The Trailing Vortex Wake Hazard: Beyond the Takeoff and Landing Corridors

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This paper focuses on issues related to the trailing vortex wake hazard beyond the takeoff and landing corridors. The operational procedures adopted by the FAA in the 1970s for avoiding wake turbulence encounters in the take-off and landing corridors have been very successful in providing commercial aviation with a high degree of safety. However, there is a growing body of evidence that encounters well beyond the immediate airport area could also prove to be hazardous. A review of commercial airline accidents for which a wake vortex encounter was considered to be a contributing factor in the accident are reviewed. Another problem that is addressed is wake encounters at cruise altitude. With the introduction of the regional jet transports into the commercial fleet we have created a very large disparity in the size of aircraft that can cruise at the same altitude. Furthermore there is evidence that wake encounters at cruise altitude do occur and should be investigated more extensively than has been done to date. In the current study the vortex induced loads created by wake vortices at cruise altitude are examined. The two cases that are presented include penetration perpendicular to the trailing vortex wake and penetration along the vortex core axis. The cross track penetration focuses on the structural loading while the along track penetration examines the potential roll excursion from the intended flight path.

I. Introduction

The trailing vortex wake generated by a large airplane has been known for many years to pose a potential safety hazard to smaller aircraft if they pass through the wake. In the early 1970’s the air traffic control authorities adopted a set of operational procedures that have provided commercial aviation with a safe solution to the problem of aircraft wakes. The operational procedures include segregating aircraft by size, controlling take-off and landing flight paths, and maintaining a fixed separation between aircraft based on the weight of the lead aircraft. Because of the uncertainty in knowing where the vortices are located relative to the flight path as well as their strength, the separation distances between aircraft are very conservative. These procedures limit the traffic capacity at many major airports.

Research in Europe and the United States has focused on increasing airport capacity by minimizing the wake vortex hazard. These research programs can be divided into two categories, vortex detection and vortex alleviation. The vortex detection program deals with developing the technology for systems that can be used to safely reduce aircraft spacing when the vortices are not a hazard to the following aircraft. The objective of the detection system is to be able to locate the trailing vortices relative to the glide slope, and then assess the potential hazard the wake may pose to a following aircraft. To accomplish this task, the system must locate the wake, predict its future trajectory, assess the extent of decay and then provide a recommendation as to whether aircraft separation can be safely reduced. The objective of the other research program is to modify the wake so that it decays faster. Both analytical and experimental studies have shown that more benign wakes can be created by exciting wake vortex instabilities. Early wake dissipation is attributed to either the Crow or the Raleigh-Ludwig instability. Crow developed a theory that predicts a sinusoidal instability of the trailing vortex system. His theory showed that two counter rotating vortices are unstable to small perturbations. The small perturbations could grow in time so the wake becomes sinusoidal. The amplitude of the instability grows until the vortices pinch together to form a series of vortex rings. It is often assumed that once the vortex ring stage has been reached the rings rapidly dissipate into a harmless turbulent state. Unfortunately there is no experimental verification that this indeed happens.

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The Rayleigh – Ludwieg instability occurs naturally for two parallel vortices having an opposite sense of rotation\textsuperscript{13-14}. The instability is caused when the destabilizing centripetal force is greater than the restoring pressure force within the vortex field. When this condition occurs the vortex system dissipates rapidly. Stuff and Vollmers\textsuperscript{14} studied this favorable wake interaction in a series of towing tank experiments.

Future demands on airport and airway capacity are expected to increase substantially during the next decade. In addition aircraft manufactures are considering developing even larger aircraft than are currently in the commercial fleet, for example, the Airbus A380. Figure 1 shows the growth in vortex strength as a function of aircraft size.

![Figure 1. Growth of Circulation.](image)

Increases in airport capacity, however, cannot be achieved until aircraft wake issues are resolved. The key issues that need to be addressed were outlined by Mack\textsuperscript{15} and are listed below.

