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AIRCRAFT WAKE TURBULENCE AVOIDANCE

by William A. McGowan

NASA Headquarters

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SUMMARY Aircraft trailing vortex systems are made up of two counter-rotating cylindrical air masses, about a wing span apart, extending aft along the flight path. Vortex systems of large aircraft contain winds which can be hazardous to other aircraft encountering them in flight. The greatest hazard potentials exist in areas where aircraft of a wide range of classes are operating (e.g., light utility/observation and heavy transport/bomber).

Results of analytical studies and flight tests are used to describe the formation and severity of trailing vortices and the spatial extent of their influence. This information is then used to outline procedures for ready application by pilots, tower operators, and others concerned with the flow of traffic. The procedures provide the necessary appreciation of the physical attributes of trailing vortices, the potential hazards involved when encountering them, and how best to avoid the dangerous portions of the wake during flight operations.

NASA has a comprehensive research effort underway to better describe aircraft trailing vortex behavior and concurrently, other studies are aimed at the development of a concept either to discourage initial formation of high intensity vortices or to encourage early dissipation of the dangerous wake, through aircraft design.

INTRODUCTION Trailing vortex systems, or the wake turbulence, of large transport type aircraft are known to have winds of hazardous intensities if encountered in flight by other aircraft (1-7). An additional troublesome aspect of the problem is that the vortices which are generally difficult to detect behind the large aircraft persist for quite some time after generation. The wake turbulence of most concern to pilots is caused by the trailing vortex system generated by the wing lift of large, heavy aircraft.

Past theoretical studies and flight tests were concerned with the extent of vortex system movement and intensity to improve our understanding and acquaint aircraft operators with the perils inherent in vortex encounters (5-7). Now, very large, heavy aircraft are being placed in service, and a substantial increase in the number of aircraft operations can be expected in the future (8). One of the limiting factors being considered in the spacing of aircraft using either the same runway or adjacent runways is the invisible trailing vortex system. There is, then, a real need to explore ways to reduce the delays and spacing between aircraft: (1) through improved understanding of trailing vortex behavior for different aircraft classes, modes of operation, and meteorological conditions, (2) by development of ways to monitor trailing vortex position and intensity in the airport area, and (3) by development of a method to either discourage initial formation of high intensity vortices or encourage early break up when once formed, through aircraft design.

In this paper, aircraft trailing vortices and the hazard potentials they present to other aircraft are discussed. Interpretations of some results from flight tests and analytical studies are outlined for operational use.

WAKE TURBULENCE CHARACTERISTICS The circulation about an airfoil, necessary for wing lift, gives rise to the two rotating cylindrical air masses trailing aft along the flight path. Tangential velocities within a vortex system close behind a heavy aircraft, as the C-5A, can be on the order of ± 3600 ft/min (7) as noted in figure 1. Flight test data (9) indicate that velocities in vortex wakes can be equal to or greater than 3600 ft/min up to 1½ miles aft of the C-5A, or 30 seconds after aircraft passage. Tangential velocities for a particular aircraft vary directly with the aircraft weight and inversely with aircraft velocity as shown in the figure. The more intense vortices then are generated when the aircraft is flying slow, as in the airfield area and during some support missions. The term in the brackets of the tangential velocity equation in figure 1 accounts for vortex velocity deterioration with time. Possibly the major factors to note are that vertical velocities about the rotating air masses of a vortex system can vary as much as ± 3600 ft/min over a very short distance (a fraction of a wing span), as shown in figure 1, and that these rotating air masses can impose large rolling moments on other aircraft. In addition, mutual interaction of the vortices induces a downward movement of the system which is discussed later.

During some flight test experiments axial flow, that is, velocities along the center of the vortex core, were observed. In figure 1 the axial flow would be perpendicular to the plane of the paper within the two smaller circles. This flow phenomenon is not well understood. An understanding of the cause and effect of this flow will be necessary for an adequate theoretical description of vortex behavior. However, it appears at this time that axial flow is of little, if any, operational concern and will not be considered further in this paper.

Elements influencing vortex system behavior are summarized in figure 2. The number of elements indicates the complexity of developing a method for precise definition of vortex movement and intensity in the many situations that could exist. In a later section the available knowledge of vortex behavior is used to develop avoidance procedures for the various flight regimes.

Jet engine wake velocities and temperatures are shown in figure 3 for the C-5A at takeoff thrust (10). The jet-engine-wake airstream is turbulent and not well organized, and velocities for even this high thrust condition dissipate to 35 mph in about 1200 feet. The rapidly dissipating jet wake is believed to present no hazard to other aircraft from an unexpected inflight encounter standpoint and is of no further concern in this paper.

HAZARD POTENTIALS In figure 4 is shown an illustration of a trailing vortex system with a velocity distribution perpendicular to a line through the vortex centers some distance behind the generating airplane. Upwash and downwash velocities are apparent. Different hazard potentials of aircraft encountering these velocities are shown. An aircraft penetrating the core of a vortex would experience imposed rolling moments. An aircraft subject to the downwash would have to contend with a loss in rate of climb or an increase in rate of descent. If the penetrating aircraft approaches perpendicular to the vortex system, as along a line through the vortex centers, structural load factors would be the principal concern and, in addition, a bumpy ride would surely result.

