# Wake Hazard Alleviation Associated with Roll Oscillations of Wake-Generating Aircraft

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

**An explanation is provided for the difference in wake vortex alleviation achieved by roll oscillations during flight tests with B-747 and L-1011 transport aircraft. Both aircraft had their landing flaps extended and several spoilers deployed. Numerical analysis shows that the growth in amplitude of the initial waves in the vortex filaments is brought about by inviscid vortex interactions. In the case of the B-747, growth is enhanced by a vortex whose strength is about the same as the tip vortex that is shed near the fuselage by the inboard end of the flaps. Conversely, the L-1011 is estimated to shed a negligible fuselage vortex and to have a relatively strong wing tip vortex. These characteristics bring about a rotation and a large amplification of the initial waves in the vortex filaments in the wake of the B-747, but not in the L-1011 vortex wake. An aircraft following the B-747 would then experience only intermittent encounters with the intense parts of the wake vortices, such that the time-averaged wake-induced rolling moment is substantially reduced.**

## Nomenclature

| | |
|---|---|
| $b$ | = wing span |
| $c$ | = wing chord |
| $\bar{c}$ | = average chord |
| $C_L$ | = lift/$qS$ |
| $C_\ell$ | = local lift/$qc$ |
| $C_{l_f}$ | = rolling moment/$qSb$ |
| $ds$ | = initial length of vortex segments |
| $q$ | = $\rho U_\infty^2/2$ |
| $r_c$ | = radius of vortex core |
| $t$ | = time |
| $T$ | = $tU_\infty/b_g$ |
| $U_\infty$ | = velocity of aircraft |
| $x$ | = distance measured in flight direction |
| $y$ | = distance measured in spanwise direction |
| $z$ | = distance measured in vertical direction |
| $X,Y,Z$ | = $x/b_g$, $y/b_g$, $z/b_g$ |
| $\gamma$ | = vortex strength, $b_g U_\infty$ |
| $\rho$ | = air density |

*Subscripts*

| | |
|---|---|
| $c$ | = vortex core |
| $f$ | = following or probe aircraft |
| $g$ | = wake-generating aircraft |

## Introduction

THE wake behind an aircraft consists of essentially two parts. The first is primarily turbulence generated by the profile drag of the various components of the airplane and by the thrust of the engines. The second consists of the lift-generated vortices shed by the wings. The turbulence in the wake caused by viscous drag and thrust is a disorganized aerodynamic motion that decays to a harmless level within a distance of several wing spans behind the aircraft. Conversely, the lift-generated vortices are not only well-organized fluid motions, but they also decay so slowly that they may pose a significant hazard to smaller following aircraft for several miles (i.e., over 200 wing spans) behind the wing that generated them. When a following aircraft encounters such a wake (see Fig. 1), it experiences an up- or downwash and/or an overturning moment from the vortex wake. The persistence of the vortices does not cause much inconvenience or hazard at higher altitudes (where the aircraft cruise at different heights and on different flight paths) because there the likelihood of encounter is extremely small and the aircraft has time to recover from any such encounter. In the vicinity of airports, however, all aircraft are constrained to fly specific corridors during landing and takeoff in order to use the same runways. Since the likelihood of vortex encounters is then much greater, the aircraft spacing is kept above certain minimums to insure safe operations. Much of the research carried out by various organizations to gain an understanding of the wake/vortex problem so that the hazard can be brought under control is summarized in Refs. 1-4. Although the programs have been active for about 15 years and several aircraft configurations with significant wake alleviation have been identified, a satisfactory solution providing greatly reduced wake velocities and specific guidelines for the aircraft has not been accomplished.

Of interest in this paper are some flight results reported by Barber and Tymczyszyn[5] that were obtained at the Ames-Dryden Flight Research Facility during a test program to evaluate the effectiveness of turbulence injection by use of spoilers[6] on the wings of Boeing B-747 and Lockheed L-1011 aircraft. In brief, the flight tests used a T-37B following or probe aircraft to first determine how much wake alleviation could be achieved by activation of the flight spoilers on the B-747 during straight and level flight. Tests were then conducted to determine the effect on wake alleviation caused by turning and rolling maneuvers such as those used in the vicinity of airports. See Table 1. It was found that the roll oscillations of the Boeing 747 enhanced the wake alleviation (i. e., reduced the wake overturning moments during a direct follow-

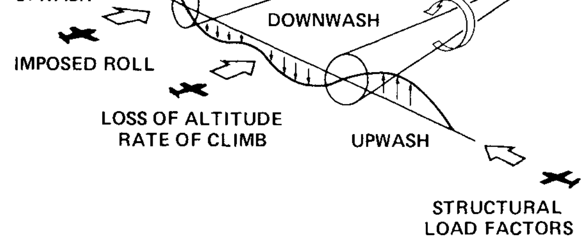


**Fig. 1 Schematic of possible encounters by a following aircraft with a lift-generated wake.**

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*Senior Scientist. Associate Fellow AIAA.

Table 1 Summary of information used here from flight tests conducted with roll or pitch oscillations (from Ref. 5)

| Aircraft | Configuration: Flaps, deg | Configuration: Spoilers | Maneuver | Results |
|---|---|---|---|---|
| B-747 | 30/0 | Locked in retracted position | Straight and level flight | Wake attenuated by about a factor of two |
| B-747 | 30/30 | 2, 3, 4 at 45 deg | Straight and level flight | Wake attenuated by about a factor of two |
| B-747 | 30/30 | 2, 3, 4 at 45 deg | Roll oscillations at 6 s/cycle | Wake devoid of coherent rotary flow at 3 n.mi. |
| B-747 | 30/30 | Locked in retracted position | Roll oscillations at 6 s/cycle | Wake similar to unattenuated wake shed during straight and level flight |
| L-1011 | 33 | 2, 3, 4, 5 | Roll oscillations at 4.6 and 9.2 s/cycle | Did not change wake hazard from straight and level flight character (very different from B-747 results) |
| L-1011 | 33 | 2, 3, 4 | Pitch oscillations at 2.3, 4.6, and 9.2 s/cycle | Excites and changes period of Scorer-Crow instability |

