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WIND-TUNNEL INVESTIGATION OF THE EFFECT OF POROUS SPOILERS ON THE WAKE OF A SUBSONIC TRANSPORT MODEL

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SUMMARY

A study was undertaken in the Ames Research Center 40- by 80-Foot Wind Tunnel to determine how porosity of wing spoilers on a B-747 airplane would affect the rolling moments imposed on an aircraft following in the wake. It was found that spoilers with 40 percent porosity and hole diameter to thickness ratio of 1.1 were just as effective in reducing the rolling moment imposed on the follower as solid spoilers, for the case of two spoilers per wing panel (6.4 percent semispan each) with a following model whose span was 20 percent of the span of the generator. When a larger following model was tested, whose span was 50 percent of that of the generator, the effectiveness of the two spoilers per wing was substantially reduced.

NOMENCLATURE

b	span of wing
$\bar{c}$	wing average chord, $\frac{S}{b}$
C_l	rolling moment coefficient, $\frac{\text{rolling moment}}{(1/2)\rho U_\infty^2 Sb}$
C_L	lift coefficient, $\frac{\text{lift}}{(1/2)\rho U_\infty^2 S}$
d	spoiler hole diameter
r	vortex radius
r_t	distance from vortex center to point of turbulence injection (see fig. 13)
S	wing area
t	spoiler thickness
U_∞	free-stream velocity
v_θ	swirl velocity

v_{rms} root mean squared turbulent velocity

z downstream distance

α angle of attack

Γ circulation

ρ air density

Subscripts

f following model that encounters the wake

g model that generates the wake

s strut fairing

w wing

INTRODUCTION

The objective of the NASA wake-vortex alleviation program is to reduce the intensity of the lift-generated vortex velocity field shed by large subsonic transport aircraft so that separation distances between aircraft can be reduced during landing and take-off. One aspect of this program has been devoted to the investigation of the effect on the wake of turbulence injection into the vortices (refs. 1-13). In these studies a wide variety of spoiler sizes and locations were considered as well as various spline configurations. Although some of the turbulence injection devices were effective in reducing wake intensity, the penalties associated with their drag, lift, unsteady loads and installation made them unacceptable solutions to the wake-vortex problem.

Recently, Croom (ref. 14) investigated the effect that deployment of the outboard spoilers that exist on the B-747 airplane would have on the rolling moment induced on a small following wing. Tests were made in the NASA-Langley Research Center V/STOL Wind Tunnel to measure the rolling moment induced on a Lear Jet or T-37B size aircraft as it encountered the wake. It was found that the rolling-moment could be reduced by a factor of about two by deployment of any two of the outboard four spoilers on each wing. On the basis of these results and some further tests by Dunham[1] using the water tow facility at Hydronautics Inc., the wake of the B-747 airplane with spoilers deployed was probed in flight by Barber (ref. 15). As predicted by the ground based results, the rolling moments induced by the wake of the B-747 on a T-37B following aircraft were reduced to about the level obtained in earlier experiments (ref. 16) with the wing span loading modified by spanwise variation of the flap deflection. In these earlier tests, it was found that the wake of

[1]Unpublished data, NASA-Langley Research Center.

the alleviated configuration (flaps 30°/1°) was adversely affected by lowering the landing gear on the generator airplane. In the tests with the spoilers deployed, the alleviation was also obtained with the landing gear down. Unfortunately, both of the two spoiler configurations tested resulted in wing buffet that was considered unacceptable for airline operation.

The simplicity of a retrofit that would only require the use of the spoilers existing on the aircraft as a solution to the wake-vortex problem prompted a search for a means to reduce the buffet to a tolerable level. An approach was suggested by some early studies made by the NACA (ref. 17) which found that buffeting caused by the use of split flaps could be suppressed by perforating the flap panels. Several airplanes, for example the Douglas SBD-1, used perforated flap panels. More recently, Buell (refs. 18, 19) found that a porous fence was effective in suppressing the pressure fluctuations that resulted from the flow over an open cavity. It was, therefore, expected that adding porosity to the existing spoilers on the B-747 airplane might suppress the buffet that had been observed. Furthermore, experimental results obtained by Orloff[2] indicated that porous spoilers were as effective as solid spoilers in reducing the swirl velocity in the wake, and the drag penalty with the porous spoiler was lower. These considerations led to the exploratory experiments reported in reference 12 and also to the investigation described herein.

The first objective of the present investigation was to determine to what extent porosity of the wing spoilers on the B-747 airplane would change their effectiveness in reducing the rolling moments imposed on a following aircraft. Wing buffet was not measured in the wind tunnel because the model was not dynamically scaled. A second objective of the present study was to determine if the wake-vortex alleviation achieved for a small following aircraft through the use of spoilers, would also be achieved for the case of a larger following airplane, for example representative of a DC-9.

TEST APPARATUS

The experimental apparatus used for this investigation was almost identical to that previously reported by the present authors (ref. 20). A brief description of that equipment is repeated here for the convenience of the reader along with those aspects that were different (i.e., the use of spoilers).

As before, the generator model was mounted at the forward end of the test section of the NASA-Ames Research Center 40- by 80-Foot Wind Tunnel. An inverted mounting of the generator (fig. 1) was required to minimize interference between the model wake and the strut wake. The generator model was centrally located in the inlet and was attached by a single strut through a straingage balance to measure lift. The angle of attack of the generator was set remotely through an actuator and indicator.

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[2]Unpublished data, NASA-Ames Research Center.

The generator model (fig. 2, table I) simulated a B-747 airplane. It was, therefore, equipped with two spanwise segments of triple-slotted trailing-edge flaps, capable of providing high lift. Full-span, leading-edge slats were installed when the trailing-edge flaps were deflected, and in addition, the landing gear was installed. Both solid and porous spoilers were tested (fig. 3). The spoiler locations were identical to the locations of the spoilers on an actual B-747 airplane. Of the twelve spoilers provided on the airplane, ten of them (flight spoilers) assist the ailerons in lateral control. Numbered from left to right, outboard spoilers are 1 through 4 and 9 through 12, and inboard spoilers are 5 and 8. Spoilers 6 and 7 (ground spoilers) are used symmetrically as speed brakes only. All spoilers are used as ground speed brakes, and spoilers 3 through 6 and 7 through 10 act as flight speed brakes. Since only the outboard spoilers and symmetrical configurations were tested here, only the numbers 1 through 4 will be used. In particular, only combinations 1, 2 and 1, 2, 3, 4 were tested. Several sets of porous spoilers were fabricated from prepunched metal plate with different values of porosity and hole diameter.[3] The five combinations of spoilers that were tested are listed on table II.

Other tests were conducted to determine why the spoilers were effective. First, the four solid spoilers were moved along the hingeline to the various spanwise locations indicated on figure 4(a) by the dimension $2y_s/b_g$, referenced to the spoiler outboard edge. Second, 35 percent of the outboard edge of the outboard flap was removed (fig. 4(b)) and the spoilers were not deflected, and finally, the outboard flap was retracted from the 46° setting shown on figure 2 (landing) to a 5° setting to simulate the take-off configuration without spoiler deflection.

Downstream of the generator model 24.4 m (80 ft), a follower model was mounted on a single strut that could be remotely positioned vertically over a 3.05 m (10 ft) range and laterally over a 4.27 m (14 ft) range. Additional geometric details of the follower models are given in table I. The follower model was attached to its strut through a strain-gage balance to measure rolling moment. Full-scale range for the balance was such that adequate sensitivity would be provided for the rolling moment encountered on each model (see table I). The following model was constructed of balsa wood to ensure a high-frequency response, and, as a result, the natural frequency of the model balance combination (31 Hz, model 1) was several times larger than rolling moment frequencies encountered.

TEST PROCEDURE

The procedure for recording the rolling moment consisted of setting the generator model and wind-tunnel conditions and selecting a lateral and vertical position for the following model. The time-varying rolling-moment signal was recorded on a light-beam strip-chart recorder. Sufficient length of record

[3]The assistance of Donald A. Buell in selecting the values of spoilers parameters is gratefully acknowledged.

was taken to obtain the highest or peak rolling moment for that location (usually about 1 min). The procedure was then repeated at successive lateral and vertical positions of the aft model in about 20-cm (8-in.) increments to determine the maximum value of rolling moment for each condition. The peak rolling moment values are interpreted as corresponding to the times when the following model is alined with a vortex center. The maximum rolling moment observed for each configuration was, then, converted to a rolling-moment coefficient, C_{l_f}. The lift on the generator model varied due to the unsteady flow in the wind tunnel and was, therefore, displayed on the same recorder as was the rolling moment signal. The average value of lift was used with the average value of dynamic pressure and the angle of attack to determine C_{L_g} vs. α_g. The maximum value of the lift on the generator was associated with the maximum value of the rolling moment because the time-dependent data indicated that the two values were correlated. Additional details on the test procedure and data reduction appear in reference 20.