In addition to the direct hazards just mentioned, there is a more subtle hazard related to pilot startle effect, because often vortex encounters are most pronounced when the atmosphere is well behaved and the pilot is experiencing smooth flight. Available reaction time to recover from vortex induced upsets near the ground can be brief enough and any unnerving effect delaying counter maneuvers would not be welcome.

Helicopters in forward flight spawn vortices with relatively intense velocities, compared to aircraft of equal weight, and can be of operational concern to light plane pilots (6). The vortex system of larger and heavier V/STOL aircraft planned for future use should be continuously assessed in the early stages of development to achieve a full appreciation of the operational problems involved.

The hazard potential of trailing vortices is greatest in areas where a wide range of aircraft classes are operating (e.g., light utility/observation and heavy transport/bomber). Certainly airport areas are relatively hazardous because of the proximity of aircraft and the number of operations. Generally speaking the magnitude of any problem imposed on aircraft encountering a vortex will depend on the magnitude of the velocities as well as the size, performance capabilities, and altitude of the penetrating aircraft.

EXTENT OF THE HAZARD It was previously mentioned that vortices have an inherent characteristic to move downward when formed. Figure 5 illustrates the vortex system movement far from the ground in a constant atmospheric density environment. Two principal factors are readily apparent: first, the vortices move downward in equal increments with time and, second, the vortex system drifts with the wind while at the same time maintaining the tendency to move downward with time, as in the no-wind case. The vortices form just inboard of the wing tips and remain so spaced, unless disturbed by turbulence or some other factor, as mentioned before. The illustration of figure 5 is not too unrealistic except that the influence of the denser air encountered by the downward moving vortices has not been taken into account.

Consider that the vortices entrain air at some altitude. These cylinders of relatively light air are forced downward into a denser atmosphere by the inherent action of the system. It is reasonable to expect then that the downward movement will slow with time, assuming there is but a gradual diffusion of energy outward to maintain an essentially constant force, over the time period of interest.

Forces acting on the vortices in a calm atmosphere were estimated and are presented in figure 6. In the estimates made, the vortices are described as cylindrical air masses which wrap up aft of the airplane, in this example along a flight path at 12,000 feet altitude. For computational purposes a 1 foot length of a trailing vortex cylinder 100 feet in diameter is used. This volume of air weighs approximately 417 pounds at 12,000 feet altitude. As this air mass is forced downward by the vortex system interaction the upward force (bouyancy) increases to about 15 pounds at a 11,000 foot altitude, at which point the upward force equals the downward force, the force inherent in the vortex system. Equalization of forces would be expected to occur following a downward movement of approximately 1000 feet as shown in the figure. Obviously at this altitude the downward movement stops, if no other outside forces come into play, as illustrated in figure 7.

The small magnitude of the forces shown in figure 6 illustrates the belief that the trailing vortex system is delicately balanced and subject to the many perturbations actually present in the atmosphere. One of these perturbations is undoubtedly thermal effects, which seem to be always present, while another might be atmospheric wave action. Figure 8 illustrates thermal effects which can be present over changing terrain. These effects on vortex system vertical travel might not be operationally significant and are discussed later; however, it would appear to be premature to state that vortices will never descend more than 1000 feet, as noted in the example of figure 6. Then, too, thermal and wave action of sufficient magnitude can lead to the early disruption of the vortices. Gentle, moving currents without marked discontinuities are expected to cause little reduction in vortex persistence.

The wake locations behind the C-5A for several test runs are given in figure 9. The vertical displacements are encompassed by a theoretical line derived from the information given in reference 7. The vertical displacement of the wake does tend to level off about 1000 feet below the flight path of the C-5A for the atmospheric conditions existing during these limited tests. The wake remained intact for distances exceeding 10 nautical miles behind the C-5A.

The roll response of three aircraft (DC-9, Cessna 210, Lear Jet) on encountering the C-5A wake at various distances astern (9) are shown in figure 10. The weight spread of these aircraft extended from about 70,000 pounds to about 3,000 pounds. The roll response was achieved despite the best efforts of the pilot to counter the bank angles imposed. Obviously upsets of this type could be hazardous. A practical limit of 30° bank angle was set and noted on the figure, assuming this bank angle would be about all a pilot would want to contend with, especially in holding patterns, during approach to landing and shortly after takeoff. Other important items, related to this 30° bank angle, are the separation distance of 8 miles and time lapse of 2.7 minutes, after the C-5 passage. These items are considered later in development of safe avoidance procedures.

Previous mention was made of the load factors which an airplane could experience when traversing the vortices, as along a line through the vortex centers. Calculated normal load factors (5) imposed on a light aircraft crossing the wake of a heavy transport aircraft (180,000 pounds), perpendicular to the flight path and along a line through the vortex centers, are shown in figure 11. Two important facts should be pointed out: the first is that relatively high load factors were reached during the elevator fixed traverse and the second is that elevator motion, initiated by the pilot to counter initial upwash of the vortex, compounded the hazard and in this instance ultimate load factors were reached.