ing encounter), so that the probe aircraft did not experience an uncontrollable coherent rolling moment. In a second series of tests (see Table 1), a comparable effect was not obtained with the L-1011 aircraft.[5] An immediate explanation for the test observation was not available. Subsequent efforts by Holbrook et al.[7] indicated that the sinuous shape of the vortices may have been large enough that the following aircraft had only intermittent encounters with the high-energy core of the vortex, so that the overturning moment was also intermittent. Hence, the rolling moment perceived by the pilot was greatly reduced even though the peak values had not been changed appreciably. In a study carried out in the Langley Vortex Research Facility, Jordan[8] approximated the flight experiment by activating the same control surface motions, but without allowing the aircraft model to roll. He found that the time-dependent changes in lift across the span caused the vortices generated at the flap edges to cross the centerline of the aircraft flight path each time the roll controls were reversed. The observations made in Jordan's experiments did not indicate whether a new kind of wake instability had been triggered or whether already known vortex mechanisms were responsible for the wake dynamics observed.

The research reported in this paper extends previous investigations by theoretical simulation of the vortex wakes generated by the B-747 and the L-1011 in the flight experiments conducted at Dryden.[5] The computations approximate the time-dependent motion of the vortices as generated by the aircraft in order to determine the characteristics of the wake that initiate large deformations of the vortices. Another objective of the analysis is to determine whether interactions brought about in the vortices by their sinuous shape lead to any new and as yet unidentified wake-vortex instabilities.

## Vortex Displacement Required for Alleviation

As mentioned above, examination of the measured rolling moments induced by the vortex wake of the B-747 on the T-37B following aircraft led Holbrook et al.[7] to suggest that the observed alleviation was associated with the intermittency of the wake encounter rather than with an overall reduction in the vortex intensity. The intermittency of the encounter may be a result of the sinuous shape of the vortex or of the vortex core becoming segmented. That is, when the T-37B flies a nearly straight path, it is exposed to a strong overturning moment only periodically if the vortex shape is sinuous or segmented enough that the probe aircraft enters and leaves the intense part of the core. In the actual flight situation, some intermittency is also caused by the motion of the probe aircraft due to control inputs by the pilot or to the aerodynamic forces on the probe by a vortex that tend to throw the aircraft away from or into the vortex core.

Consideration is given in this section to the magnitude of the displacement of the vortex center required to yield the apparent reduction in the wake hazard perceived by the pilots, assuming that the probe flies a straight line. It is not intended to rule out some sort of segmentation of the vortex, but rather to provide information on the amount of vortex meander, excursion, or displacement required to obtain the observed flight results.

In order to obtain an estimate for the displacement of vortex centers required for an appreciable amount of wake alleviation, consider the contours of the equal rolling moment coefficient presented in Fig. 2. The computed curves[2] indicate the steady-state rolling moment induced on a probe aircraft of the Learjet or T-37B size when it is located at any point in the figure relative to the vortex center. Let it now be assumed that the vortex center is displaced from the level flight location by roll of the generator aircraft, vortex interactions, or both. The new location of the probe aircraft relative to the vortex center yields another higher or lower imposed rolling moment on the probe aircraft—depending on the direction of relative motion. Fluctuations in the value of $C_{l_f}$ would appear similar to a less hazardous wake because the average (or pilot perceived) value would be somewhere between the maximum and the minimum values of $C_{l_f}$ that are encountered during a cycle and on the relative amount of time spent in each part of the vortex. The contours of $C_{l_f}$ in Fig. 2 indicate that vortex displacements on the order of 0.1-0.5 of a generator span length are needed, depending on the direction of the displacement or relative motion. Apparently, a much smaller horizontal displacement than the vertical is required when the probe is in the plane of the vortex centers. According to Fig. 2, a horizontal displacement of less than 0.2 $b_g$ brings about a reversal in the sign of the imposed rolling moment. If, however, vertical displacement is achieved only by rolling the generator aircraft, the roll angle needed could be as much as 45 deg (displacement $\approx 0.5$ $b_g$) to yield a rolling moment that is smaller but still of the same sign. These considerations indicate that some sort of enhancement and reorientation of the initial displacement of the wake of the B-747 must have taken place before the T-37B probe aircraft encountered the wake.

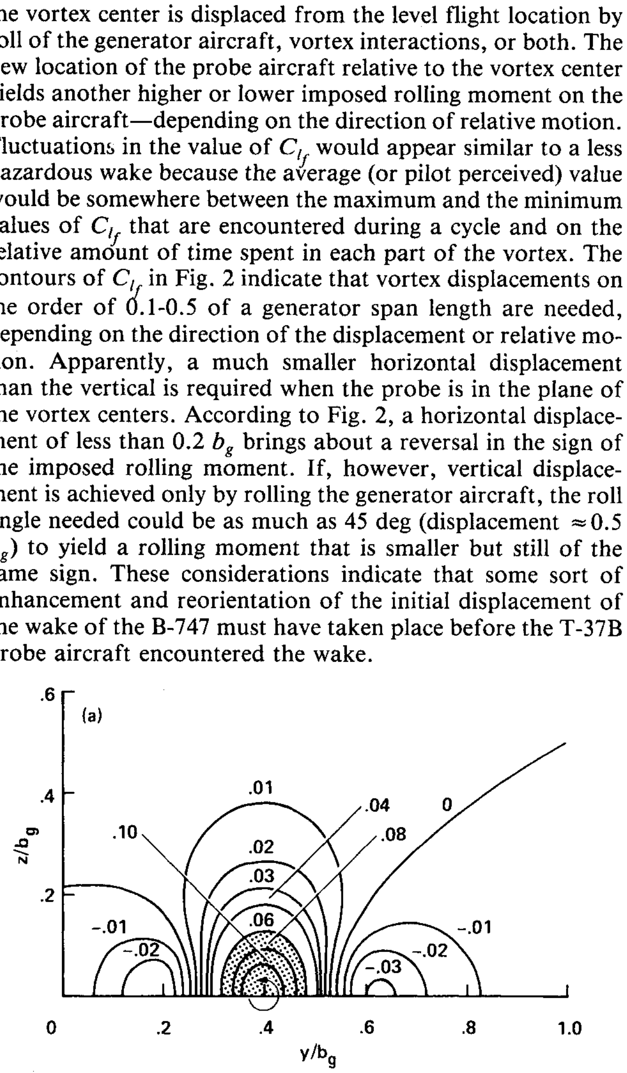



Fig. 2 Contours of equal rolling moment parameter $C_{l_f}/C_{L_g}$ for a T-37B size aircraft encountering the wake of a jumbo jet on an axial penetration ($b_f/b_g = 0.29$).