RESULTS

Rolling Moment

Effect of Spoilers - The rolling moments imposed on both the small and large following models appear on figure 5 for the case of the solid or nonporous spoilers on the generating wing at positions 1,2. These results indicated that, for the case of the small follower, the rolling moment is reduced by about a factor of two by deployment of the solid spoilers. These results are in close agreement with those obtained by Dunham[4] in this water tow facility tests on the same configuration. The wind tunnel results of Croom (ref. 14), obtained originally, show a similar percentage reduction in C_{l_f} due to spoiler deflection, but the levels of C_{l_f} are quite different. Patterson's data (ref. 21) (not shown here) taken in an air tow facility on the same configuration with the large follower and no spoilers but at double the downstream distance as we used in the present study is in close agreement with Dunham (ref. 9). The data in figure 5 indicate that spoilers are much less effective for a large span follower. For example, at a C_{L_g} of 1.2, the solid spoiler reduced C_{l_f} by 44 percent for the small follower but only 18 percent for the large follower. The effect of porosity was to increase rolling moment by varying amounts depending on the porosity. The porous spoilers with hole diameter to thickness ratio of 1.1 (fig. 6(a)) provided the greatest alleviation which was essentially the same for the small following model as for the case with the solid spoiler.

In order to improve the effectiveness of spoilers for the case of the large follower, four spoilers per wing (locations 1, 2, 3, 4) were tested in both the solid and 70 percent porous configurations (fig. 6(b)). The four solid spoilers reduced the rolling moment at $C_{L_g} = 1.2$ by 24 percent of the spoiler off case as compared with 18 percent for the two solid spoiler configuration. Adding 70 percent porosity to the four spoiler configuration increased C_{l_f} to about the same level as was obtained with two solid spoilers.

[4]loc cit.

Comparison with span load modification - In earlier studies it was found that setting the inboard flap to the landing setting with the outboard flap undeflected was effective in reducing the rolling moment in the wake (ref. 20). The result for the outboard flap at the take-off position with the inboard flap set to the landing position and the spoilers undeflected (labeled ldg/T.O.) is compared in figure 7 with two of the spoiler configurations and with the conventional landing configuration. The effectiveness of the ldg/T.O. configuration is equivalent to four 70 percent porous spoilers with both flaps set to the landing position.

The four solid spoilers were moved from their 1, 2, 3, 4 locations to each of three spanwise locations (fig. 4(a)) to determine the sensitivity of the rolling moment to spanwise position. The rolling moment on the follower was found to be sensitive to the spanwise location (fig. 8), with the original 1, 2, 3, 4 locations providing the lowest rolling moment.

The outboard 35 percent of the outboard flap was removed (fig. 4(b)) to simulate a possible change in span loading caused by the spoilers. As shown on figure 9, this change had no effect on the rolling moment. It appears, therefore, that the effectiveness of the spoilers is not simply the result of a span loading change of that kind in the vicinity of the spoiler.

Sensitivity of the Results to Model Mounting - The results presented here and in reference 20 were obtained during three wind tunnel entries. It was initially determined that considerable interference could occur between the wake of the model and the wake of the support strut when the model was mounted right side up. This interference was most pronounced for those configurations with wake vortices near the plane of symmetry, i.e., near the support strut. The model was therefore, mounted inverted. Even with the inverted mounting, however, the effect of strut geometry is believed to have not been completely eliminated as shown on figure 10 for the conventional landing configuration, where strut fairing B was more streamlined than strut fairing A. The results with strut fairing A differ somewhat from the results for strut fairing B especially for the smaller following model, even though repeat measurements with the same configuration for different wind tunnel entries, as well as repeat measurements within any tunnel entry (not shown) compare very well. Also, a run was made with strut fairing B removed (not shown), leaving an exposed circular strut and actuator mechanism capable of generating considerable turbulence but not a trailing vortex due to strut side load. There was no effect on rolling moment of removing strut fairing B. It was, therefore, concluded that there was no interference due to strut fairing B since removing the fairing was a major change. It is conjectured that an additional vortex was present with the fairing A configuration that resulted from a fairing side load.

Lift on the Generator Model

The effect of porosity on lift coefficient for the various spoiler configurations is presented in figures 11 and 12. As expected the larger spoiler surfaces decrease lift by larger amounts at a given angle of attack. The effect of 40 percent porosity for the small holed spoiler was to increase lift only slightly. Considerably more lift could be recovered by using 70 percent porosity.

DISCUSSION OF ALLEVIATION MECHANISMS

It was found in the present study and in the studies at the NASA-Langley and Flight Research Centers that spoilers are effective in reducing the rolling moment induced on an aircraft flying in the wake. There are at least four possible mechanisms acting to reduce the wake intensity: 1) spoilers change the span loading so that their effect is similar to the effect of retracting the outboard flap; 2) spoilers add turbulence to the wake which enhances the decay of the wake by turbulent diffusion; 3) spoilers change the axial velocity distribution in some favorable way that caused the wake to become disorganized; and 4) spoilers shed vortices which cause the wake to break up. The results for the outboard flap partly removed (fig. 9) suggests that span loading changes alone do not account for the reduction in rolling moment caused by the spoilers. The effect of turbulence injection into vortices has been studied by Donaldson and Bilanin (ref. 22) through the use of a second-order closure theory to compute the effect of turbulence. In their theoretical calculations they introduced turbulence axisymmetrically at various radial distances from the vortex center to determine 1) whether the addition of turbulence would enhance the decay of the vortex and 2) the location of the turbulence injection for maximum effect. Figure 13, taken from various figures of reference 22, indicates that the peak swirl velocity is reduced by turbulence injection, however, outboard of $r/b_g = 0.1$ there is little effect of the turbulence injection. Also shown of figure 13 is the portion of the vortex occupied by the two following wings used in the present study, when the following wings are centered on the vortex. The rolling moments on these following wings, predicted by the method of reference 12, are reduced 14 percent and 4 percent by the addition of turbulence for the small and large followers, respectively. These predicted reductions are substantially less than those measured in the present study for the various configurations with and without spoilers. One conclusion is that the addition of turbulence alone does not account for the measured reduction in rolling moment. However, another interpretation of the calculation is that the axisymmetry assumed in the calculation creates a stabilizing mechanism that resists turbulent diffusion (ref. 22, section 4.1). In the wind-tunnel tests, spoilers add turbulence to the vortex in a nonaxisymmetric way. Further theoretical research on the effect of turbulence in a nonaxisymmetric vortex is, therefore, required.

CONCLUDING REMARKS

The present study was undertaken to determine how porosity of wing mounted spoilers would change the rolling moments imposed on a following aircraft. The measurements reported here indicate that spoilers with 40 percent porosity and hole diameter to thickness ratio of 1.1 are as effective as solid spoilers at locations 1, 2, 11, 12 with the small following model ($b_f/b_g = 0.2$). It was also found that spoilers were considerably less effective for the large following model ($b_f/b_g = 0.5$) as compared with the small following model. An explanation for the effectiveness of the spoilers was not resolved in the present study. It was found, however, that the rolling moment was not reduced when, instead of deploying the spoiler, the portion of the trailing edge flap in the wake of the spoiler was removed. It appears, therefore, that the effectiveness of the spoilers is not simply the result of a change in span loading. Further research is required using a nonaxisymmetric flow model to assess the role of turbulence injection in diffusing the vortex.

It is recommended that flight tests be conducted using the 40 percent porosity, d/t = 1.1 spoiler configuration to 1) verify the effectiveness of the porous spoiler and 2) assess the effect of porosity on wing buffet. It is also recommended that both a small and a large follower aircraft be used in the flight tests and that four spoilers per side be considered as a means for increasing the effectiveness of the spoilers in reducing the rolling moment imposed on a large following airplane.

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TABLE I.- MODEL DIMENSIONS AND WIND-TUNNEL CONDITIONS.

Model dimensions

Following model	$b_f/b_g = 0.5$	0.2
Span, cm (in.)	87.4 (34.4)	33.3 (13.1)
Chord, cm (in.)	9.8 (3.9)	6.1 (2.4)
Aspect ratio	8.9	5.5
Wing section	NACA 0012	NACA 0012
Fuselage diameter, cm (in.)	5.1 (2.0)	5.1 (2.0)
Balance full-scale range, N-m (in.-lb)	11.3 (100)	3.4 (30)

Generator model	
Wing	
Span, cm (in.)	179 (70.5)
Root incidence	+2°
Tip incidence	-2°
Area, m^2 (ft^2)	0.459 (4.94)
Average chord, cm (in.)	25.6 (10.1)
Aspect ratio	7
Horizontal stabilizer	0°
Spoiler, cm (in.)	
Chord	3.05 (1.2)
Span per panel	5.7 (2.3)
Strut fairing B, cm (in.)	
Chord	45.7 (18)
Thickness	12.7 (5)

Wind-tunnel conditions

U_∞, m/s (ft/sec)	40 (131)
Reynolds number, based on average chord	7×10^5

TABLE II.- SPOILER DIMENSIONS, cm (in.)