1. Defining an accurate basis for wake vortex separation.
2. Evaluating the significance of the wake characteristics on safe flight.
3. Determining the far-field characteristics of the wake.
4. Understanding the influence of meteorological conditions on vortex wakes.
5. Develop the technology to mitigate capacity constraints associated with wake vortices.

While the research in detection systems has demonstrated that vortex detection and avoidance systems could be used to safely reduce aircraft spacing, it is important to examine how the increased air traffic affects wake vortex safety beyond the take-off and landing corridors.

This paper will examine several wake encounter scenarios that may become more important in the future due to potential changes in the airline industry fleet makeup and operational procedures. Although the FAA operational procedures for avoiding wake turbulence in the take-off and landing corridors has been successful there is a growing body of evidence that encounters well beyond the immediate airport area need to be examined. The other region of concern is encounters at cruise altitude. Aircraft/wake encounters at cruise altitude have generally not been a safety concern; however this may no longer be the case.

Two factors that warrant further examination of cruise altitude encounters are the previously mentioned mix of large and small jet transports and the free sky concept. With the free sky concept and altitude separation of 1000 ft. the possibility of an encounter with a vortex wake increases compared to the current operational procedures. Early flight tests of trailing vortex wakes showed that at altitude the vortices descend by mutual induction but level off at about 1000 ft below the altitude where they were generated\textsuperscript{16}.

In the following sections we will try to show the need to examine aircraft/wake vortex encounters just beyond the take-off and landing corridors and at cruise altitude. Our argument will be supported by a review of aircraft
accidents and analysis. Before discussing the reasons for revisiting the aircraft/wake safety issue a discussion of vortex decay and computer simulation capabilities will be presented.

II. Wake Vortex Decay

Early experiments to understand the decay process of the trailing vortex wake showed several interesting features. Ciffone and Orloff\textsuperscript{17} found that the maximum circumferential velocity within the vortex at first remained relatively constant with time and then decayed inversely with the square root of time. Figure 2 shows a plot of Ciffone and Orloff’s data as a function of a non-dimensional distance behind the generating wing. The constant or plateau region is clearly evident prior to the beginning of the decay process.

These experimental findings prompted J. D. Iversen\textsuperscript{18} to develop a correlation function based on a self-similar variable-eddy viscosity decay model. Iversen used the derived correlation function to correlate a series of wind tunnel, towing tank and flight test measurements. The scaling parameters were found to collapse the data as illustrated by Figure 3.

Later Nelson and Tartaglione\textsuperscript{19} used Iversen’s approach to correlate a series of experiments conducted by the Federal Aviation Administration at the National Aviation Facilities Experimental Centre (NAFEC) in the 1970s. Garodz et al\textsuperscript{20-23} conducted experiments to measure the wake behind various transport aircraft using an instrumented tower. Hot film sensors mounted on horizontal booms that were located at various vertical spacing along the tower. The sensors were used to measure the velocity through the vortex system. The test aircraft were flown along a course so that the cross wind and wake descent would cause the trailing vortices to sweep across the tower. The age of the wake measured by the tower sensors could be changed by adjusting the altitude and lateral distance of the test airplane from the tower. A detailed list of the experimental studies is included in the excellent review article on trailing vortex wakes by Rossow\textsuperscript{1}. Figure 4 shows an excellent correlation of the NAFEC data using Iversen’s scaling parameters. As indicated by these figures the decay of the trailing vortex wake is quite slow, however, it must be noted that the data included in these figures was generally taken when the atmosphere was calm. The trailing vortex wake does decay much more rapidly when the atmosphere is turbulent. Unfortunately predicting the influence of atmospheric conditions on vortex decay with a high level of confidence is currently not possible. Therefore the separation distance between aircraft in the terminal area is based on data obtained under calm atmospheric conditions. This of course is the only prudent approach the can be taken by the air traffic control authorities.