Table 2 Summary of strengths and locations of wake vortices trailing from starboard half of wing

| Aircraft | Configuration: Flaps, deg | Configuration: Spoilers | $C_L$ | Vortex 1: $Y_1$ | Vortex 1: $\gamma_1$ | Vortex 2: $Y_2$ | Vortex 2: $\gamma_2$ | Vortex 3: $Y_3$ | Vortex 3: $\gamma_3$ | Vortex 4: $Y_4$ | Vortex 4: $\gamma_4$ | Vortex 5: $Y_5$ | Vortex 5: $\gamma_5$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B-747 | 0/0 | Stowed | 1.38 | 0.381 | +0.130 | | | | | | | | |
| B-747 | 30/0 | Stowed | 1.38 | 0.455 | +0.064 | 0.219 | +0.110 | 0.058 | −0.063 | | | | |
| B-747 | 30/30 | Stowed | 1.38 | 0.465 | +0.054 | 0.346 | +0.065 | 0.225 | −0.021 | 0.185 | +0.052 | 0.060 | −0.061 |
| B-747 | 30/30 | 2, 3, 4 at 45 deg | 1.38 | 0.455[a] | +0.064[a] | 0.219[a] | +0.110[a] | 0.058[a] | −0.063[a] | | | | |
| L-1011 | 0 | Stowed | 1.33 | 0.464 | +0.0765 | 0.225 | +0.0545 | | | | | | |
| L-1011 | 33 | Stowed | 1.33 | 0.433 | +0.103 | 0.266 | −0.020 | 0.188 | +0.046 | | | | |
| L-1011 | 33 | 2, 3, 4, 5 deployed | 1.33 | 0.41[a] | +0.097[a] | 0.18[a] | +0.045[a] | | | | | | |

[a]Approximate value.

## Estimate of Steady-State Span Loadings

The normalized steady-state span loadings on the B-747 and L-1011 (e. g., Refs. 2 and 9) are presented in Fig. 3. The approximate weights of the aircraft [263,000 kg (580,000 lb) for the B-747 and 159,000 kg (350,000 lb) for the L-1011] during the flights at an altitude of about 10,000 ft above sea level and at an indicated velocity of 150 kt were used to determine the lift coefficients and angles of attack on the aircraft. The span loadings presented in Fig. 3 were then used to determine a theoretical value[10] for the strenghts and locations of the vortex centers for both aircraft in their various flap configurations shown in Table 2.

Since a reliable method for determining the span loading when the spoilers were deployed was not available, the span loadings and the wake-vortex distributions for the aircraft were estimated by assuming that the lift was reduced on the wing where the spoilers were deployed. For example, the loading on the B-747 with spoilers 2-4 deployed [5] was assumed to be approximated by the span loading when the flaps were set at (30/0 deg). Such an approximation was suggested by the observation that the wind tunnel measurements of wake-induced rolling moments are about the same for the two configurations.[2,6] Although an experimental confirmation of the span loading in the spoiler case is not available, a measurement of the strengths of the vortices shed by the B-747 in the (30/30 deg) and (30/0 deg) cases has been made in Ref. 3. Of particular interest here is their confirmation of the presence of the relatively strong fuselage vortex shed by the inboard end of the inboard flap.

The wake of the L-1011 with its flaps at 33 deg and spoilers activated is approximated by the two vortices listed in Table 2. It should be noted that the strong vortex shed by the inboard edge of the inboard flap on the B-747 is not present on the L-1011. (An experimental confirmation of the vortex strengths and the lack of a fuselage vortex was not available for the L-1011.) The differences in the flap design and placement on the wings of the two aircraft probably account for the difference in the two wakes in the landing configurations. Another difference that appears to impact the wake vortex hazard potential is the somewhat tapered span loading on the B-747 as compared with the more elliptical loading on the L-1011. Experience indicates that alleviation is easier to achieve on tapered loadings than on wings that shed a strong tip vortex.[2-6]

## Two-Dimensional Simulation of Wakes

If the wakes listed in Table 2 do not vary significantly in the flight direction, the motion of the vortices can be predicted by two-dimensional time-dependent numerical schemes[2] that approximate the wake by following the vortex trajectories in the so-called Trefftz plane. Even though some vortex dynamics (like those described by Scorer[11]) are automatically eliminated by such a simplification, comparison of these results with three dimensional predictions will assist in the identification of any vortex dynamics instigated by roll and pitch oscillations. The lines shown in Figs. 4 and 5 depict an end view of the trajectories taken by the vortices from their initial positions listed in Table 2 to their locations 60 spans behind the generating wing. A distance of 60 spans is about 2 n.mi. behind the B-747 and about 1.53 n.mi. behind the L-1011. Intermediate distances are not marked on the figures. The single vortex pair shed by the B-747 with flaps at (0,0 deg) descends unchanged as indicated in Fig. 4a. Four of the five pairs of vortices shed by the aircraft in its landing configuration [i.e., flaps at (30,30 deg)] orbit about one another to form periodic cauliflower patterns (see Fig. 4b). The fifth and most inboard pair first moves downward and inboard until the influence of the other vortices has diminished to the point where they can move upward as an isolated pair. In flight, turbulence from the fuselage and landing gear would cause this inboard vortex pair to coalesce.

