# Effect of Wing Fins on Lift-Generated Wakes

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**A theoretical and experimental study has been made of the effect of wing-mounted fins on the vortex wakes of subsonic aircraft. The lateral lift on the fins injects vortices into the wake and redistributes the lift on the wing. The revised wake vorticity then interacts convectively to form a new configuration with low rotational velocities. The theory is used 1) to gain an understanding of wake alleviation by vortex injection and 2) to guide the experimental investigation. Wind-tunnel tests were used to evaluate the alleviation achievable and to find the optimum values for the various fin parameters. It was found that vertical fins mounted on the upper surface of a wing could lower the wake-induced rolling moments on an encountering wing by a factor of 3 or more. The most promising fin configuration found for the Boeing 747 model is a fin positioned 48% outboard from the centerline to the wingtip with a height equal to 0.014 wingspan, a chord equal to 0.085 wingspan, and an 18-deg angle of attack. This fin configuration caused a 10% increase in drag but no lift penalty.**

## Nomenclature

$AR$ = aspect ratio
$b$ = wingspan
$b_g$ = wingspan of wake-generating model = 1.79 m (70.5 in.)
$C_L$ = lift coefficient, lift/$(\frac{1}{2}\rho U_\infty^2 S)$
$C_\ell$ = local lift coefficient
$C_l$ = rolling-moment coefficient, $\dfrac{\text{rolling moment}}{\frac{1}{2}\rho U_\infty^2 Sb}$
$C_{l_{f0}}$ = rolling-moment coefficient on following model when generating model has no fins
$C_v$ = vortex interaction parameter, see Eqs. (4) and (5)
$c$ = wing chord
$\bar{c}$ = mean geometric chord
$c_{\text{fin}}$ = chord of fin
$h_{\text{fin}}$ = height of fin, $b_{\text{fin}}/2$
$J$ = second moment of circulation, see Eq. (1)
$\ell(y)$ = local spanwise lift
$N$ = number of vortices
$q$ = dynamic pressure, $\frac{1}{2}\rho U_\infty^2$
$r$ = radius from centroid of circulation
$S$ = wing area
$T$ = dimensionless time, $4t\Gamma_v/b^2$
$t$ = time
$U_\infty$ = freestream velocity aligned with $x$ axis
$u,v,w$ = velocity components in $x$, $y$, and $z$ directions
$v_\theta$ = circumferential velocity
$x,y,z$ = streamwise, spanwise, and vertical coordinates, respectively
$Y$ = $y/(b_g/2)$
$\alpha$ = angle of attack
$\Gamma$ = circulation
$\gamma$ = circulation in point vortices
$\rho$ = air density

*Subscripts*

$a$ = auxiliary vortex or injected vortex
est = estimated
exp = experimentally determined
$f$ = following model that encounters wake
fin = characteristic of fin mounted on wing
$g$ = model that generates wake
$R$ = wing with rectangular planform
sh = vortex sheet
splrs = spoilers
$v$ = vortex or vortical region

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## Introduction

PREVIOUS theoretical and experimental studies[1-3] have shown that certain vortex wakes of aircraft are stable and persistent, whereas others are initially unstable so that they change into different configurations that are stable. These transitions occur convectively without the benefit of turbulent mixing or viscosity. The objective of the Ames wake-vortex minimization program is to find those initially unstable wakes that provide a given lift on the generating wing while making a transition or change into a nonhazardous final vortex wake.

The results in Refs. 4 and 5 indicate that, if the transition is to substantially reduce the wake velocities and the attendant hazard, the vortex interactions should either: 1) bring about a merger of vortices of opposite sign so that the wake is neutralized, or 2) disperse the lift-generated circulation. Both of these mechanisms require that the wake shed by the generating wing first roll up into several pairs of vortices that alternate in sign across the span.

The difficulty associated with this approach is the requirement that spanwise variations in lift be large enough that the opposite vortices are of comparable magnitude. If such a vortex wake is to be produced with a planar wing using flaps and spoilers, the deflections required cause large performance penalties. Possibly one way to reduce the lift penalty is to use vertical surfaces or fins at large angles of attack mounted on the wing to produce the auxiliary or negative vortices required for wake alleviation. Since the fins lift sideways, they do not (to a first approximation) change the total lift on the wing. However, the lift on the wing and the circulation in the wake are redistributed by the addition of the fins. This redistribution and the effect that it has on the rolling moment imposed on encountering wings is the subject of this paper. Both theoretical and experimental methods are used to explore how and to what extent wakes can be modified by adding one or more pairs of fins to the wing of a subsonic widebody transport. The theoretical study is used primarily to explore and screen concepts, whereas tests in the Ames 40- × 80-ft wind tunnel are used to quantitatively evaluate the effectiveness of various configurations so that an optimum configuration can be found.

Specifically, the goal of the investigation is to find lifting systems that leave behind a wake with overturning velocities low enough so that smaller aircraft experience maximum induced roll angles of less than about 10 deg. Estimates based on simulator studies[6,7] and on flight encounters with wakes indicate that, if the wake is to be tolerable at 2 miles behind the generator, the rolling moment it imposes on a smaller follower at that distance must be below the roll-control capability of the following aircraft by a factor of 2 or 3. Such a low level has not been achieved[3] with any of the modifications previously tried on models of large subsonic transports. The present investigation was therefore undertaken to find out whether acceptably alleviated wakes, (i.e., $C_{l_f} \lesssim 0.03$) could be achieved by adding fins to the wing of the wake-generating aircraft.

## Analysis of Wake Alleviation by Vortex Injection

The theoretical study that follows was made to find those locations in lift-generated wakes that will disperse the shed vorticity most effectively. These results provide guidance for placement of the devices used to inject vortices into the wake. Although wing-mounted fins were used in the experiment, the first part of the theoretical analysis is independent of the method used to generate the extra or auxiliary vortices. The results are then applicable whether the auxiliary vortices are produced by 1) fins (or fences), 2) strakes, 3) engine-thrust deflected spanwise, or 4) introducing swirl into the engine exhaust.

