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Vortex-Free Flight Corridors for Aircraft Executing Compressed Landing Operations

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A factor that limits airport arrival and departure rates is the need to wait between operations for the wake vortices of preceding aircraft to decay to a safe level. As airport traffic demand increases, creative methods will be needed to overcome the limitations caused by the hazard posed by vortex wakes so that airport capacities can be safely increased. The problem addressed here is the design of vortex-free trajectories for aircraft as they fly from their cruise altitudes down to their final approach paths and to a landing. The guidelines presented recommend that the flight path of each aircraft in a group executing nearly simultaneous landings be spaced far enough apart laterally along organized flight paths so that the vortex wakes of preceding aircraft will not intrude into the airspace to be used by following aircraft. An example is presented as to how a combination of straight lines and circular arcs is able to provide each aircraft in a group with a vortex-free trajectory for nearly simultaneous landings on a set of closely spaced parallel runways. Although the guidelines are described for aircraft on approach, the concepts presented are also applicable to departure, and to en route operations.

Nomenclature

B	=	breadth, ft (m)
b	=	wing span, ft (m)
b'	=	distance between vortex centers, ft (m)
D	=	depth, ft (m)
nmi	=	nautical miles
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	=	variations in y and z velocities ft/s (m/s)
x	=	distance in flight direction, ft (m)
y	=	distance in spanwise direction, ft (m)
z	=	distance in vertical direction, ft (m)

Subscripts

corr	=	flight corridor
eff	=	effective
f	=	following aircraft
g	=	wake-generating aircraft
hz	=	hazardous region of wake
offst	=	offset distance
ops	=	aircraft operations
pr	=	vortex pair
slf	=	self-induced
stn	=	wake station
wnd	=	wind
∞	=	ambient condition

Introduction

IT has long been known that the hazard posed by lift-generated vortex wakes of aircraft is one of the factors that limits the capacity of airports for landing and takeoff operations [1–3]. When the problem was first studied, it was hoped that an efficient method could be found to reduce the intensity of wake vortices to a level where they would no longer be a safety impediment to air-traffic density. However, after extensive research, it was concluded that such a method would not be found in the near future [1]. As a consequence, a large amount of research effort was diverted to the development of more effective and efficient ways to avoid vortex wakes in the airport vicinity. One such investigation was directed at an avoidance method that explores the use of short-term weather predictions to determine when side winds will be sufficient to transport vortex wakes out of, and away from, the flight paths and runways to be used. If successful, the airspace/runway combinations could be recycled more rapidly for an increase in runway capacity on the order of 10% with comparable safety [2,3]. If the method explored had been successful, it could have been implemented with small modifications to existing equipment and procedures being used at airports and on aircraft.

A recent study by the Federal Aviation Administration (FAA) [4], estimated that the demand for landing and takeoff operations at airports would approximately double in the next 20 years. In response to this estimate, an avoidance method is being studied [5–7] that has the capability to safely and efficiently make it possible for aircraft to avoid the vortex wakes of preceding aircraft. It is shown that both the equipment and the procedures currently being used at and near airports for landing and takeoff operations will need to be modified to achieve an increase in airport capacity by a factor of 2 [8–10]. For example, if such a method is to be implemented, it will be necessary to upgrade the precision of aircraft flight paths [e.g., accurate aircraft positions in the airport vicinity will be available from the global positioning satellite (GPS) system coupled with the wide area augmentation system (WAAS) [10] to an accuracy of a few feet (m)] so that very closely spaced multiple parallel runways can safely be used for what might be called compressed or compact airport operations; Fig. 1. Another aspect of the procedures to be used is that capacity increases are achieved by scheduling groups of aircraft into nearly simultaneous landings so that the vortex wakes of aircraft do not have time to move very far by the wind, nor to spread much due to self-induced velocities in the wake, and thereby do not intrude into nearby closely spaced runways until they have been used. Nearly simultaneous landings insure that uncertainties in the locations of the hazardous parts of vortex wakes are small, so that aircraft operation during compressed airport operations are safe.

