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Wake–Vortex Separation Distances when Flight-Path Corridors are Constrained

Vernon J. Rossow*
NASA Ames Research Center, Moffett Field, California 94035-1000

Improved precision of the flight paths used by aircraft to approach and depart airports will become available when the global positioning system (GPS) is implemented for air traffic control. It is suggested here that the improved precision be used to constrain the approach and departure corridors so that their cross-sectional sizes are small and constant in size. Such a constraint controls the flight paths of the aircraft, and consequently where their vortex wakes are placed, so that the likelihood of a wake–vortex encounter is reduced. If such a program is coupled with a wake–vortex advisory system, and with the operating system being planned for airports when GPS is implemented, preliminary indications are that the wake–vortex spacings currently being used for instrument flight conditions can be reduced to a uniform distance of 3 n mile. Furthermore, if the smaller GPS flight corridors are utilized by vortex advisory or forecast systems that are currently under development, the requirements to be placed on their capabilities can be substantially reduced.

Nomenclature

B = breadth, ft
b = wingspan, ft
b' = spanwise distance between vortex centers, ft
C_L = lift coefficient, L/qS
C_l = rolling-moment coefficient, M/qSb
c = wing chord, ft
D = depth, ft
L = lift, lb
M = rolling moment, ft-lb
q = dynamic pressure $\rho U_\infty^2/2$, lb/ft^2
S = wing planform area, ft^2
t = time, s
U_∞ = velocity of aircraft, ft/s
Wt = weight of aircraft, lb
x = distance in flight direction, ft
y = distance in spanwise direction, ft
z = distance in vertical direction, ft
Γ = vortex strength, ft^2/s
ρ = air density, slugs/ft^3

Subscripts
ac = aircraft
app = approach
dep = departure
f = following aircraft
f cr = flight corridor
g = wake-generating aircraft
hz = hazardous region of wake
int = intersection
m = maximum
td = travel distance
v = vortex
wk = wake
wind = wind
0 = centerline

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*Senior Scientist, Low Speed Aerodynamics Branch, M/S N247-2. Associate Fellow AIAA.

Introduction

IT has been known for some time[1,2] that the lift-generated wakes of aircraft persist long enough that following aircraft must delay their arrival at or departures from an airport until the vortices shed by previous aircraft have either moved out of the flight corridor or decayed to a harmless level. A flight corridor is defined as the region, such as a tube, tunnel, or cone, through which aircraft are directed by air traffic control (ATC) during approach and departure from an airport. While a fairly firm constraint is exercised on aircraft spacing and their flight corridors, during the time that instrument flight rules or instrument meteorological conditions are in place, more lenient restraints are used during visual meteorological conditions. Since the hazard posed by lift-generated vortices is the one factor that now dominates the minimum allowable spacing between aircraft, separation guidelines have been established between aircraft to ensure safe operating conditions. The current minimum separation distances, listed in Table 1, have been in place for over 20 years and are designed to accommodate worst-case conditions when instrument meteorological conditions are being used. Note that larger separation distances are specified for small aircraft following larger aircraft. The greater distances allow more time for the vortices to move out of, and farther away from, the flight corridor and to decay. The greater distances ensure comparable margins of safety for the smaller aircraft, which are more susceptible to the vortices of the larger aircraft.

If the distance at which an aircraft follows a preceding aircraft is below the recommended guideline, the likelihood that it will encounter a vortex increases. If an encounter occurs, the rolling moment induced on the following aircraft may exceed its onboard roll capability with ailerons, so that unacceptable and dangerous roll excursions occur.[1–7] The efforts to reduce the hazard posed by the wake vortices has been directed at finding ways either to reduce the intensity of the vortices[7–10] or to avoid the vortices.[9–13] Thus far, it has been shown that the intensity of the vortices can be reduced by changing the lift distribution on the generating wing so that its wake is nonhazardous, but the degradation in the performance of the wake-generating aircraft is unacceptable.[8,14,15] Wing designs that shed nonhazardous wakes, and have acceptable pen-

Table 1 Minimum wake–vortex separation distances, n mile

Following aircraft	Wake-generating aircraft		
	Small	Large	Heavy
Small	3	4	6
Large	3	3	5
Heavy	3	3	4

Note: Aircraft sizes are defined by weight ranges as, small: $0 < Wt < 12{,}500$ lb; large: $12{,}500 \text{ lb} < Wt < 300{,}000$ lb; and heavy: $Wt > 300{,}000$ lb.

alties, are still being sought,[14,15] because the benefits to airport capacity are substantial.

At the present time, effort is being devoted to the search for a satisfactory procedure by which wake vortices can be monitored or detected, and then avoided if it is not safe to penetrate them. Within the U.S., NASA is conducting the research for the Federal Aviation Administration (FAA) under the terminal area productivity (TAP) program.[11–13] The TAP program has four elements: 1) air traffic management, 2) aircraft–air traffic control systems integration, 3) low-visibility landing and surface operations, and 4) reduced spacing operations. The research on wake vortices by NASA at Langley and Ames Research Centers falls under the reduced spacing operations element.[11–15] One of the efforts, underway at NASA Langley Research Center,[11–13] has the goal of enabling safe improvements in the capacity of the nation's air transportation system by bringing about a reduction in the in-trail spacing of airplanes. As pointed out in Ref. 13, the scientific basis does not currently exist to quantify the wake transport and decay properties of lift-generated vortices, nor the aircraft–vortex interaction dynamics, with sufficient accuracy to put into use weather-dependent aircraft separations, that are significantly different from current standards. The major goal of the research is to provide the technology base and systems to permit the same airport capacity levels during instrument operations that are presently experienced during visual airport operations. In support of that goal, Hinton[13] clearly and concisely presents a description of the components that make up an aircraft vortex spacing system (AVOSS) under development at Langley. When completed, AVOSS will provide a system concept that uses available knowledge of aircraft wake generation, atmospheric modification of those wakes, wake-encounter dynamics, and operational factors to provide dynamical wake–vortex spacing criteria for use at airports by air traffic control. The results to be described here pertain to the discussion[13] on the corridor dimensions being considered in the AVOSS system. In particular, the study reported here indicates that the tasks within the AVOSS concept can be greatly simplified if the cross-sectional sizes of the approach and departure corridors are constrained to as small a size as is feasible with existing technology.[16–19] The simplification comes about because the small flight corridors made possible with the global positioning system (GPS) can be used to limit drastically the locations where wake vortices are located and where aircraft that might encounter them can fly.