Fig 2. Maximum circumferential velocity as a function of downstream distance by Ciffone and Orloff\textsuperscript{17}.
Fig. 3. Maximum circumferential velocity as a function of downstream distance by Iversen\textsuperscript{18}.

Fig. 4. Correlation of wake measurements behind commercial jet transports taken by NAFEC, Nelson and Tartaglione\textsuperscript{19}.
III. Aircraft/Wake Vortex Simulations

An assessment of the hazard of trailing vortex wake encounters has been investigated by flight test experiments and simulation. Figure 5 is a sketch of three potential aircraft encounters with a trailing vortex wake. The type of upset that can occur depends upon how the airplane penetrates the wake. McGowan 24-25 examined the effect on an aircraft crossing perpendicular to the trailing vortex wake of another aircraft. His analysis showed that crossing the wake in this manner could result in significant structural loads during the wake encounter. If the airplane flies between the trailing vortices (i.e. in the downwash region) the penetrating airplane will experience a reduction in its rate of climb (for a climbing aircraft) or an increased rate of descent for a descending aircraft. The final encounter depicted in Fig. 5 is when the airplane penetrates along the vortex axis. The velocity field of the vortex wake induces a roll moment on the penetrating aircraft. This type of encounter is believed to be the most dangerous because the vortex may cause a large roll excursion that would be unacceptable at a low altitude. Flight test results have shown that relatively large aircraft can be susceptible to significant roll excursions. 26-29

![Possible Vortex Encounters](image)

**Assessment of current simulation capabilities.**

Computer simulations of aircraft/vortex wake encounters have been used to assess the wake vortex hazard. These simulations typically include a six degree of freedom model of the penetrating aircraft, a method to estimate the vortex induced loads on the wing and empennage, and a mathematical model of the pilot and/or autopilot system. The trailing vortex wake is generally represented as a pair of straight line vortex filaments, and a vortex decay model. The vortex induced loads are calculated using a modified lifting line or strip theory. The lifting surfaces are usually divided into series of segments and the normal component of the induced velocity at each segment is obtained using the Biot-Savart law. The vortex induced normal velocity changes the local angle of attack on each segment creating a change in the loading on the aircraft. The forces and moments are then used in the aircraft equations of motion to compute the trajectory of the aircraft for the next time step.

The simulations of wake encounters have shown that the magnitude of the response is very dependent on the entry angle into the vortex system 30-39, the relative size of the penetrating to generating aircraft, and the strength of the vortex wake. Furthermore simulations have also shown the pilot or autopilot control system can aggravate the upset excursion.

Although the strip theory approach to modeling the vortex induced aerodynamic loads may seem at first to be an inaccurate method, earlier studies on vortex induced loads 1, 40, 41 have shown that strip theory can yield accurate results. An example of the validity of strip theory for estimating vortex induced loads the technique was evaluated using experimental data obtained in the National Full-Scale Aerodynamics Complex (NFAC) at NASA Ames Research Center. 31
The test setup consisted of an aircraft model located in the upstream portion of the test section followed by a wing model located downstream of the aircraft model. The downstream wing was mounted on a sting support that could position the wing at different locations in the vortex wake. The vortex induced lift and rolling moment were measured with an internal balance. In addition, hot wire measurements of the velocity distribution through the wake of the generating aircraft were made at several downstream locations corresponding to where the induced roll measurements were made. Figure 6 shows a comparison of strip theory with the experimentally determined vortex induced roll moment measurements. Using the measured velocity field data and the geometric characteristics of the wing estimates of both the wing lift and rolling moment as a function of the position of the wing in the wake were computed. The strip theory estimates clearly provide a good estimate of the vortex induced loads. Similar favorable results were found for estimates of the lift coefficient on the wing as it traversed the vortex wake.