Because simultaneous operations are currently being conducted on a number of very closely spaced parallel runway systems at airports, the avoidance method being studied is considered an

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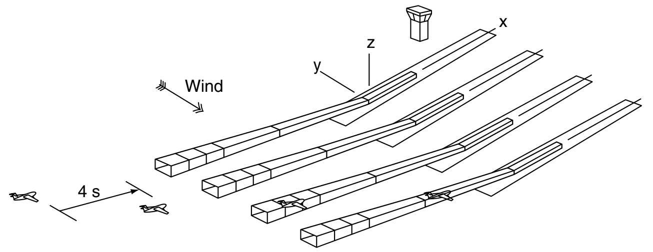

Fig. 1 Diagram of final segments and runways for compact arrangement of four nearly simultaneous landings.

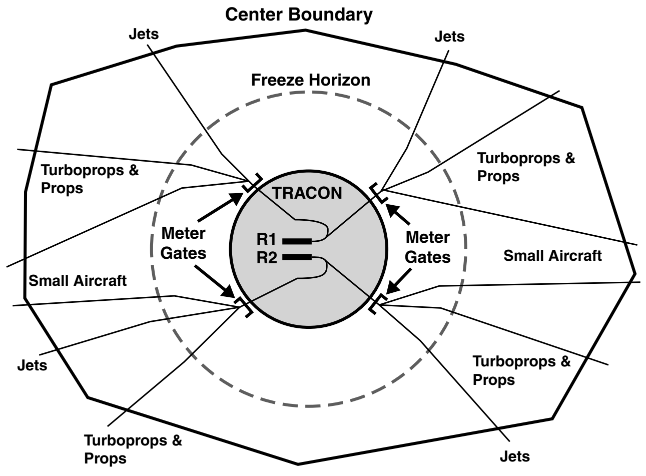

Fig. 2 Arrival traffic configuration of Center–Tracon Automation System (CTAS) showing how traffic is channeled through Meter Gates for arrival on two runways [19].

extension of existing systems and procedures used during visual meteorological conditions (VMC). Items like locations of flight paths and scheduling processes will need to be identified and upgraded for implementation to insure that compressed operations will provide vortex-free flight paths for safe and efficient operations [8–10]. The new procedures consider flight paths and groupings of aircraft from when they leave cruise altitude down to where each aircraft touches down and rolls out on the runway. Factors other than the wake–vortex hazard, such as flight-technical accuracies, pilot guidance-following accuracies, navigation errors and blunders, which also limit the minimum distances between parallel runways, have been discussed elsewhere [10–14]. These problem areas will need to be treated further if safe compressed operations are to be fully realized. Proposed methods for managing flight paths are being studied to bring efficiency and safety to the air-traffic problems at and near airports [15–19].

As part of finding a technique for safe wake avoidance, the study reported here concentrates on the aspect of wake avoidance that exists while a group of aircraft is being formed. The results apply during the time that a group of aircraft descend from cruise altitude down through any meter-gate system (Fig. 2) used at air-traffic centers [19] to the entry of their final respective precision flight corridors that guide them to nearly simultaneous landings. This more dense flow of approach traffic must be integrated by use of special arrival traffic configurations that provide a robust wake-avoidance arrangement for aircraft flight paths. The three-dimensional flight paths must be coordinated spatially and temporally so that flight along the final segments of the flight corridors is within the time window needed for effective and efficient wake–vortex avoidance through nearly simultaneous landings.

The analysis presented uses wake–vortex avoidance guidelines [4–6] to design vortex-free approach flight corridors when nearly simultaneous landings are being employed. Vortex wakes pose a hazard not just near the ground, but at all altitudes where multiple aircraft fly. Because any compression in traffic flow aggravates the problems associated with avoiding aircraft wakes, enhancements of airport productivity will need to carefully consider how to safely bring aircraft to and from airports. For example, if the compressed traffic flow is to be safely managed, the approach paths for a group of aircraft must be vortex free from cruise altitudes through a center to a landing (e.g., Fig. 2). That is, the flight paths must be laid out so that they do not intersect or lie close enough to each other for aircraft to possibly encounter energetic wake vortices. Compression of aircraft flight paths through narrow gates for controlled passage should be avoided, because such a practice substantially increases the possibility of aircraft encounters with vortex wakes.

