight corridor, the wake-encounter probability becomes high (Fig. 10b) along the intersection region of the wake and the lower 3-deg corridor. Note in Fig. 10b that the encounter probability drops to essentially zero in front of, and behind, the parts of the flight corridor where the lower corridor and the wake region intersect. Some flight research conducted by Kurkowski et al.[29] also indicates that such a mixture of flight corridors would pose an increased hazard to any following aircraft that uses a single-segment approach path.

Observation on Runway Capacity

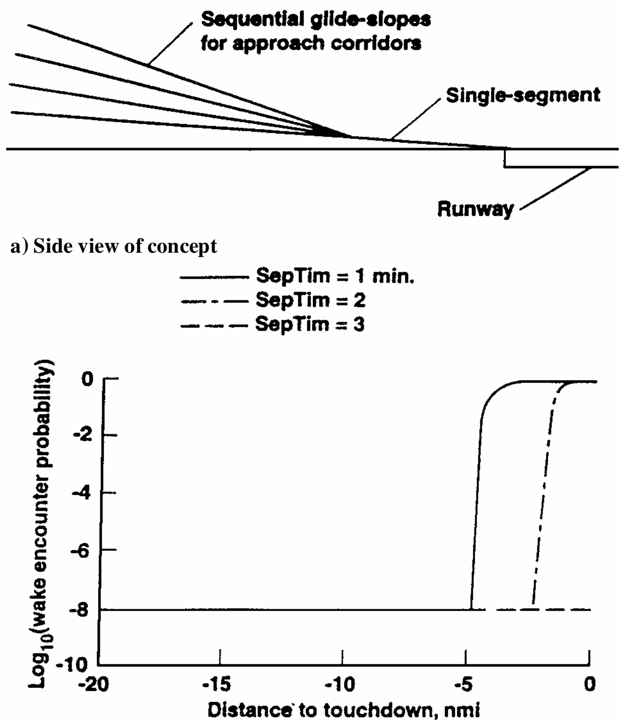
The wake-encounter probability data presented in Figs. 8–10 indicate that if a strong side wind is not blowing, vortex wakes will not vacate even small flight corridors within the 1-min goal desired at airports. Implementation of the recommendations for reduced uncertainties would improve the safety, and provide a small enhancement of capacity, of runways at airports. However, the restraint on capacity brought about by the rapidly growing and spreading hazardous region surrounding the wake vortices offsets the benefits provided by the reduction in the magnitude of the other uncertainties associated with the location of vortex wakes. That is, reduction of uncertainties is, by itself, not sufficient to safely achieve 1-min in-trail spacings between aircraft operations. (These 1-min spacings were a goal of the NASA/FAA wake-vortex program. Smaller spacings are then only prevented by factors associated with air traffic operations at airports and not by the hazard posed by lift-generated vortices.) Because the growth and spread of vortex wakes with time is a natural process, a method for reducing its impact does not appear possible at this time.

Therefore, on the basis of the avoidance models used so far in this analysis, it is recognized that new procedures and technologies will be needed for approach to airports if capacity on existing runways is to be safely increased by an appreciable amount. It was then reasoned that greater airport capacity might be achieved by substitution of flight corridor rotations for in-trail spacings to increase lateral and vertical distances between flight corridors, so that wake encounters do not occur even at close in-trail spacings. Such a process is only possible when the improved instrumentation for uncertainty reduction is implemented. To illustrate a possible development process toward a useable multiple flight corridor system, several multiple flight corridor examples are presented in the sections to follow.

Sequential Two-Segment Flight Corridors

Assume now that only 5 or 10 aircraft are in a landing sequence and that a period of five or more minutes will pass before another aircraft or sequence of aircraft will arrive. Also assume that all of the aircraft have the ability to fly steep approach segments (i.e., as much as −6-deg glide slopes), that all have the capability to fly GPSS flight corridors that are 80 × 80 ft in cross section, and that wind measurements are available along the flight corridor. The procedure uses multiple flight corridors wherein each aircraft has its own two-segment flight corridor, and the steep or outer segment of its flight path is above previous flight paths (Fig. 11a). It is found that the increments between flight corridors need only be large enough (both 0.25- and 0.5-deg increments were found to be sufficient) to ensure that the flight path of each following aircraft is far enough above previous flight paths, so that no part of the wake of previous aircraft is encountered. Such a small change in glide slope for the steep segment is, of course, only possible when aircraft are constrained to flight corridors of small cross section and would not be safe for ILS corridors. As shown in Fig. 11b, the wake encounter probability is zero until the approach corridors converge closely enough that the wake-hazardous regions overlap adjacent corridors, for example, near to and along the lower common segment.

