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Jet Transport Response to a Horizontal Wind Vortex

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The dynamic response of a twin-jet transport aircraft encountering a horizontal wind vortex (or rotor) on final approach to landing is investigated. Computer simulations determine the effects of vortex strength, vortex length, lateral entry position, vertical entry position, and encounter incidence angle on the aircraft's roll response. Maximum roll rate and roll angle increase proportionally with vortex strength and length until a saturation length is reached. Roll response is highly dependent on entry location: changes in lateral entry position largely affect maximum roll angle while changes in vertical entry position affect maximum roll rate. Peak roll rate and roll angle obtain their largest values at near-zero incidence angles. The response is highly dependent on the precise initial conditions of the encounter—even small variations in initial condition cause significant changes in aircraft roll response.

Introduction

AIRCRAFT that encounter strong vortical winds during flight can experience violent angular and translational motions. Rotating wind fields are produced by the tip vortices of other aircraft or by naturally occurring sheared wind flows. As a consequence of structural similarities in the flows, studies of aircraft encounters with wake and wind vortices are complementary. Greater knowledge of aircraft-vortex interactions is needed for the investigation of unsolved accidents and for preventing future accidents through the development of new vortex detection and warning systems, pilot training programs, and departure-preventing control system designs.

The importance of understanding aircraft/wind-vortex interactions was highlighted by a recent jet transport accident that may have been caused by a mountain-wave wind vortex (also called a "wind rotor").[1] On March 3, 1991, a twin-jet transport aircraft on final approach to landing rolled upside down and pitched nose down before contacting the ground at high speed. The entire event, from steady, level flight 1000 ft above the ground to impact, took less than 10 s. All passengers and crew members perished.

The National Transportation Safety Board (NTSB) considered a mountain-wave wind vortex as a possible cause of the accident. Strong winds flowing over mountains prevailed on the day of the accident; such winds can produce "downslope windstorms" characterized by wave features extending for many miles beyond the mountains.[2–4] If encountered at the proper orientation, a wind vortex may well have the strength to roll the aircraft to an unrecoverable roll angle. Nevertheless, limited knowledge of how a wind vortex affects a transport aircraft along with lack of flight evidence prevented positive determination of this accident's cause.[1]

While the research reported here is motivated by the referenced accident, it is not a study of that specific accident. Instead, it is an exploration of the wind rotor and aircraft flight conditions that could lead to severe flight path upset for small jet transports, with emphasis on "open-loop" aircraft response (i.e., unopposed by pilot control). This analysis uses computer simulation to better understand how mountain-wave-induced wind rotors can affect aircraft flight. Details of the study, and of closed-loop control effects, are contained in Ref. 5.

Background

There is considerable qualitative evidence to support the existence of hazardous wind rotors, but because they are rare events, there is an absence of quantitative observational data. The principal perceived risk occurs when an aircraft encounters a rotor axially, i.e., along the core of a cylindrical vortex, although substantial normal load factor could be experienced in a transverse encounter. Mountain-wave wind vorticity has contributed to numerous aviation accidents and incidents,[6,7] and the dynamic effects of aircraft encountering clear air turbulence at cruising altitude have been studied.[8,9] However, the impact of large-scale wind vorticity on landing aircraft remains to be determined.

Mechanisms for low-altitude wind rotor formation typically involve a high-speed wind flowing over one or more mountain ridges. In one model, an air mass trapped between ridges sloshes in a resonant cavity, with a fully formed vortex occasionally spilling over the peak of the leeward ridge.[10] In a ground-based temperature-inversion model, a high-speed flow down the leeward slope of a mountain encounters denser air and undergoes a hydraulic jump, forcing the air to roll up into a horizontal vortex.[2,4] In a third model, an unsteady wind surge over an obstacle produces a "starting" vortex that is shed downstream.[11] Once formed, the wind rotor convects with the prevailing winds away from the mountains. Traveling over flat terrain, the wind rotor is relatively stable, not dissipating until it has progressed perhaps tens of miles from the formation point. A wind rotor may be assumed to have a classical vortex profile (discussed below), much like a single tip vortex shed by an aircraft wing; however, its core radius is measured in hundreds of feet, whereas the radius of a hazardous wingtip vortex is measured in feet.

