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Wind-Tunnel Measurements of Hazard Posed by Lift-Generated Wakes

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The results obtained during a wake-vortex test conducted in the NASA Ames Research Center 80- by 120-ft Wind Tunnel are described. The wind-tunnel test is part of an FAA and NASA program to study the characteristics of lift-generated vortices in order to safely increase airport capacity for subsonic transports. Data was first obtained to confirm that measurements in the 80- by 120-ft Wind Tunnel are in agreement with those taken in the 40- by 80-ft Wind Tunnel during the test program of the 1970s. Measurements are then presented on the maximum rolling moment induced on following models of various sizes when they encounter the vortex wakes shed by several configurations of a subsonic transport. Finally, measurements are presented of the lift and rolling moment induced on various following models, and of the downwash, as a function of spanwise distance in the wake. The wing spans of the followers vary from 0.085 to 1.022 times the span of the wake-generating model.

Nomenclature

AR = aspect ratio
b = wingspan
C_L = lift coefficient, L/qS
C_l = rolling-moment coefficient, M/qSb
c = wing chord
f = natural frequency
L = lift
M = rolling moment
q = dynamic pressure, $\rho U_\infty^2/2$
r = radius
r_c = radius of vortex core
S = wing planform area
t = time
U_∞ = freestream velocity
u, v, w = velocity components in x, y, z directions
x = distance in flight direction
Y_{max} = spanwise location of maximum rolling moment/b_g
y = distance in spanwise direction
Z_{max} = vertical location of maximum rolling moment/b_g
z = distance in vertical direction
Γ = bound circulation
γ = wake vorticity
ρ = air density

Subscripts
av = averaged over time at a given point
f = following model
g = wake-generating model
max = maximum on one side of centerline
mi = minimum at a given point
mx = maximum at a given point
p = pitch
r = roll

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Introduction

THE objective of the NASA/FAA wake-vortex research program is to safely increase the rate at which aircraft can land and takeoff from a given runway. Such a program was undertaken because the current capacity of airports is limited by the hazard posed by vortices that are shed by the wings of subsonic transport aircraft,[1-5] and not some other aspect of traffic in the airport environment. Although the wake of a lead aircraft induces lifting, yawing, and pitching motions on a following aircraft, the most hazardous feature of the wake occurs as an overpowering rolling moment near the center of one of the vortices.[6-8] As a consequence, the potential hazard posed by wake vortices has become a limiting factor on the capacity of airports because they are intense behind large aircraft and because they persist as coherent entities for a number of span lengths behind the wake-generating aircraft. This is quite different from the disturbance caused by the engine exhaust that dissipates to a harmless level in just several span-lengths.

The persistence of the vortices observed in flight was confirmed in ground-based experiments. It was found that the maximum swirl velocity in lift-generated vortices undergoes negligible decay in the first part of their history, which lasts from several spans to tens of spans.[9-11] Downstream of this so-called plateau region where very little change occurs, the vortices decay or disperse approximately as $1/t^{1/2}$, or as the inverse of the square root of the distance behind the generating aircraft. Measurements made of vortices generated behind aircraft in flight indicate that, in most cases, the vortices eventually break up and disperse due to vortex instabilities and atmospheric disturbances rather than due to viscous and turbulent diffusion alone. It is this persistence of vortices, and the organized rotary motion in their flowfields that poses a hazard to following aircraft that venture into a region occupied by a vortex wake.

In support of the airport capacity program of the FAA and NASA, the program at Ames Research Center[12-18] has two primary long-term objectives. The first is directed at evaluating the potential hazard posed by various subsonic transports as their wakes interact with a variety of following wings. The second objective is to find out how to design the high-lift systems of aircraft so that their wakes disperse more rapidly to allow spacings to be safely decreased. The experiment conducted in the 80- by 120-ft Wind Tunnel was designed to produce data that would support both of these objectives. Concern for possible misleading results because of the large differences in Reynolds number of the flow over the model and over the full-scale device suggests that the results always be used with caution and with eventual backup with flight hardware before serious commitments are made. In spite of the large difference in Reynolds number, the very good qualitative and quite good quantitative agreement with flight results[6-8] suggests that the flow over the wing of the model must represent most of the essential features of the full-scale vehicle. Over the 20 or so years that the larger wind tunnels have been used in the wake-vortex program, it has been found that it is a cost effective and reliable method for studying the dynamics of wake vortices, for obtaining preliminary data on configurations, and for screening concepts.

This article first describes the experimental setup and the procedures used to obtain the data. Comparisons are then made to confirm that data measured recently in the 80- by 120-ft Wind Tunnel are in agreement with those measured in the 40- by 80-ft Wind Tunnel during the test program[12-18] of the 1970s. As will be described in the text to follow, the results from the two facilities are in good agreement. Measurements are then presented of the lift, rolling moment, and downwash angle as a function of spanwise distance.