The concept being explored in this article is illustrated in Fig. 1. The two-part figure contrasts, for the approach situation, control that is lacking or present when the cross-sectional size of the flight corridors used by aircraft to approach and depart from airports are either large or small. In Fig. 1a, the wake-generating and following aircraft are free to approach the runway along a wide variety of paths. Since the following aircraft does not know where the preceding aircraft flew, nor where its vortex wake is located, the encounters shown are possible. If, however, the permissible flight corridor is constrained to a small cross-sectional area, as shown in Fig. 1b, the following aircraft knows the flight path of the preceding aircraft, and where its vortex wake was deposited. Since the flight path of the following aircraft is also restricted to the same small cross-sectional region as the wake-generating aircraft, the vortex wakes need to move only a small distance to become avoidable and the flight corridor safe for passage of the following aircraft. Furthermore, movement of the vortex wake over a small distance takes only a short time before the vortex wake is convected out of the flight corridor so that it need not be followed or monitored for long periods of time. Since vortices are never penetrated, vortex decay and the encounter dynamics of the aircraft (both of which have large uncertainties) need not be a part of the vortex advisory system. In addition, the fact that the vortices are avoided allows the concept to be applied to any combination of aircraft without the need to consider the relative sizes of the wake-generating and following aircraft. Nevertheless, it is advisable to have some sort of vortex analysis or advisory system, such as AVOSS (Ref. 13), that uses the wind and meteorological conditions along the flight corridor and on the ground to monitor the motion and structure of the wake vortices in and near the flight corridors to ensure that vortex wakes do move out of the flight corridor and do not re-enter it. Since the cross-sectional size of the GPS flight corridors can be made small, the chore associated with keeping track of the locations and strengths of the wake vortices is reduced.

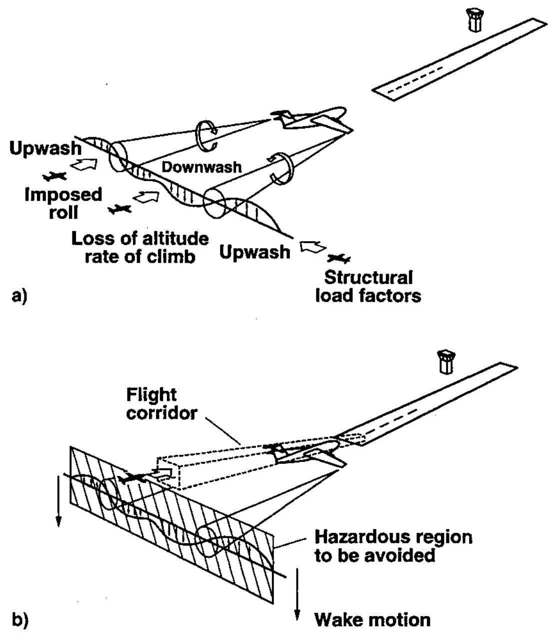

Fig. 1 Possible encounters with a lift-generated wake by a following aircraft: a) large and b) small flight corridors.

Now review the characteristics of the GPS (Refs. 16–19) provided by the Department of Defense that is planned for implementation at airports. The accuracy with which an aircraft can be located by the GPS currently being planned[17] varies along the flight path as the aircraft flies from one airport to another. Present plans call for accuracies that range from ±33.5 m (±110 ft) in the horizontal direction, and ±9.5 m (±31 ft) in the vertical direction, to less than 1 m at the runway threshold. Research has shown that the accuracy can be improved considerably so that aircraft locations are known within distances much less than 1 m (Refs. 18 and 19). For comparison, the flight corridors in current use are roughly conical in shape so that the smallest dimension is at the runway. The cross-sectional size of the flight corridors are then a minimum at ground level, which is about equal to the runway width, to over 460 m (1500 ft) in diameter at 3 or more nautical miles from the airport. An important difference between the present ATC system and the GPS system is that the flight corridors for the GPS system are fixed in size along specified segments of the route, whereas the present corridors are conical in shape so that they become quite large in cross section at the outer limits of the approach corridor to the airport. The GPS-controlled system, which is about constant in cross-sectional size, is sometimes referred to as a tunnel or tube in the sky through which the aircraft fly.

The text that follows describes a preliminary study of the characteristics to be desired in the flight-path corridors to most effectively use the smaller constrained corridors when they become available. In general, it is assumed in the study that the reduction in the cross-sectional size of the flight corridors is part of a larger ATC system that need not be changed in other ways to any great extent. To carry out the study, a determination is first made of the effect of the size of the flight corridors and of the hazardous region posed by the wake vortices on spacing guidelines. With this information, several hypothetical flight corridors are considered to investigate how size, shape, and arrangement of flight corridors affect the spacing guidelines. Lastly, an assessment is made of some of the information needed, and how it can be procured, for implementation into an air traffic control system. Throughout this article, emphasis is placed on the cross-sectional size of the corridor because the only vortex motions that are of any consequence for avoidance considerations are those across the flight corridor. Distance, or time, along the flight path is important only in that it provides a time basis for the vortices to move out of, and away from, the flight corridor. Since the decay of vortices is small[20,21] over the flight-path distances of interest in this study, it is assumed that the vortices do not decay with time or distance. Location uncertainties by the GPS system along the flight path of the aircraft also have little, if any, influence on hazard criteria, and will therefore be ignored.