The goal here is to show how to apply the guidelines for wake avoidance [4–6] to the design of flight corridors or paths from a point near where aircraft leave cruise altitude down to where aircraft reach runway threshold and touchdown. The method focuses primarily on how to plan the approach paths of arriving aircraft so that the lateral spacings between their flight paths are large enough to prevent an encounter with any hazardous part of any vortex wake shed by preceding aircraft. A nonhazardous vortex wake is defined as one wherein the rolling moment induced on the encountering aircraft is so small that the aircraft remains easily controllable, and the pilot cannot distinguish the encounter from one with ordinary atmospheric turbulence. After the guidelines are described, application is made to the design of the flight paths for a group of four aircraft to a system of four closely spaced parallel runways. The example presented is not a unique design, nor is it suggested as an appropriate pattern for any particular airport. It is intended as an illustration of how the guidelines can be applied to approach paths leading to a system of parallel runways. Integration of corridors and buffer zones into existing air-traffic management systems and procedures at airports is being studied by others [15–19]. Although the material contained here is directed at approach corridors to, and landings at, airports, the same guidelines also apply to takeoff and en route operations.

Guidelines for Vortex-Free Flight Corridors

The parameters that affect the location and motion of lift-generated vortex wakes shed by aircraft are

1) Location accuracy of wake-generating aircraft, because that is where vortex wakes begin their time history;

2) Size and time-dependent 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 air motions convect and disperse vortex wakes;

5) Location accuracy of following aircraft, so that they can be directed along flight paths that do not intersect or come close to any part of a wake region while it is hazardous.

As mentioned in the introduction, wake avoidance is not possible without accurate knowledge of the aircraft location relative to vortex wakes in the vicinity of an airport (numbers 1 and 5 in the preceding list), and it assumes that all aircraft are equipped with a navigation system that can locate an aircraft within several meters (e.g., accurate aircraft positions in the airport vicinity will be available from the GPS system coupled with the WAAS system to an accuracy of a few feet) [10]. The location accuracy of aircraft governs how compactly airport operations can be safely conducted, and thereby determines the ultimate capacity of an airport. However, knowledge of the locations of the wake generator and the following aircraft by itself is not enough. As indicated by factors 2 and 4, each flight corridor/runway combination must be far enough away from the flight paths of preceding aircraft so that no part of any wake is transported or dispersed into parts of a flight corridor until aircraft have gone past the station being contaminated by a part of a vortex wake. Because vortices are nearly stationary relative to the air in which they are embedded, their structure depends on the atmosphere, and not on the distance behind the wake-generating aircraft. As a consequence, vortex dispersion and motion depend mostly on time rather than distance. Therefore, the small time intervals between aircraft passage employed by nearly simultaneous landings restrain wake size, and thereby tends to minimize the amount of lateral spacing required between parallel flight corridors and runways.

It is also known that the vortex pair inside of each wake causes the wake to descend at a small velocity that depends on the weight and velocity of the generating aircraft; that is, factor no. 3. The self-induced downward velocity of the vortices may become of importance when close to the ground plane because it usually causes lateral travel, and possible intrusion into nearby flight corridors. However, at altitudes where ground effect is negligible as far as lateral travel is concerned, the small downward velocity is not a significant factor as long as the wake-generating and following aircraft operate on nearly the same plane. The simplest and most efficient vortex avoidance method is probably one where aircraft all descend from cruise altitudes along a funnel-shaped surface with a slope of about 3 deg to the horizontal so that aircraft are never stacked above each other. As the flight paths converge to precision flight paths for nearly simultaneous landings, stacked trajectories encourage vertical penetrations of vortex wakes and make avoidance more difficult. Orderly passage of aircraft from cruise altitudes with the precision required for compact simultaneous landings requires time-based planning at an early stage for proper synchronization of landings [10,16–19].

If the time-based locations of all aircraft can be defined with satisfactory precision, it remains to lay out flight corridors that are separated laterally by enough air space so that aerodynamic interference from vortex wakes does not occur. To satisfy such a criteria, it seems best to make the paths as simple as possible with minimum changes in direction, so that they are less likely to cross or come near to one another. Wake-avoidance guidelines recommend that the flight paths of aircraft should be sufficiently far apart so that it is not possible for the vortex wake of one aircraft to spread or to be windblown far enough to reach another flight path or corridor, and intrude on it, until the wakes are so weak that they are harmless. Extra space between flight paths might also be necessary to serve as a buffer zone in case aircraft deviate from their intended flight paths due to such causes as flight-technical errors, navigation errors and blunders. The analysis to follow considers the flight-path separation distances needed for wake–vortex avoidance, and does not allow for any additional space that may be required because of human or other factors. In- or along-trail spacings along flight paths for a following group of aircraft must also be large enough (2–3 min) to allow time for the wakes shed by preceding group of aircraft to decay to a harmless level, so that the disturbances caused by wakes are indistinguishable from those caused by atmospheric turbulence.