Experimental Setup and Test Procedures

The experimental results on induced lift and rolling moment to be presented here are obtained with the following wing technique because it has been found to be direct, easily applied, and to provide results that agree with flight test results.[6-8] The test installation (Fig. 1) and the wind-tunnel conditions (Table 1) are about the same as the ones used in the latter part of the 1970s test program[17,18] in the 40- by 80-ft Wind Tunnel. The wake-generating model (0.03 scale model of a B-747, Fig. 2) is again mounted in an inverted attitude on a single strut with a strain-gauge balance to measure the lift, drag, and pitching moment. An inverted mounting of the generator model is used to minimize interference of the strut wake with the vortex wake of the generator model. The model wake then moves upward away from the strut wake that tends to go straight downstream. The angle of attack of the generator is set remotely through an actuator and indicator mechanism. As in the past, and as indicated in Table 2, a designation of flaps (30 deg/30 deg) is used to indicate that the wake-generating model is in its full landing configuration with the leading-edge slats, landing gear, and trailing-edge flaps fully deployed. The other two configurations[16-18] are part of the study to find design guidelines that will make it possible to build efficient aircraft with acceptably alleviated wakes. In the (30 deg/0 deg), or modified landing configuration, the inboard landing flaps are fully deployed and the outboard ones are stowed. The rest of the model is in its full landing configuration. A third configuration[17,18] that was tested (Table 2 and Fig. 2), consists of the landing configuration with a fairly large fin mounted on the upper surface of each side of the wing to accelerate the dispersion of the vortex wake.

The traverse mechanisms that support the following model and the hot-film anemometer probe are located 81 ft downstream of the trailing edge of the wake-generating model. The trailing model or wing is mounted on a strut (Fig. 1) which can be raised and lowered over a height of about 8 ft by a vertical traverse mechanism. This vertical traverse mechanism is attached to a tower that can be translated laterally, or spanwise, across the airstream over a range of about 20 ft. The follower model is attached to its strut through a strain-gauge balance located inside the centerbody of the wing so that the wake-induced lift and rolling moment can be measured. Both a 1- and a 2-in. internal-type balance were used in the tests to more adequately cover the wide range of loads encountered with the smallest up to the largest following wings. The following models are all made with a NACA 0012 airfoil section and have the planforms indicated in Table 3 and as shown in Fig. 3. The models are constructed of wood and aluminum, and then covered with fiberglass to ensure a smooth, durable finish along with structural rigidity and adequate frequency response. As a result, the natural frequencies in roll and pitch, f_r and f_p, respectively, of the model-balance combinations (Table 3) are several times larger than the lift and

Table 1 Wind-tunnel conditions

Freestream velocity = U_∞ = 131 ft/s
Dynamic pressure = q_∞ = 20 lb/ft^2
Reynolds no. based on $\bar{c}_g$ = Re_g = 660,000
Distance to follower model = x_f = 81 ft

Table 2 Data on wake-generating (B-747) model

Wingspan = b_g = 70.5 in.
Average chord of wing = $\bar{c}_g$ = 10.1 in.
Aspect ratio = AR_g = 6.96
Wing area = S_g = 4.94 ft^2
Horizontal stabilizer angle = 0 deg
Landing gear deployed
Flaps
30 deg/30 deg, no fins
30 deg/30 deg, 4 × 6 in. fins, α_{fin} = +18 deg
30 deg/0 deg, no fins

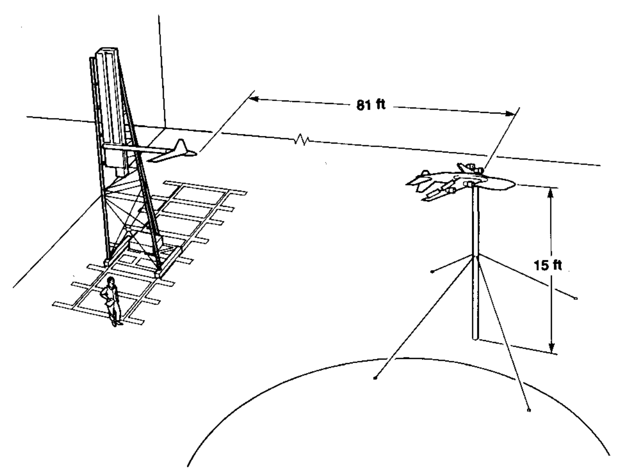

Fig. 1 Sketch of experimental setup in 80- by 120-ft wind tunnel.