Spoiler	Thickness, t	Hole diam., d	d/t	No. holes per cm^2	Porosity, %
1	0.15 (0.060)	0	0	0	0
2		0.17 (0.067)	1.1	17.5	40
3		.32 (.128)	2.1	5.4	40
4		.36 (.140)	2.3	5.4	50
5		.40 (.160)	2.7	5.4	70

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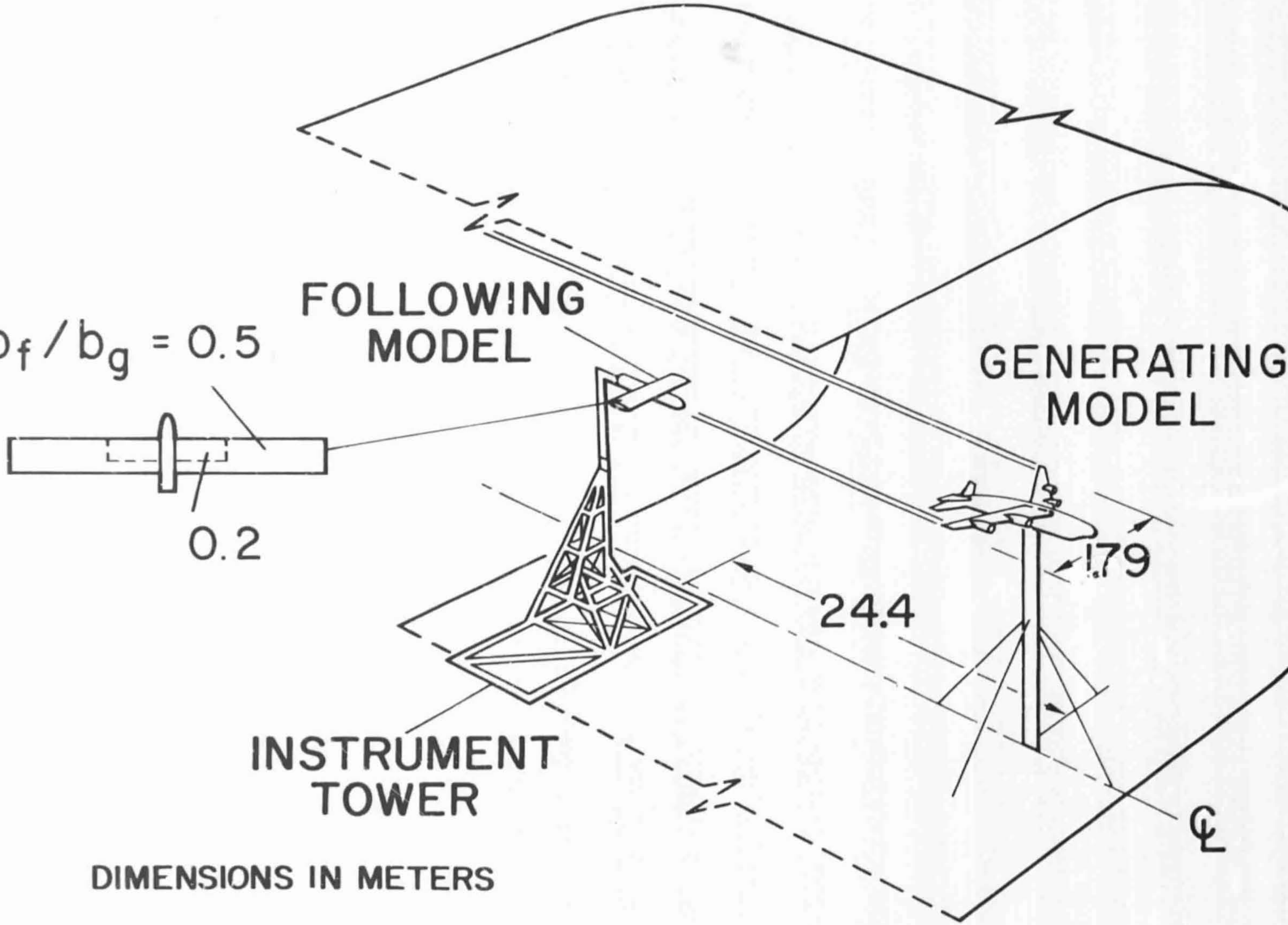


Figure 1.- Experimental setup in the NASA-Ames Research Center 40- by 80-Foot Wind Tunnel.

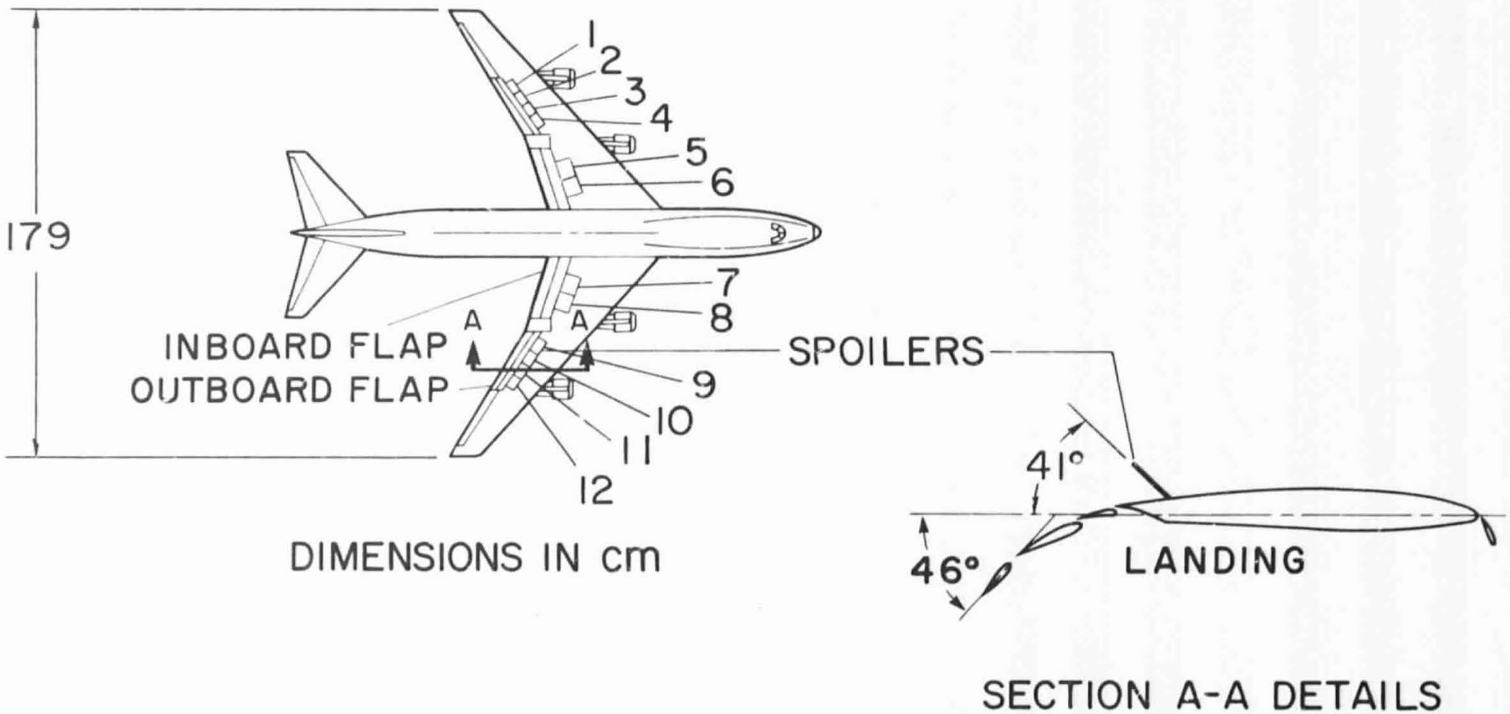


Figure 2.- Geometric details of the subsonic transport model used to simulate a B-747 airplane.