### Interaction Guidelines from Vortex Invariants

The invariants for two-dimensional vortex systems are examined here to find directions as to the strength, location, number, etc., for the auxiliary vortices above and/or below the wing for wake alleviation. No information on wake velocities is expected from the first moment of vorticity, because it locates the centroid of vorticity in the wake. However, the second moment of vorticity for one side of the wake is an indicator of the radius or area over which the vorticity is spread. This radius or area determines the magnitude of the overturning velocities in the wake. It also has the property of remaining nearly constant throughout the rollup portion of the wake history. It is examined, therefore, to find guidelines for the optimum placement and strength of the auxiliary vortices to maximize the area over which the circulation is spread when extra vortices are added above or below the wing.

The second moment for the vorticity shed by one side of the wing is given by

$$J=\sum_{i=1}^{N}\gamma_i r_i{}^2=\Gamma\bar{r}^2 \tag{1}$$

where $r_i$ is the radius from the centroid of circulation to each point vortex used to represent that half of the lift-generated wake. The symbol $\Gamma$ represents the circulation for one side of the wake and $\bar{r}$ is the characteristic or square-root average radius over which the circulation is spread. The objective is to find rules that will maximize $\bar{r}$ with a minimum value of circulation in the auxiliary vortex. This consideration assumes that a large value of $\bar{r}$ indicates that the circulation in the wake is spread out or diffused, which makes it relatively less hazardous than one with a small value of $\bar{r}$. It is necessary, then, to find those features of the auxiliary vortices that make $\bar{r}$ as large as possible with a minimum addition of circulation.

If the lift-generated vortex sheet lies initially on the $y$ axis, the second moment is given by

$$J=\int_0^{b/2}\gamma(y)\left[(y-\bar{y})^2+\bar{z}^2\right]\mathrm{d}y+\Gamma_a\left[(y_a-\bar{y})^2+(z_a-\bar{z})^2\right] \tag{2}$$

where the location of the centroid is given by

$$\bar{y}=\frac{\Gamma_{sh}\bar{y}_{sh}+\Gamma_a y_a}{\Gamma_{sh}+\Gamma_a}\qquad \bar{z}=\frac{\Gamma_a z_a}{\Gamma_{sh}+\Gamma_a} \tag{3}$$

These relationships suggest that the auxiliary vortices should be placed as far from the sheet centroid as possible. Such a criterion ignores the fact that a vortex far from the sheet will exert negligible influence on the motion or final structure and would, therefore, be ineffective in diffusing a wake. That approach will then not be fruitful. If, however, the circulation in the auxiliary vortex is opposite that of the sheet, another maximum in $\bar{r}$ occurs when $\Gamma_a=-\Gamma_{sh}$. Then, the second moment becomes infinite because the centroid is at infinity, no matter where $\Gamma_a$ is located.

A second approach is to consider the parameter

$$C_v=\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\gamma_i\gamma_j r_{ij}^2 \tag{4}$$

which was derived by the author during the present study as a combination of the first and second moments of vorticity as

$$C_v=\left(\sum_{i=1}^{N}\gamma_i\right)\left(\sum_{j=1}^{N}\gamma_j r_j^2\right)-\left(\sum_{i=1}^{N}\gamma_i y_i\right)^2-\left(\sum_{i=1}^{N}\gamma_i z_i\right)^2 \tag{5}$$

The parameter $C_v$ given by Eq. (4) is an invariant of inviscid vortex wakes, which is independent of the location of the centroid of vorticity because $r_{ij}^2=(y_i-y_j)^2+(z_i-z_j)^2$. The double summation is made in order to include the interaction of all the vortices with each other. Since the distances $r_{ij}$ between vortices determine how strongly they interact, the parameter $C_v$ is a measure of the interaction within the system. A small increase in $C_v$ when an auxiliary vortex is added indicates that the vortices interact strongly, and a large value signifies a weak interaction. A minimum contribution to $C_v$ by the addition of an auxiliary vortex to the system occurs then at the spanwise station where the vortex interacts most strongly with the vortex sheet. It is found that such an optimum position is at the centroid of the sheet vorticity.

### Numerical Examples

Since the guidelines developed in the last section provide only gross directions for the desirable characteristics of the auxiliary vortices, several different situations were analyzed to better define the dynamics of the interaction between the vortex and the sheet. A series of cases was therefore calculated to determine how the sign and strength of the extra or auxiliary vortices and the position spanwise and the distance above and/or below would affect the dynamics of several different vortex sheets. The numerical analysis was made using the two-dimensional time-dependent method,[5,8] which approximates the dynamics of lift-generated wakes with the motion of point vortices. As a result, the wake-alleviation schemes are assumed to depend mostly on self-induced convective velocities, wherein viscosity and turbulence play a secondary role.

After a series of numerical examples were calculated, it was found that, as expected, the spanwise location of an auxiliary vortex that provides the most interaction with the vortex sheet is near the centroid of the vortex sheet. Because the sheet induces a lateral or spanwise motion on the vortex, the interaction is improved if the vortex is located slightly inboard of the centroid when it is under the sheet and slightly outboard of the centroid when above the sheet. The motion induced by the sheet on the vortex then carries it nearer to and past the centroid, providing a greater interaction with the sheet.

An analytical guideline for the most effective distance for the auxiliary vortex above or below the sheet was not found. Numerical examples showed that the effectiveness of a vortex did not vary greatly from when it was quite near the sheet to when it was as far away as 30% of the semispan. A difference noted is that a vortex near the sheet has a more localized influence in the early stages of the interaction than a vortex farther away. The $\bar{r}$ guideline derived from the second moment of circulation appears therefore to be valid only when the vortex is very near the sheet. As the distance increases, the dispersion of the sheet does not increase as fast as a direct $\bar{r}$ relationship would appear to indicate. In the limit wherein the vortex is far from the sheet, the $\bar{r}$ guideline is misleading because negligible interaction occurs. These numerical examples indicate that there is not a strong dependence on vortex height, but that the best distance for the vortex from the sheet depends on the initial spanwise structure of the sheet and on the final wake structure desired.