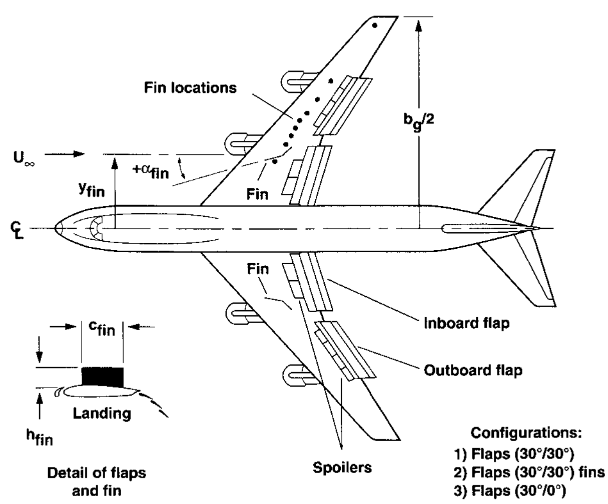

Fig. 2 Top view of wake-generating model (B-747), b_g = 70.5 in.

Table 3 Data on following models

No.	b_f, in.	c_{CL}, in.	c_{tip}, in.	Λ_{LE}, deg	Λ_{TE}, deg	AR_f	S_f, ft^2	b_f/b_g	f_r, Hz	f_p, Hz
1	13.12	2.41	2.41	0	0	5.44	0.220	0.186	156.0	13.0
2	13.13	2.84	0.85	30	15	7.14	0.168	0.186	156.0	13.0
3	6.00	6.00	6.00	0	0	1.00	0.250	0.085	190.0	12.0
4	35.97	7.86	2.41	30	15	7.00	1.283	0.510	30.5	11.5
5	72.04	15.67	4.72	30	15	7.06	5.100	1.022	12.0	7.3

Table 4 Locations of maximum rolling moments and lateral surveys

Run no.	Following wing	Port side		Starboard side	
		Y_{max}	Z_{max}	Y_{max}	Z_{max}
		Landing, flaps (30 deg/30 deg)			
13	1	−0.370	−0.471[a]	+0.427	−0.342[a]
28	3	——	−0.471[a]	——	——
19A	4	−0.342	−0.471[a]	+0.370	−0.342[a]
35	5	−0.367	−0.471[a]	+0.370	−0.352[a]
36	Hot-film	——	−0.471[a]	——	−0.342[a]
		Modified landing, flaps (30 deg/0 deg)			
15A	1	−0.475	−0.627[a]	+0.501	−0.426[a]
17	4	−0.475	−0.627[a]	+0.501	−0.426[a]
34	5	−0.430	−0.627	+0.398	−0.482
38	Hot-film	——	−0.627[a]	——	−0.426[a]
		Landing, flaps (30 deg/30 deg) with fins, α_{fin} = 18 deg, y_{fin}/b_g = 0.240			
23	1	−0.372	−0.512[a]	+0.431	−0.400[a]
25	3	——	−0.512[a]	——	——
26	4	−0.397	−0.512[a]	+0.457	−0.400
33	5	−0.313	−0.512[a]	+0.340	−0.454
37	Hot-film	——	−0.512[a]	——	−0.400[a]

[a]Spanwise survey taken.

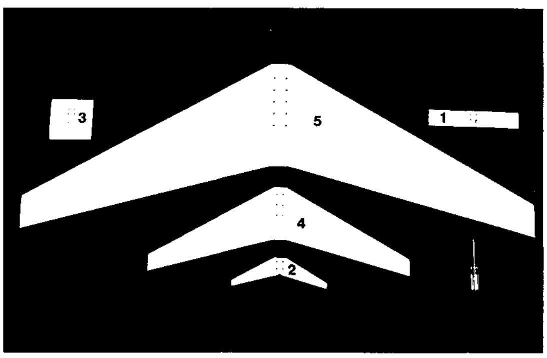

Fig. 3 Overhead photograph of following models used in test program.

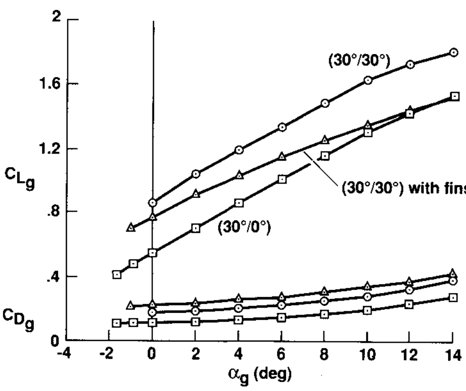

Fig. 4 Lift and drag on configurations of wake-generating model as a function of angle of attack.

rolling-moment frequencies encountered. As a reference, the natural frequency in roll of the model/balance combination tested during the 1970s was 30 Hz; i.e., when a wing equivalent to model no. 1 was used.

Because the physical distance between the wake-generating model and the following model is quite large (81 ft), a probe to measure the dynamic pressure (i.e., total and static pressure) was attached to the support strut or tower of each model. A correction could then be applied to the coefficients of the follower if the variations were too large. It was found that the dynamic pressure near the wake-generating model always agreed within measuring accuracy with the test section value, but that the dynamic pressure at the following model was about 1% larger. An analysis of the effect of a difference in dynamic pressure between the two stations showed that both the lift and rolling-moment coefficients should be adjusted by a factor that is the one-fourth power of the ratio of the two dynamic pressures. Since the correction for these test results is then 1.0025, an adjustment in the data was not made.