Self-Induced Descent Velocity of Vortex Pair

The downward momentum imparted to the air by the lifting surfaces on the aircraft brings about a pair of counter-rotating vortices at the edges of the downward moving air. The downward or descent velocity of the vortex centers (and consequently their hazardous regions) for a specific aircraft requires a knowledge of its weight, its slat and flap arrangement for the span loading, and its flight velocity and altitude to derive an accurate value. A less accurate value for the vortex wakes of subsonic aircraft is estimated here by first calculating a representative value for the circulation contained in each vortex. Since the lift equals the weight of the aircraft, the circulation in the vortex is estimated as

$$\frac{\Gamma_0}{b_g U_\infty} = \frac{1}{2}\frac{b_g}{b_g'}\frac{C_{Lg}}{\mathrm{AR}_g} \tag{1}$$

The downward velocity of the vortex pair is given by $w_v = -\Gamma_0/2\pi b_g'$, where Γ_0 is the centerline circulation on the wing of the wake-generating aircraft. Combination of these equations yields

$$w_v/U_\infty = -\frac{1}{4\pi}\left(\frac{b_g}{b_g'}\right)^2\frac{C_{Lg}}{\mathrm{AR}_g} \tag{2}$$

Since subsonic transports all have about the same wing aspect ratio, and have about the same landing and takeoff velocities, the downward velocities of their trailing vortex wakes are also about the same. Insertion of values typical of a subsonic transport during landing yields $w_v/U_\infty \approx -0.028$, or $w_v \approx -7$ ft/s, when $U_{ac} = 250$ ft/s (150 kn). For the examples to be given here, and to be conservative, a value of $w_v = -5$ ft/s will be used as typical. If any avoidance scheme is to be implemented, the descent velocity of all aircraft and the size of their hazardous region should be estimated individually. When the downward velocity of the vortex wake for a variety of aircraft are computed, it is found that larger aircraft usually have higher descent velocities. Their higher descent velocities will offset somewhat the larger hazardous region posed by the larger aircraft so that the spacing between aircraft need not necessarily be increased, when even larger aircraft are introduced into the fleet.

Hazardous Region Around Vortex Pair

Size of Hazardous Region

Although the vortex wake of a lift-generating aircraft induces lifting, yawing, and pitching motions on a following aircraft, the most hazardous feature of the wake occurs as an overpowering rolling moment near the center of a vortex. For this reason, research into the characteristics of the vortex wakes produced by lift generation has concentrated on the structure of the wakes and, in particular, on the rolling moments that they induce on the following aircraft that encounter them.[1-10,14,15] The wake-induced rolling moment on a following wing that is in the vicinity of a vortex wake can be measured or computed for a range of locations to produce lines of constant rolling-moment coefficient for one quadrant of the wake (Fig. 2). The center of the wake, and not the center of the wake-generating aircraft, is located at the origin. The contours presented in Fig. 2 are taken as representative of the wake structure from about seven span lengths, or one-fourth mile, to about 80 span lengths, or three miles behind the wake-generating aircraft. The strength of the vortices does decay over those distances, but some amplification may also occur because of the vortices taking on a sinuous shape caused by atmospheric (or wind-tunnel) turbulence.[15] The computations are presented for $C_{Lg} = 1.5$, and a ratio of the span of the following wing to that of the generating wing of $b_f/b_g = 0.29$; e.g., a wake-generating aircraft with a wingspan of about 200 ft and a following aircraft with a wingspan of about 60 ft. The example presented is typical of a small aircraft behind a heavy aircraft and is not directly applicable to any two particular aircraft. Contours for aircraft more nearly equal in size are similar, but have smaller induced rolling moments near the vortex centers.[21]

Superposition of the contours for one quadrant in Fig. 2 form estimated contours for the entire wake (Fig. 3). The wake is assumed to be symmetrical above and below the vortex centers (located at $y/b_g = 0.4$, $z/b_g = 0.0$), and antisymmetrical port and starboard. It is then possible to define a boundary outside of which the lift-generated wake does not pose a rolling-moment hazard. Identification of the hazardous boundary begins with the observation that the maximum aileron-induced rolling moment is typically $|C_{l\delta m}| \approx 0.06$ for subsonic transports.[21] The inner cross-hatched regions around the vortex centers and inside the $|C_{lf}| = 0.06$ contours then denote those regions where the wake-induced rolling moments exceed the maximum aileron-induced rolling-moment of the encountering aircraft. Note in Fig. 3 that, even for such a wide disparity in the size of the following and wake-generating aircraft, the over-

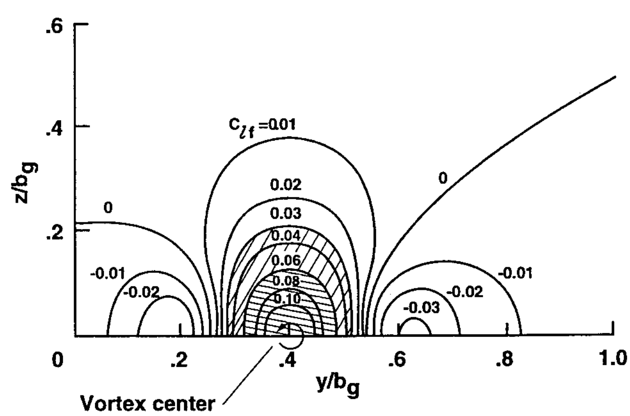

Fig. 2 First quadrant contours of constant rolling-moment coefficient induced on a following wing by a vortex pair shed by large transport aircraft: $C_{Lg} = 1.5$, $b_f/b_g = 0.29$, $|C_{lfm}| = 0.12$.