A similar result was obtained for the ratio of the strength of the auxiliary vortex to that of the sheet; that is, stronger vortices have a larger influence on the sheet, but they also pose a greater hazard in themselves and impose a larger penalty in drag (and possibly in lift) than weaker vortices. The best strength, location, number, etc., for auxiliary vortices must then be chosen in a trial and error process to provide the desired wake dynamics from a given initial lift-generated wake.

Figure 1 illustrates the changes in wake dynamics that occur when various auxiliary vortices are added to a wake. For simplicity, the vortex sheet to be modified is assumed to be of constant strength, as if it were shed by a wing with triangular span loading. The motion of the vortices was calculated by using the numerical technique from Refs. 5 and 8. The process for generating the vortices (whether by fins, fences, strakes, engines, etc.) is set aside for the present, and any effect that the vortex-generating process might have on the span loading is ignored. Also, in the cases presented in Fig. 1, the strengths of the auxiliary vortices were taken to be 20% of the strength of the vortex sheet so that the wake dynamics for the various vortex configurations could be readily compared. The spanwise position chosen for the auxiliary vortices was near the centroid, a little over halfway to the wingtip. The interactions in Fig. 1 are presented as sequential positions of the vortex elements for the same time increments after the beginning of the event so that the promptness or delay of any merger or dispersion can be detected. In these examples, the vortex was placed quite near the sheet ($\pm 0.025\ b$) to ensure a strong interaction and to enable the vortices to be produced by short fins on the wing for testing purposes.

The numerical examples in Fig. 1 show that some of the details of the wake dynamics depend on whether the vortex is above and/or below the vortex sheet. A greater difference occurs in the subsequent vorticity distributions when the sign of the vortex changes from positive to negative (Figs. 1 b and 1 c). A negative vortex first tears the sheet and then appears to disperse the sheet more than a positive vortex. A negative auxiliary vortex also has the advantage that it reduces rather than increases the net circulation on each side of the centerline. Negative auxiliary vortices appear to produce wake motions comparable to sawtooth loadings.[8]

#### Fin Size and Angle of Attack Required for Alleviation

The foregoing numerical study of the effect of vortex injection on wake dynamics indicated that the strength of the auxiliary vortex should be about 20% or more of the wing circulation. At first, this would seem to require large fins, until estimates are made of the circulation shed by small-aspect-ratio fins at large angles of attack.

In the early part of the study, the vortex estimates were based on equations for the linear part of the lift curve (e.g., see pages 95 and 101 of Ref. 9). Since the fins used in the present wake-vortex tests had rectangular planforms with sharp side edges, a better estimate for the lift on the fins is