Because airspace distances between flight corridors along approach paths at altitude are not necessarily constrained to be the same as the separation distances between runways, it is recommended that all separations be computed on the basis of the largest aircraft in the fleet expected to use the airport being considered. The analyses carried out previously [5,6] retained wingspan as a parameter to show how it could affect airport capacity. Now, however, the spacings between flight-path corridors will be based only on the wingspan b_g of the largest aircraft, so that all smaller aircraft can safely use the same flight-path rules, if so desired. Analysis [1,5] indicates that the initial size of the hazardous region for a heavy aircraft behind another heavy is about $2.5b_g$ in the breadth (B_{hz}) or y direction of the aircraft, and b_g in depth D_{hz} or z direction of the aircraft; is about 500 by 200 ft (152 by 61 m). If an aircraft with a larger wake size arrives and intends to use the same runway system, increased lateral spacing can be obtained with equal safety by leaving adjacent runways/flight corridors vacant during each of those operation. Airport capacity is, of course, then reduced during those types of operations.

When the foregoing sizes of the hazardous region are applied to the wake of an aircraft, the finite size of the flight corridor must be added to the size of the hazardous region. Measurements made at cruise altitudes of the depth and/or breadth of condensation trails as a function of time are then used to determine the magnitude of the distances that vortex wakes spread laterally and vertically as a function of time [7]. Although the flight data contain a lot of scatter, because the persistence of ice crystals was not the same in all cases, wake boundaries appear to spread roughly as $\sqrt{\Delta t}$. When scaling factors are included, an empirical equation for the breadth or depth of the hazardous region as a function of time may be written as

$$D_{\mathrm{hz}} \approx B_{\mathrm{hz}}(t) \approx 0.5 b_g \sqrt{\Delta t_{\mathrm{ops}}} \tag{1}$$

where the time Δt_{ops} is the age of the wake in seconds between aircraft operations, and b_g is 200 ft (61 m).

To have a continuous formulation for the size of wake-hazardous regions, the guidelines for wake size are each used when they provide the largest value. When wake monitoring begins, its size is based on the initial size of hazardous region. At $\Delta t_{\mathrm{ops}} = 0$, Eq. (1) does not apply because it indicates that the hazardous region is of zero size, which is unrealistic. However, after a short time on the order of 5–10 s, Eq. (1) for wake spreading exceeds that predicted for the beginning sizes, and should be used instead. In computations, the larger of the two quantities would be used at any given time so that the size of the hazardous region is realistic, provides safe spacings at all times, and conforms with observations. It must be remembered that the sizes so determined are added onto the size of the flight corridor, because each aircraft may fly anywhere with its centerline inside of its assigned flight corridor. In addition, allowances must also be made for the fact that when a wake-generating aircraft is flying near the side of its corridor, half of its wake-hazardous region will extend outside of the flight corridor [5,6].

An analytical expression for minimum required offset distance (or separation) between flight corridor/runway combinations is then based on the amount of lateral or horizontal offset (Fig. 3) between flight paths along the outer parts of the flight trajectories is determined theoretically by

$$\Delta y_{\mathrm{offst}} \geq B_{\mathrm{hz}}(t)/2 + B_{g\mathrm{corr}}/2 + B_{f\mathrm{corr}}/2 + \Delta t_{\mathrm{ops}} |w_{\mathrm{pr}}| + |V_{\mathrm{eff}}| \Delta t_{\mathrm{ops}} \tag{2}$$

The absolute value of the maximum self-induced downward velocity of the wake $|w_{\mathrm{pr}}|$ is included at all altitudes (even though it is operable only when the aircraft is about one wingspan or less above ground level) so that Eq. (2) is also applicable in ground effect. Because $|w_{\mathrm{pr}}|$ is small, the added safety margin at larger altitudes does not appreciably increase separation distances. The subscripts in Eq. (2) identify, respectively, the breadth of the wake-hazardous region $B_{\mathrm{hz}}(t)$, which is a minimum just behind the wake-generating aircraft, and then increases with time. In Eq. (2) the parameter $B_{g\mathrm{corr}}$ represents the breadth of the flight corridor being used by the wake-generating aircraft, and $B_{f\mathrm{corr}}$ represents the breadth of the flight corridor being used by the following aircraft; an allowance for each is taken as 200 ft (61 m), because that is currently the wingspan of the largest subsonic transport in the fleet. Both quantities are assumed to be constant along the entire length of the flight-path/corridor, and to remain so with time. The influence of a side wind on offset distance is contained in the last term in Eq. (2) by V_{eff}. It represents the velocity that is effective in translating a side of the hazardous region laterally with time. As aircraft descend to lower altitudes, their flight paths are tapered to bring about touchdown on a runway, and their times to touchdown adjusted to insure that wake intrusion does not occur before each aircraft has retained a vortex-free flight path. The safe