Because of its localized meteorological scale, transient nature, and lack of visual signs, a wind rotor is difficult to detect.[11] The presence of rolling, elongated cloud formations may infer wind vorticity at high altitude, and ground soil or vegetation could be visibly disturbed by a low-altitude rotor. Neither of these is a quantitative or deterministic indicator of wind vorticity. Doppler radar or lidar can measure slant-range rate of the rotor from an airborne or ground-based installation (given enough suspended particles for signal return), but there are problems of coverage, alignment, accuracy, and rotor signature to be surmounted. The low-altitude wind rotor haz-

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ard is geographically restricted and strongly dependent on prevailing weather conditions. It is never a hazard in some locales, but is a potentially serious hazard in others. Limited measurements and weather forecasts at those airports where rotors are most likely to occur may provide a basis for predictive hazard alerts.

Smaller aircraft trailing larger aircraft are at considerable risk, especially when the following aircraft is aligned with one of the leading aircraft's tip-vortex cores. A number of investigations have described the dynamics of such an encounter and possible control strategies.[12-18] While the general problem of rolling upset due to wind- or wake-vortex encounter is the same, aerodynamic moment generation is substantially different in the two cases because of the differing vortex scales. In axial wake-vortex encounter, core diameter is small compared to the following aircraft's wingspan, whereas in wind-vortex encounter, the opposite is true.

Modeling for Dynamic Simulation

Aircraft motions are modeled by six-degree-of-freedom nonlinear differential equations. The aerodynamic model includes the spatial shear-gradient effects on the aircraft forces and moments, in the spirit of Ref. 19, but containing the corrections of Refs. 20 and 21. The cylindrical horizontal wind vortex is based on the Lamb-Oseen model, in which a classical rectilinear line vortex is modified to account for viscosity.[22] The model is further simplified, as noted below.

Aircraft Equations of Motion with Wind Terms

It is convenient to express translational velocity in an air-relative frame, whereas body-axis rotational rate, translational position, and angular orientation are expressed in an Earth-relative frame. Because the wind field is changing, the air-relative frame is non-Newtonian, and so coriolis and wind acceleration terms are added to the differential equation for translational velocity:

$$\dot{\boldsymbol{v}}_B = (\boldsymbol{F}_B/m) + H_E^B \boldsymbol{g}_E - \tilde{\omega}_B \boldsymbol{v}_B - \dot{\boldsymbol{w}}_B \tag{1}$$

$\boldsymbol{v}_B$ is the body-axis, air-relative velocity vector (u, v, w), $\boldsymbol{F}_B$ is the body-axis vector of aerodynamic and thrust forces, m is aircraft mass, H_E^B is the direction-cosine matrix for Earth-to-body-axis transformation, $\boldsymbol{g}_E$ is the Earth-relative gravitational-acceleration vector, $\tilde{\omega}_B$ is the cross-product equivalent matrix of body-axis angular rate ω_B (p, q, r), and $\dot{\boldsymbol{w}}_B$ is the time-rate-of-change of the wind velocity field, expressed in body axes. The corresponding Earth-relative translational position equation is

$$\dot{\boldsymbol{r}}_E = H_B^E \boldsymbol{v}_B + \boldsymbol{w}_E \tag{2}$$

where $\boldsymbol{r}_E$ is the position vector (x, y, z), H_B^E is the inverse of H_E^B, and $\boldsymbol{w}_E$ is the Earth-relative wind field. The differential equations for angular-rate and angular-position vectors are

$$\dot{\omega}_B = I_B^{-1}(\boldsymbol{M}_B - \tilde{\omega}_B I_B \omega_B) \tag{3}$$

$$\dot{\boldsymbol{\Theta}} = L_B^E \omega_B \tag{4}$$

where I_B is the inertia matrix, $\boldsymbol{M}_B$ is the vector of aerodynamic and thrust moments, the vector $\boldsymbol{\Theta}$ contains the roll-pitch-yaw Euler angles (ϕ, θ, ψ) that describe body orientation in the Earth-relative frame, and L_B^E transforms body-axis angular rates to Euler-angle rates.