![Fig. 6. Predicted vortex induced rolling moment coefficient compared with experimental data](image)

The real utility of computer simulation of the aircraft/wake encounter problem is to be able to examine a wide range of possible encounters so that potentially hazardous encounters can be identified. We need to improve the aircraft wake simulations in at least two areas if we want to be able to identify critical flight scenarios. One major limitation in most of the previous simulations is the restriction on the wake geometry. In these earlier studies a straight line wake made sense because the focus of these simulation studies was on the take-off and landing approaches where the flight path is restricted. However, beyond the take-off and landing corridors it is more likely that the penetrating airplane will encounter a wake having a highly distorted geometry. In addition the loadings on all the lifting surfaces need to be monitored and compared to structural load limits.

### IV. Encounters Beyond the Landing and Take-off Corridors

A recent study of aircraft accidents where a trailing vortex wake encounter was suspected as a possible cause indicate that it may be time to examine operational procedures beyond the take-off and landing corridors. Two accidents are reviewed in the next section.

As stated earlier, the procedures used to control aircraft in the take-off and landing corridors have provided commercial aviation a high level of safety from encounters with aircraft trailing vortices. The operational procedures in the take-off and landing corridors are designed to avoid wake encounters. However, it will be argued in this section that the wake-upset issue needs to be re-examined beyond the take-off and landing corridors. There have been a number of fatal commercial aircraft accidents in which a wake upset was suggested as a possible cause or contributing factor to the accident.

The National Transportation Safety Board (NTSB) explores a wide variety of possible causes when investigating an airline crash. Many theories are examined and eventually if there is enough information available from the crash site the NTSB investigating teams can determine the most probable cause of the accident. The NTSB is currently investigating the crash of American Airlines flight number 587. One of the theories being investigated for the crash of the A-300 is an encounter with the vortex wake of a JAL 747 that had departed several minutes
before the American Airlines flight. From the transcript of the cockpit voice recorder the pilots comment about encountering wake turbulence just seconds before losing control of the airplane.

The flight data recorder (FDR) showed that the A-300 aircraft experienced lateral accelerations to the right and then to the left just prior to the failure of the vertical fin. In the same period the FDR shows rudder deflections from 5-10 degree then a rudder reversal of 10 degrees just before the fin failed. One possible scenario that could explain a fin failure and the rudder activity is depicted in Fig. 7. As illustrated in this figure the A-300 is passing across the vortex wake of the B-747 airplane so that the vortex core is passing just above the vertical tail. Assuming the penetrating aircraft crosses the wake from right to left then one would expect the side load on vertical tail to increase to the right and reach a maximum when the vertical fin is just below the right vortex core. As the airplane moves toward the left vortex the fin load decreases and is exactly zero when the fin is in the middle of the wake. As the fin moves toward the left vortex the side load again begins to increase but is directed to the left. If the A-300 was crossing the wake as illustrated in Fig. 7 the load could change quite rapidly depending on the penetration angle into the wake. For a rapidly changing load the pilots rudder input could easily be out of phase with the vortex-induced load.

Figure 8 is an estimate of the vortex induced load on a fin having the size and shape identical to that of the A-300. Simple strip theory was used to estimate the loading on the vertical as a function of the position of the fin relative to the vortex wake. The magnitude of the side load is both a function of the strength of the vortex (i.e. the weight of the generating aircraft) and the speed of the penetrating airplane. If we assume the weight of the generating airplane is of the order of 600,000 lbs. the side load can range from 24,000 to 39,000 lbs. for different penetrating speeds. Now if the pilot tried to control the motion resulting from an encounter with the right vortex the rudder input would be in the wrong direction when the fin encounters the second vortex. In this situation the total load on vertical tail would be due to a combination of the vortex and rudder induced loads. Estimates of the combined load make it plausible that such a scenario could result in a structural overload on the vertical tail.

Fig. 7. Scenario for Vertical Tail Failure from a Vortex Wake Encounter.