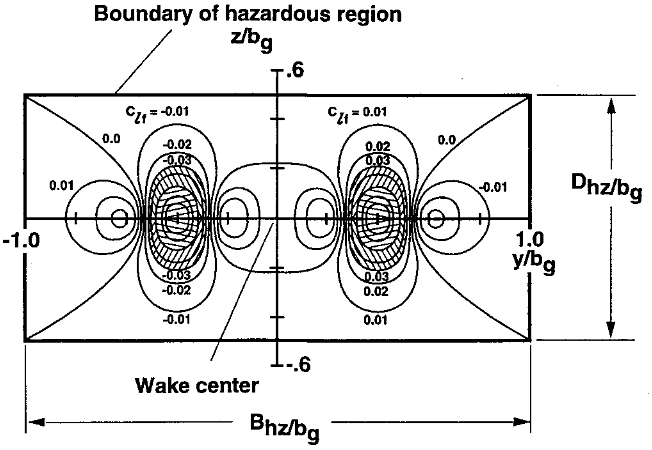

Fig. 3 Combination of contours of constant rolling-moment coefficient shown in Fig. 2 to produce contours for entire flowfield to indicate boundary of hazardous region outside of which $|C_{lf}| < 0.01$: $C_{L_g} = 1.5$, $b_f/b_g = 0.29$.

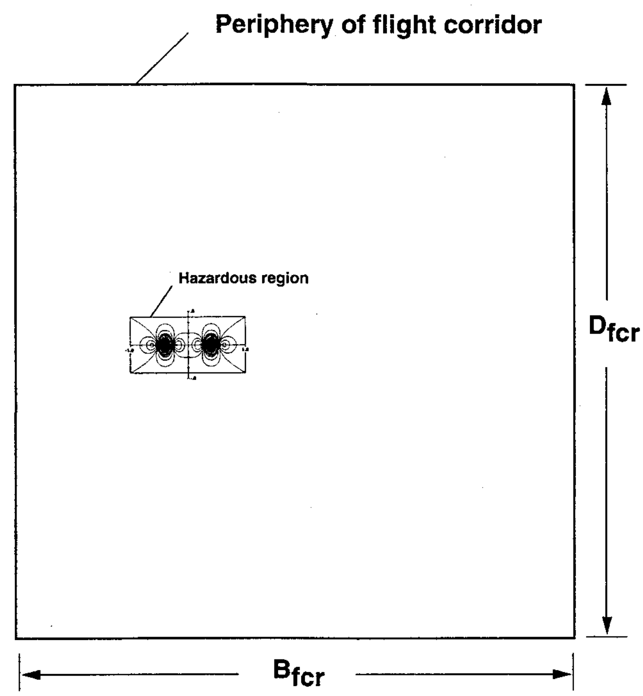

Fig. 4 Hazardous region inside of permissible flight corridor of current size at about 3 n mile from touchdown.

powering hazardous regions (the inner cross-hatched areas) where the wake-induced rolling moment exceeds the maximum aileron-induced rolling moment are restricted to the two small approximately elliptically shaped regions around the vortex centers. The two larger areas that are singly cross-hatched and centered around the vortex centers, identify regions of the wake where the vortex-induced rolling moment exceeds one-half of the maximum aileron-induced rolling moment. Outside of these regions, the wake-induced rolling moment on the following aircraft is always less than 0.03, i.e., $|C_{lf}| \leq 0.03$. Under those circumstances, it is estimated that the encountering aircraft has enough roll control power for the ailerons to cope with and recover from any vortex-induced roll excursion.[21] To be conservative, the hazardous region is taken as extending one span in the vertical and two in the horizontal direction to be well outside of the $|C_{lf}| = 0.01$ contours where an encounter would be barely perceptible.

Relationship of Flight Corridor and Hazardous Region

Figure 4 illustrates how a large size for the cross section of the flight corridor brings uncertainty into the relative location between the following and wake-generating aircraft. The cross section of the flight corridor is assumed to be roughly 1600 ft wide by 1600 ft high. Since an aircraft is permitted to fly anywhere in the corridor, its vortex wake can also be placed anywhere within the corridor. A following aircraft is also permitted to use any part of the corridor. Therefore, the presence of a vortex, or a vortex pair, anywhere inside the corridor poses a hazard to any following aircraft in the same corridor, and an encounter constitutes the same hazard as if the corridor was small. The large size of the corridor also means that a substantial amount of time is required for any vortices to be convected out of the corridor by the wind or by self-induced velocities. In the example shown in Fig. 4, the longest time for a vortex pair to clear the corridor occurs when the generating aircraft deposits the vortices near the top of the corridor in still air. Under those circumstances, the vortices need to descend about 1600 ft to clear the corridor. If a downward speed of 5 ft/s persists long enough for the vortex pair to exit the corridor, about 320 s are required. However, even more time is usually required to accomplish the total distance because vortices often only descend about 500–1000 ft before their downward motion slows or stops. If the downward motion stops, time must be allowed for the vortices to decay to a harmless level. These considerations illustrate the importance of restricting the cross section of the flight corridors to the smallest size possible with current technology.