Aerodynamic Modeling

The aerodynamic model represents a twin-jet transport aircraft, and it includes wind-gradient effects. Because the rotor scale is large compared to aircraft dimensions, the sheared wind flow produces approximately linear flow gradients over the wing, horizontal tail, and vertical tail; hence, the aerodynamic shear effects are equivalent to angular rates of the individual surfaces.[19,20] Consequently, the shear-induced moments are related to the aircraft's rotary stability derivatives, accounting for aircraft geometry, and they add to the more conventional contributions due to angle of attack, sideslip angle, angular rates, and control deflections. For example, a spanwise normal-velocity gradient changes pressure distributions on the wing and horizontal tail, but has negligible effect on the vertical tail.[20] Similarly, a vertical gradient in lateral velocity affects the vertical tail, but has little effect on the wing and horizontal tail.[5]

Horizontal-Vortex Wind Model

The two-dimensional Lamb-Oseen model[22] can be expressed as

$$V_t = \{k_c[1 - e^{(-r^2/r_0^2)}]\}/r \tag{5}$$

where V_t is the tangential flow velocity, k_c is a constant, r is the radius from the axis, and r_0 is a reference length. The vortex core can be defined as the area within the radius for maximum tangential velocity, which occurs when $r \approx 1.12r_0$; hence a vortex can be specified by two parameters: core radius r_c and core tangential velocity V_c, with $k_c \approx 1.4V_c r_c$. The vortex is extended into the third dimension as a line vortex, with zero radial and axial components. Near the core's axis, the flow rotates as a solid-body, while far from the axis, tangential velocity is inversely proportional to the radius (Fig. 1).

A piecewise-linear model provides a simple approximation to the Lamb-Oseen vortex (Fig. 1):

$$V_t = \begin{cases} V_c r/r_c & 0 < r/r_c < 1 \\ V_c(1.15 - 0.15r/r_c) & 1 < r/r_c < 3 \\ V_c(0.88 - 0.06r/r_c) & 3 < r/r_c < 7 \\ 0 & r/r_c \geq 7 \end{cases} \tag{6}$$

This model produces a two-dimensional solid-body-rotational core with constant intensity inside the core and decreasing velocity outside the core. It has a finite extent, yielding undisturbed flow outside a radius of $7r_c$. The flow is extended to the third dimension along an axis perpendicular to the rotary motion. In application, the wind velocity and gradient at the aircraft's origin are rotated into the aircraft's instantaneous body axes, and moments generated by the equivalent rotary stability derivatives described above force the aircraft's rotational motion.

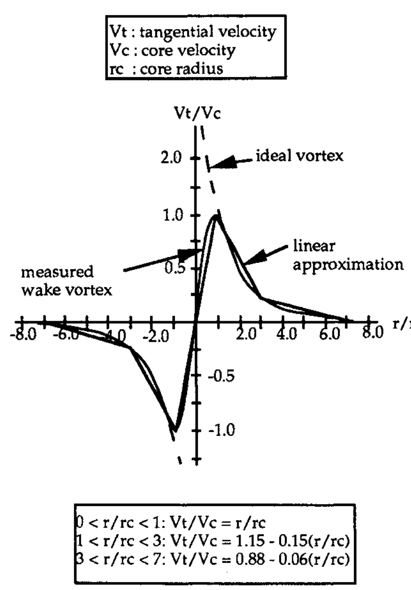

Fig. 1 Single-axis vortex velocity profile.

Results and Discussion

Simulation conditions for the nominal vortex encounter are presented. The roll response to a single-axis horizontal wind vortex is examined for a range of vortex initial conditions, including vortex strength η, vortex axis length l, distances from the vortex centerline (including lateral entry position y_0 and vertical entry position h_0), and encounter incidence angle ψ. The roll parameters of particular interest are the aircraft's roll rate p and roll angle ϕ.

The nonlinear nature of the aircraft's controls-fixed response to a wind vortex is demonstrated by performing a full-length simulation for a 60-deg incidence-angle, off-center encounter and comparing the response to that of a coaxial, direct-center encounter. Both of these cases can result in large roll angles, even though the forcing dynamics are quite different. The 60-deg off-center encounter is primarily affected by sideslip-angle effects that are strongest near the core radius, whereas the coaxial encounter is affected by the shear over the wing (Fig. 2).