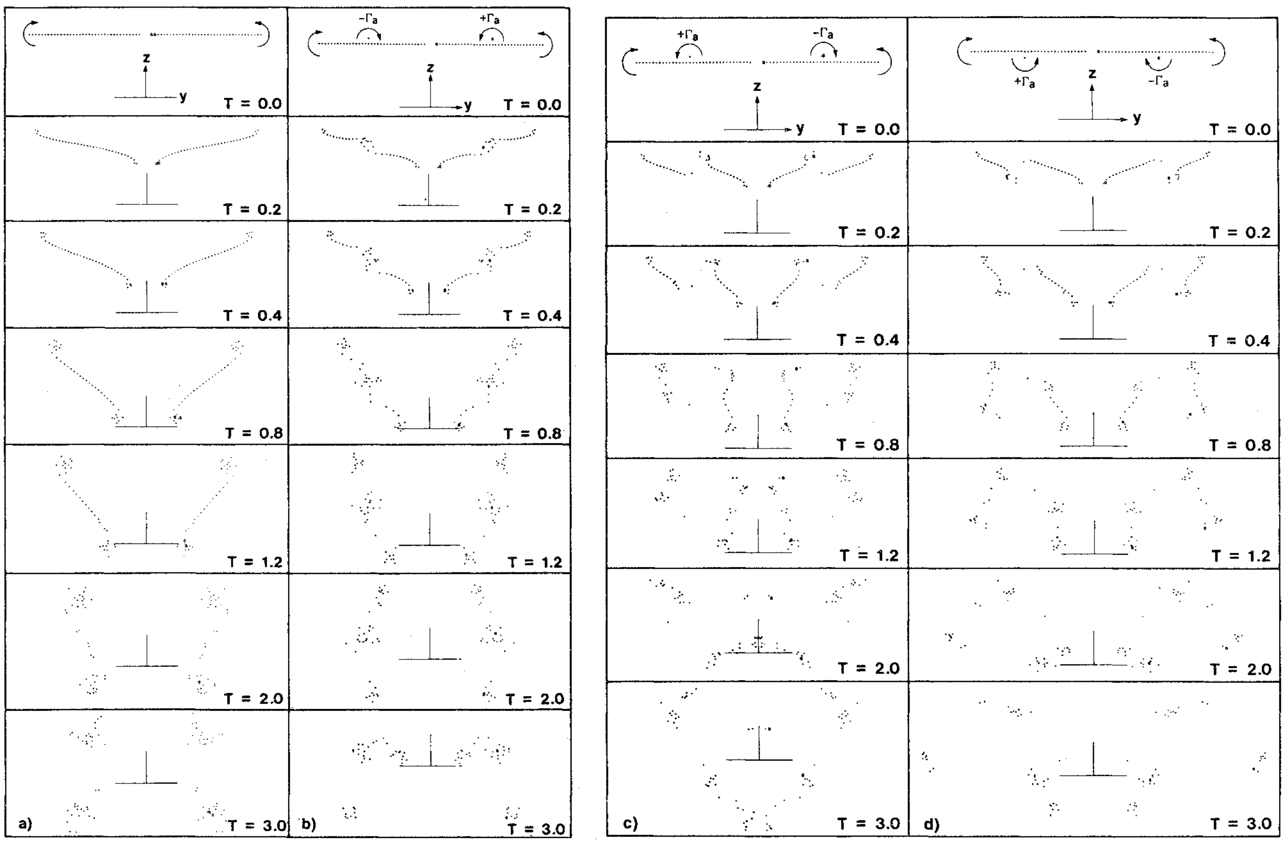


**Fig. 1 Effect of vortex injection on lift-generated wake shed by wing with triangular span loading: vortex strength = $\pm 0.2 \times$ sheet strength = $\pm 0.7\ bU_\infty$; vortex distance above or below sheet = $\pm 0.025\ b$. a) Wake without vortex injection. b) Positive vortex over sheet. c) Negative vortex over sheet. d) Negative vortex under sheet.**

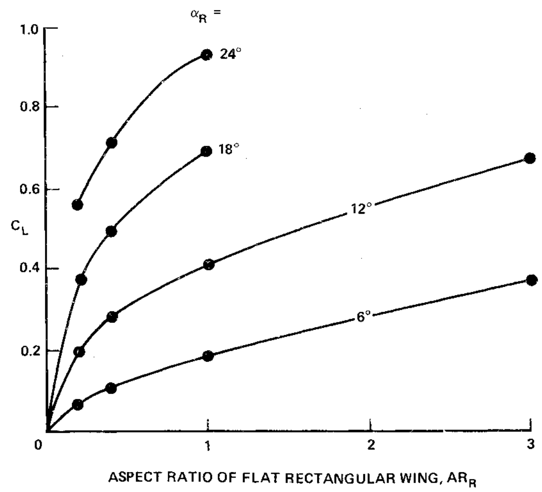


**Fig. 2 Lift on flat rectangular sharp-edged wings (from Ref. 10).**

obtained from experimental data[10] which have been cross-plotted in Fig. 2 at the angles of attack used in the tests. A rectangular planform was used because that shape would shed the strongest vortex for a given fin height, $h_{\text{fin}}$. Since the chord or streamwise extent of the fins was less than the local chord of the wing, the wing is assumed to be a reflection plane so that the aspect ratio of the fins is given by

$$\mathcal{R}_{\text{fin}} = 2h_{\text{fin}}/c_{\text{fin}}$$

The circulation shed by a fin is then related to the lift coefficient by

$$\text{lift} = C_{L_{\text{fin}}}(\rho U_\infty^2/2)S_{\text{fin}} = \rho U_\infty \Gamma_{\text{fin}} 2h_{\text{fin}}$$

or

$$\frac{\Gamma_{\text{fin}}}{b_g U_\infty} = \left(\frac{c_{\text{fin}}}{b_g}\right)\frac{C_{L_{\text{fin}}}}{2}$$

for the rectangular planforms used here.

An estimate can now be made of the fin size that will yield a wake dispersion comparable to those shown in Fig. 1. The circulation shed by one side of the wing of the B747 model at $C_{L_g} = 1.2$ was measured to be[11]

$$\Gamma_g/b_g U_\infty \simeq 0.10$$

The circulation required of the fin is then

$$\frac{\Gamma_{\text{fin}}}{b_g U_\infty} = 0.20 \times \frac{\Gamma_g}{b_g U_\infty} = 0.02$$

For example, if $\mathcal{R}_{\text{fin}} = 1$ and $\alpha_{\text{fin}} = +18$ deg, the lift coefficient on the fin is $C_{L_{\text{fin}}} = 0.69$ (from Fig. 2). The fin size required is then determined as

$$\frac{c_{\text{fin}}}{b_g} = 2 \times \frac{0.02}{0.69} = 0.058$$

or, since $b_g = 1.79$ m (70.5 in.), $c_{\text{fin}} = 10.5$ cm (4.1 in.) and $h_{\text{fin}} = 5.25$ cm (2 in.) for the wake-generating model of the B747 used in the experiments.

Fin sizes both larger and smaller were tried theoretically and experimentally to determine how their size affected wake alleviation. Since strong fin vortices are desired, large angles of attack just below stall appear to be the most promising.

## Wind-Tunnel Tests

### Apparatus and Test Procedure

Since neither the complex geometry of the B747 model nor the effects of viscosity and turbulence were accounted for in the theory, experiments in the Ames 40- × 80-ft wind tunnel were used to quantitatively evaluate the wake alleviation achievable with vortex injection by means of wing fins. The present test setup differs from that used in Ref. 12 only in that a smaller and more streamlined strut was used to support the wake-generating model. The test was again conducted at a constant freestream velocity of 40 m/s ($q = 20$ lb/ft$^2$). The following model consisted of a rectangular wing [$b_f = 33.3$ cm (13.1 in.), $\mathcal{R}_f = 5.5$, $b_f/b_g \approx 0.19$] to represent the Gates Learjet or the T37 aircraft at a scale distance one-half mile ($x_f/b_g = 13.6$) downstream of a B747. The B747 model (Fig. 3) was configured with trailing-edge flaps set at their full landing position (30 deg/30 deg), with leading-edge slats and landing gear down for all tests except when the fins were mounted on the bottom of the wing. The B747 was tested at angles of attack of $\alpha_g = 0$, 4, 8, and 12 deg. During the last part of the tests, data were taken at $\alpha_g = 4$ deg, only to expedite a larger number of fin configurations during the available wind-tunnel time. The same data acquisition procedures were used as in Ref. 12.

The aft one-third of the rectangular fins (Fig. 3) was bent at about 18 deg to produce a slight camber in order to improve the side-force capability. The forward two-thirds of the chord was used as the reference surface on which the fin angle of attack, $\alpha_{\text{fin}}$, was set relative to the freestream direction. Several preliminary runs were made with $\alpha_{\text{fin}} = 5$, 10, and 15 deg, but the data in the two recent tunnel entries were taken at $\alpha_{\text{fin}} = 6$, 12, 18, and 24 deg (0.1, 0.2, 0.3, and 0.4 rad). Since the larger angles of attack are the most effective, most of the tests were made at $\alpha_{\text{fin}} = 18$ deg.