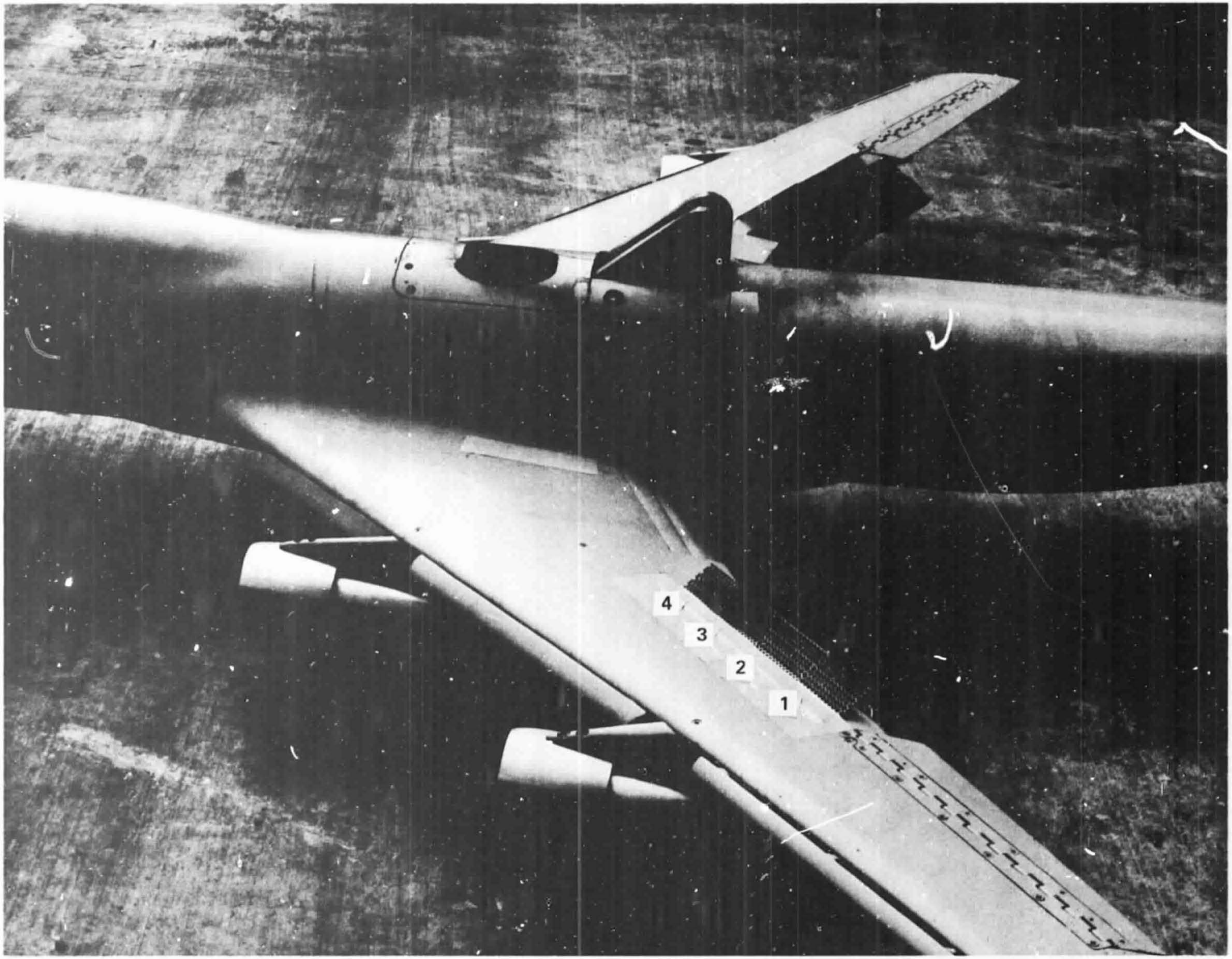
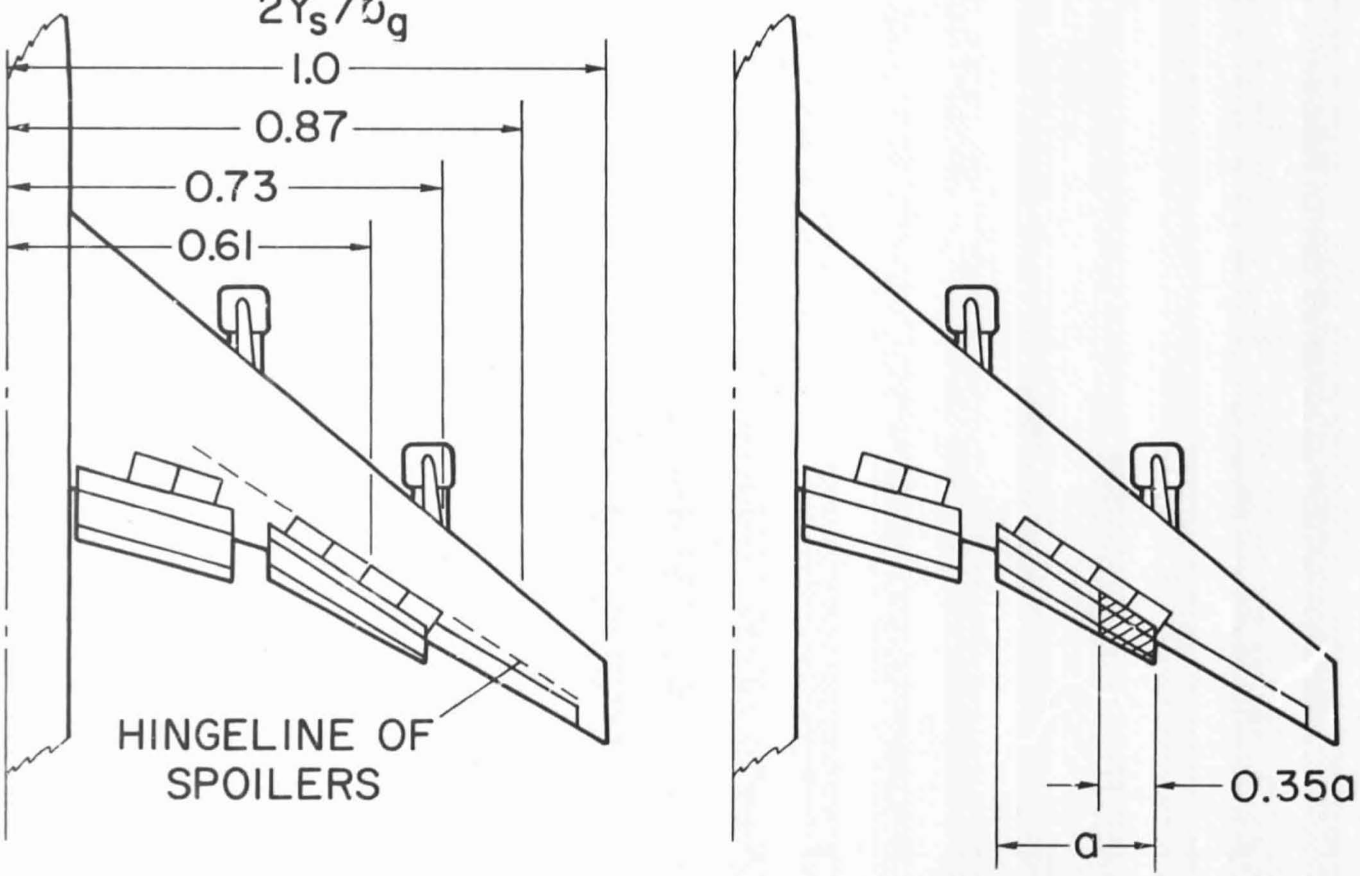


Figure 3.- Photograph showing the 70 percent porous spoilers installed on the generator model.



(a) SPANWISE LOCATIONS OF SPOILER

(b) PORTION OF OUTBOARD FLAP REMOVED

Figure 4.- Additional flap and spoiler configurations tested.