Next, assume that the flight corridor is 80 ft wide by 80 ft high, which is slightly larger than the present location goal of GPS (Ref. 17) and is well within current technology.[18,19] When the vortex wake of an aircraft of 200-ft span is centered on the corridor (Fig. 5), the hazardous region is much larger than the flight corridor so that the hazardous contours extend out well beyond the sides of the corridor, even when the wake-generating aircraft is centered on the corridor. To further illustrate the relative sizes of the two regions, they are superimposed in Fig. 6 so that the flight corridor is centered on the overpowering region of one of the vortices. This situation could occur under the proper atmospheric conditions. The problem being addressed, however, is how to locate the flight corrridor so that the hazardous region moves out of it as quickly as possible, and stays out.

The movement required of the hazardous region relative to the flight corridor, which is fixed in space, to make an approach or departure safe, is illustrated in Figs. 7 and 8. First, consider an initial location for the centerline of the wake-generating aircraft at the top of the flight corridor (Fig. 7a). Such a location requires that the wake hazardous region move the

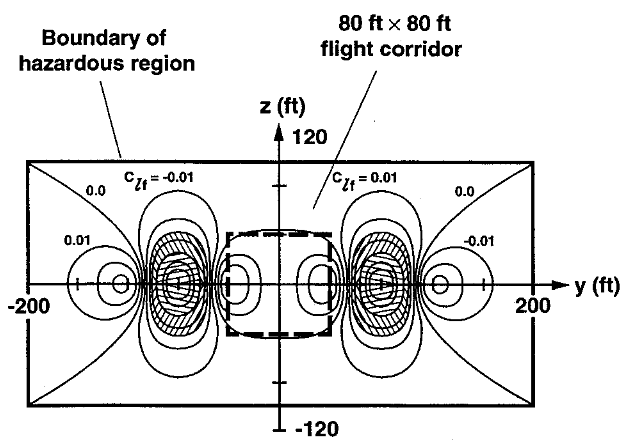

Fig. 5 Superposition of hazardous region of large transport aircraft and 80 by 80 ft flight corridor with centerlines aligned.

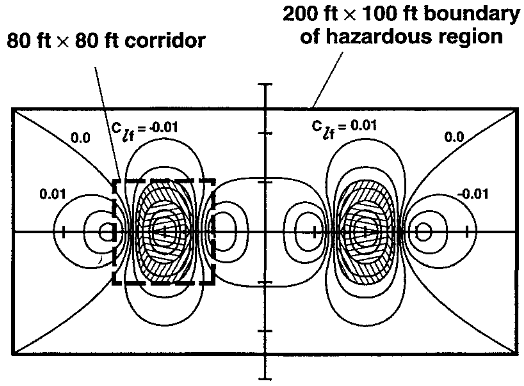

Fig. 6 Comparison of most intense part of hazardous region of vortex wake of large transport aircraft with 80 by 80 ft flight corridor.

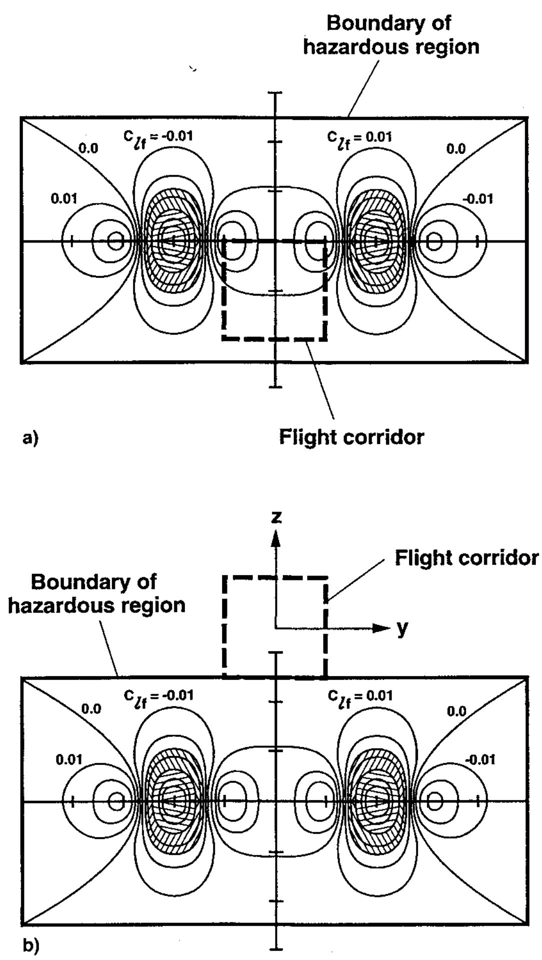

Fig. 7 Superposition of hazardous region and flight corridor to illustrate how far wake must move to clear flight corridor of wake hazard: a) initial and b) final relative positions.