At this point in time the above scenario is only a theory. However, the combination of a large vortex induced load on the vertical tail coupled with an out of phase rudder input certainly is a plausible explanation for this accident. The NTSB may find evidence that supports a different theory for the cause of this accident; however the important point here is that a wake induced load coupled with large rudder input could cause a serious overload
of the vertical tail. The A-300 is a heavy wide body aircraft and based on the hazard criteria published in the literature one might conclude that a wake encounter would not be a problem for this class of aircraft. It is fair to say that the proposed encounter discussed above has not been adequately addressed in earlier vortex wake hazard assessment studies.

In alternate theory proposed by Brown\textsuperscript{43} postulated a scenario based upon an encounter with a series of vortex rings formed by the Crow instability. Basically the Crow instability is a long wave length interaction between the trailing vortices. Figure 9 is a photograph of the trailing vortices first undergoing a sinusoidal oscillation. As the amplitude of the oscillation grows in magnitude, the vortices eventually link and form a series of vortex rings. The Crow instability is often visible by observing the aircraft contrails at cruise altitude.

The photograph below shows the trailing vortex wake at three different times.

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\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{vortexLoads.png}
\caption{Vortex Loads on a Vertical Tail\textsuperscript{42}}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{vortexInstability.png}
\caption{Trailing vortex wake undergoing a Crow Instability.}
\end{figure}
Once the vortex rings are formed they rotate so they are perpendicular to the original plane of the straight line vortex filaments. Brown examined the loading that would result on the vertical tail passing through the core of the vortex rings. Brown simulated the response of a second aircraft penetrating the vortex rings from another aircraft. His simulation included vortex induced loads, aircraft dynamics, yaw damper and pilot input.

To the author’s knowledge this is the first time anyone has examined the influence of a Crow-like wake on a penetrating airplane. Brown’s study showed that a wake composed of vertical ring vortices could trigger a hazardous loading scenario on the vertical tail of a large jet transport. The side loads induced by the vortex rings coupled with pilot rudder input could produce tail loading exceeding the ultimate load factor. Figure 10 shows a sketch of penetration scenario and the loading predicted by Brown.

There have been several accidents involving the Boeing 737 for which a vortex encounter theory was explored by the NTSB. The accident that will be discussed here is the fatal crash US AIR Flight 427, a Boeing 737 aircraft. One of the possible causes or contributing factors investigated for the crash of Flight 437 near Pittsburgh on September 8, 1994 was an encounter with the wake of a Boeing 727 aircraft. As the 737 was descending through an altitude of 6,000 feet the airplane was suddenly rolled over and the pilots were unsuccessful in recovering the aircraft. The FAA and Boeing conducted a flight test at the FAA’s facility in Atlantic City, New Jersey.

Fig. 10. Vertical tail loading due to an encounter with three vortex rings predicted by Brown.

The tests consisted of flying a 737 into the vortex wake of a Boeing 727. The wake of the 727 was marked with smoke so the pilots of the 737 could maneuver their airplane into one of the vortex cores. The 727 wake was strong enough to roll the 737 to a roll angle greater than 60 degrees before the pilots regained control. However, in the flight test the pilots knew what was going to happen so they could anticipate the appropriate control input once the encountered occurred.

The final NTSB report attributed this accident to a loss of control due to a rudder malfunction. The report states that the rudder most likely deflected in a direction opposite to that commanded by the pilot due to a failure in the rudder control system. The malfunction was blamed on the possibility that the power control unit could jam causing a control reversal. One of the reasons the NTSB looked at the rudder control system was due to the number of un-commanded rudder inputs reported by 737 pilots. The pilots referred to the unexplained yawing motion as rudder bumps. There is another possibility of rudder bumps that could be related to aircraft wake turbulence. As has been shown earlier it is possible to induce a large side load on the vertical tail if the airplane passes just below the trailing vortex system of another aircraft. The rapid change in side load on the vertical tail would feel like an un-commanded rudder input.
The Boeing 737 has an excellent safety record and is the most popular aircraft with the airlines in its class. Another popular aircraft in this category is the DC-9 and its derivative the MD-80. Figure 11 is a sketch of both aircraft. The major design differences between the two airplanes are engine placement and horizontal tail location. As this figure attempts to illustrate the T-tail configuration would act to shield the vertical fin from the full effect of the vortex wake. The Boeing 737 would be more susceptible to vortex induced loads on the fin and rudder than a T-tail configuration when approaching the vortex from below. The pilots would sense the load on the tail due to the motion it causes, however since the author is not familiar with the rudder control system it is not clear whether the pilots get any sense of the external load on the rudder surface through the rudder peddles. The point of this hypothetical argument is not to question the NTSB’s conclusion but to suggest the possibility that a vortex wake encounter with the vertical tail could be interpreted by the pilot as a rudder anomaly.