A parametric study determined that roll response is difficult to characterize due to numerous nonlinearities and coupling effects.[5] The forces and moments depend on aircraft entry location and path relative to the vortex core. The moments are also affected by the shear gradients that act over the aircraft's aerodynamic surfaces, including the angular orientation of the individual surfaces with respect to the incident winds. Such shear effects may exhibit large magnitudes, particularly in the vortex core region.

Nominal Flight Condition

During landing approach, the aircraft maintains a low airspeed and flies close to the ground, leaving little margin for upset or error. Because mountain-wave wind vortices typically occur in turbulent or gusty conditions, a 20-kt "pad" is added to the nominal 140-kt approach speed. The nominal trimmed condition is

True airspeed	= 160 kt
Altitude	= 1000 ft above ground level
Flight-path angle	= −3 deg
Thrust coefficient	= 0.45
Weight	= 76,000 lb
Center of gravity location	= 25.7% root chord, measured from leading edge
Elevator deflection	= −0.04 deg
Flaps	= 30 deg

The controls are fixed, and the yaw damper is off.

Vortex Parameters

The vortex velocity profile is specified by the core velocity V_c, and the core radius r_c. Vortex rotational strength η is defined by the ratio of core velocity to core radius:

$$\eta = V_c / r_c \tag{7}$$

The core velocity was chosen to be V_c = 125 ft/s, and the core radius was fixed at r_c = 200 ft, corresponding to a vortex rotational strength η = 0.625 s^{-1}. This model is consistent with wind rotors considered in Ref. 1. The vortex length was arbitrarily chosen to be 2500 ft.

Coaxial, Centered Wind Vortex Encounter

The aircraft, trimmed at the nominal condition, encounters the direct center (y_0 = 0 ft, h_0 = 0 ft) of the wind vortex at an altitude 1000 ft above the ground. The vortex axis is parallel to the ground plane and is aligned with the flight path (ψ = 0 deg). Peak values of aircraft roll response and time in the vortex core are presented for each change in vortex parameter. Previous studies of aircraft response to a wake vortex indicate that the coaxial, centered encounter represents a great hazard to aircraft.[12–18]

Effects of Vortex Strength

The vortex strength η was varied through the specification of the core velocity V_c. Core velocity values between 50–175 ft/s produced vortex strengths of 0.25–0.875 s^{-1}. Increasing the vortex strength increases the magnitude of the shear over the wing. In the coaxial encounter, the primary effect of increasing vortex strength is on the roll-moment response. The roll rate increases in a nearly linear manner with increasing strength. For the highest vortex strength tested, the maximum induced roll rate is 45 deg/s (Fig. 3).

The vortex strength has a significant effect on the peak roll magnitude, but it does not have a substantial effect on the forces that cause translation from the core center. For the range of values tested, the time the aircraft spends in the core varies by only 1.5 s. The aircraft tends to remain in the core even with increased vortex strength, and so the strong shear-induced rolling moments act for a relatively long time, producing a large peak roll angle. For η = 0.875 s^{-1}, the maximum-induced roll angle is 218 deg (Fig. 3).

Effects of Vortex Axis Length

The effect of vortex axis length l on aircraft dynamic response is tested for length values from 300 to 2500 ft. Peak responses vary for changes in length up to 1500 ft; for greater lengths the response is unchanged. For these values, the aircraft has already departed the vortex core and is in a region where the vortex-induced effects are considerably smaller. This "saturation" length depends on the specifics of each encounter.

For vortex lengths below 1500 ft, the aircraft exits the end of the vortex without encountering the strong tangential-velocity components near the core radius. Because roll rate is due primarily to the shear effects of the inner-core region, the maximum roll rate is largely unaffected by changes in vortex axis length (Fig. 4). The maximum roll angle increases from 36 to 169 deg with increased time in the vortex core, although the roll rate remains approximately constant.

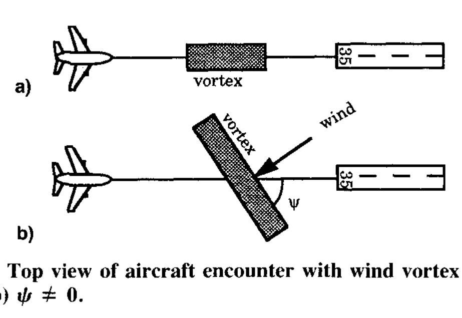

Fig. 2 Top view of aircraft encounter with wind vortex for a) ψ = 0 and b) $\psi \neq$ 0.