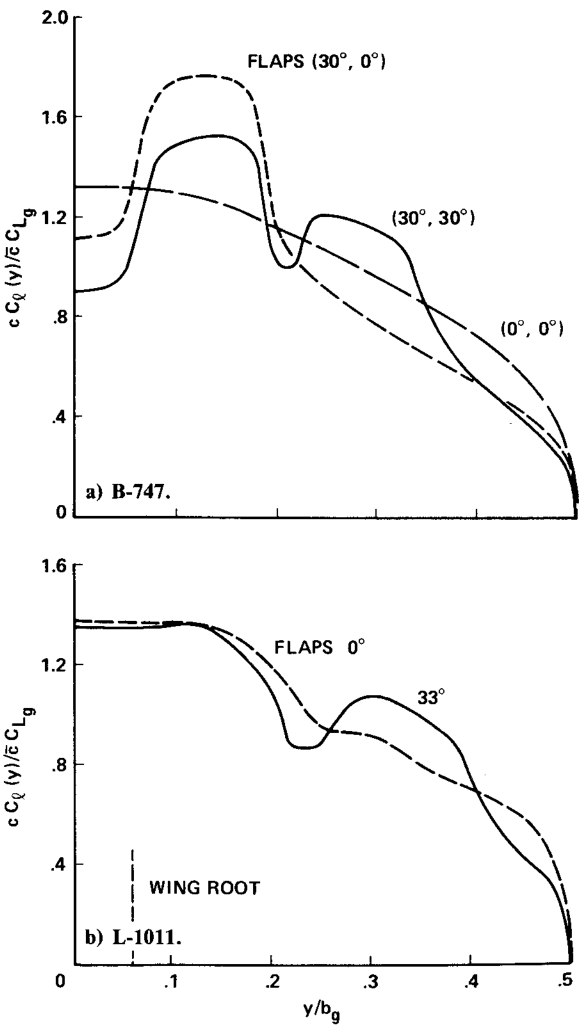



Fig. 3 Estimated span loadings for test aircraft.

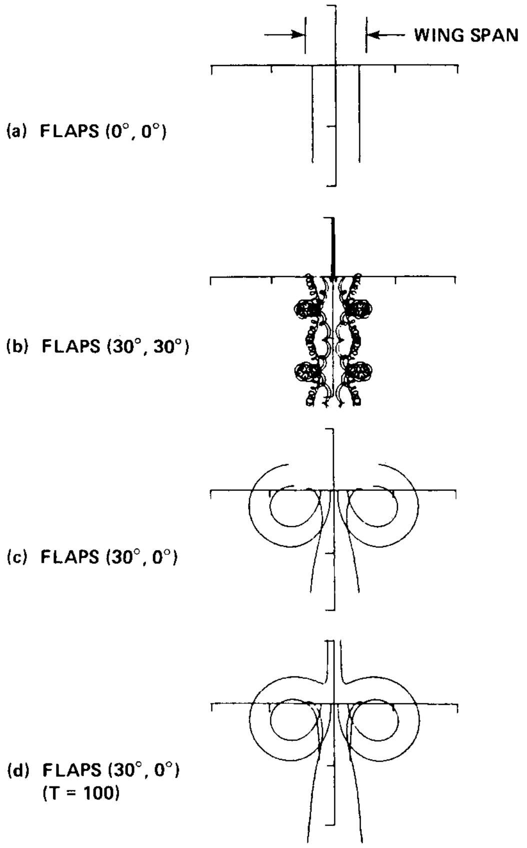



**Fig. 4 End view of two-dimensional trajectories of vortices in wakes of B-747 from initial locations to positions at $T=60$ (or $T=100$ as noted).**

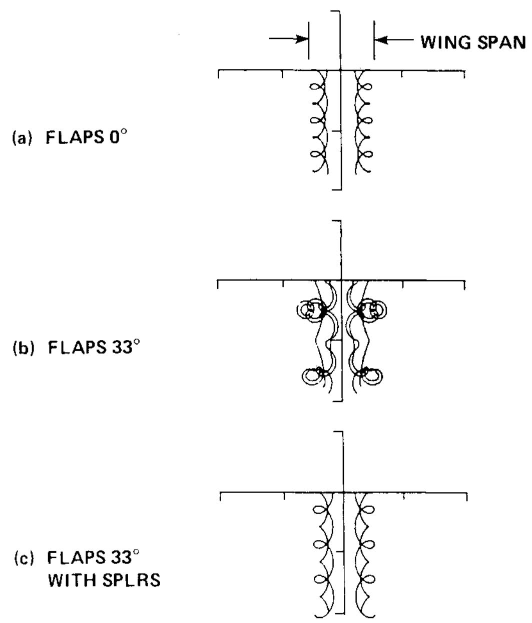



**Fig. 5 End view of two-dimensional trajectories of vortices in wakes of L-1011 from initial locations to positions at $T=60$.**

A contrasting vortex motion develops when the outboard flap is withdrawn on the B-747 so that only three vortex pairs remain in the wake, see Figs. 4c and 4d. The tip vortices first move inboard and then downward to form an isolated pair. However, the two vortices shed by the inboard flap execute a large circular orbit and then reassociate to form new pairs of vortices that move off separately. The effect of turbulence, finite core size, three-dimensional interactions, and changes in vortex strength from those estimated here can all effect the details of the trajectories presented in Figs. 4c and 4d. However, the presence of the negative inboard vortex pair and its ability to influence strongly the other flap vortices suggests that the large vortex excursions needed to explain the flight results observed at Dryden[5] might be produced thereby.

The wakes shed by the various L-1011 configurations (Fig. 5) consist of either two or three vortex pairs. Since the vortices in the two-pair cases are both of the same sign, the vortices simply rotate about one another while the entire wake descends (Figs. 5a and 5c). The presence of a third vortex pair in the flaps 33 deg configuration produces a different pattern from the two-pair cases, but the trajectories resemble the pattern in Fig. 4b more than the ones in Figs. 4c and 4d. Thus, it appears that large vortex excursions are not to be expected for the L-1011 cases.