V. Cruise Altitude Encounters

One of the fastest changes to take place in the airline industry during the past decade was the rapid switch from turboprop commuter aircraft to the regional jet transports. In the past the turboprop commuter fleet would cruise at 20,000 feet and below, however the regional jets can cruise at the same altitude as the larger commercial fleet. With the introduction of the regional jet transports into the commercial fleet we have created a very large disparity in
aircraft size that can cruise at the altitude. Furthermore there is evidence that wake encounters at cruise altitude do occur and should be investigated more extensively that has been done to date.

A recent study conducted in the United Kingdom found that approximately 5% of all trailing vortex wake encounters involved aircraft at cruise altitude. Information on vortex encounters was collected as part of a study conducted by the Civil Aircraft Airworthiness Data Recording Program. In this program aircraft from collaborating airlines were equipped with additional sensors and recording equipment. Britton\textsuperscript{44} describes one such encounter. The incident occurred when a medium size jet transport encountered the wake of a large wide body transport. Both aircraft were cruising at the same altitude and were between 16 and 20 miles apart when the wake encounter occurred. The medium size transport aircraft rapidly rolled to a roll angle of approximately 70 degrees and experienced rapid excursions in normal accelerations of up to $\pm 0.6$ g. The pilots regained control of the aircraft after losing altitude and having a significant heading change.

Rossow and James\textsuperscript{45} presented an excellent overview of the trailing vortex wake hazard at cruise altitudes. In there study they examined cross track encounters with vortex wakes at altitude. They concluded that it was not possible to predict when a safe cross track encounter was possible due to the variability of vortex decay time caused by atmospheric effects. They showed that the trailing vortex wake at cruise altitude can be as hazardous to following aircraft as the wakes that can be encountered during take-off or landing. Their study showed vortex encounters at altitudes along the vortex cores would be hazardous for up to several minutes or nearly 20 miles behind the generating aircraft.

The following is an analysis similar to that presented by Rossow and James\textsuperscript{45}. The circulation of the trailing vortex wake can be shown to be

$$\Gamma = \frac{W}{\rho V_\infty b^1}$$  \hspace{1cm} (1)

where, $W$ is the weight of the generating airplane, $\rho$ is the air density, $V_\infty$ is the flight speed and $b^1$ is the span of the trailing vortices. Now if we ratio the circulation estimate at take-off to the cruise condition we obtain the following equation

$$\frac{\Gamma_{TO}}{\Gamma_{cruise}} = \left[ \frac{W_{TO}}{W_{cruise}} \right] \left[ \frac{\rho_{cruise}}{\rho_{TO}} \right] \left[ \frac{V_{TO}}{V_{cruise}} \right]$$  \hspace{1cm} (2)

Assuming a cruise altitude of 40,000 ft. and typical transport take-off and cruise speeds, the following ratio can be estimated to be:

$$\frac{\rho_{cruise}}{\rho L} = 0.25$$  \hspace{1cm} (3)
$$\frac{V_{cruise}}{V_{TO}} = 3.75$$  \hspace{1cm} (4)

and

$$\frac{W_{TO}}{W_{cruise}} \approx 1$$  \hspace{1cm} (5)

therefore

$$\frac{\Gamma_{TO}}{\Gamma_{cruise}} \approx 0.94$$  \hspace{1cm} (6)