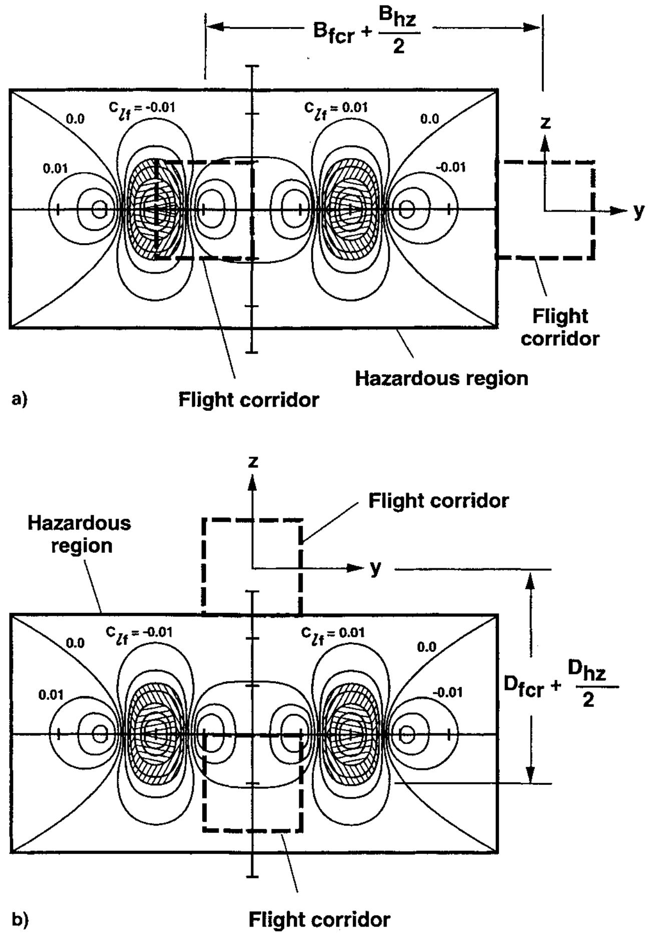

Fig. 8 Indication of amount of relative motion required to clear flight corridor of wake hazard: a) horizontal and b) vertical travel.

farthest distance relative to the flight corridor before the situation is safe. In Fig. 7b the hazardous region has just cleared the flight corridor, so that they are adjacent and not overlapping, to bring about a safe situation. The greatest relative horizontal and vertical distances that the wake must move to vacate the flight corridor, and make it safe for the next aircraft, are illustrated in Fig. 8. The distances shown are the maximum when the centerline of the wake-generating aircraft is at the side or top of the flight corridor so that its wake has a maximum distance to move to vacate the flight corridor. In equation form, the maximum horizontal and vertical travel distances are given by

$$\Delta y_{td} = B_{fcr} + B_{hz}/2 \tag{3a}$$

$$\Delta z_{td} = D_{fcr} + D_{hz}/2 \tag{3b}$$

where B_{fcr} and D_{fcr} are the breadth and depth dimensions of the flight corridor, and B_{hz} and D_{hz} are the breadth and depth dimensions of the hazardous region of the wake as defined previously; i.e., for most subsonic transports, $B_{hz} = 2b_g$ and $D_{hz} = b_g$. Equations (3) point out the importance of the size of the flight corridors because they can be changed. At present, the sizes of the hazardous regions that encompass the vortex wakes shed by aircraft cannot be changed with efficient designs.[8] Obviously, the minimum amount of time for the flight corridor to become safe occurs when the flight corridor is of zero size; i.e., when the flight of all aircraft are constrained to fly along a given line so that $B_{fcr} = D_{fcr} = 0$. Any increase in the size of the flight corridor to allow for deviations from a small corridor adds to the time for the hazardous region of the vortices to move out of the flight corridor.

The foregoing distances are used to determine separation guidelines for flight corridor arrangements to be considered. The separation distances are based on the time required for the lift-generated vortices, and their associated hazardous region, to move out of the flight corridor to make it safe for a following aircraft to proceed to a landing. In equation form, the time required for the hazardous region to vacate the flight corridor is given by

$$\Delta t_y = [B_{fcr} + B_{hz}/2]/v_{wind} \tag{4a}$$

$$\Delta t_z = [D_{fcr} + D_{hz}/2]/w_v \tag{4b}$$

For convenience, and to be conservative, the span of the largest aircraft in the current fleet ($b_g \approx 200$ ft) is used for the reference hazardous region. If the flight corridor is taken as 80 by 80 ft, and the wind is not blowing, the hazardous region needs to move downward by (80 + 100 ft) to vacate the flight corridor. At $w_v = 5$ ft/s, 36 s is required. A 1-min (or 3-n mile) spacing would then provide safe separation distances for aircraft. When smaller wake-generating aircraft are considered, the self-induced velocity of the vortex pair is sometimes smaller. Some or all of their reduced downward speed is offset by the smaller distance, $B_{hz}/2$ or $D_{hz}/2$, that the vortices have to travel to clear the flight corridor and become avoidable.

Note that the centerline (i.e., not necessarily the entire aircraft) of the following aircraft is constrained to the flight corridor. Certain parts of the aircraft will usually protrude outside of the flight corridor. It is not necessary, however, to allow extra time or space for the two regions to become separated because the rolling-moment computations are based on the relative locations of the centerline of the wake and the centerline of the following aircraft. Thus, the computations already take into account the entire velocity field of the vortex wake and the entire wing of the following aircraft.

Configuration of Flight Corridors

Consideration is first given here to the preferred shape for the flight corridor (i.e., straight vs curved). Next, the concept whereby a straight flight corridor is relocated after each aircraft has arrived or departed from the airport is explored.

Straight or Curved Flight Corridors

The desire for simplicity in any avoidance procedure almost dictates that straight-line flight corridors be used because any curvature of the flight corridor complicates the programming for approach and departure operations. It seems prudent, however, to at least consider curved corridors in case a particular shape has a decided advantage over the straight-line flight path. The question to be answered then is whether curved flight corridors lead to conditions that significantly decrease the likelihood of a vortex encounter and thereby merit the extra effort needed to execute them. Curved paths in the discussions to follow can mean a path with continuous curvature, or a path that has two or more straight-line segments that approximate a curve.