The curved surfaces of the fuselage and wing made it difficult to accurately position the fins with less than about 1 or 2 deg of error. The fins were changed from side to side for negative values of $\alpha_{\text{fin}}$ so that the camber was always positive. The dimensions of the fin were varied to allow the following combinations of chord: $c_{\text{fin}} = 7.6$, 15.2, and 22.8 cm (3, 6, and 9 in.); height, $h_{\text{fin}} = 2.5$, 5.1, 7.6, 10.2, 15.2, 22.8, and 30.5 cm (1, 2, 3, 4, 6, 9, and 12 in.). One set of fins (0.5 in. high by 6 in. chord) was also tested to determine the effect for low fin heights. The aerodynamic load on the fins required that they

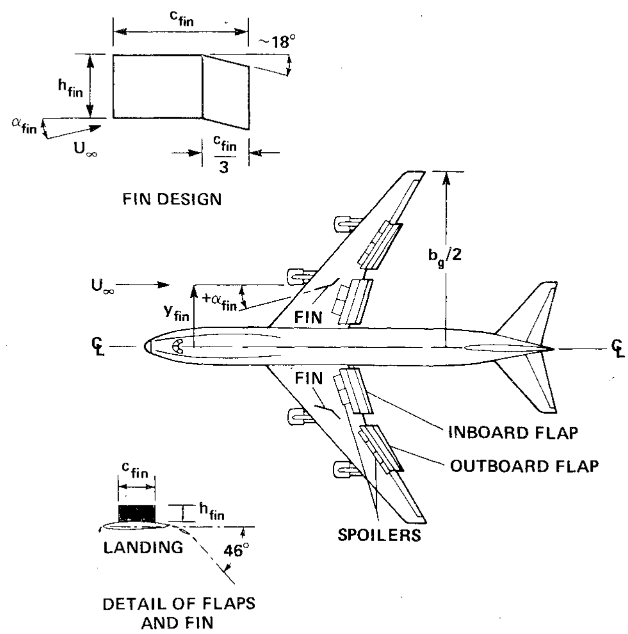


**Fig. 3 Subsonic transport model used in wind-tunnel tests to simulate a Boeing 747.**

be bolted to the wing. These holes were then used as pivot points for changing fin angle of attack. When the fins were rotated to vary the angle of attack, the one-third chord position remained at a fixed spanwise station, and that point was used as the spanwise reference value (see Fig. 3) for presentation of the data.

**Rolling-Moment Results**

The large number of test parameters (i.e., $\alpha_{\text{fin}}$, $\alpha_g$, $c_{\text{fin}}$, $h_{\text{fin}}$, and $y_{\text{fin}}$) required that the various possibilities be scanned rapidly to ensure ample test time for finding those configurations that are optimum. One shortcut considered was to measure the rolling moment in the wake on only one side – that is, either the port or starboard side, but not both sides. Unfortunately, it was observed both in previous tests[12,13] and in these tests that the B747 model used in the wake-vortex program was slightly asymmetrical; consequently, the starboard side usually yielded a slightly higher rolling moment than the port side. This asymmetry in the wake is not observed in the lift because the measured steady-state or average rolling moment on the generator model was approximately zero. To take into account the asymmetry, both sides of the wake were measured. Generally, only values for the maximum rolling moment are presented as final data. Moreover, any difference between the two sides would not change the conclusion drawn as to optimum values of the parameters.

First, the rolling-moment data, $C_{l_f}$, were usually plotted for each configuration as a function of lift on the generator model, $C_{L_g}$ (e.g., Fig. 4). To arrive at the values of the various parameters that yield optimum alleviation, these data were then cross-plotted.

Figure 4 includes 1) the landing configuration (30 deg/30 deg) without[12] and with[13,14] the two outboard solid spoilers deployed and 2) the modified landing configuration (30 deg/0 deg).[12] Also shown in Fig. 4 are the results for the landing configuration with two fins of about the same size and at the same location as the two outboard spoilers in the spoiler configuration. These results are presented because the investigation of wing fins was originally stimulated by results of a numerical simulation of vortex wakes (as an extension of Refs. 5 and 8) which suggested that the diffusion of wake vortices by spoilers might also be accomplished with fins in the same location. A preliminary test of this possibility was, therefore, made with one fin on each wing; each fin has an area equivalent to the two outboard spoilers (Fig. 3). They were tested at the spoiler location on each wing, with fin angles of attack, $\alpha_{\text{fin}}$, from $-15$ to $+15$ deg. (The angle of attack is always taken as positive when the fin and wingtip vortices have the same sign.) Negative and small positive values of $\alpha_{\text{fin}}$ yield less alleviation than the larger positive angles. From Fig. 4, it can be seen that the fin configuration tested was as effective as when the two outboard spoilers on each wing were deployed. Also shown in Fig. 4, and to be discussed later in this paper, are data for the best fin configurations of the current tests.

*Fin Angle of Attack*

Although it was anticipated that the fins would not stall until $\alpha_{\text{fin}}$ exceeded 12-18 deg, it was not certain at what angle the optimum alleviation would occur (Fig. 5). As the angle of attack of the fins was varied from $-18$ to $+18$ deg, the alleviation consistently indicated that $+18$ deg was about the best fin angle for the shorter fins. The $\alpha_{\text{fin}} = 0$ deg case shown in Fig. 5 is about the same as the no-fin case. Negative fin angles of attack usually produced little alleviation. This apparent contradiction of the theoretical results is probably due to inadequacies in the numerical modeling of the wake. For these reasons, most of the latter tests were conducted at $\alpha_{\text{fin}} = +18$ deg. Only occasionally was a test made at $+12$ and $+24$ deg to determine whether the alleviation achieved with a given fin configuration was affected by stall on the fins.