The procedure used to measure the rolling moment on the following wing consists of several steps. The generator model is first setup in its desired configuration and angle of attack. After the loads on the wake-generating model are recorded (Fig. 4) the following wing is placed at various locations in the vortex wake of the generator model. Since the airstream is not perfectly uniform, the position of the vortex wake moves about with time to cause different amounts of lift and rolling moment to be induced on the following wing. In order to obtain a measurement of the variation of these quantities with time and to find the maximum at each location, the time-varying rolling moment indicated by the strain-gauge instrumentation is recorded. The data is processed by first calculating the value of each parameter when time-averaged over 0.1 s. In order to obtain one full minute of data, 600 such samples are recorded end-to-end. The permanent record consists of the maximum and the minimum of all of the 0.1-s values that occurred during the 1-min test interval, and also the average or mean value of all 600 samples. A total sample

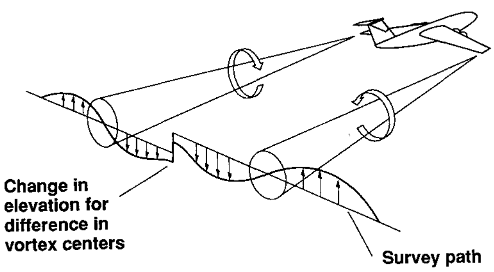

Fig. 5 Path used to carry out spanwise surveys with following models and with hot-film anemometer probe.

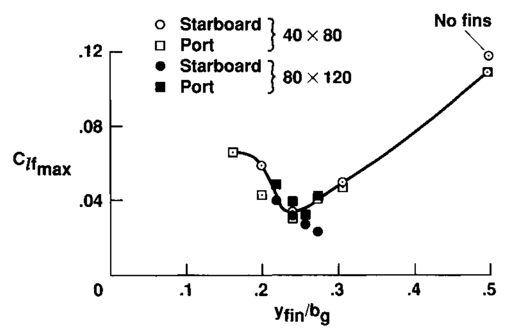

Fig. 6 Maximum rolling moment induced on following wing no. 1 by wake of (30 deg/30 deg) configuration with fins mounted on top of wing at various spanwise locations, h_{fin}/b_g = 0.057, c_{fin}/b_g = 0.085, α_{fin} = 18 deg.

of about 1 min in duration was found to be long enough that two to four peak values of about the same magnitude would occur. These data are taken at a number of spanwise and vertical positions of the follower until the entire active wake region has been surveyed[14,18] for the maximum or most intense value of the rolling moment on both sides of the wake centerline.

If the span of the following model is small relative to the span of the generator model, the largest rolling moment is assumed to occur when the centerline of the following model is aligned with the axis of one of the vortices in the wake. These values are then used as the elevations at which spanwise surveys are conducted with various following wings or with a hot-film anemometer probe. Since the vortex centers are located at different elevations on each side of the centerline (Fig. 5) the survey elevation on each side of the wake is changed at the centerline so that both surveys pass through the vortex center for their respective sides. Table 4 lists the locations of the maximum rolling moments for the various configurations that were tested.

Comparison of Data from 40- by 80-Ft and 80- by 120-Ft Wind Tunnels

Since the test described in this article was carried out in a wind tunnel not previously used for wake-vortex research, and since the wake-generating model (borrowed from NASA Langley Research Center) and the following models, centerbodies, strain-gauge balances, and support hardware were all new, it seemed prudent to first compare the new results with those obtained in the 40- by 80-ft Wind Tunnel. Therefore, the test was begun by measuring the rolling moment on several configurations of the B-747 that had been tested previously. When the data from the two facilities are compared, it was found that they agreed within the data scatter, or within about ±5%. Another comparison (Fig. 6) shows that the maximum rolling moments for the (30 deg/30 deg) configuration with fins from both facilities[18] are also in good agreement. The solid line is drawn through the data from the 40- by 80-ft Wind Tunnel.

Maximum Rolling Moments on Swept Followers

The most intense, or maximum, rolling moments found in the port and starboard portions of the vortex wakes for the three generator configurations tested are presented in graphical form in Fig. 7. The following wings used in the evaluation include the three swept wings, nos. 2, 4, and 5, which all have the same planform that is a generic average of many of the subsonic transports now in service. As mentioned in the Introduction, the maximum values are believed to be representative of the most hazardous rolling moments in the wake, even though vortex meander causes uncertainty in the spanwise location of the distributions. The data for both the port and starboard sides of the wake are presented as positive values in Fig. 7. A dashed line at C_{l_f} = 0.06 is used to indicate the approximate rolling-moment capability typical of subsonic transport aircraft. Any points above the C_{l_f} = 0.06 line indicate situations where a following aircraft would have insufficient roll-control capability onboard to resist that imposed by the wake of the wake-generator. In fact, an analysis[19] of results obtained with flight simulators suggests that an encounter with a wake near the ground is probably unsafe unless the imposed rolling moment is down to about half of the roll authority onboard the follower. Such a restraint leaves a reserve of control power available to compensate for the surprise of the encounter and to allow enough roll control to bring the following aircraft back to a level attitude.