Load factors measured during flight tests are shown by the cross hatched areas in figure 11. The load factors, measured on a T-33 aircraft and a U-3A (Cessna 310) aircraft during penetration of wakes from large aircraft, are of a preliminary nature. The large aircraft were not at maximum weights and the exact locations of the penetrating aircraft relative to the center of the wake are not known. The point is that measured load factors are about what was expected. It appears that even higher load factors could be experienced when light aircraft encounter the wake of heavier, large transport aircraft under more adverse conditions. The penetrating aircraft in each of these incidents was relatively close behind the heavier aircraft generating the wake--about 1.5 miles or about 30 seconds after passage. Large load factors could be imposed on light aircraft for vortex ages up to 1½ minutes or approximately 5 miles behind large, heavy transports.

Another important feature of the situation wherein large load factors can be imposed on a light aircraft is that, at least one of the vortex cores must be penetrated. There is a marked reduction in the magnitude of imposed load factors when the aircraft is but a short distance (~25 feet) above or below the line through the vortex centers (5). In other words, to experience high load factors it is necessary to pass close to at least one of the vortex cores, possibly an explanation of why catastrophic accidents related to structural failures (1) are fortunately rare.

Vortex system movement near the ground is illustrated in figure 12. With no wind the settling rate continues until the vortices approach to within about a wing span of the ground.

At this distance the settling rate slows and the lateral spread commences, here again, at a rate equal to the settling rate (7). The vortices spread out at a height above the ground equal to about a wing semispan. The effects of a crosswind are illustrated in figure 12. For example, with a crosswind component countering the lateral spread, one vortex remains stationary over the ground while the other vortex drifts laterally at an increased velocity as shown in the figure. In addition, head wind and tail wind components would cause the vortices to drift along the runway, in addition to the lateral movement. Factors involved in application of these characteristics for operational procedures are discussed next.

To put some reasonable bound on the time vortices might be of concern to other aircraft the estimated duration obtained from reference 7 was modified to represent the more recent flight experience given in figure 10. It was noted that 30° bank angles could be imposed for separation times of 2.7 minutes after C-5A passage. For these calculations a maximum vortex duration time of 3 minutes (see figure 13) was selected for use in the development of bounds beyond which safe flight would be assured.

Maximum vortex travel near the ground was calculated, using the information of reference 7 and figure 13, and is shown in figure 14. It can be seen that maximum wind drift occurs at wind speeds of between 10 and 20 knots. Also, the lateral movement of the vortex, due to inherent characteristics discussed previously, is seen to reach about 1400 feet in 3 minutes, the maximum age for which the vortex is expected to be a threat to other aircraft. The maximum lateral travel, realized when conditions are such that the wind drift and lateral movement compliment each other, is over 3000 feet. A value of 3500 feet was selected to represent the maximum lateral vortex travel from the runway centerline, as shown in figure 15.

Of course the wind can come from many angles. In figure 16, the vortex movement near the ground with the wind from 30° port is shown. The displacements of the right and left vortices are shown for winds up to 40 knots. The extent of movement is limited by the vortex duration times of figure 13. An interesting point is the location of the left vortex position in a 10 knot wind from 30° port. The vortex is located directly over the runway at a time 2 minutes after generation. The vortex from the right wing tip has drifted off to the right of the runway in the same period, as shown.

Calculations of vortex movement for wind directions of zero degrees to 90° and from the port and from the starboard results in a family of curves. An envelope about this family of curves is shown in the shaded area of figure 17 and sets the bounds of vortex travel, within which vortex velocities could be of concern.

The vortex travel shown in figure 17 seems rather extensive. However, flight tests (7,11) made near the ground indicate that the vortices move about as expected for the conditions investigated. An accident (4) caused by a vortex that drifted a distance possibly exceeding 600 feet also tends to substantiate the calculations to a further degree. Observations of flight tests near the ground suggest that vortices can drift for a considerable time without apparent disruption (on the order of 2 minutes) under relatively calm wind conditions.

There is an uncertainty related to the minimum aircraft altitude at which the trailing vortex system has the time and inclination to roll up fully, as shortly after takeoff. In figure 18 the vortex envelope and footprint are illustrated under the flight path from rotation to an altitude of 1000 feet. The vortex envelope is positioned for several locations along the flight path for which full vortex roll-up is assumed; (1) at rotation, (2) at an altitude equivalent to a wing semispan, and (3) at an altitude equivalent to a wing span. The footprint aligned with the rotation point, as shown previously in figure 17, was selected and used in the next section to make sure that pilots of following aircraft can avoid the vortex hazard.

<u>AVOIDANCE PROCEDURES</u> The previous discussion dealt with results of analytical studies and flight tests to describe the behavior of trailing vortices generated by large transport aircraft. This information is now used to develop procedures for avoiding the damaging manifestations of vortex systems.

Information from figures 9 and 10 was used to derive the envelope of vortex vertical location aft of a large transport aircraft as shown in figure 19. Pilots could possibly encounter large load factors, bank angles, and roll rates in the shaded area. Atmospheric turbulence as well as aircraft which generate vortices of less intensity can shrink these areas. The lateral displacement envelope shown in figure 19 accounts for wind drift of the vortices under crosswind conditions, as described in figure 14. An aircraft penetrating the shaded areas would not necessarily encounter a vortex because of their respective locations, but wise pilots should avoid this air space by staying either above the flight path of the large aircraft or at least 1000 feet below. Of course, time spacing and distance separation of 3 minutes and up to 10 miles, respectively, of aircraft behind the large aircraft would be adequate to avoid dangerous encounters.