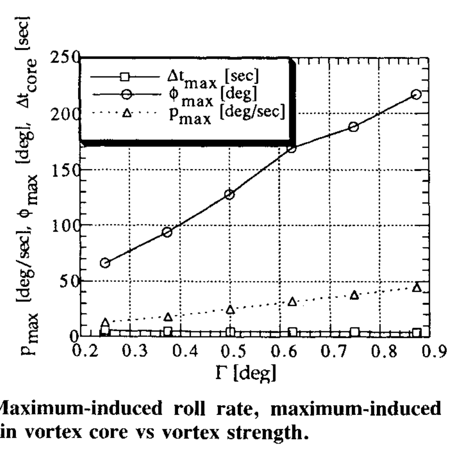

Fig. 3 Maximum-induced roll rate, maximum-induced roll angle, and time in vortex core vs vortex strength.

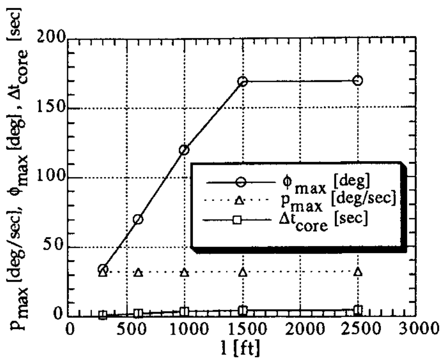

Fig. 4 Maximum-induced roll rate, maximum-induced roll angle, and time in vortex core vs vortex axis length.

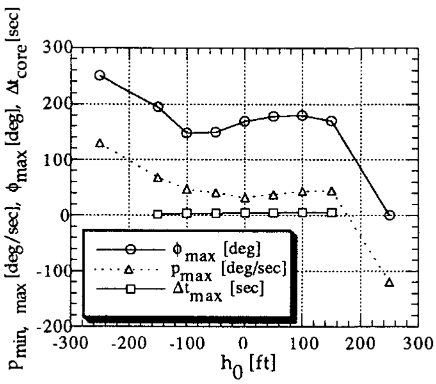

Fig. 6 Peak-induced roll rate, peak-induced roll angle, and time in vortex core vs vertical entry position.

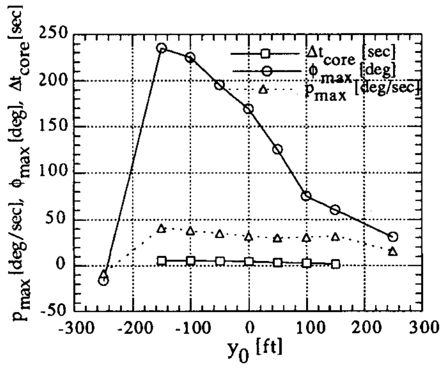

Fig. 5 Peak-induced roll rate, peak-induced roll angle, and time in vortex core vs lateral entry position.

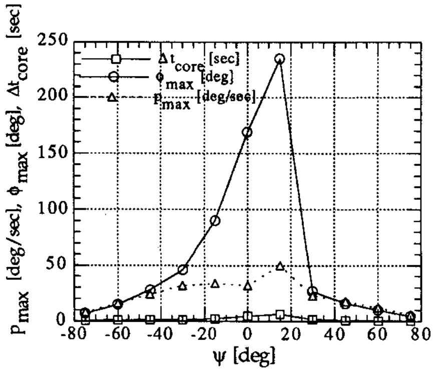

Fig. 7 Maximum-induced roll rate, maximum-induced roll angle, and time in vortex core vs vortex incidence angle.

Effects of Lateral Entry Position

The lateral entry position is varied ±250 ft from the vortex center. The extreme points are outside the core radius, and the remaining points are within the core. Simulation responses are qualitatively different inside and outside the core.