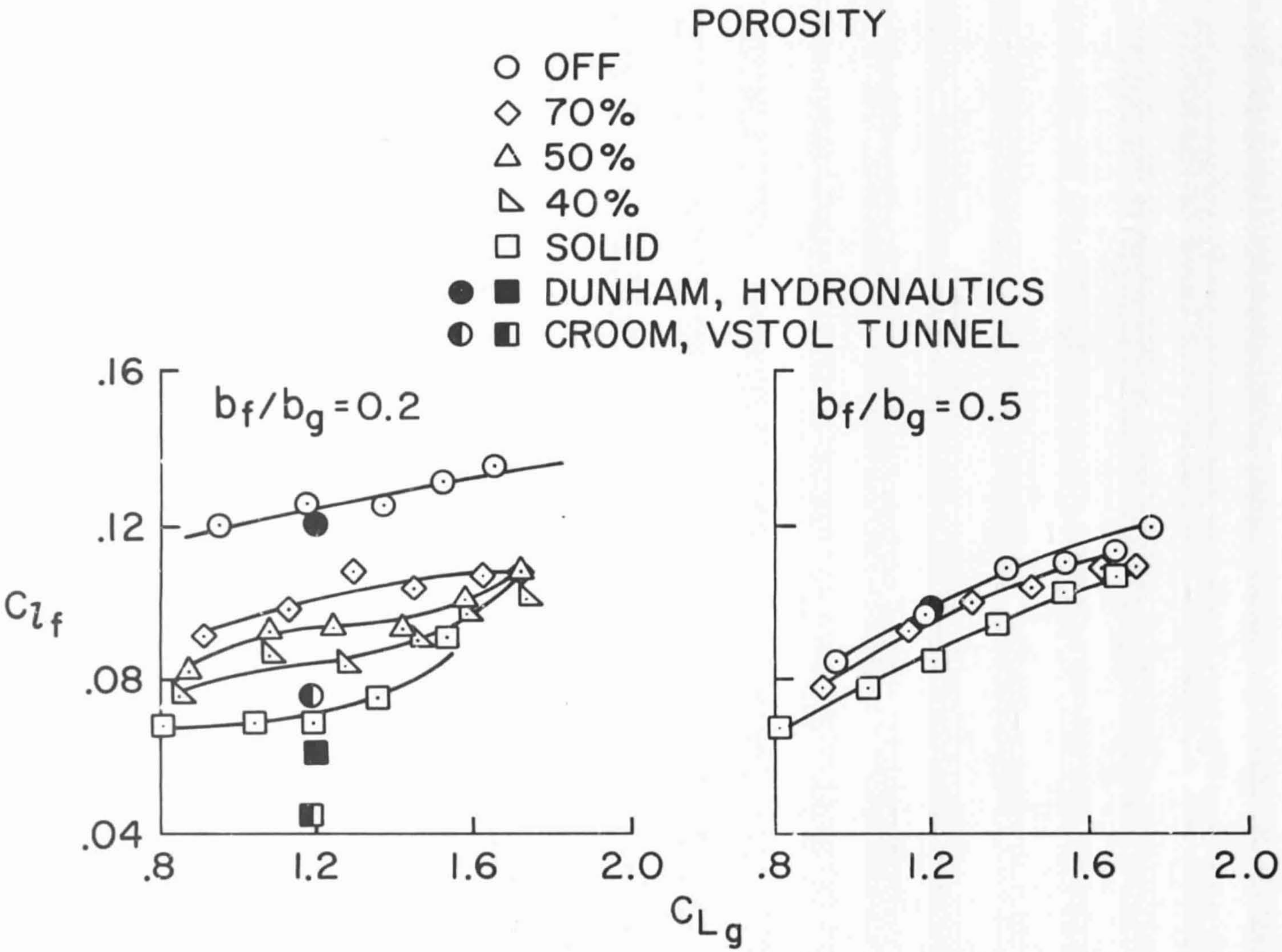
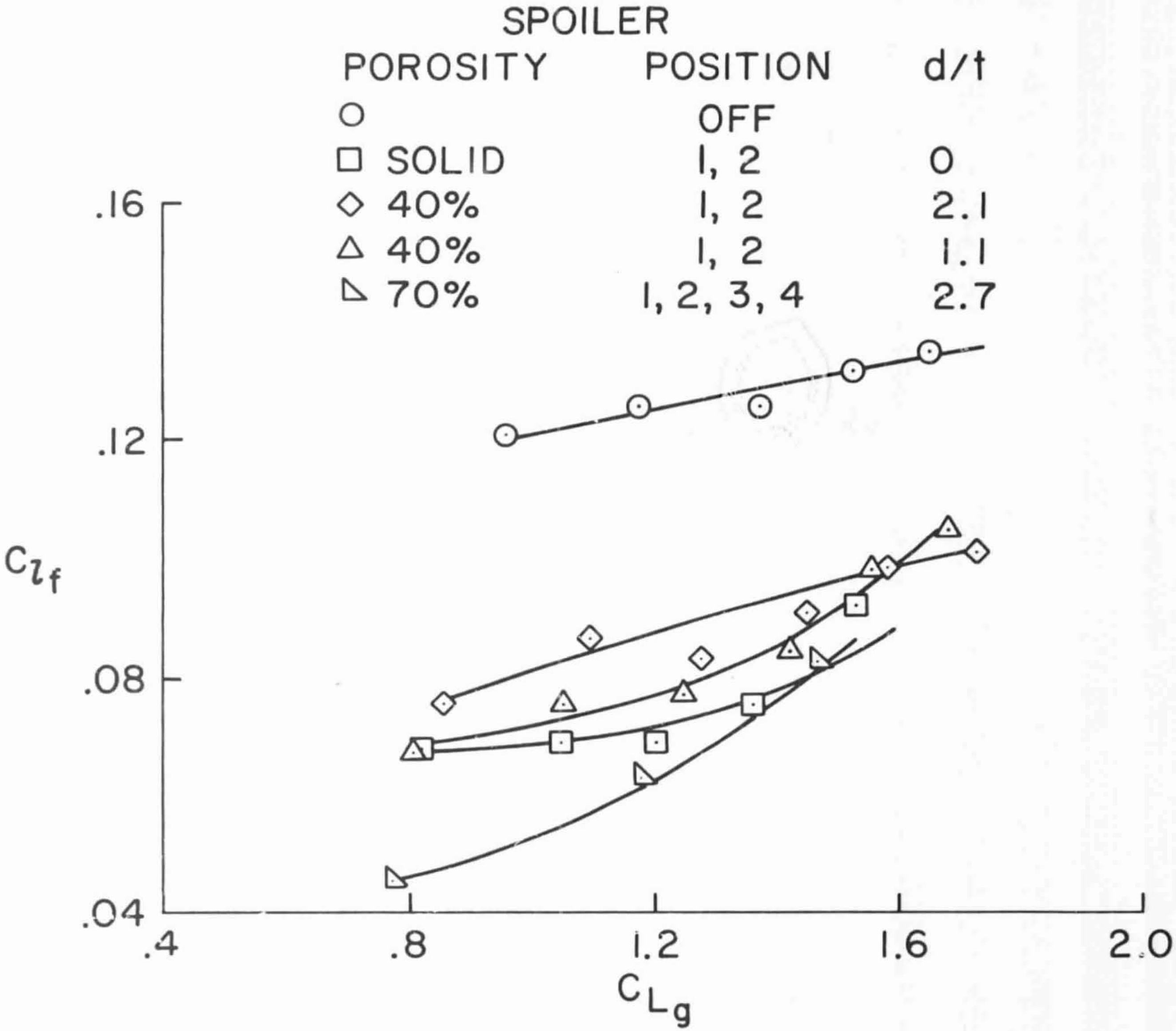
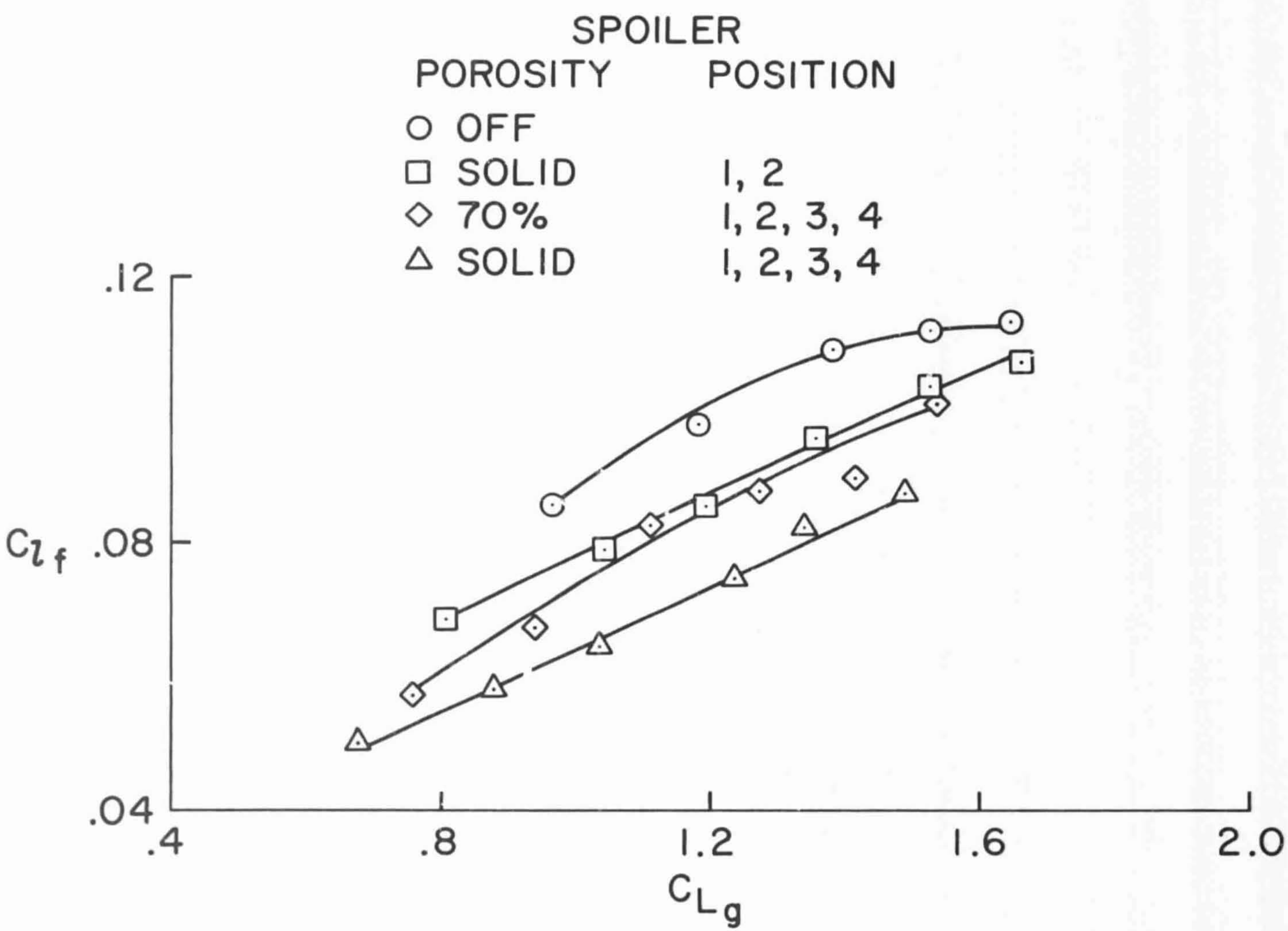


Figure 5.- The effect of spoiler porosity with the configuration with two spoilers mounted symmetrically on both wing panels on the rolling moment imposed on the following model. Locations 1, 2, 11, 12.



(a) $b_f/b_g = 0.2$.

Figure 6.- The effect of spoiler hole size, porosity, and spoiler span on the rolling moment coefficient imposed on the following model with the spoilers mounted symmetrically on both wing panels.



(b) $b_f/b_g = 0.5$.

Figure 6.- Concluded.