Using information from figure 17 the suggested takeoff profile for light aircraft following heavier aircraft is shown in figure 20. In general, an aircraft can avoid a possible encounter with the wake by lifting off 3000 feet short of the rotation point of the preceding heavy aircraft. Following takeoff it would be to the light plane pilot's advantage to remain on the upwind side and above the flight path of the larger aircraft. Adequate runway would be available if the smaller aircraft starts the takeoff roll at the same location on the runway as did the larger aircraft. Pilots should take special care if the takeoff roll is started at other points along the runway, as at an intersecting runway or taxiway, where liftoff can occur nearer than 3000 feet to the rotation point of the larger aircraft.

It was shown in figure 17 that the vortices might drift to runways other than the one used by the larger aircraft. Therefore pilots planning to take off on parallel or intersecting runways should consider the possibility of a vortex hazard and plan accordingly, using the information provided in figures 17 and 20. An example of the application of this information to particular airfield situations is shown later.

The envelope of figure 17 is also applicable to approach and touchdown procedures. The rotation point noted in the figure can be considered the touchdown point for this application. Under some landing conditions, with a small tail wind component, the vortices can drift 500 feet down the runway (7) following touchdown of the large aircraft under the most adverse condition. This drift and the suggested touchdown procedure for light aircraft following heavy aircraft are sketched in figure 21. In general, light aircraft pilots should plan to touch down 2500 feet beyond the touchdown point of the larger aircraft. As an example, if a large aircraft touches down 1500 feet from the threshold the light aircraft should land 2500 feet beyond or at about the 4000 foot marker to avoid a possible vortex encounter.

Light aircraft, using the instrument landing system (ILS) and visual approach slope indicator (VASI) (at airfields used by large heavy aircraft), should stay on the high side of the glide slope and to the upwind side as shown in figure 22. Smaller, slower aircraft are sometimes routed in airport traffic at a lower altitude and in tighter patterns than the larger faster aircraft. If the light plane pilot is faced with this situation while turning from the downwind leg to the base leg it is essential that he remain above the flight path of the larger aircraft if at all possible. A high percentage of vortex accidents seems to be caused when the light aircraft approaches the airport on final leg at a lower altitude than the preceding aircraft (2). In addition, should the large aircraft execute a missed approach special precautions should be exercised by the following aircraft as can be surmised from previous discussions.

The envelope of figure 17 is shown plotted on an airport layout in figure 23 to depict that vortices from a large aircraft using one runway might well influence the takeoff or landing of aircraft using the same or another runway. Numbers in the runway indicate distances from the threshold in thousands of feet. The parallel runways 9L and 9R are 5000 feet apart. Four examples are used to illustrate use of the vortex system envelope to permit pilots, following large aircraft, to avoid vortices that could impose a hazardous situation.

In the upper left of the figure a large aircraft is shown at touchdown 1500 feet from the threshold on runway 9L. A following light plane, using the same runway, should touch down 2500 feet further down the runway or 4000 feet from the threshold as shown for example A, keeping in mind previous procedures of remaining above the approach path of the heavy aircraft. In example C, a light plane landing on runway 12 following the heavy aircraft that just landed on runway 9L at the 1500 foot marker should touch down 3500 feet from the threshold to surely avoid the vortices located somewhere in the plotted envelope, possibly along the first 1000 feet of runway 12.

Another example (B) of envelope application is given for the large aircraft taking off from runway 9L, where liftoff or rotation occurred at the 9500 foot mark. A following light aircraft should lift off no later than at the 7000 foot marker to avoid possible wake turbulence. After liftoff the light plane pilot should follow previously discussed procedures of remaining above and just to the upwind side of the flight path of the heavier aircraft.

In the fourth example (D), a large aircraft is shown lifting off from runway 9R at the 7500 foot mark. The envelope covering possible vortex locations for a variety of wind conditions that might exist is shown to cover parts of three runways - 9R, 12, and 17. A light aircraft planning to use runway 12 should plan the takeoff roll so as to lift off just beyond the 3000 foot marker, to avoid possible wake turbulence from the heavy aircraft that took off previously from runway 9R.

It appears that pilot application of the vortex system envelope at airfields could be done with readily available information during preflight planning exercises. Generally the runway length and airfield layout as shown in the example of figure 23 are available for pilot use, as for instance, in reference 12. The pilot would require knowledge of the large type aircraft operating at the airfield in order to estimate the point of rotation and make the best use of the vortex system envelope during preflight planning. This probably is a logical and necessary requirement for safe operational planning under any circumstances.

PILOT POCKET AID It is recognized that the avoidance procedures discussed and explained previously are not in the most convenient forms for ready application by pilots and others. Hence, any advantages that might be realized from the information accrued and flight experience gained on the trailing vortex hazard problem would probably not be put to optimum use.

To help with this problem, it is suggested that the essential information be made available on a pocket size card (6), as shown in figure 24, which the pilot could use in preflight planning. One side lists the operational tips on how best to avoid the vortex wake. On the other side is a sectional grid, marked at 1000 foot intervals, allowing a pencil sketch to be made of the runway layout for particular airfields being used (a plasticized surface is suggested to permit easy erasures and reuse). In the upper right corner is the scaled vortex envelope for replotting by the pilot to the runway point where heavy aircraft land or take off, as it might affect his use of the airfield, in a manner similar to the example of figure 23.