Because the elevation angle between aircraft corridors is small, a number of aircraft can utilize the sequence of glide slopes before it



a) Side view of concept

b) Wake encounter probability

Fig. 11 Sequential two-segment flight corridors wherein first corridor is − 3-deg glide slope and each following aircraft use flight corridor with steep segment 0.5 deg greater than preceding one; segments join at − 1 n mile, no wind, 80 × 80 ft GPSS approach corridors.

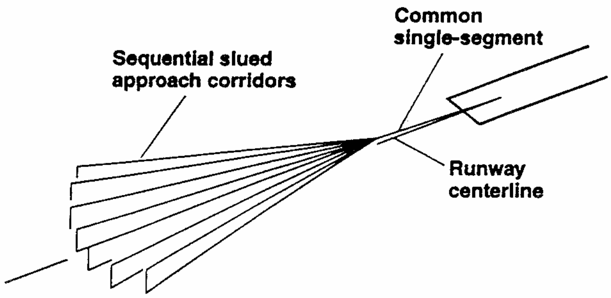


Fig. 12 Diagonal view of corridor concept that uses sequential two-segment flight corridors wherein outer segments have slue angles that range, for example, from +9 to − 9 deg at − 3-deg increments; all at − 3-deg glide slope.

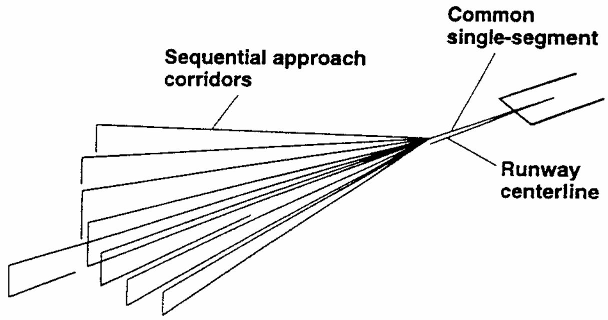


Fig. 13 Diagonal view of corridor concept that uses sequential two-segment flight corridors wherein outer segments have both slue-angle and glide-slope variations.

is necessary to recycle the pattern. When it is decided to recycle the pattern, a waiting period of 2–5 min or more is necessary between the last aircraft of one cycle and the first of the next cycle to be certain that the wakes of previous aircraft have either decayed to a harmless level, or have been convected away from the air space used by the sequential two-segment corridors. Such a procedure was computationally found to be effective whether aircraft in the series were all small, or large, or a mixture of the two. It was also found that a side wind from port or starboard did not have an adverse affect on encounter probability for aircraft on the steep segment. As pointed out for single-segment flight corridors in the foregoing section on side winds, sequential two-segment flight corridors cannot tolerate upwardly directed winds or a wind in the direction of flight, but a headwind is beneficial because of the direction that vortex wakes are convected.

Sequential Slued Flight Corridors

Because the sequential two-segment glide-slope procedure cannot be recycled immediately, other possibilities were tried. One of the procedures tried was the use of small changes in the lateral direction of approach to the touchdown point, which are referred to as slue-angle changes, that is, the deviation of a GPSS flight corridor from the runway centerline to either port or starboard (Fig. 12). Because vortex wakes extend over greater distances in the horizontal direction than in the vertical direction, it was found that increments in slue angle of about 3 deg or larger are adequate for satisfactory wake avoidance. In the analysis, the maximum slue angle was limited to ±9 deg. Maximum slue angles are only of concern in that aircraft must be able to execute easily a turn from the incoming slued corridor to alignment with the runway centerline, along the second segment of the flight corridor.

Computations of wake-encounter probability for such a flight corridor sequence indicate that it is safe only when a side wind is not blowing. That is, if the wind is blowing in the direction of increasing slue angle, vortex wakes are convected into the path of aircraft following in adjacent corridors. If the wind blows in the direction opposite to increasing slue angle, it is not possible to recycle the sequence until all of the vortex wakes have decayed to a harmless level. It was concluded, therefore, that slue angle by itself was also not an attractive alternative to a single flight corridor because it is too dependent on wind direction and magnitude, thereby causing the recycle time to be excessive. As with the procedure that uses sequential glide slopes, wake-encounter probabilities are sizeable in the vicinity of the common nonslued part of the approach path, for example, similar to that in Fig. 11.