As is well known, a second factor that affects the induced rolling moment is the span of the following wing (Fig. 7). When the wake-generator is in its conventional landing or (30 deg/30 deg) configuration, the rolling-moment coefficients are noted to decrease markedly as the span ratio b_f/b_g increases. As expected, a similar response does not occur when the wake is shed by a configuration designed to increase the rate of dispersion of vorticity. Since the swirl velocities have been reduced and the vortex core diameters increased, it is uncertain whether the rolling moments will increase or decrease with span ratio. It is gratifying, therefore, that in the alleviated-wake cases the wake-induced rolling-moment coefficients do not rise significantly with span ratio. The general trend of the plotted results tends to indicate that if an alleviated wake is safe for small following aircraft, it is also likely to be safe for larger aircraft. It remains to produce similar results with practical configurations.

Another observation to be noted in the data presented in Fig. 7 is the fact that when the following wing is the same size as the span of the wake-generator, the imposed roll is about the same as the typical roll control available. This characteristic of wake encounters has been noted in the past by test pilots flying in the wake-vortex program. When the encounter of the aircraft with a vortex is of short duration or intermittent, a follower of the same size as the generator (or larger) should not experience overpowering rolling moments. A sustained encounter could, however, be judged to be marginally safe or unacceptable during landing or takeoff.

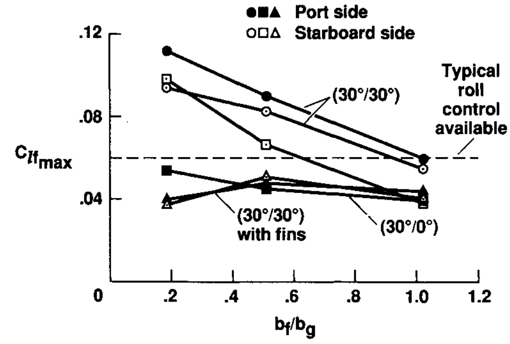

Fig. 7 Maximum rolling moments induced on following wings of swept planform (i.e., models nos. 2, 4, and 5).

Spanwise Distributions

The purpose of the spanwise surveys to be described is to provide experimental data on the interaction of various following wings with vortex wakes as a function of their spanwise location. It is planned that the data will be used for simulation of the encounters of aircraft with wake vortices, for the development of techniques that model the structure of vortex wakes, and for the development of methods that construct the velocity field of the entire vortex wake[20] from a spanwise distribution of lift, rolling moment, or downwash. In the surveys taken, each side of the vortex wake was treated separately (Fig. 5), because the vortex center (i.e., the location of the largest rolling moment) is usually at a different elevation on each side of the centerline, i.e., by amounts from zero to $0.06b_g$ (Table 4). As described previously, the survey is carried out by sequentially placing the wing at a number of spanwise locations from the centerline of the generator out to well beyond its wingtip (usually out to about $1.5b_g$), to establish the upwash in the outer parts of the vortex. Once again, the data taken were the maximum, the minimum, and the mean or time-average of the lift and rolling moment imposed by the vortex wake on the following wing at each spanwise location.

After the locations of the vortex centers were found with following wing no. 1, as discussed previously, spanwise surveys were made with it (Fig. 8), with several of the other following wings and with a hot-film anemometer probe. The data points are shown in Fig. 8 to illustrate their distribution and scatter. In Figs. 9–15, however, a line between the measured points is shown to reduce the clutter in the figures. All of the data was taken with the wake-generator model at 4-deg angle of attack. In the hot-film surveys (Fig. 15), only the streamwise and vertical velocity components were measured. The two velocity components were then combined to yield the distribution of up- and downwash angle w/u across the wake. A single spanwise survey was made with model no. 3, the following wing with a 6- by 6-in. planform, in order to explore the possibility that a wing of small span would produce more accuracy and a better representation of the vortex wake being surveyed than following wings of larger span. Only one survey was made because the loads were too small to achieve acceptable accuracy with the strain-gauge balances chosen for