AIRCRAFT VORTEX RESEARCH The NASA is carrying out detailed aerodynamic research with the aim of uncovering candidate schemes to promote either early break up of the vortex system or alteration of the flow to eliminate unfavorable characteristics of concern to following aircraft. Either of these solutions would be an acceptable means to remove all of the elements of the trailing vortex problem; the hazards, the economic penalties, and the passenger discomfort.

Those concerned with the research have considered several different basic ideas that might warrant further study, such as wing tip shape, engine location, air jets, lift modulation, etc. These ideas are discussed in more detail in reference 13. Closely related to any successes in the wind tunnel or water channel will be the flight test phase both to verify the model tests and evaluate the scheme as a practical way to solve the problem.

One question often raised is in regard to the possible vortex intensity of new type aircraft, as the STOL vehicles and the supersonic transports. NASA scientists working with experimental aircraft are aware of the trailing vortex problem and hopefully will cope with this aspect of aircraft development to the extent possible.

CONCLUSIONS Aircraft wake turbulence, or trailing vortex systems, of heavy transport aircraft extend aft along the flight path for considerable distances. The vortical winds in these systems are of magnitudes hazardous to other aircraft. Aircraft encountering these winds can experience problems associated with large bank angles, changes in rate of climb or descent, and structural load factors.

It is difficult to know precisely the location and severity of wake turbulence in operational situations, due in part to the lack of both fine-scale environmental information and knowledge of operating factors of the generating aircraft. For this reason, the whereabouts and intensity of the wake turbulence for a particularly severe situation were determined for a wide range of circumstances. The travel and persistence of this wake turbulence were used to define bounds from which general avoidance procedures were derived for ready use. In part, the bounds of turbulence intensity and movement were verified by flight test information.

NASA has a comprehensive research effort underway to better describe aircraft trailing vortex formation, persistence, and whereabouts and concurrently, other studies are aimed at the development of a concept either to discourage formation of intense trailing vortices or to induce early dissipation of the dangerous wake.

The short term goal of this work is to develop optimum avoidance procedures. The final goal is to eliminate wake-turbulence-related problems of general aviation pilots, commercial carriers, passengers, and the air traffic system.

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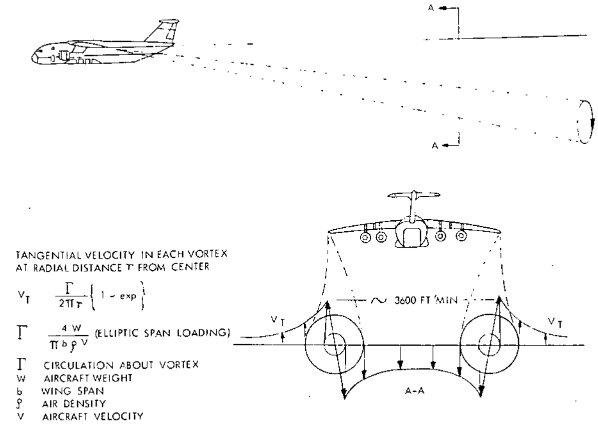


Figure 1. Elements of the Aircraft Trailing Vortex System

- AIRCRAFT TYPE, WEIGHT, CONFIGURATION, SPEED
- CHANGE OF FLIGHT PATH, MANEUVERS
- AIR DENSITY
- WIND INTENSITY, FLOW DIRECTION
- TURBULENCE
- HEAVY PRECIPITATION
- GROUND PROXIMITY/ROUGHNESS

Figure 2. Elements Influencing Vortex System Behavior

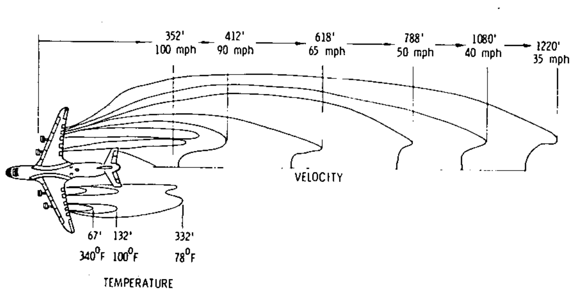


Figure 3. C-5A Jet Wake Characteristics (Takeoff Thrust)

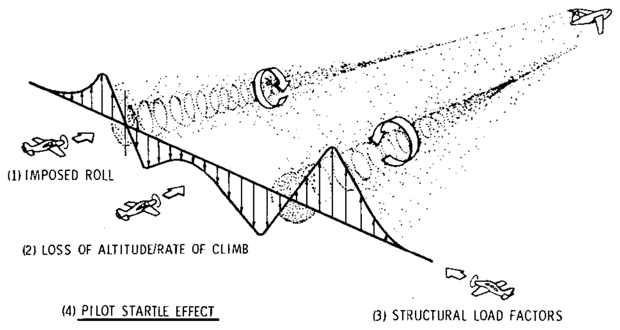


Figure 4. Hazard Potentials of Trailing Vortices

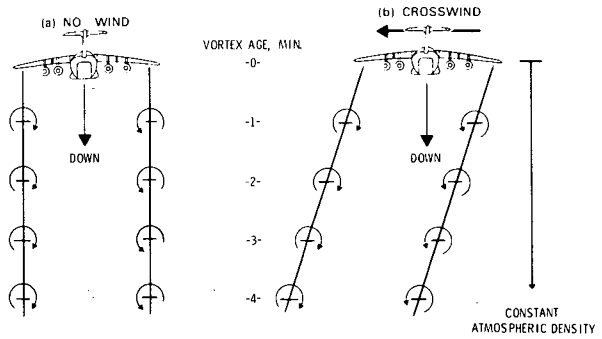


Figure 5. Vortex-System Movement Far From the Ground (Inherent Characteristic)