The most significant effect of varying the lateral entry position is in the pitch response. Peak angle of attack increases with the stronger vortical velocities incident on the aircraft as the initial point moves away from the vortex center in either direction. This pitching motion is a short-period-mode transient in which the aircraft responds to the large induced angle of attack. Lateral-directional dynamics are affected indirectly through kinematic coupling. Sideslip angle is induced by the nonzero angle of attack combined with nonzero roll rate, primarily affecting the yaw dynamics. Peak roll rate remains nearly constant at about 40 deg/s (Fig. 5).

The core shear rolls the aircraft to the right; therefore, initial encounters to the left of the vortex center roll the aircraft toward the core center. Aircraft encounters to the right of the vortex center tend to roll the aircraft away from the center and out of the core. As a result, the time in the core decreases from 5.5 to 2.2 s as the entry point moves from the farthest point left of center, $y_0 = -150$ ft, to the farthest point right of center, $y_0 = 150$ ft. This increased time spent in the core has a large effect on peak roll angle. The maximum roll angle (238 deg) occurs for entry to the left of the vortex center, and it steadily decreases to 60 deg as the entry position moves to the right, even though roll rate is relatively constant (Fig. 5).

Effects of Vertical Entry Position

The vertical entry position is varied ±250 ft from the vortex center. Responses to the entry points inside and outside the core radius are qualitatively different. As vertical entry position is varied, the initial response is a perturbation to sideslip angle. For entries below the vortex center, large sideslip angles combine with the core shear to produce enormous peak roll rates. The maximum roll rate (for points inside the core) is 69 deg/s (Fig. 6). Peak roll rates for entries above the vortex center are reduced by the sideslip angle, since it is in the opposite direction.

The time in the core decreases as the entry point is moved from above to below the vortex core. Loss of wing lift due to redirection of the lift vector in roll causes the aircraft to lose altitude. Thus, entries above center cause the aircraft to descend through the core and eventually exit through the bottom of the vortex. Entries below center rapidly exit the core. The time in the core decreases from 6 to 2.6 s as the entry point is changed from 150 ft above to 150 ft below the vortex center (Fig. 6).

The maximum roll angle due to changes in vertical entry position remains relatively constant near 180 deg, even though roll rate varies significantly. The effects of roll rate and time in the vortex core offset each other. Encounters below the vortex center spend less time in the core, although the roll rates are larger, whereas the more moderate roll rates experienced for entries above the center spend more time in the core (Fig. 6).

Effects of Vortex Incidence Angle

The effect of the vortex incidence angle ψ on aircraft roll response is studied for incidence angles within ±75 deg (Fig. 2). The largest roll rates are experienced as the vortex angle approaches the coaxial case. The maximum roll moment is almost entirely due to shear across the wing; in the coaxial orientation, the shear effects are directly aligned with the wingspan. Maximum roll rate achieves a value of 48 deg/s for a vortex incidence angle of 15 deg (Fig. 7).

Smaller vortex incidence angles cause the aircraft to spend more time in the core because the flight path is nearly aligned

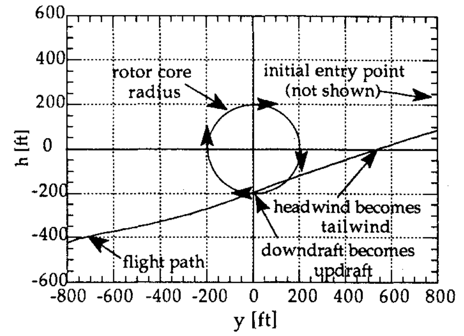

Fig. 8 Flight path with respect to vortex for nonzero incidence angle and entry point wind vortex encounter.

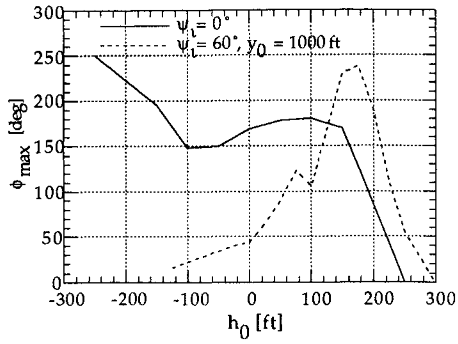

Fig. 9 Maximum roll angle vs vertical initial entry position for two wind vortex encounters.

with the vortex. Conversely, the aircraft quickly crosses through the core for large vortex incidence angles. The time in the core varies from 6.1 s for a 15-deg incidence angle, to less than 1 s for incidence angles outside ±60 deg. Larger peak roll rates combined with a greater length of time in the core cause the more severe roll angles for smaller vortex incidence angles. The maximum roll angle is 235 deg for a vortex incidence angle of 15 deg (Fig. 7).