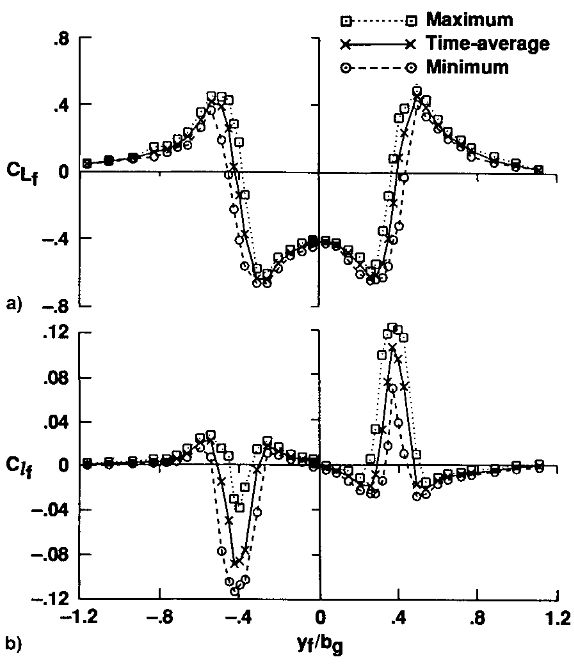

Fig. 8 Typical measured loads on following wing no. 1 as it makes a lateral traverse through wake of (30 deg/30 deg) configuration: a) lift and b) rolling moment.

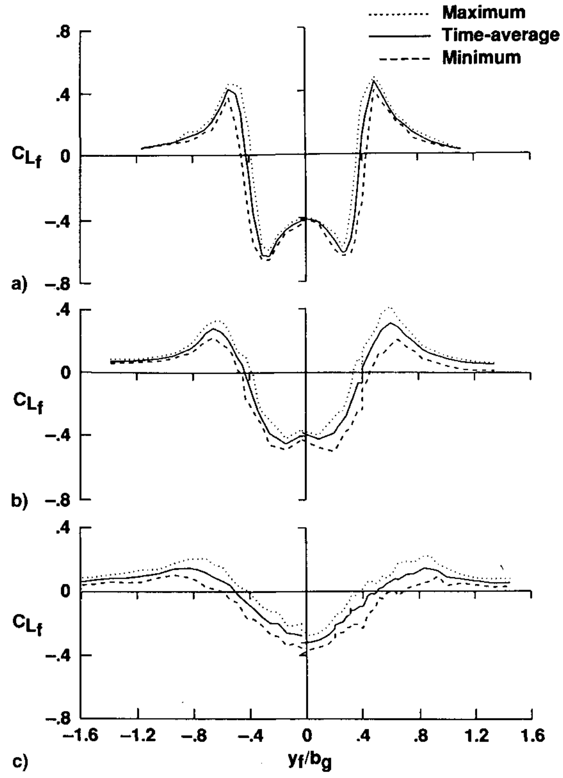

Fig. 9 Measured lift induced on various following wings as they traverse laterally through the wake of the (30 deg/30 deg) configuration. Following model nos. a) 1, b) 4, and c) 5.

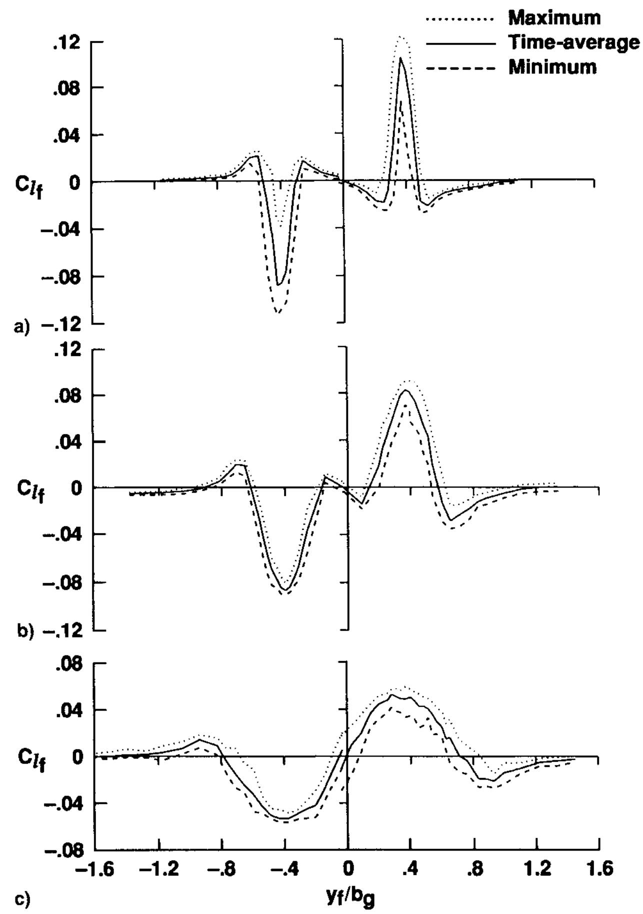

Fig. 10 Measured rolling moment induced on various following wings as they traverse laterally through the wake of the (30 deg/30 deg) configuration. Following model nos. a) 1, b) 4, and c) 5.