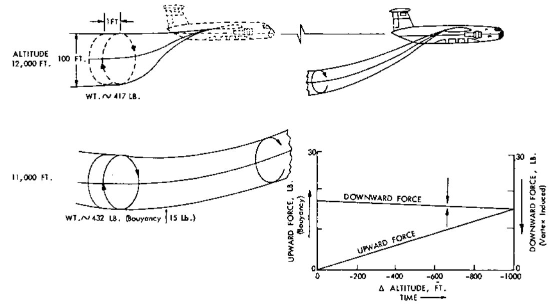


Figure 6. Estimate of Forces Affecting Vortex Vertical Position

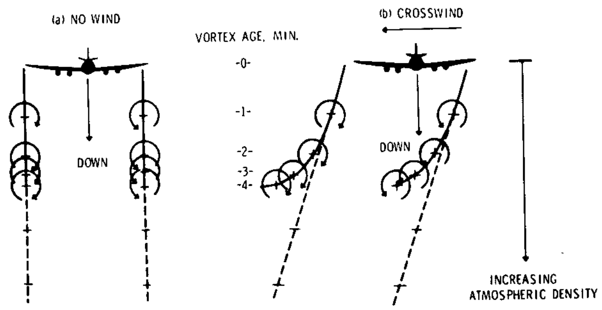


Figure 7. Vortex-System Movement Far From the Ground (Atmospheric Density Effect)

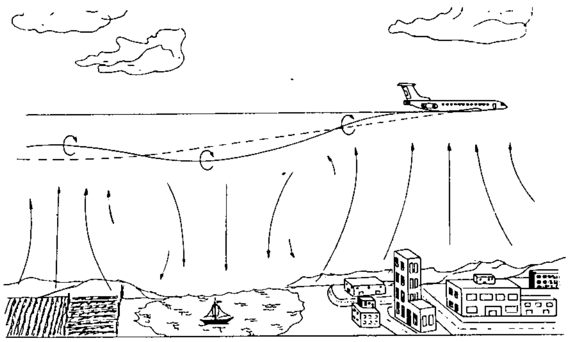


Figure 8. Thermal Effects on Vertical Position of Vortex Wake

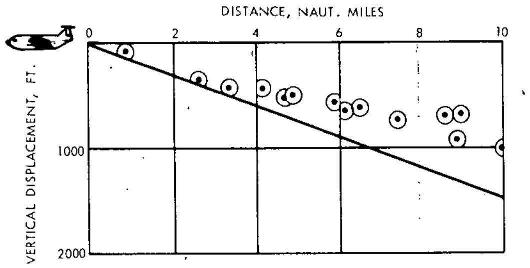


Figure 9. Vertical Location of Vortex Wake Aft of the C-5A

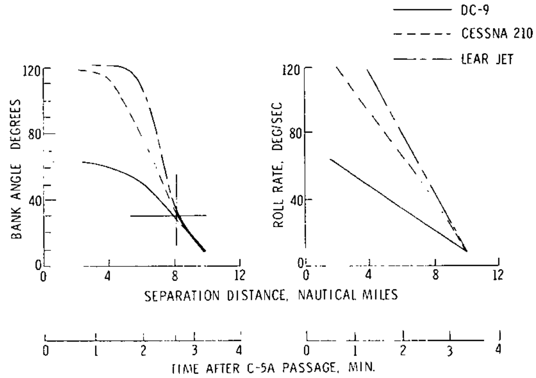


Figure 10. Maximum Roll Response of Test Aircraft in the C-5A Wake

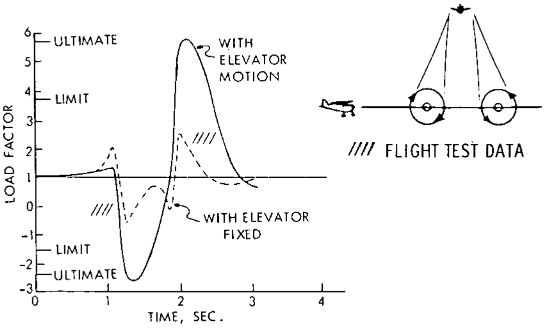


Figure 11. Vertical Loads Imposed on Light Aircraft Crossing the Wake of Heavy Transport