When the curvature is only in the horizontal plane as the aircraft descends for landing or ascends after takeoff, the vortex hazardous region descends in still air as it would if the flight path were straight. However, if a wind is blowing parallel to any part of the curved trajectory (Fig. 9), the downward motion of the vortex wake is influenced by a head- or tailwind effect. The apparent descent of the vortex wake may then be enhanced or nullified depending on the wind direction and magnitude, and whether the aircraft is landing or taking off. It is therefore concluded that a curved, or segmented turn in the horizontal plane while on approach or departure is more complex to monitor and has a higher risk for wake encounters than a straight-line flight corridor. Finally, no difference appears to exist between curvature because of a turn to port or starboard.

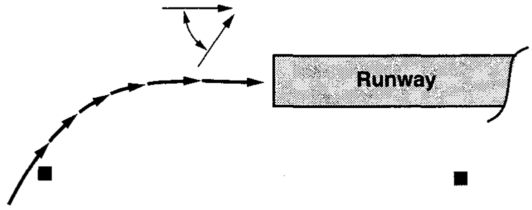

Fig. 9 Plan view of curved approach path in horizontal plane.

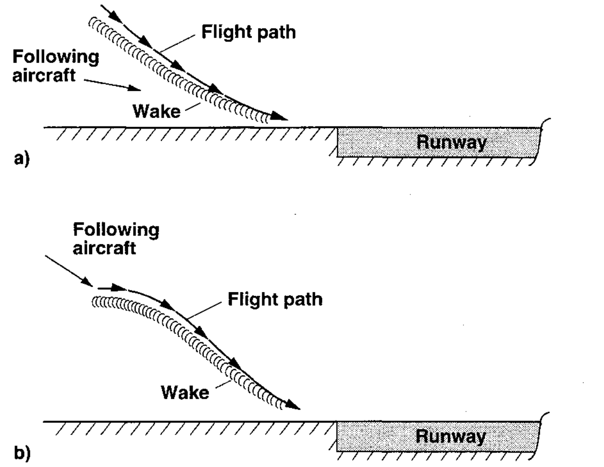

Fig. 10 Side view of curved approach path in vertical plane: a) positive and b) negative curvatures.

Consider next both positive and negative flight-path curvatures in the vertical plane (Fig. 10). Note that the angles of the flight paths relative to the ground are much larger than actual ones to better illustrate possible hazardous situations. If all aircraft follow the same flight corridor, and the vortex wakes descend in still air according to their self-induced velocity, the risk of an encounter with the hazardous-wake region is not increased for either type of flight path. However, if a head- or tailwind is blowing, the steeper parts of the flight paths are more susceptible for the wake moving into the path of a following aircraft. A straight-line flight path has the minimum slope for a given altitude change within a given distance along the ground. Hence, once again a straight-line flight path is less susceptible to wind-caused unacceptable motion on the part of the vortex wake. In addition, if aircraft are allowed to follow either a straight-line or one of the curved flight paths shown in Fig. 10, the mixed trajectories cause the aircraft carrying out a straight-line flight to cross the vortex wake of the preceding aircraft. In a study of a proposed two-segment approach, it was found that the mixture of straight-line and two-segment approaches were particularly hazardous.[22] Without going into other possibilities, it is apparent that flight-path curvature in the vertical plane can also be more hazardous, is more complex to operate, and certainly does not present an advantage over flight corridors that are straight.

Relocation of Flight Corridors

Consider the case wherein the flight paths of the wake-generating and following aircraft can each be controlled separately within narrow limits. A reduction in wake–vortex spacing distances would then seem possible because the system would be able to guide the following aircraft along a path where the vortices shed by the preceeding aircraft will not be encountered, no matter how closely they follow one another. For example, the flight path of one aircraft would be laid out so that it would land at or near the beginning of the runway. Since the vortex wake of the leading aircraft will descend when there is no wind, the next or following aircraft would be directed along a flight path that is directly above the one used previously (Fig. 11). Such a procedure is one that has been used in the past during conditions when visual flight rules can be followed. Similarly, if the wind is blowing, the following aircraft can avoid a vortex encounter by moving its flight path to port or starboard, up or down, by an amount that depends on the magnitude and direction of the wind. The basic idea is to place the relative locations of succeeding flight paths so that the wind and the self-induced velocities do not allow vortices to move into the flight path of following aircraft. The amount of relocation of each flight corridor depends on the size of the cross section of the flight corridor and of the wake–vortex

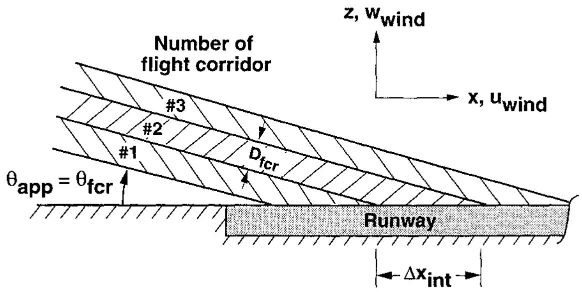

Fig. 11 Side view of relocation of flight corridors along runway to illustrate large amount of space required.

hazardous region, and magnitude in the wind and its uncertainties. In that way, each succeeding aircraft has its own flight corridor located so as to avoid all other corridors and vortex wakes of other aircraft. Furthermore, the corridors should all be straight and parallel so that flight paths do not cross the wakes of preceding aircraft.

Since relocation of the flight corridors cannot be continued indefinitely, previous corridors must eventually be recycled. If a flight corridor is to be reused, sufficient time must be allowed for the vortices to decay to a harmless level, or to move far enough away that they do not pose a hazard when a corridor is recycled. In addition, the time required for an aircraft to transit its entire approach or departure flight path is usually longer than the time interval between aircraft. Several flight-path corridors will therefore need to be active at a given time for both landing and takeoff, which introduces more complications.