*Spanwise Position of Fin*

Two fin sizes were tested (Fig. 6) at several spanwise stations to determine the effectiveness of fins as a function of spanwise position. Other fin sizes were not tested as extensively, but they all exhibited a similar trend. The exact minimum in rolling moment is affected slightly by lift on the generator and by the size of the fins but, in general, any position near 50% of the semispan would be near optimum for the Boeing 747 model. This location is just outboard of the inboard nacelle. Also, the present test results for fins mounted at the wingtip are in approximate agreement with those found for winglets.[15] It is interesting to note that Patterson and Jordan[16] found that the position for greatest alleviation by engine thrust is at the 55% semispan station, which is near the 50% station found for the fin. However, the optimum location for turbulence injection with spoilers[14] or splines[3] appears to be at a more outboard location near 60 or 70%.

The theoretical guideline, presented in an earlier section, recommended that the vortex should be injected near the centroid of shed circulation. This guideline is difficult to confirm in an experiment unless the position of the centroid can be reliably determined. The span-loading theory used here is not complete enough to predict accurately the lift carryover on the fuselage and, therefore, the strength of the vortex shed by the inboard end of the inboard flap. Since that negative vortex has a strong influence on the spanwise position of the centroid, a satisfactory theoretical estimate for the centroid position relative to the fin position could not be made.

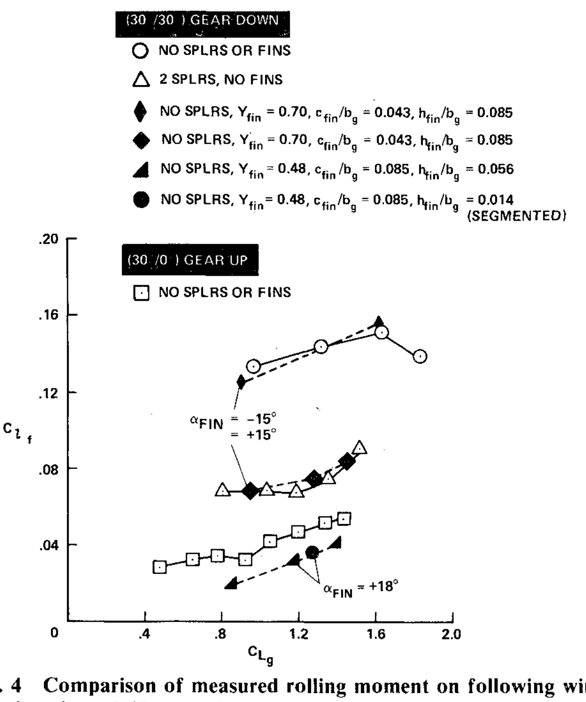


**Fig. 4 Comparison of measured rolling moment on following wing as a function of lift on wake-generating aircraft (Boeing 747 model) for various configurations: $b_f/b_g = 0.19$, $x_f/b_g = 13.6$.**

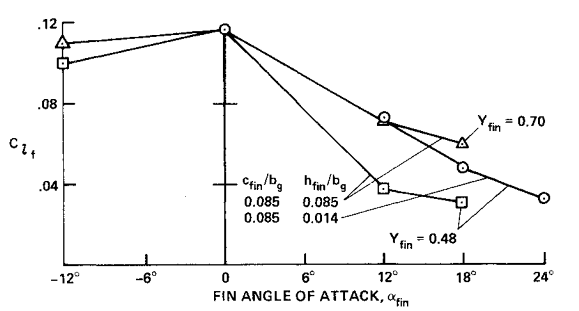


**Fig. 5 Variation of wake rolling moment with fin angle of attack.**

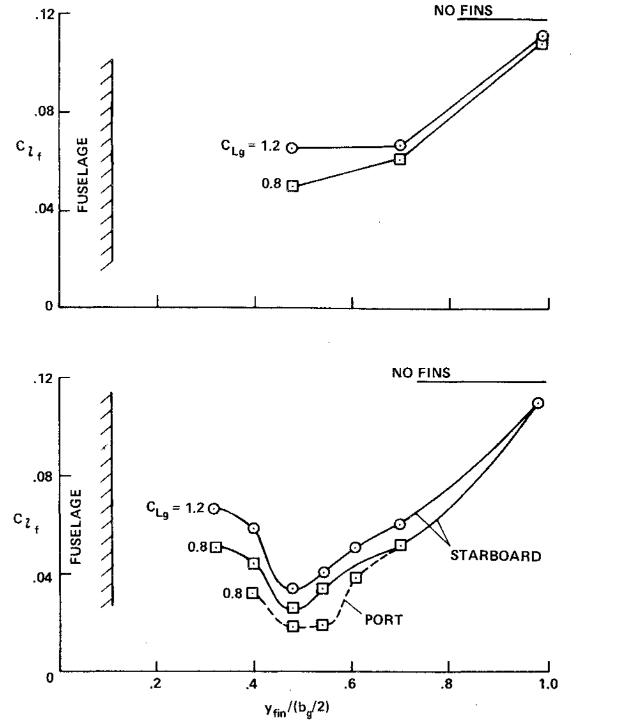


Fig. 6 Variation of rolling moment with spanwise location of fin. a) $c_{fin}/b_g = 0.043$, $h_{fin}/b_g = 0.085$, $Æ_{fin} = 4$, $\alpha_{fin} = +18$ deg. b) $c_{fin}/b_g = 0.085$, $h_{fin}/b_g = 0.085$, $Æ_{fin} = 2$, $\alpha_{fin} = +18$ deg.