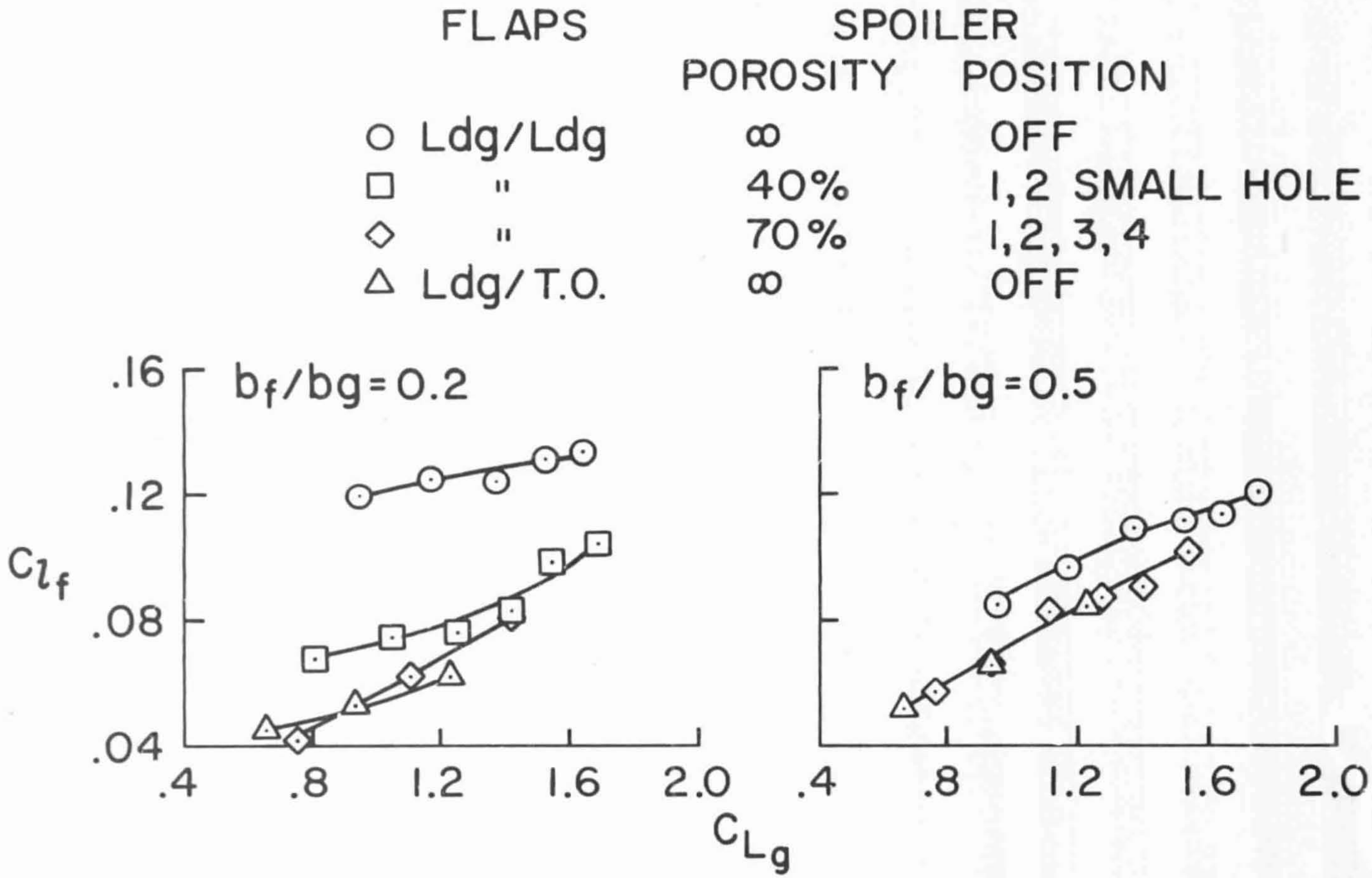


Figure 7.- Comparison of the effects of porous spoilers with the effects of retracting the outboard flap to the take-off setting (labeled ldg/T.O.).

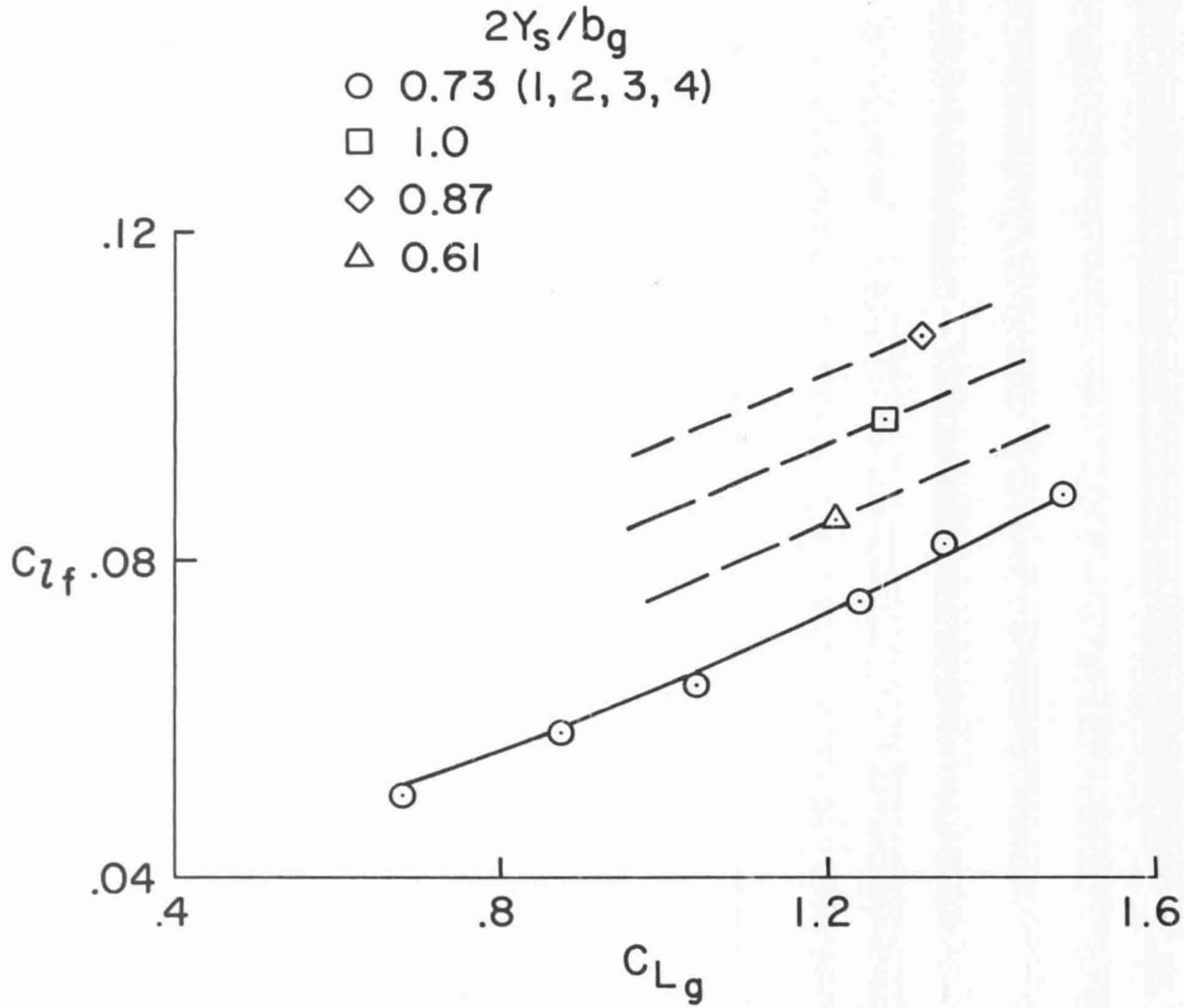


Figure 8.- The effect of spanwise position of the four solid spoilers per wing panel on rolling moment coefficient (see fig. 4(a)). $b_f/b_g = 0.5$.