If we assume that vortex field at altitude behaves in a manner similar to approach altitudes, the rolling moment induced on an aircraft wing penetrating along the vortex axis can be estimated.

$$L_y = 2 b \int_{-\alpha}^{\beta/2} \gamma C_{\alpha, \phi} \left[ \frac{V_\phi(y)}{V_\infty} \right] Q c dy$$  \hspace{1cm} (7)

Rearranging this equation yields,

$$L_y = \rho V_\infty \int_{-\alpha}^{\beta/2} \gamma C_{\alpha, \phi} V_\phi(y) c dy$$  \hspace{1cm} (8)
The integral is only a function of the vortex velocity field $V_y(y)$ and the wing’s aerodynamic and geometric characteristics. Having shown that the vortex strength at cruise is roughly the same as during take-off and assuming the velocity field is identical then the integral would yield the same value for either cruise or sea level flight. The ratio of $L_{cruise} / L_{SL}$ can be expressed as follows:

$$\frac{L_{cruise}}{L_{SL}} = \left[ \frac{\rho_{cruise} V_{cruise}}{\rho_{SL} V_{TO}} \right]$$

$$= \left[ \frac{1}{4} \right] [3.75] = 0.875 \quad (9)$$

From this simple order of magnitude analysis we see that the induced rolling moment at altitude is comparable with what can be experienced during take-off or landing.

Currently a study is being conducted at Notre Dame to examine the potential risks of vortex encounters at altitude. The procedure for predicting the structural load factors was similar to that used by McGowan$^{24}$. A cross track penetration is defined as one in which the penetrating aircraft is at the same altitude and flying perpendicular to the path of the trailing vortex wake. In the cross track penetration the structural load factors and the influence of pilot control action on the loading is being studied. Preliminary results have been computed for cross track penetration without pilot input by Cobb and Mathieson$^{46}$. Figure 12 shows the induced change in angle of attack and load factor for a regional jet transport at 35,000 feet. The curves are plotted as a function of both distance traveled and time. There are two curves on each plot, the curves that achieve the highest induced angle of attack or load factor (red curves) were computed without the including the Kussner function that accounts for the lag in lift during a gust penetration. The lower magnitude curves show the affect of including the lag in lift term. Both the peak induced angle of attack and load factor are attenuated by the lag effect.

![Fig. 12. Vortex induced loads in a cross track encounter.](image)

VI Summary

Based upon the discussion and analysis of the wake vortex hazard beyond the take-off and landing corridors presented in this paper the following observations and conclusions were made.

1. Because of the increase in air traffic as well as the disparity in commercial aircraft size we need to examine the trailing vortex risk beyond the take-off and landing corridors. The one thing we should learn from the A300 accident is that we need to broaden our perspective in looking for potential wake hazards. Although the wake induced load on the vertical tail was below the structural limit the combination of the pilot’s corrective action with the rudder resulted in loads that did cause the tail to fail. This type scenario was simply not examined in the past. Most of the focus was on assessing the magnitude of an in line penetration of the vortex where the hazard would be a roll upset. In the case of an airplane like the A300, simulations would have predicted only a small roll excursion that would be easily controlled by the pilot. There is clearly a need to reexamine the types of hazardous scenarios that may occur beyond the take-off and landing corridors.
2. A computer simulation of an aircraft/wake vortex encounters offer the most efficient way to examine potential hazards. The simulation should include; pilot and/or autopilot input, and variable wake geometry. The code should be able to handle curved wakes including Crow-like ring vortices. Furthermore, the vortex induced loads and control loads on all lifting surfaces will need to be examine to identify any encounters that may be approaching large structural loads.

3. At cruise altitude the vortex induced rolling moment can be as large as that created in the terminal area for wakes that are of similar age.

Acknowledgments

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