Combination of Two-Segment and Slued Flight Corridors

Because glide-slope and slue-angle sequences by themselves each provided some wake-avoidance advantages along the outer segment of the flight corridor, a combination of the two (Fig. 13) was investigated. That is, can a combination of corridor angle changes be found that leads to a procedure that safely permits immediate recycle of the sequence and that is also insensitive to winds? After several incremental sizes were studied, it was found that the outer segment of the flight corridor sequence would provide adequate avoidance assurance if the corridors were designed to have 0.5-deg increments in glide slope and 3-deg increments in slue angle between flight corridors in the sequence. The sequence illustrated in Fig. 13 is not to scale, and only the centerlines of the flight corridors are shown. When such a procedure was tested for sensitivity to side winds, it was found that the first cycle was completely insensitive to side winds in either direction. The reason for insensitivity on the first cycle comes about because, in one direction, wakes are blown away from the starting region of the sequence, in which case the wakes are blown under soon-to-be-active corridors. When the wind blows in a direction against increasing slue direction, vortex wakes are blown away from prospective corridors and those in use.

Consider now the case when the glide slope/slue angle is recycled. If a side wind is blowing in the direction of increasing slue angle, vortex wakes are convected under flight corridors to be used in the same sequence. However, as before, if the wind blows in the direction opposite to increasing slue angle, the vortex wakes of one sequence are blown onto the flight corridors to be used in the next sequence and those to follow. Because side winds are not a problem when they are in the direction of increasing slue angle, the solution is to design the procedure so that slue angle always increases in the same direction as the side wind. This option is available because, even though glide slope must increase whether slue angle increases in the port or starboard direction, the slue angle can proceed either to port or to starboard. If this is done, glide-slope/slue-angle sequences are robust and wake-encounter probabilities are negligible everywhere except near the junction of the corridors and along the common flight corridor segment just before touchdown.

The foregoing sequential flight corridor system is found to be effective along the approach corridors except for the regions where the corridors converge and join to form a common path to touchdown. It remains then to find a safe avoidance procedure along the regions where the corridors converge to form a common segment to touchdown. One such possibility is to traverse these regions at low altitude and close to touchdown so that the interaction of the wakes with the ground plane causes them to decay rapidly to a harmless level well within 1 min after passage. Previous studies of wake decay when near ground planes indicate that even though vortex wakes do decompose more quickly in ground effect, more study is needed to determine whether vortex wakes can definitely be made harmless, before a 1-min time period occurs, especially during calm wind conditions.[5,7,28,30] To achieve such a goal, it may be necessary to distribute trees of graduated height along the lower parts of the approach corridors to increase substantially the effective friction between the ground and vortex wake.

Conclusions

The study reported here recommends that a reduction in the magnitude of the uncertainties associated with the location of vortex wakes during approach of aircraft to airports be accomplished by application of existing technology:

1) Reduce location uncertainties of wake-generating and following aircraft by use of technology like that provided by the GPSS.

2) Improve the modeling of the growth in the cross-sectional size of the wake-vortex hazardous region as a function of time.

3) Improve instrumentation on aircraft to provide more accurate measurement of the velocity of flight, weight, and type of wake-generating aircraft in the approach corridor so that the self-induced downward velocity of the vortex pair being shed can be accurately calculated. It appears that uncertainties of 1 ft/s or less may be possible to achieve.

4) Improve accuracy and reduce uncertainties in measurements made by aircraft of the magnitude and direction of the time-averaged and unsteady values of the three components of the wind, that is, variance and turbulence. The best systems found in the literature are probably marginal; if uncertainties are to be brought much below 5 ft/s; accuracies of 1 ft/s are preferred.

Implementation of the foregoing recommendations will greatly reduce the uncertainties associated with aircraft being able to avoid vortex wakes on arrival and departure from airports. These improvement will enhance both safety of flight and capacity of runways. In addition, and perhaps more importantly, the foregoing study suggests that reductions in uncertainty provide a capability to develop radically new and much more effective wake-vortex avoidance procedures not possible with current instrumentation onboard aircraft and at airports. For example, it may be possible to safely arrange a sequence of multiple flight corridors to and from airport runways that more effectively and efficiently avoids the vortex wakes of preceding aircraft. The examples presented indicate one concept to be considered.

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