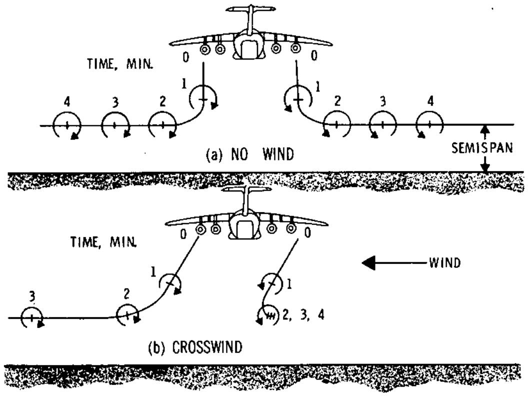


Figure 12. Vortex-System Movement Near the Ground

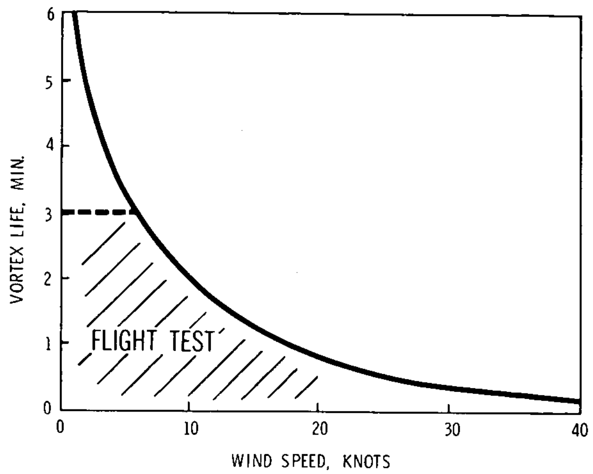


Figure 13. Estimated Duration of Trailing Vortices with Velocities Significant to Other Aircraft