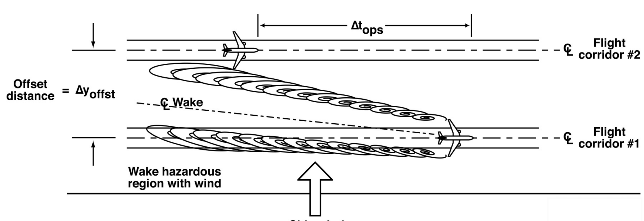

Fig. 3 For a given lateral spacing between runways, illustration of along-trail spacing required between two aircraft because of wake motion due to a side wind and self-induced spreading.

maximum along-trail time intervals between aircraft operations before wake intrusion occurs is then determined as t_{ops}.

The objective of the present guideline for approaches to runways is to separate the flight corridors in each group by a large enough lateral distance so that vortex wakes of leading aircraft will not intrude into the airspace of following aircraft until the wakes of leading aircraft have aged and decomposed to a nonhazardous level. The situation shown in Fig. 3 depicts wake intrusion behind the following aircraft, which is acceptable when nearly simultaneous landings are planned. However, because considerable airspace is available at 5 miles or more from runway touchdown points, it should be feasible to separate flight corridors by enough lateral distance so that the vortices become nonhazardous before they intrude into the flight corridors of any other aircraft.

First consider what might be the largest possible estimate for the minimum distance by which two parallel flight corridors must be separated to insure that the vortex-wake-hazardous region does not enter the flight corridor of another aircraft when a time factor Δt_{ops} of 3 min is required. Equation (2) yields $\Delta y_{\text{offst}} \geq =8740$ ft $=$ 1.44 nmi when the across-track component of the wind is equal to 40 ft/s (12 m/s), which is about twice the maximum acceptable value. When a side wind of 20 ft/s (6 m/s) is chosen, Eq. (2) yields $\Delta y_{\text{offst}} \geq =5140$ ft ≤ 1 nmi. It appears then that an offset between runways of 1 nmi would be sufficient for most side-wind situations along the outer parts of the flight trajectories. An offset distance of such an amount is about the same as the 4300 ft (1311 m) offset required between two runways if they are to operate independently of each another. However, at moderate altitudes above ground level where lateral space is available, it is recommended that lateral spacings of about 2 nmi be used to provide a safety factor against wake–vortex encounters, and also possibly due to hazards associated with the proximity of other aircraft.

As far as in-trail waiting times between groups of nearly simultaneous operations are concerned, it is recommended that they should be longer than presently deemed necessary for operations when aircraft are operated in isolation, because it is not yet known whether close proximity of aircraft causes their wakes to interact so that they decompose more quickly, more slowly, or at about the rate as a wake shed by an isolated aircraft. Therefore it is recommended that compact operations begin with a required time interval of about 3 min (rather than 2 min) between each operation until reliable data become available to provide a guideline for how rapidly air and runway space can be recycled. An effort will also need to be made, however, to insure that the landing velocities of all aircraft in a group are about the same so that a special effort is not required for the timing of each aircraft.

Suggested Design

The foregoing guidelines are now applied to the flight corridors needed for aircraft that will use compressed landing systems such as the one illustrated in Fig. 1. A time interval of about 4–10 s [800–2000 ft (244–610 m)] for the along-trail spacings of aircraft in a nearly simultaneous landing group is used, because it is short enough that wake spreading will not yet have gone far enough for vortex wakes of a leading aircraft to have intruded into the airspace of aircraft following on adjacent runways. What might be called along-trail spacings of 4 to 10 s are recommended so that exact side-by-side aircraft locations are avoided in case aircraft are not able to hold flight-path accuracy, or a wave off is required. In those cases, along-trail spacings reduce the likelihood of collision. Minimum lateral spacings between runways will then probably also be based on other across-trail factors that are greater than the minimum needed for complete wake–vortex avoidance. At present, minimum across-trail spacings between runway centerlines range from about 750 to 1000 ft (230–305 m). In the example to be presented, the runways are assumed to be about 10,000 ft (3050 m) long, about 200 ft (61 m) wide, and with 1000 ft (305 m) between runway centerlines.