## Three-Dimensional Wake Simulations

### Description of Numerical Method

The method used here to compute the dynamics of vortex wakes is an incompressible inviscid technique similar to that used by others.[1,12-14] That is, the curved wake vortex filaments are first approximated by straight line segments. The shape and locations of the resulting vortex lines are then monitored by following the points where adjacent segments or links are connected. The velocity components of these points are calculated as a summation of the separate contributions of all of the vortex links in the flowfield, except for the two that touch the point itself and thereby have singular contributions. Since the velocity induced by the two adjacent links is not included, the vortex lines are essentially cut off at a distance of one link length $ds$ on both sides of the point in question. The length of the link and, consequently, the cutoff distance are chosen so that the numerical results agree with the velocity of propagation of a vortex ring. That is, on the basis of reasoning similar to that used by Crow,[15] the link length in the present numerical method is adjusted until the velocity of propagation of a vortex ring agrees with the closed-form expression for a ring with a small but finite core.[16] The core is assumed to have a uniform vorticity over a diameter comparable with the vortices trailed from the test aircraft. Agreement is achieved with the present numerical method when $ds = 0.36\ d_c$. The value used by Crow[15] in his computations is 0.321. The value of 0.36 recommends a link length of $ds = 0.1\ b_g$ for use in the computations of aircraft wakes when the vortex core diameters are about $r_c = 0.14\ b_g$. In order to study the sensitivity of the method to segment length, calculations were made of several cases using a link length of 0.1 and 0.2 $b_g$. The two results were indistinguishable from one another when plotted to the scale used for the figures presented here. Such a result is not too surprising because the vortex filaments are usually nearly straight, so that the two-dimensional contributions to the vortex velocities probably dominates the self-induced contributions due to vortex curvature.

Both symmetric and antisymmetric wave systems were studied with the computational scheme. The beginning and end of each set of waves was always blended smoothly into the straight line segments used to represent the straight and level flight of the test aircraft before and after the roll and pitch oscillations were executed. This was done by use of a one-quarter cycle of the sine-squared variation in the displacement of the vortex links lying between the straight portion of the vortex and the oscillating part. Furthermore, two spans of undeflected segments were added at both ends of the wavy part of the wake to give added flexibility to the oscillating part of the wake. It was found that three cycles of waves were adequate to approximate a large number of waves, because disturbances from the ends of the wavy portion propagate slowly. Therefore, the center wave was believed to be insulated well enough from the starting and stopping parts of the waves to represent the motion experienced in an infinite wave train.

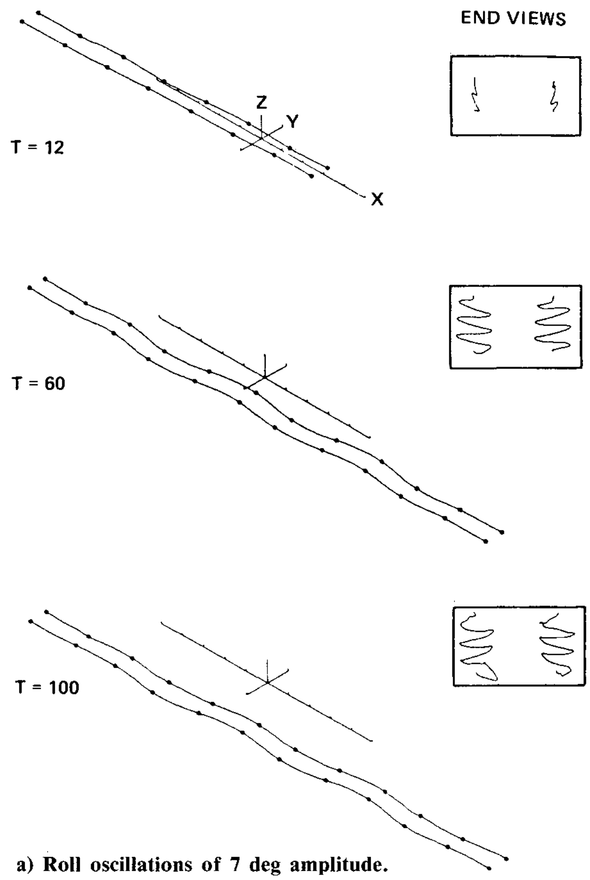
The spanwise vortices bound to the wing were not included because they did not appear to affect the wake dynamics significantly and also complicated the computations. Also not included are the spanwise vortices in the wake.[17] Spanwise segments of vorticity no doubt occurred in the flight test because changes were brought about in the span loadings as a function of time when various control inputs were used to roll or pitch the aircraft. As a consequence of these assumptions, the vortex filaments were of constant strength along their entire length throughout the computations.

The dynamics of the vortex wakes were computed by assuming that the wake was generated as a function of time. The long straight segments of the vortices that extend from the flexible parts to the far reaches of the wake are assumed to be in place at the beginning of the event, $T=0$. The wake motion is computed as if the aircraft enters at the left, moves across the field of view at the rate of one coordinate marker per time unit $T$, and exits at the right. The computations were all carried out using the dimensionless parameters indicated in the nomenclature list. As a result, the dimensionless time indicated in each figure represents the spans of travel of the wake-generating aircraft from the beginning of the event. In the figures to follow, the wakes are displayed on a 30/30/90 deg oblique graphical view to yield a three-dimensional perspective of the wake. Only the flexible portions of the wake are displayed. The end views of the wake are presented at a larger scale (i.e., four times) to show more clearly the size of the waves and their change in shape with time. Not all of the axes are labeled to reduce the clutter on the figures. Also, the symbols are placed on the filaments every two spans to assist in the understanding of the vortex shapes. In order to compare the cases more readily, the numerical results presented here assume that one oscillation cycle is completed within six spans of travel by the aircraft and a roll amplitude of 7 deg. Since the aircraft flew at 150 kt, or 1.28 spans/s, the theoretical oscillation period is about 4.7 s for the B-747.