Before proceeding further, consider the amount that a flight corridor must be shifted so that overlap with previous flight corridors does not occur. From Fig. 11, the intersection of a flight corridor on approach with the runway surface is given by

$$\Delta x_{\mathrm{int}} = D_{f\mathrm{cr}}/\tan\,\theta_{\mathrm{app}} \tag{5a}$$

where $D_{f\mathrm{cr}}$ is taken as the vertical uncertainty in the location of the aircraft. If the size of the hazardous region is the determining factor

$$\Delta x_{\mathrm{int}} = D_{\mathrm{hz}}/\sin\,\theta_{\mathrm{app}} \tag{5b}$$

where D_{hz} is the depth of the hazardous region perpendicular to the flight path, and not the vertical extent.

Consider, for example, the size of the intersection of an 80 by 80 ft corridor with the runway. For approach angles of $\theta_{\mathrm{app}} = 3$ and 5 deg, the footprint of the corridor intersection with the runway, is found by Eq. (5a) to be 1526 and 914 ft, respectively. If the corridor depth is based on the depth of the hazardous region for a large aircraft, its imprint along the runway is even larger. Similarly, the impracticality of the corridor relocation method is also apparent when lateral relocations are considered. In those cases, the relocation distance needs to be based on the width of the hazardous region B_{hz}, which is $2b_g$ in width, or about 400 ft for a large aircraft (Fig. 3). For comparison, commercial runways vary from 150 to 300 ft in width and from 8000 to 12,000 ft long. The two runways at Moffett Field, California that are used by NASA Ames Research Center are both 200 ft wide and are 8100 and 9200 ft in length. For the foregoing reasons, it is concluded that relocation of flight path corridors to avoid vortex wakes is impractical.

Data Monitoring Recommendations

The analysis presented here shows that even very small flight corridors require that, if flight safety is to be ensured, the motion of the wake vortices of aircraft be followed by a system such as AVOSS. As part of the monitoring system, the self-induced descent velocity of the vortex pair shed by all aircraft should be known for the maximum, minimum, and typical landing and takeoff weights and velocities for all of the aircraft that will use the airport where a system is planned. With such a data set in hand, it will be possible to determine the compliance of each aircraft with the assumptions made in the scheme to be implemented. It will also then be possible to determine whether it is necessary or advantageous to include the size of the aircraft in the wake–vortex avoidance system, or if the spacing can be the same for all aircraft combinations and simply be based on the largest aircraft.

A second item of concern is the influence of the wind and atmospheric structure on the motion and persistence of wake vortices.[23,24] In any wake–vortex monitoring system presently being considered, it appears necessary to monitor the wind direction and magnitude along the approach and departure corridors. One way to receive an essentially continuous stream of data on the wind and atmosphere in the flight corridor is to take the data by use of aircraft that use the flight corridors as they proceed along their flight path. Any aircraft that uses the constrained corridors will be equipped with instrumentation that uses GPS so that their velocity relative to the ground and to the atmosphere are known along the corridors. The difference between the ground- and airspeeds of the aircraft then determines the wind velocity. The wind velocity data could then be transmitted to a computer system at the airport where it is used to estimate the structure of the turbulence in the atmosphere and to determine the affect of atmospheric motion and turbulence on wake vortices.[23,24]

Any new vortex avoidance system should be applied in an experimental situation where it can be put into practice stepwise to find out how well it functions and whether alterations or additions or simplifications are advisable. Initially, the planned instrument approaches and departures could be carried out under visual conditions before proceeding to full instrument conditions. Practice cases not only check out the system, but also provide training for the operators. The importance of and necessity for data accuracy and timeliness can then also be assessed. Finally, as with any ATC system, the flight paths of aircraft as they enter and leave the constrained corridors for approach and departure, and as they touch down onto and leave the runway, will need to be identified so that inadvertent encounters with wake vortices of previous aircraft do not occur.

Concluding Remarks

A preliminary study is reported on the characteristics and preferred design features for the flight corridors of small size that could be used for approach and departure of aircraft from airports. If implemented, the smaller or constrained corridors would help to minimize the impact of the hazard posed by lift-generated vortices on traffic volume and safety. It is concluded that the flight corridors should primarily be as small in cross section as practical from a guidance point of view. Indications are that the corridors should also be straight (i.e., no curvature) and fixed in space for a given runway (i.e., frequent relocations should be avoided). Even though the use of flight corridors that are small in cross section, straight, and fixed in space does reduce the liklihood of a vortex encounter over the present system, it still seems prudent to employ a wake–vortex monitoring system (like AVOSS, Ref. 13) that accounts for the wind and atmospheric structure to estimate vortex motions to ensure that the vortex wakes shed by all previous aircraft do not pose a hazard to following aircraft. Reduction of the cross section of the flight corridors to the smallest practical size also simplifies the task of monitoring the wake vortices.

The preliminary study presented here indicates that, if the cross section of the flight corridors is reduced to a size possible with current GPS technology, it should be possible to safely reduce the current wake–vortex separation distances being used at airports to a uniform 3-n mile distance that is independent of the relative sizes of the wake-generating and following aircraft. It is assumed in the study that the reduction in the cross-sectional size of the flight corridors is a part of a larger ATC system that need not be changed in other ways to any great extent. Although the concept proposed here is primarily intended to expedite air traffic during instrument meteorological conditions at airports, it is recommended that, for additional safety, consideration also be given to its use during visual meteorological conditions. Other problems with the implementation of a system that uses constrained flight corridors, such as the requirements on the pilot or autopilot to hold the flight path of the aircraft within the limits of the specified flight path corridor, are not addressed.

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