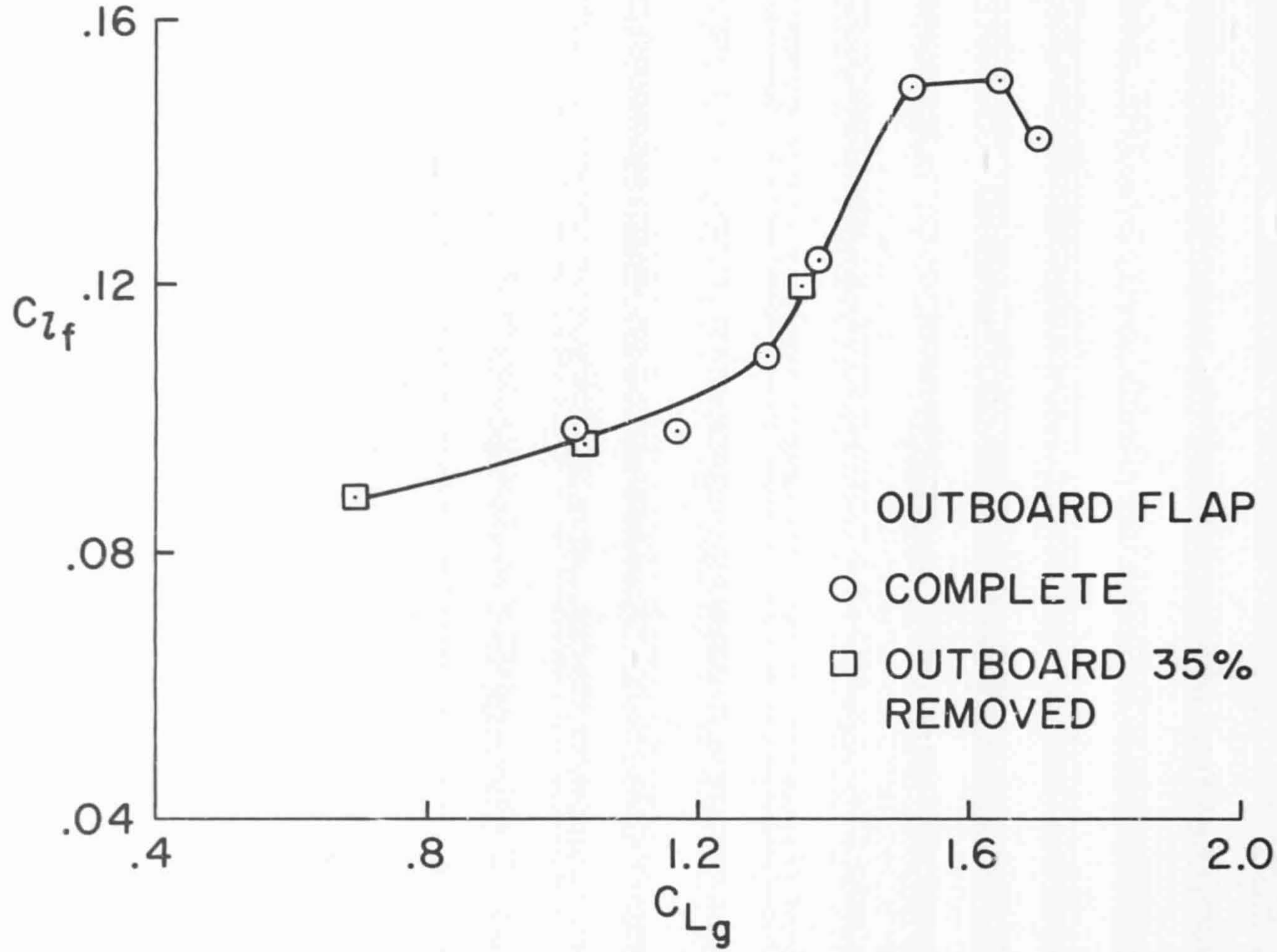


Figure 9.- The effect of removing the portion of the outboard flap in the wake of the spoilers at locations 1, 2, 11, 12. $b_f/b_g = 0.2$, spoilers undeflected, strut fairing A (see figs. 4(b) and 10).

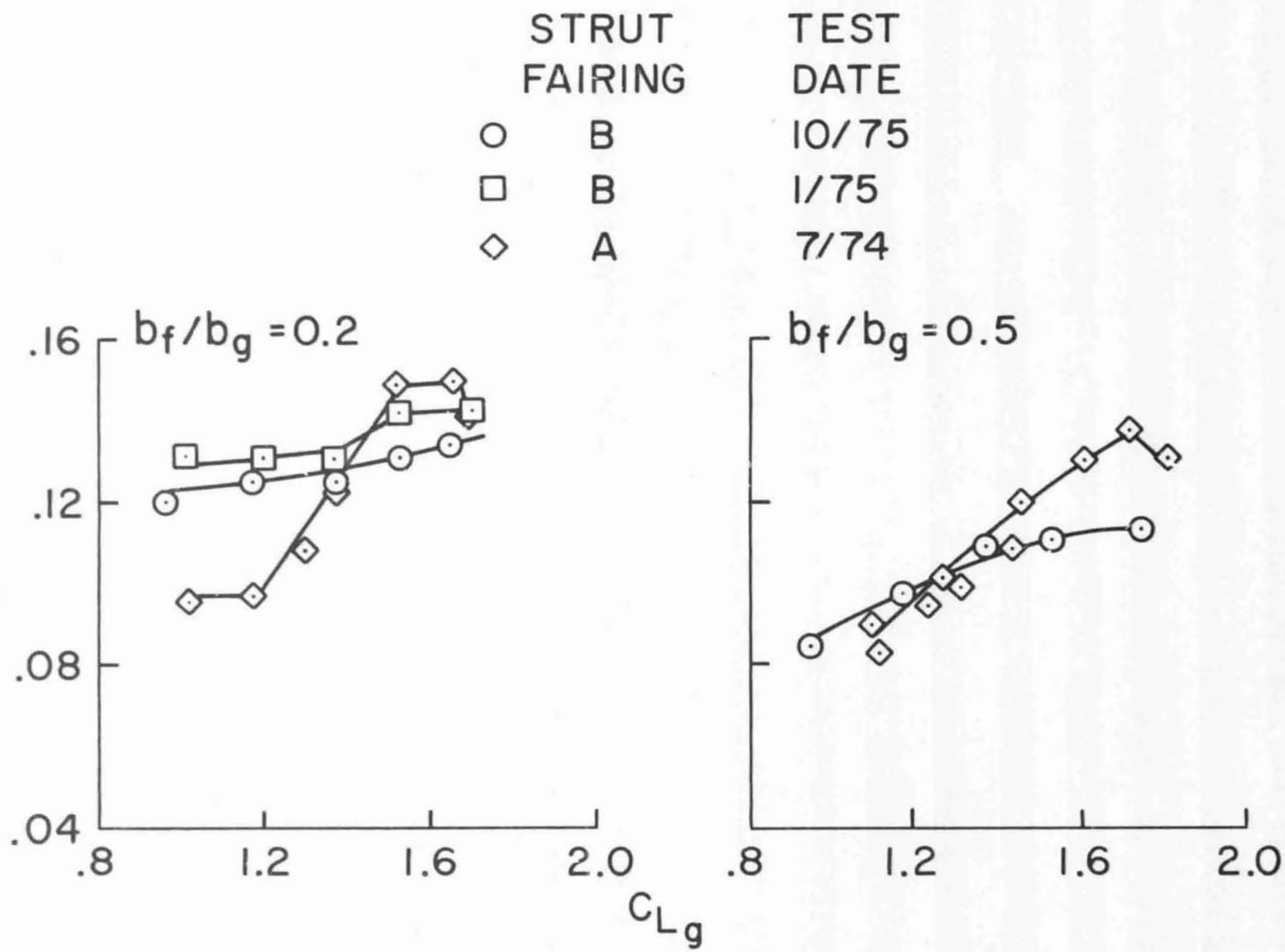


Figure 10.- Sensitivity of the rolling moment to the strut fairing.

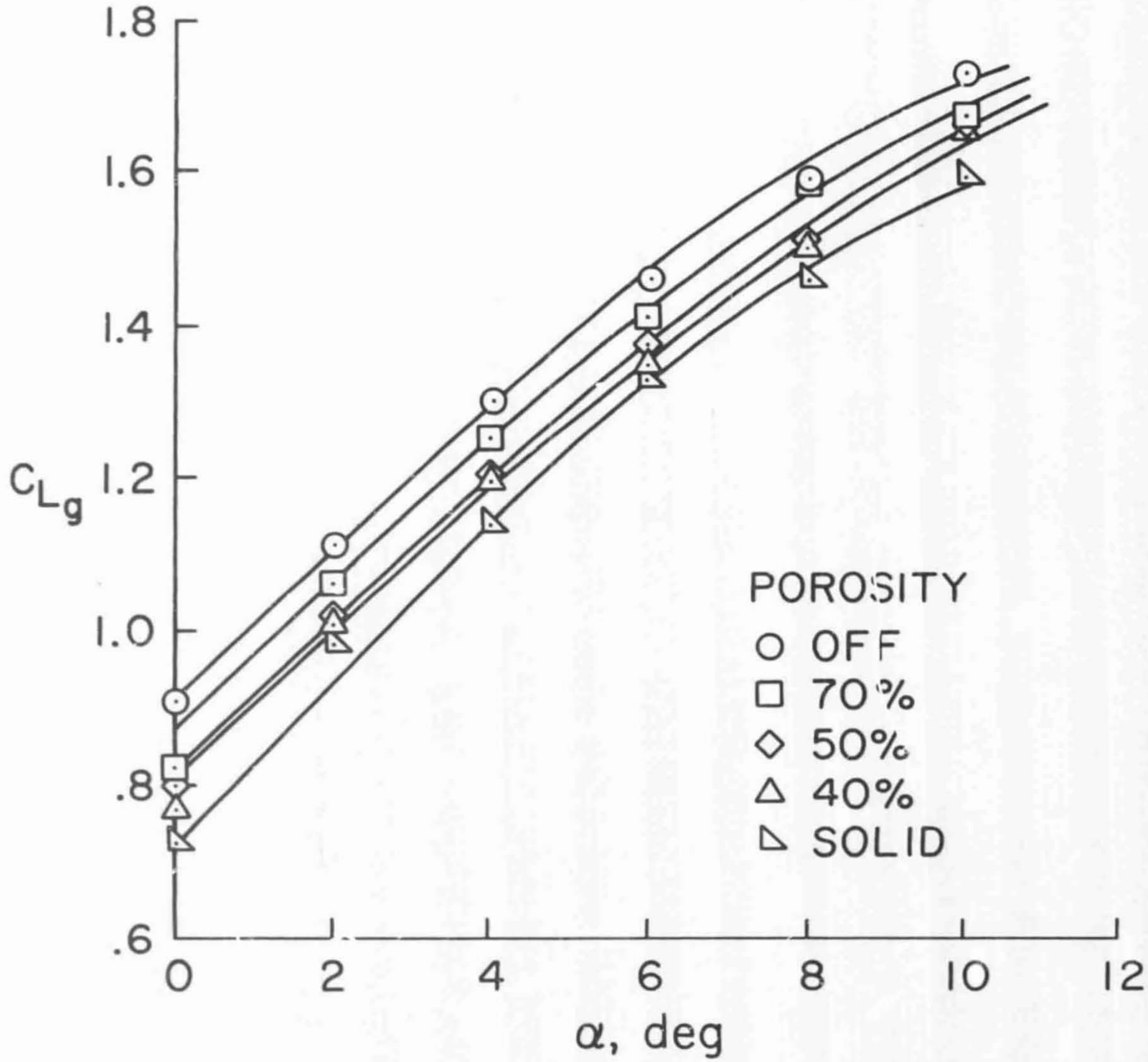


Figure 11.- The effect of spoiler porosity on the lift coefficient of the generator model with two spoilers mounted symmetrically on both wing panels. Spoiler positions 1, 2, 11, 12.