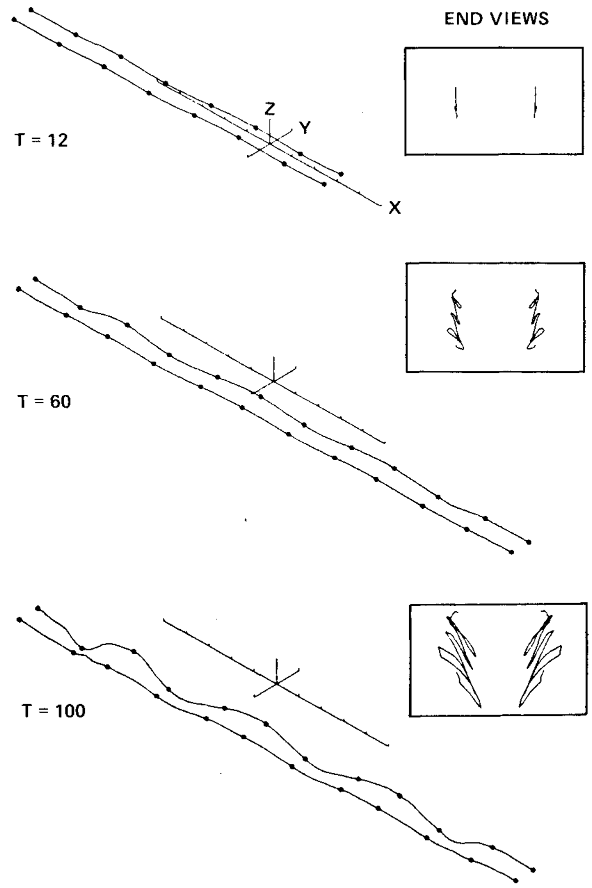
### B-747 Wakes

As mentioned previously, the wake of the B-747 does not undergo any significant changes when no flaps or spoilers are deployed and when no disturbances are imposed on the wake. However, when the same configuration [i.e., cruise configuration or flaps at (0,0 deg)] executes a series of roll oscillations, the planes of the disturbance waves rotate through 90 deg, while the wave amplitude grows from about 0.09 $b_g$ to about 0.4 $b_g$, in roughly 60 time units; see Fig. 6a. Thereafter, the wave shape and size appears to stay about the same at $T=60$-100 and probably until the wake decays by diffusion. The vortex filaments then appear to have emanated from an aircraft executing lateral or yawing oscillations, i.e., a snaking motion. The initial part of the wake dynamics was analyzed by Crow[15] using a small-disturbance theory to study the stability of antisymmetric waves on a pair of vortex filaments. It is interesting to note that the predicted initial growth does occur, but the wave amplitude appears to reach a maximum after the wave planes have rotated in the retrograde direction (i.e., opposite to that of vortex rotation) to an approximately horizontal plane where the vortex configuration becomes approximately stationary. If only one sinusoidally shaped vortex filament were present in the flowfield, it would rotate indefinitely almost unchanged.[12] The addition of the second vortex appears to bring about an increase in the wave amplitude by about a factor of four, while the planes of the waves rotate from the vertical to a horizontal attitude.

For comparison purposes, the wake of the B-747 with its flaps at their (0,0 deg) position executing pitching oscillations is presented in Fig. 6b. The wave planes of the vortices are noted to rotate slowly in the retrograde direction until they reach an angle of about 40 deg to the centerplane. The waves then grow in amplitude until the lower part of the vortex




a) Roll oscillations of 7 deg amplitude.




b) Pitch oscillations with same wingtip amplitude as roll oscillations in Fig. 6a.