Oblique, Offset Wind Vortex Encounter

An encounter that combines several of the above vortex initial conditions is examined. The trimmed aircraft enters a vortex aligned at a 60-deg angle to the flight heading, at a vertical entry point 180 ft above the vortex centerline, and 1000 ft to the right of the vortex centerline. This simulation is like the 60-deg-incidence-angle case considered above, except that the vortex length is extended, causing the aircraft to encounter strong vortex winds at the perimeter of the vortex core before traversing the core.

The initial effect is a nose-up pitch attitude due to the strong headwind that is experienced as the aircraft descends upon the vortex core (Fig. 8). There also is a crosswind component that results in a counterclockwise roll and left yaw due to the airplane's weathercocking stability. As the aircraft encounters the peak vortical winds near the core radius, large angles of attack and sideslip are induced, dominating the force and moment response. The core encounter time is short, but the large roll rates and pitch rates result in extreme aircraft attitudes. The maximum roll angle before ground contact is 238 deg.

The response is highly dependent on the relative location of the aircraft with respect to the vortex core, rather than to the magnitude and orientation of the shear effects with respect to the aerodynamic surfaces. As a result, the dynamic response is extremely sensitive to initial conditions—even small variations in a single condition may significantly reduce the vortex-induced roll. The maximum-induced roll angles as functions of vertical entry position for $\psi = 60$ deg and $y_0 = 1000$ ft are shown in Fig. 9. The plot depicts a narrow peak roll angle response that is largest at $h_0 = 180$ ft. Even small changes in vertical entry position—on the order of 50 ft—result in much smaller roll angles. The maximum roll angles from the case where vertical entry point is varied from the baseline encounter are shown on the same plot; the roll angle obtains a large value for a much broader range of vertical entry positions.

This encounter highlights the nonlinearity of the aircraft/wind-vortex system. Results from varying single parameters do not accurately predict the aircraft response when multiple initial conditions exist simultaneously. Large roll rate and angle result from the combination of entry conditions, even though previous results suggest that roll should be minimal. For vortex incidence angles greater than 60 deg, the maximum roll rate remains below 15 deg/s and the maximum roll angle remains below 20 deg (Fig. 7). However, the roll response to the encounter considered here is even more severe than that of the coaxial case.

Conclusions

Simulations of jet transport aircraft encountering a horizontal wind vortex reveal that the most significant performance hazard is the moment response. Moments are induced both by vortex core shear effects that arise from spatial gradients acting over the aerodynamic surfaces and by the vortical-velocity components that are strongest near the vortex core radius. For the coaxial-incidence-angle, direct-center entry case, the roll moments are primarily affected by the shearing effects of the inner-core region.

A parametric study yields considerable information about the effects of vortex encounter conditions on aircraft roll response for a coaxial, direct-center encounter. As vortex strength increases, the maximum roll rate and roll angle increase proportionally. As vortex axis length is increased, the dynamic response remains constant beyond a certain length value; above this "saturation length," increases in vortex axis length have no effect on aircraft dynamics, as the aircraft has exited the vortex core. Peak roll parameters achieve larger values up to the point of exit. Lateral entry position affects the longitudinal dynamics, but peak roll rate is largely unaffected. Entries to the left of the vortex core produce roll "into" the vortex, causing larger peak roll angles. Vertical entry position produces sideslip angles that increase with distance from the core center. Sideslip combines with shear for entries below vortex center to produce large peak roll rates; however, peak roll angle is relatively unaffected. Peak roll rate and roll angle are both largest for near-coaxial encounters.

The nonlinear nature of aircraft response to a wind vortex is demonstrated by a simulation with multiple variations in initial conditions. Such an encounter produces a severe roll response, even though results from individual parameter variations suggest that roll angle response should be minimal. The response is highly dependent on the precise initial conditions of the encounter—even small variations from this initial condition cause large changes in aircraft roll response.

Acknowledgments

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