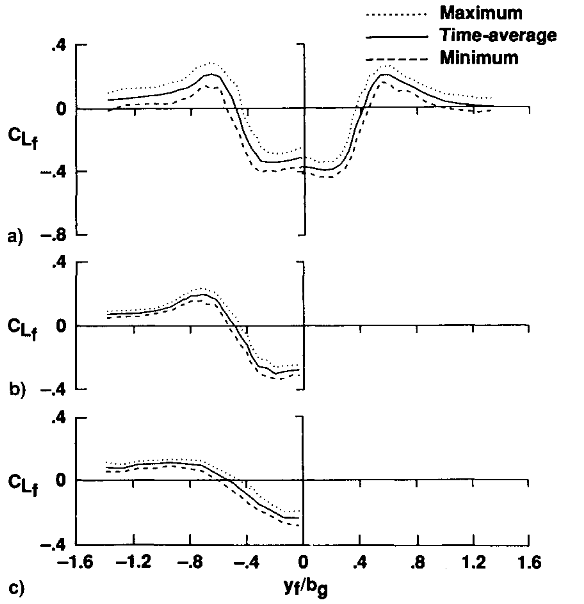

Fig. 11 Measured lift induced on various following wings as they traverse laterally through the wake of the (30 deg/30 deg) configuration with fins. Following model nos. a) 1, b) 4, and c) 5.

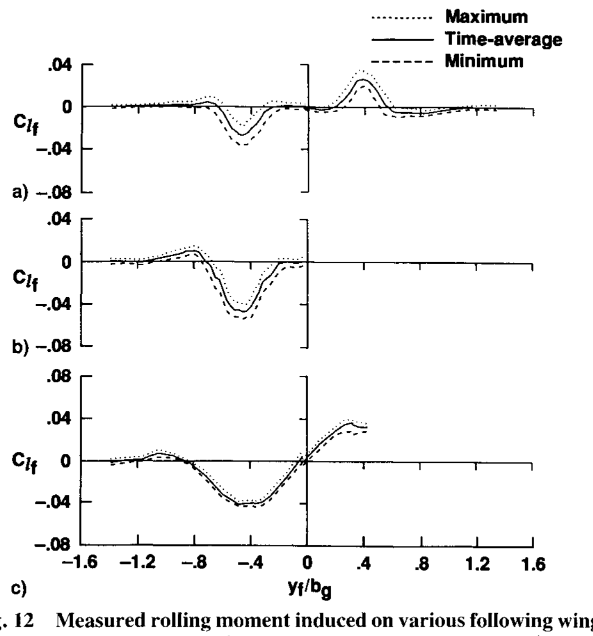

Fig. 12 Measured rolling moment induced on various following wings as they traverse laterally through the wake of the (30 deg/30 deg) configuration with fins. Following model nos. a) 1, b) 4, and c) 5.

the test. An obvious extension of the smaller-is-better argument is to go to an upwash sensor of the smallest size possible; namely, a hot-wire or hot-film probe. As a result, lateral surveys of upwash were made with a hot-film anemometer on the three test configurations of the wake-generating model (Fig. 15).

All of the measured distributions presented in Figs. 8–15 exhibit a spread vertically (due to vortex meander) between the maximum and the minimum data that is about equidistant from the mean or time-averaged curve. The spanwise shift between the maximum and minimum lift curves near the location of the vortex centers (which is the most vertical part of the curves), is an indicator of the amount of lateral travel by the vortex center due to meander. When the data are taken far from the centerline (which is far from the vortex centers), the mean or time-averaged curves differ only slightly from the maximum and minimum curves because the displacement of the vortex due to meander does not have much of an affect on the vortex-induced loads. At those points, the vertical spread is probably due more to turbulence in the airstream than to vortex meander.

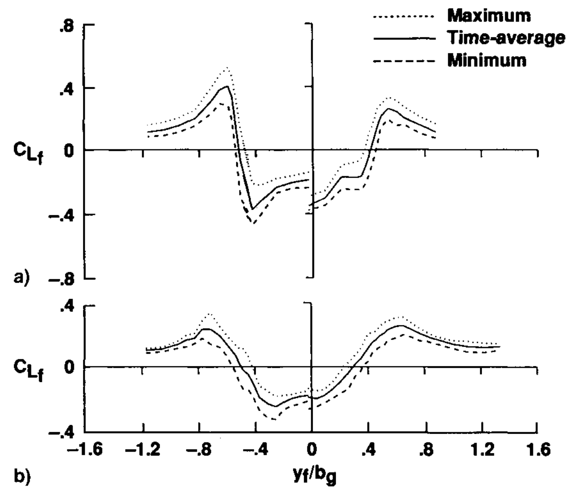

Fig. 13 Measured lift induced on various following wings as they traverse laterally through the wake of the modified landing (30 deg/0 deg) configuration. Following model nos. a) 1 and b) 4.