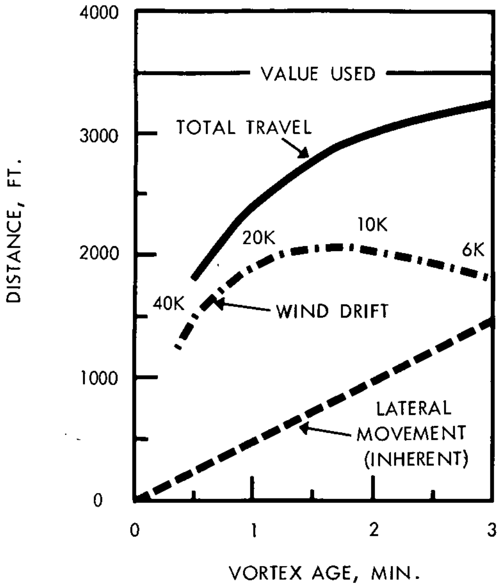


Figure 14. Maximum Vortex Travel Near the Ground

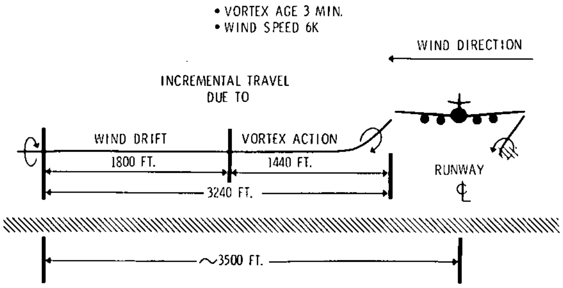


Figure 15. Maximum Lateral Travel of Vortex Near the Ground

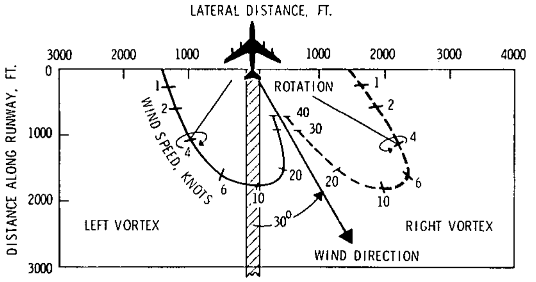


Figure 16. Vortex Movement Near the Ground with the Wind from 30° Port

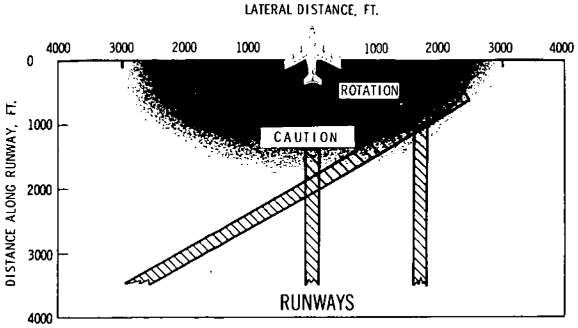


Figure 17. Envelope of Vortex-System Movement Near the Ground

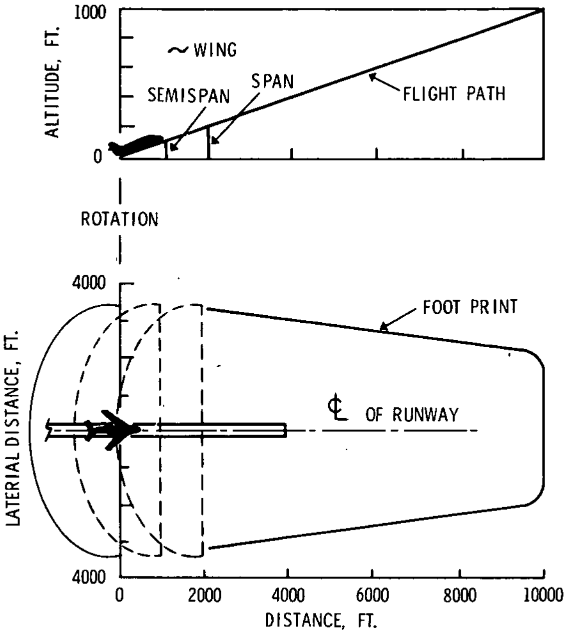


Figure 18. Vortex Footprint Under Takeoff Flight Path

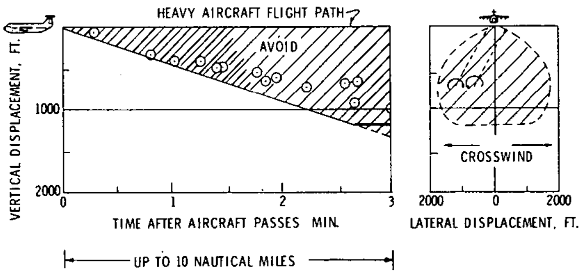


Figure 19. Suggested Envelope of Vortex Vertical Location for Operational Use (No Ground Effect)

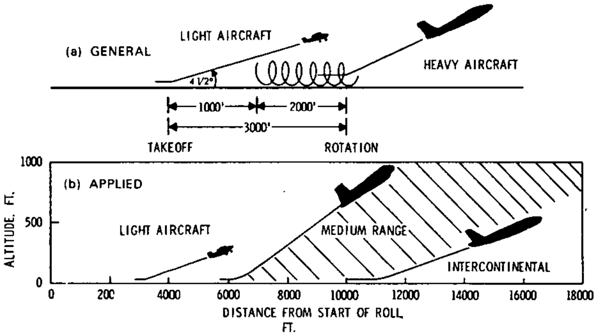


Figure 20. Suggested Takeoff Profile for Light Aircraft Following Heavy Aircraft

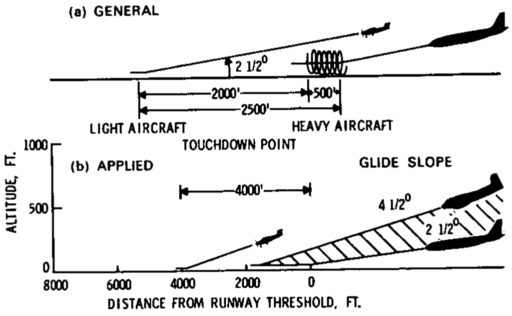


Figure 21. Suggested Touch Down Point for Light Aircraft Following Heavy Aircraft

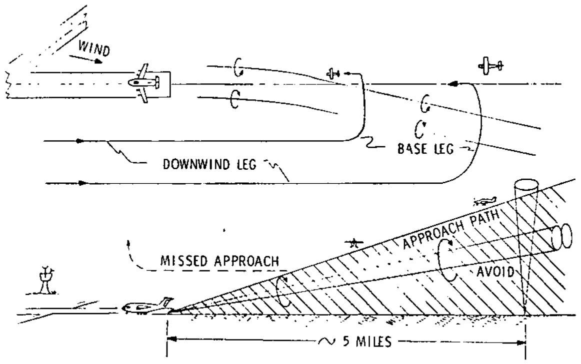


Figure 22. Vortex Avoidance Along Approach Path

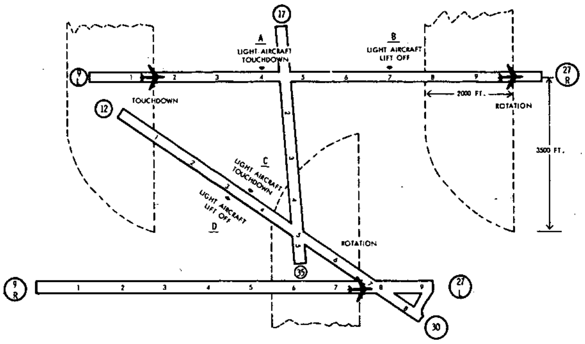
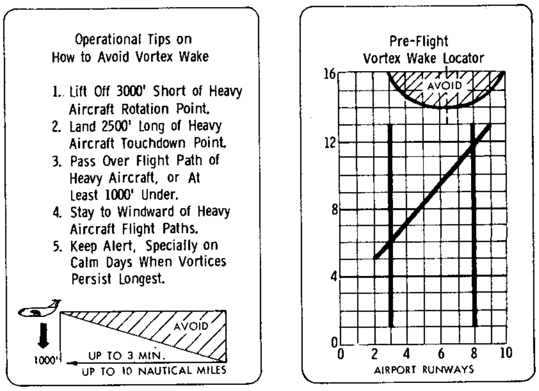


Figure 23. Airfield Use of Vortex-System Envelope



Operational Tips on
How to Avoid Vortex Wake

1. Lift Off 3000' Short of Heavy Aircraft Rotation Point.
2. Land 2500' Long of Heavy Aircraft Touchdown Point.
3. Pass Over Flight Path of Heavy Aircraft, or At Least 1000' Under.
4. Stay to Windward of Heavy Aircraft Flight Paths.
5. Keep Alert, Specially on Calm Days When Vortices Persist Longest.

Figure 24. Pilots Pocket Card - Aircraft Trailing Vortex Avoidance Facts