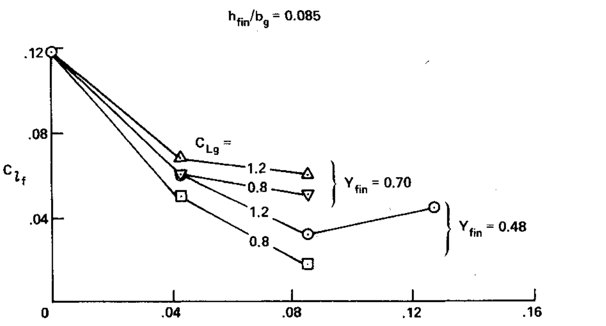


Fig. 7 Variation of wake rolling moment with fin chord: $h_{fin}/b_g = 0.085$, $\alpha_{fin} = +18$ deg.

Consequently, the centroid rule for vortex injection was not verified in these tests.

*Chordwise Location of Fins*

In general, the leading edge of the fins was located near the one-quarter chord of the wing. A systematic measurement of the variation of wake properties with chordwise location of the fin was not made. It is believed, however, that improved effectiveness of the fins can be obtained by integrating the fin aerodynamics with the pressure field of the wing to utilize the highest local velocities over the wing. The fins will then shed the strongest vortex possible for a given size.

*Fin Chord*

The effect of fin chord length on the wake-induced rolling moment is presented in Fig. 7. Although more data near the optimum chord length would be desirable, the available data indicate that values in the range of $c_{fin}/b_g = 0.08$-$0.10$ are near the optimum. As with optimum spanwise location, the optimum chord length for the fin was found to be insensitive to lift on the generator wing and to the location and height of the fin.

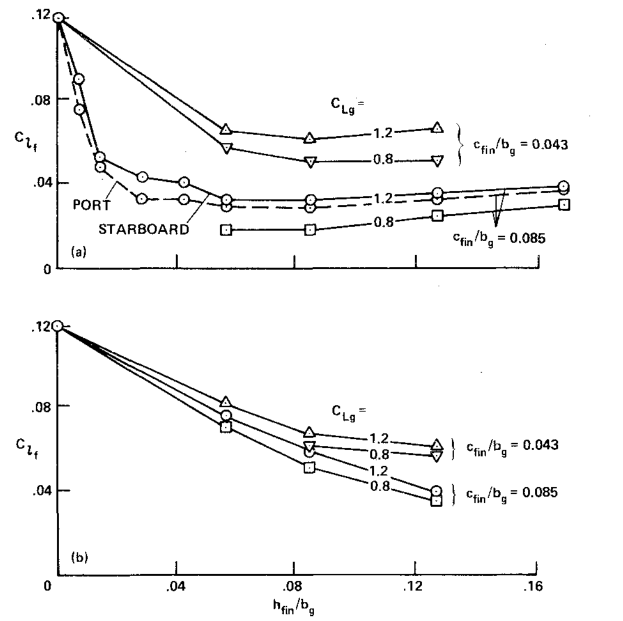


Fig. 8 Variation of wake-imposed rolling moment with fin height for two spanwise locations of fins, $\alpha_{fin} = +18$ deg. a) One fin per wing located at optimum spanwise location, $y_{fin}/(b_g/2) = 0.48$. b) One fin per wing located outboard of optimum location, $y_{fin}/(b_g/2) = 0.70$.

*Fin Height*

The measured effect of fin height on the wake rolling moment (Fig. 8) indicates that different optimum values occur for different fin chord lengths and spanwise positions. When the chord length of the fin is held at the optimum value ($c_{fin}/b_g = 0.085$) while the height is varied (Fig. 8a), the fin effectiveness is relatively constant down to small fin heights. The results for a more outboard fin location (Fig. 8b) indicate that the optimum fin height is larger for the $Y_{fin} = 0.70$ than for the $Y_{fin} = 0.48$ location. These experimental results confirm the observation made in the numerical study that the wake dispersion achieved by injecting a vortex of a given strength is nearly independent of the height at which it is injected if the height does not exceed about $0.15\ b_g$.

Variation of the aircraft lift, $C_{L_g}$, and drag, $C_{D_g}$, with fin height are presented in Fig. 9. Also presented are an estimate of the strength of the vortex shed by the fin and the variation of a parameter that represents the fraction to which the wake rolling moment is alleviated. The reference quantity, $C_{l_{f0}}$, is the wake-induced rolling moment for the B747 model without fins. Note that the ratio of the circulation shed by a fin (estimated from the data in Fig. 2) to that shed by the wing changes with fin height, in a manner very similar to that measured for the alleviation parameter, $(C_{l_{f0}} - C_{l_f})/C_{l_{f0}}$. In other words, the alleviation (bottom figure of Fig. 9) is nearly proportional to the strength of the injected vortex, $\Gamma_{fin}/\Gamma_g$, independent of the height at which the vortex is injected. That guideline, derived earlier from the numerical examples, is therefore considered to be reliable when applied to the optimum spanwise location and fin chord length.

As may be seen from Fig. 9, the drag on the generator model increases almost linearly with fin size. The lift is also adversely affected when the fin is large, but a slight enhancement occurs when the fin height is equal to or less than 0.014 $b_g$. This increase is believed to be brought about by a scrubbing action of the fin vortex on the trailing-edge flaps. It is not then certain whether a comparable effect would be realized at flight Reynolds numbers.