**Fig. 6 Oblique and end views of wake of B-747 flaps (0,0 deg) at three time intervals after beginning of maneuver.**

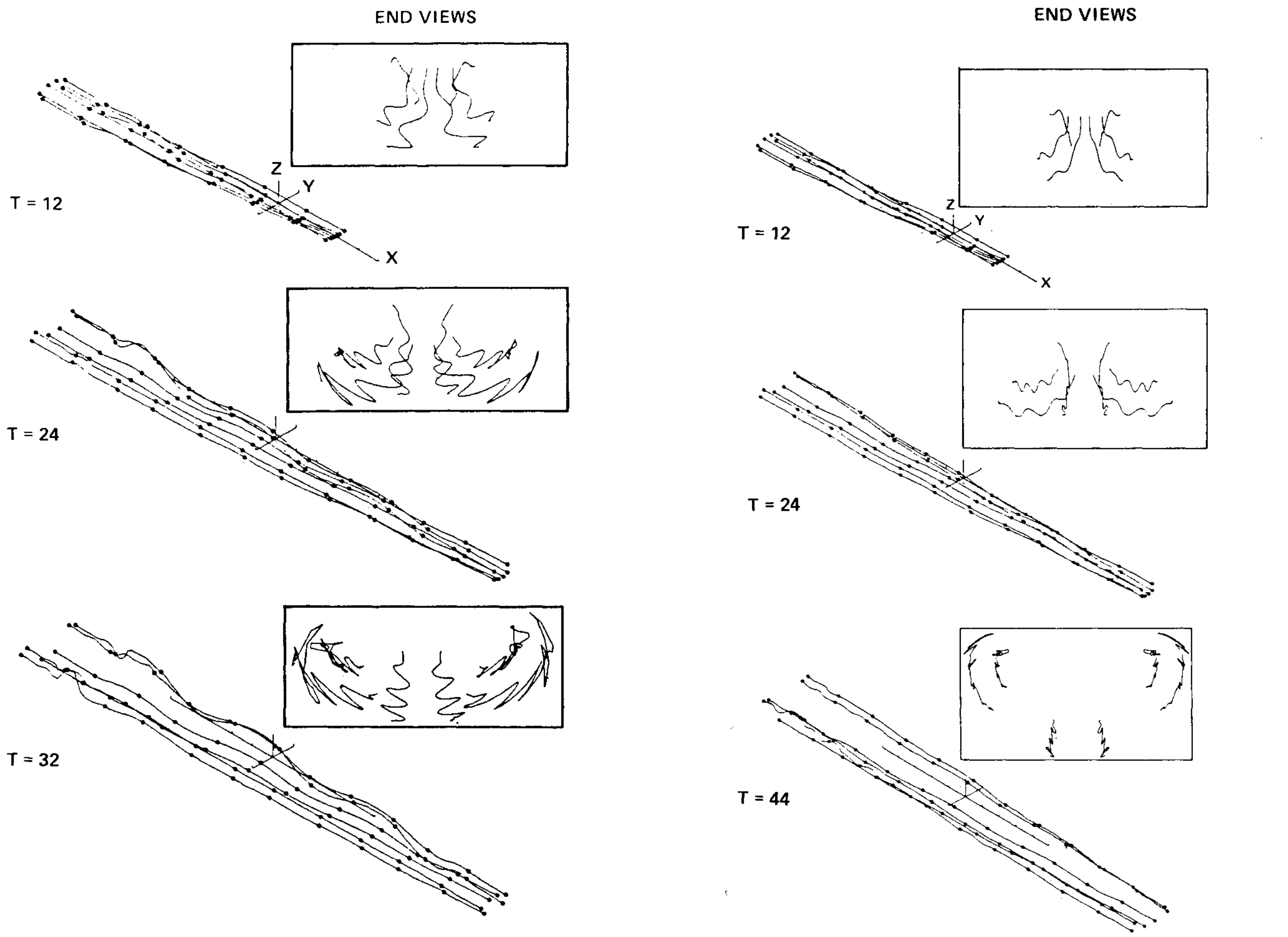



**Fig. 7 Oblique and end view of wake of B-747 flaps (30,0 deg) at various time intervals after start of maneuver. a) Roll oscillations of 7 deg amplitude. b) Pitch oscillations with same wingtip amplitude as roll oscillations in Fig. 7a.**

waves closely approach each other. By that time, the amplitude of the waves has grown considerably and is still continuing to grow at a fast rate. In a flight situation, the vortices would then break at the trough locations and link up across the pair to form irregularly shaped loops of vortex filaments. When first described by Scorer,[11] this process was attributed to buoyancy differences. However, Crow[15] showed that the velocities induced by the vortices themselves are responsible for the growth of the waves and that small-amplitude waves grow over a wide range of wavelengths. The second part of the interaction, where the vortices break or disconnect and then connect with the opposite vortex in the pair to form loops, appears to be understood, but has not been analyzed. This fluid dynamic sequence is important because various versions or parts of it occur in a variety of situations. Therefore, the entire process from wave growth through the breakoff and linking process is referred to here as the Scorer-Crow process or interaction.

As mentioned in a previous section, the vortex wake of the B-747 when both flaps (30,30 deg) and spoilers 2-4 are deployed (Tables 1 and 2) is approximated by the span loading of the (30,0 deg) flap. It is noted that the lift-generated wake then consists of three vortex pairs; that is, a tip vortex and two fairly strong vortices that are shed by the ends of the inboard flap. The wake dynamics initiated by rolling and pitching flight maneuvers are presented in Fig. 7. A different response by the vortex wake is noted for the two different initial displacements imposed on the wake. The roll oscillations place waves on the two-dimensional trajectories of the two flap vortices. As the waves grow, the vortices orbit and the planes of the waves rotate from nearly vertical to curved diagonal planes. Wave growth first occurs while the planes of the two vortices are nearly parallel. During the later stages of the event, a linking-type interaction appears to be taking control of the vortex motions. The present numerical results therefore suggest that the initial sinusoidal displacements of the vortex filaments brought about by the roll oscillations executed by the B-747 lead to vortex interactions which greatly amplify the vortex displacements at those stations where each wing tip is at its highest positions. The numerical results suggest that periodic linking and loop formation may also be starting to occur at about $T=32$ at the location where each wing reaches its most upward position. Examination of the motion pictures taken of smoke flow visualizations during the flight tests[5] indicates the same kind of vortex motion and thus supports the proposed explanation. The interaction that leads to wave growth is probably a mixture of the antisymmetric and symmetric cases analyzed by Crow.[15] Once again, however, the amplitude appears to be reaching a limit if the linking process does not begin between each set of flap vortices. It was not possible to discern in the flight flow visualization whether linking actually took place or not.

The ingredient in the wake that seems essential for wave growth (and the special vortex motions after roll oscillations) is the presence of the two vortex pairs shed by the inboard flaps that are of opposite sign and of comparable strength. The vortex pair shed at the wing tips does not become involved in the swinging interaction of the flap vortices, but simply moves inboard and then descends as predicted by two-dimensional theory without the appearance of significant wave growth or an instability. These characteristics were also observed in the flight flow visualizations. The similarity of the numerical results and the flight flow visualizations suggests that the span loading and subsequent wake vortex distribution assumed in the numerical work is not too far removed from the one occurring in flight.

The results presented in Fig. 7b for pitching motion illustrate an interaction that is a version of the Scorer-Crow process. The small waves on the vortices appearing on the older parts of the wake (left side of the figures) are the beginnings of waves that will probably lead to linking. Presence of the third vortex pair does not seem to enhance or hinder the wave growth nor the approach to the linking process. If the aircraft is flown on a straight and level path, the end views of the vortex wakes are about the same as predicted by two-dimensional theory until the vortices undergo the wave growth that leads to linking. The occurrence of this sequence of vortex interactions was confirmed by flight test at Rosamond Dry Lake with the B-747 in the (30,0 deg) configuration with the gear up and spoilers stowed (see Fig. 17 of Ref. 18). Subsequent calculations by Leonard[13] also showed that the observed vortex dynamics were brought about by inviscid vortex interactions. Comparison of the computations with the photographs in Ref. 18 suggests that the linking process probably occurred sooner in the flight than predicted by the computations.

Not so obvious was the finding that a small amount of turbulence injected into the wake by deployment of any of the landing gear or by a 5 deg yaw of the aircraft was sufficient to inhibit the Scorer-Crow process (see Ref. 2 and Fig. 17 of Ref. 18). Such a result is not surprising since theoretical analyses had shown that core size and axial flow inhibit or slow the Scorer-Crow process.[1,19] The results obtained from the flight tests with the B-747 suggest that, if an initial displacement of sufficient amplitude is given to the waves on the wake vortices by roll oscillations, the kinds of wave growth predicted by the present numerical results occurs in spite of the turbulence injected into the wake. It appears then that the amplification of the waves and their reorientation through vortex interactions are adequate to bring about the intermittent encounters observed in the flight tests. It is concluded therefore that the dynamics observed in the wake of the B-747 following roll oscillations can be attributed to the span loading, which is responsible for the special wake vortex structure.