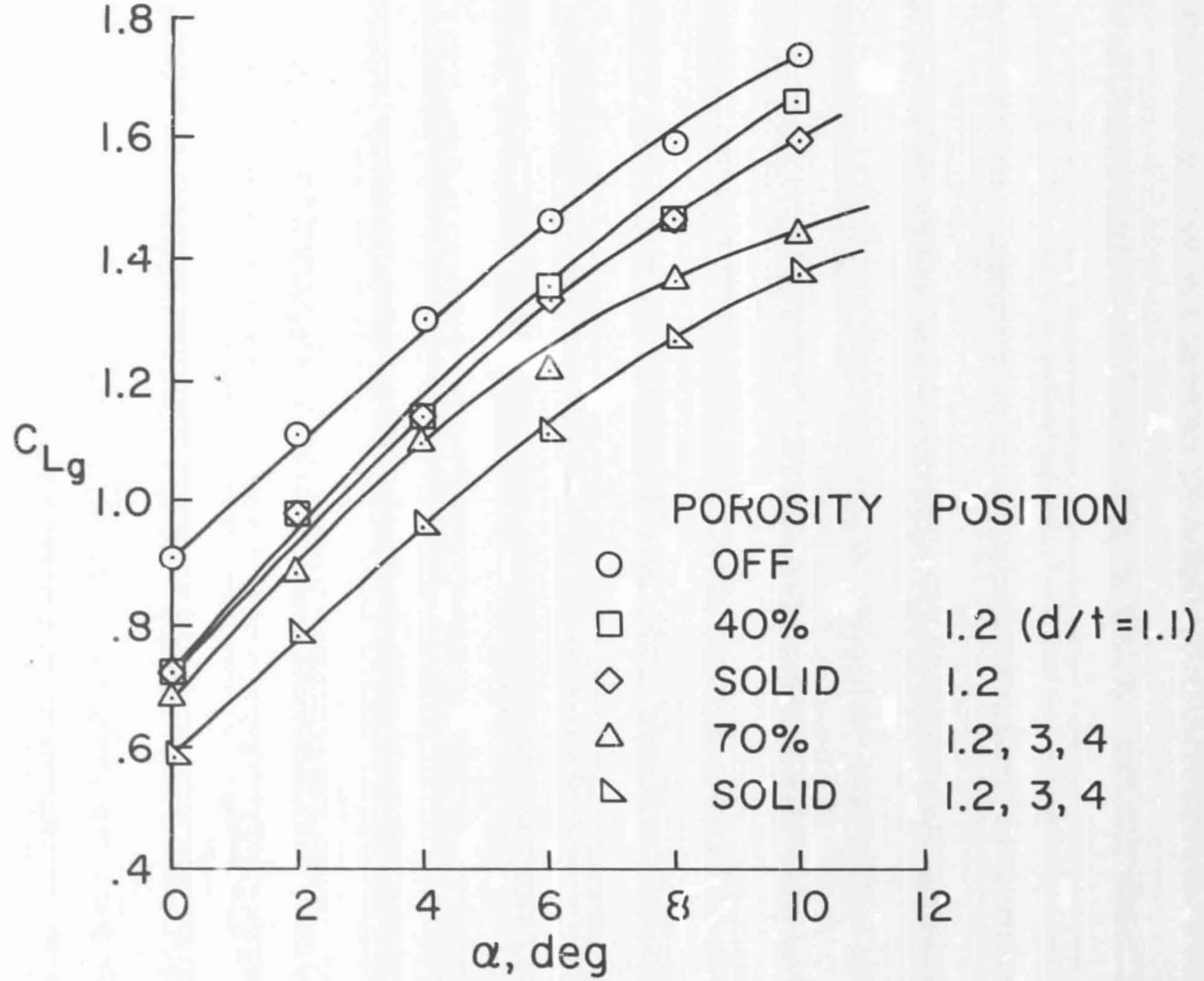


Figure 12.- The effect of spoiler hole size, porosity, and spoiler span on the lift coefficient of the generator model with the spoilers mounted symmetrically on both wing panels.

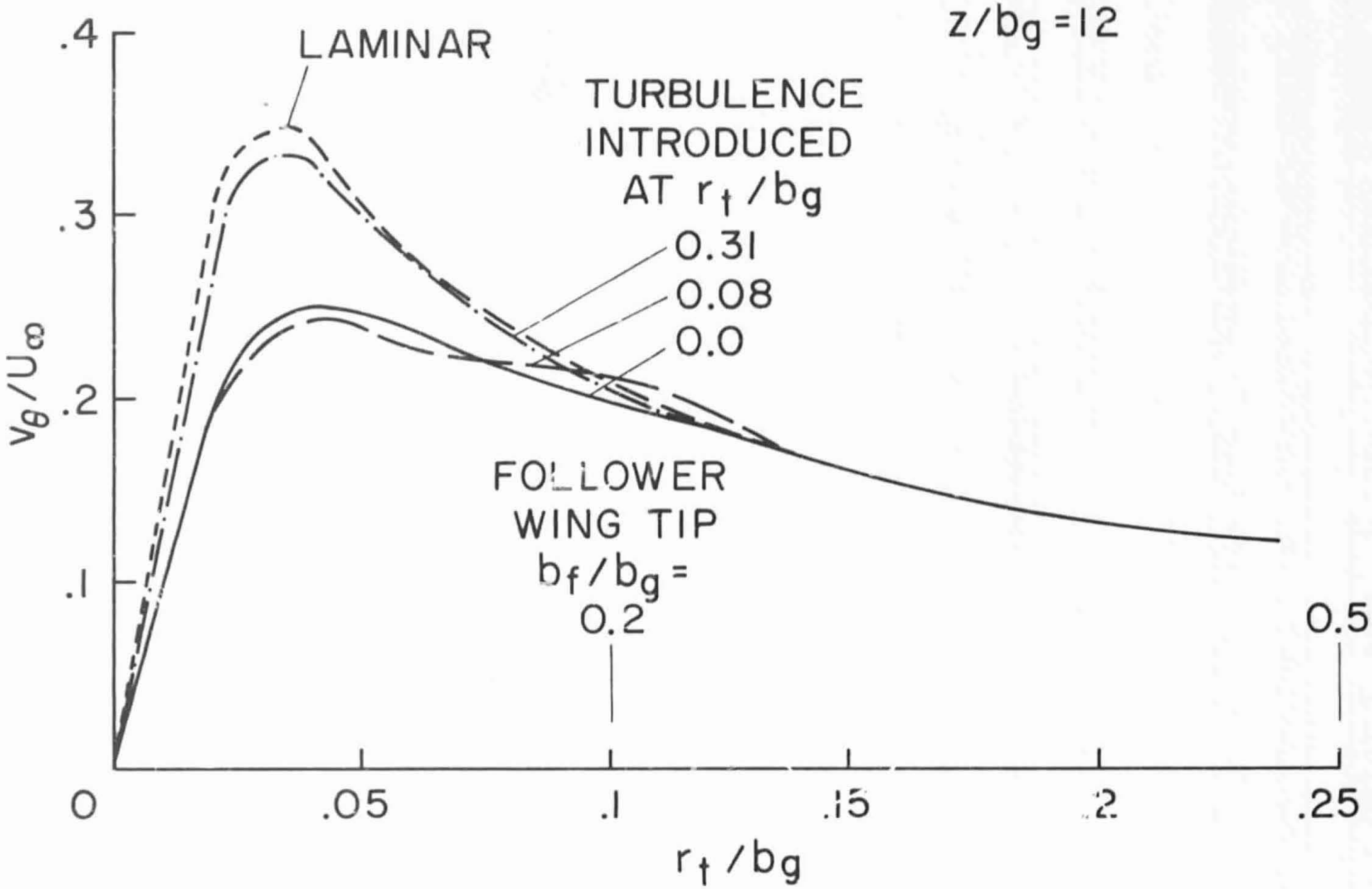


Figure 13.- Predicted swirl velocity with turbulence injection using second-order closure theory by Donaldson and Bilanin (ref. 22). Betz profile for elliptic loading with core, $z/b_g = 12$, $v_{rms}/U_\infty)_{max} = 0.8$ for $r_t/b_g = 0.0$.