The various segments of the flight corridors are now described by beginning at the runway end of the entire flight corridor; Fig. 4. The inner segment of the flight corridor, which is aligned with the runway centerlines, begins at the touchdown end of the runways and, in this example, extends about 1 nmi to provide a final straight-in flight path to touchdown. The second segment of the flight corridor begins at the end of the first segment out to some distance (e.g., the outer marker) when operational factors guide the length. If the length is based on the minimum altitude necessary for an aircraft to recover from a wake–vortex encounter [5], the length of the segment must be greater than about 20 nmi for a 3 deg glide slope. The altitude at the beginning of its assigned approach path is then about 4000 ft (1220 m), so that aircraft are able to recover from any inadvertent encounter with the vortex wake of a preceding aircraft. Because the approach flight paths must be designed so that wake encounters do not occur, the 20 nmi requirement should not be necessary, and the length of the second segment can be based on factors other than the wake–vortex hazard. It is recommended that the second segment of flight corridors be splayed at a comfortable angle to each of their runway centerlines in order to provide more lateral space between flight corridors at entry, which will help to funnel aircraft down towards a landing. It is assumed that aircraft timing and guidance accuracy are precise enough that flight along the tapered and final segments of the flight corridors to provide safety along these more compact flight paths.

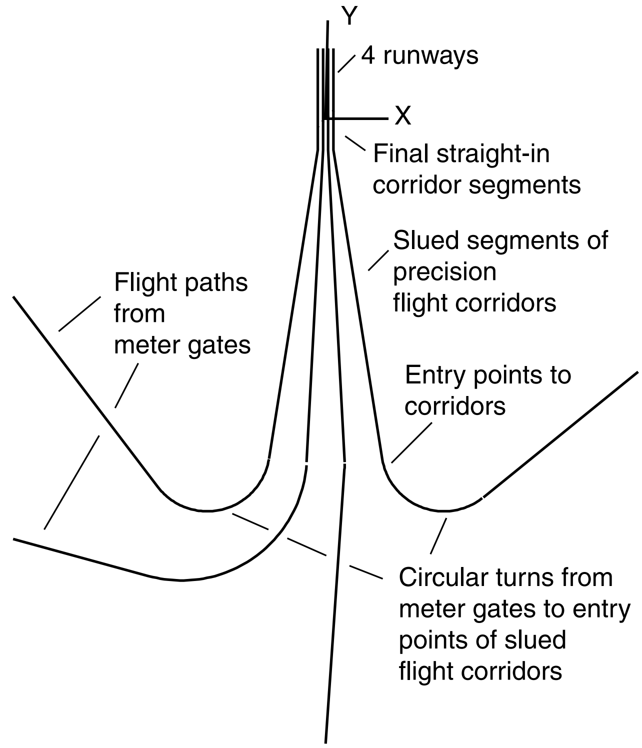

Fig. 4 Plan view of example of vortex-free approach flight corridors from cruise altitude or meter gates to touchdown on runways.

From the end of the second segment of the approach flight corridors to where aircraft leave cruise altitude, incoming flight corridors should be as simple as possible to ease the chore of laying out flight corridors that are free of vortex wakes. For these reasons, the flight corridors shown in Fig. 4 consist of straight line segments mixed with circular turns of large radii. The circular turns can be made large enough to maintain a 2 nmi, or some other, roughly equal-separation distance between corridors along the outer segments of the flight paths. It seems preferable to restrict the number of turns as much as possible to more easily avoid stacking, crossing, or overlapping of flight corridors.

Conclusions

The guidelines recommended here for vortex-free flight corridors while aircraft are on approach to an airport are simple and reliable, and the suggested spacings are probably not excessively larger than needed. To insure safety of flight, it is imperative that the guidelines be applied throughout the approach path from cruise altitude to touchdown for each aircraft. The combination of straight line and circular arc segments for approach paths is not a unique technique for generating vortex-free trajectories, but it is a simple way to insure that flight paths are far enough apart that vortex wakes do not intrude into the flight paths to be used by other aircraft. Although not specifically discussed here, the concepts presented may also be applied to en route, takeoff, and departure operations to insure that wake encounters do not occur.

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