### L-1011 Wakes

The three vortex wakes presented in Table 2 were used to carry out numerical simulations in flight tests. However, only the flaps 33 deg-spoilers deployed case is presented because the two other cases were quite similar and showed no significant wave amplification that was new. It is to be noted in Fig. 8 that the vortices shed by the L-1011 (with flaps and spoilers deployed) rotate around each other in much the same way as indicated by the two-dimensional theory and shown in Fig. 5. Distortions of the filaments due to roll oscillations are again superimposed on the two-dimensional paths. It is difficult to determine in the end views just what kinds of vortex interactions are taking place. The computations shows that, throughout the computational interval, the vortices stay grouped together closely enough that they would probably coalesce into a single pair much the same as they do when the roll oscillation maneuver is not being used. Subsequent examination of the flow visualization sequences taken during the flight tests[5] show that the vortices trailed by the L-1011 coalesce fairly quickly into a single pair at about one-half mile or so behind the aircraft. The lack of another vortex pair in the merged wake, which is of comparable strength and of opposite sign, made the wake dynamics observed in flight appear almost the same as the numerical results displayed in Fig. 6a. That is, the wake responded to roll oscillation of the generator aircraft as if it were composed of a single pair. Wake alleviation was not experienced by the probe aircraft, apparently because the amplitude of the sinuous waves was not large enough to yield the intermittent encounters needed for alleviation, even though the wave planes rotated to the horizontal.

Therefore, it is concluded that wave amplification requires at least two vortex pairs of comparable strength that are separated by a large enough spanwise distance to prevent them from coalescing before other wake dynamic processes can have time to work. This approach can be tested by adding a vortex pair of opposite sign and of comparable strength near the fuselage of the L-1011. Modification of the inboard flaps on a model of the aircraft to produce such an extra vortex pair leads to two-dimensional trajectories like the ones shown in Figs. 4c and 4d. Two-dimensional computations carried out during this study, but not presented here, showed that only the stronger fuselage vortex cases show promise. Since the strong tip vortex shed by the L-1011 tends to dominate the wake dynamics, the degree of alleviation to be expected will be less than that achieved with the B-747. Ground-based tests with configurations having fuselage vortices would help to clarify and possibly quantify further the wake ingredients necessary to bring about the differing responses of the B-747 and L-1011 wakes to the roll oscillation maneuver.

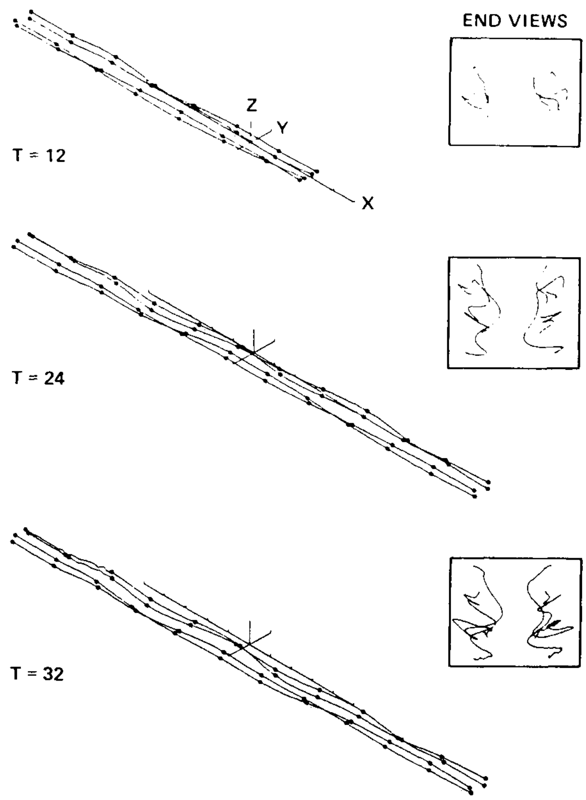



**Fig. 8 Oblique and end views of wake of L-1011 flaps 33 deg with spoilers deployed at various time intervals after beginning roll oscillation maneuver of 7 deg amplitude.**

## Conclusions

The numerical results presented here extend the study carried out by Holbrook et al.[7] by illustrating how the wakes of transport aircraft are affected by roll oscillations of the generating wing. Two ingredients in the vortex wakes of the test aircraft appear to cause the different responses to the roll oscillation maneuver: 1) the B-747 sheds a fairly strong vortex near the fuselage and the L-1011 does not; and 2) the L-1011 sheds a vortex near its wing tip that is stronger relative to the flap vortices than the B-747. These two factors combine to bring about much larger vortex distortions in the B-747 wake than in the L-1011 wake. The vortex filaments in the wake of the B-747 then have a sinuous shape of large enough amplitude that a probe aircraft experiences only intermittent encounters with the intense parts of the vortices. Because the wake of the L-1011 acts roughly as a single pair, the initial wave amplitude grows only modestly so that the vortex filaments still appear to be fairly straight when encountered by a probe aircraft. Even though the present analysis is based on faily crude estimates of the span loadings and the vortex wakes they trail, comparison of the numerical results with the flight motion pictures of smoke flow visualization shows that the dominant features of the wake dynamics have been at least qualitatively simulated. It is concluded that the instability that brought about the observed alleviation in the wake of the B-747 in roll is not of a new type, but probably just a combination of the symmetric and antisymmetric instabilities that result from multiple-vortex interactions. Finally, it should be noted that the apparent alleviation obtained for an axial probe of the wake may be of no benefit for cross-course penetrations. In those cases, segments of the vortex wake are still of full strength and capable of rendering the same damage that would have occurred if the wake-generating aircraft had been on a straight and level path.

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