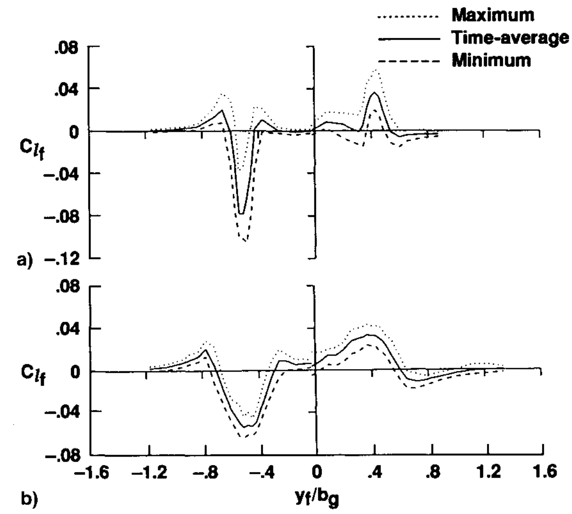

Fig. 14 Measured rolling moment induced on various following wings as they traverse laterally through the wake of the modified landing (30 deg/0 deg) configuration. Following model nos. a) 1 and b) 4.

Before the data points were plotted in Figs. 8–15, a correction was applied to their spanwise location to correct for a lateral offset in the centerline of the wake relative to the centerline of the wake-generating model. A vertical shift was then applied to the measured upwash angle and to the lift to compensate for such items as flow angularity in the wind tunnel, any nonzero angle of attack of the following wing (or hot-film gauge) relative to horizontal, and possible deflections of the support sting and traverse tower and rail assembly due to air loads. Although these displacements are each small, the combination appears to be enough to cause a significant offset in the measured curves. These adjustments to the upwash and lift data were obtained by specifying symmetry in the circumferential velocity near the centers of the vortices after the influence of the opposite vortex is removed. A similar offset in the rolling-moment distributions (probably due to a slight twist in the following wings) was obtained by specifying that the rolling moments far from the centerline are equally antisymmetric port and starboard.

The lift, rolling moment, and downwash curves in Figs. 8–15 reflect how the larger following wings sense the induced loads over larger distances than the smaller wings. As a con-

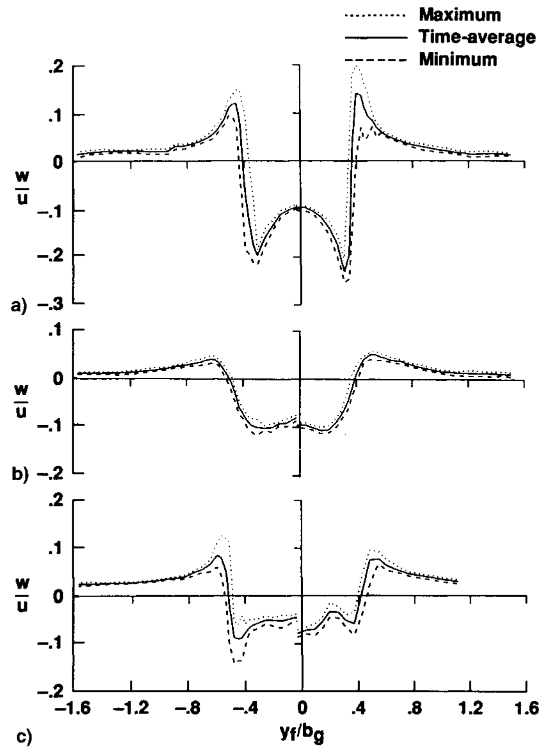

Fig. 15 Up- and downwash distributions measured with hot-film probe along a lateral traverse through vortex centers of wake: a) 30 deg/30 deg, b) 30 deg/30 deg fins, and c) 30 deg/0 deg.

sequence, the onset of the induced forces and moments are more gradual and less intense for the larger wings. The downwash curves for the three configurations tested indicate that the vortex core diameters are increased slightly when the model is modified for alleviation, but most of the reduction in rolling moment appears to have been accomplished by a reduction in the magnitude of the up- and downwash velocities.

Concluding Remarks

The test program described here first confirmed that data obtained in the 80- by 120-ft Wind Tunnel is in agreement with that obtained in the 40- by 80-ft Wind Tunnel. Data not obtained previously with following models of different sizes and shapes were then obtained to provide a basis for evaluating the rolling-moment hazards associated with wake-vortex encounters. It is interesting to note that the data indicates that a following aircraft of the same span as the wake-generator has approximately enough roll control to compensate for wake-induced rolling moments. The data on the maximum rolling moment also showed that, when the wake being studied is of an alleviated variety, the magnitude of the rolling-moment coefficients measured with small following wings does not change appreciably with span ratio as the size of the follower increases. Hence, if a given wake is measured as safe for small followers, it will probably also be safe for larger followers.

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