*Fins Mounted under Wing*

Several configurations were tested with the engine pylons and nacelles removed and fins mounted under the wing of the

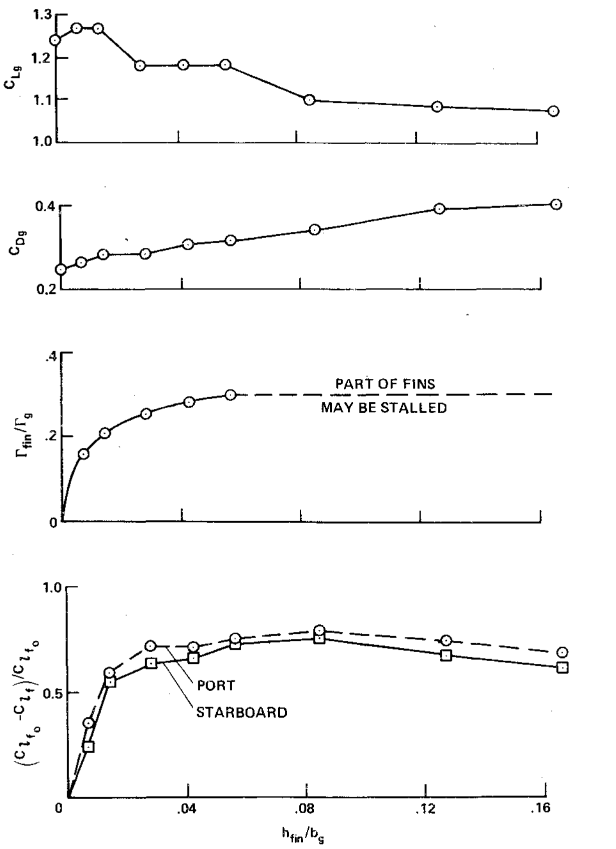


**Fig. 9 Variation of aerodynamic parameters with fin height: $c_{fin}/b_g = 0.085$, $\alpha_{fin} = +18$ deg, $\alpha_g = 4$ deg.**

B747 model. The fin effectiveness was found to be much less than for top-mounted fins; i.e., $C_{l_f}/C_{l_{f_0}} = 0.9$ for $c_{fin}/b_g = 0.085$ and $h_{fin}/b_g = 0.085$, compared with 0.3 for the same fin mounted on top of the wing. This difference is probably associated with the difference in the velocity fields (and, hence, side force and shed vorticity of the fin) between the lower and upper surfaces of the wing – that is, due to the bound circulation or lift on the wing. It is expected, therefore, that a bottom mounting will always be inferior to a top mounting because the vortex injected will always be weaker for a given fin size.

*Multielement Fins*

Since the best fin configuration is the smallest one that yields the required alleviation, several runs were made with segmented fins whose combined chord length was $c_{fin}/b_g = 0.085$ and whose height was $h_{fin}/b_g = 0.014$. Although the designs were intuitive and not based on a theoretically or experimentally determined optimum, a reduction in maximum wake-induced rolling-moment coefficient to 0.038 at $C_{L_g} = 1.27$ for $\alpha_g = 4$ deg was attained. This point, presented in Fig. 4, is the best configuration obtained to date in terms of the most alleviation for the least performance penalty. It is believed that this configuration could be optimized further by proper use of camber, chordwise position, and segmenting of the fins to better utilize the pressure field of the wing.

*Multiple Fins per Side*

After a number of configurations were studied with one fin per side, several arrangements were tried with two fins mounted on each side of the wing. To obtain maximum alleviation, the $c_{fin}/b_g = 0.085$ by $h_{fin}/b_g = 0.085$ fins were mounted at the $Y_{fin} = 0.48$ spanwise location. Several fins of different sizes were mounted outboard at $Y_{fin} = 0.70$ and at the tip. The alleviation was found nonadditive, so that only a small increase was realized. However, because the lift and drag penalties were additive, the multiple-fin configurations were less desirable. Guidelines for the optimum design of multiple fins are not available, and the large number of possibilities makes it difficult to determine whether they can be made superior to single-fin configurations.

*Fins Added to Modified Landing Configuration (30 deg/0 deg)*

Since the rolling moment induced by the wake on the small following model was considerably reduced (Fig. 4) by retracting the ouboard flap,[3,12] consideration was given to the possibility that addition of a fin might bring about further vortex dispersion. It was found, however, that the two effects were not additive, that alleviation was not significantly improved, and that the performance of the generator aircraft is degraded.

## Concluding Remarks

It has been determined theoretically and verified experimentally that vortex injection is an effective way to disperse lift-generated wakes. The wing-mounted fins used to generate the injected vorticity were studied to find those characteristics that maximize wake-vortex alleviation and minimize the performance and weight penalties imposed on the generating aircraft. The following general guidelines for optimizing the design of these vortex injection devices were established:

1) The strength of the injected vortex should be a sizable fraction (20-30%) of the wing circulation.

2) The spanwise location of the injection (or of the fin) should be near the center of the circulation shed by the wing. (Since it was not possible to reliably determine the centroid of vorticity in the experiment, the location of the centroid relative to the center of the wake was uncertain.)

3) The effectiveness of the injected vortex is almost independent of the height of injection (if less than $\approx 0.15\, b_g$). Hence, it is recommended that the vortex be injected as close to the wing upper surface as practical to minimize the size of the injection device (fin).

4) To the downstream distances tested (13.6 spans), positive fin angles of attack (side force directed inboard) were more effective than negative fin angles. The fin angle of attack should be the maximum possible below stall.

5) To maximize the strength of the fin vortex, it should be a highly cambered multielement lifting device, located in the high-velocity field on top of the wing near its leading edge.

Specific guidelines established for the fins that maximize wake alleviation for the Boeing 747 model with minimum performance penalties are: 1) $\alpha_{fin} = +18$ to $+24$ deg, 2) $c_{fin}/b_g = 0.085$, 3) $h_{fin}/b_g = 0.014$, 4) $AR_{fin} = 0.333$, and 5) $y_{fin}/(b_g/2) = 0.48$. This fin configuration was chosen because it lowered the wake-induced rolling moment to the lowest level achieved ($C_{l_f} = 0.038$ at $C_{L_g} = 1.27$), caused only a 10% increase in drag, and had no lift penalty. Such a reduction in rolling moment hazard at $x_f/b_g = 13.6$ (½ mile scale distance) approaches the goal of $C_{l_f} \lesssim 0.03$ at $x_f/b_g = 55$ (2 miles scale distance) set forth in the introduction. However, further tests are required as proof of concept to determine whether wing fins provide sufficient alleviation to prevent more than a 10-deg roll excursion on the part of an encountering aircraft.

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