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EFFECTIVENESS OF SPOILERS ON THE GA(W)-1 AIRFOIL WITH A HIGH PERFORMANCE FOWLER FLAP

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16. Abstract

Two-dimensional wind-tunnel tests have been conducted at a Reynold's number of 2×10^6 to determine effectiveness of spoilers applied to the GA(W)-1 airfoil. Tests of several spoiler configurations show adequate control effectiveness with flap nested. With 40^o flap, many spoiler configurations result in negative control response for small deflections, followed by highly non-linear control response at higher deflections, including substantial aerodynamic hysteresis for several configurations. It was found that providing a vent path allowing lower surface air to escape to the upper surface as the spoiler opens alleviates control reversal and hysteresis tendencies. Spoiler cross-sectional shape variations generally had modest influence on control characteristics. A series of comparative tests of vortex generators applied to the (GA-W)-1 airfoil show that triangular planform vortex generators are superior to square planform vortex generators of the same span.

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SUMMARY

Two-dimensional wind tunnel tests have been conducted to determine effectiveness of spoilers applied to the GA(W)-1 airfoil. Tests of several spoiler configurations show adequate control effectiveness with flap nested. With 40° flap, many spoiler configurations result in negative control response for small deflections, followed by highly non-linear control response at higher deflections, including substantial aerodynamic hysteresis for several configurations. It was found that a properly designed vent path allowing lower surface air to escape to the upper surface as the spoiler opens alleviates control reversal and hysteresis tendencies.

The spoiler non-linear control characteristics observed in the present tests are quite similar to characteristics reported by earlier researchers for airfoils with high-lift coefficient Fowler flaps. Several of the vented spoiler configurations tested exhibit positive, monotonic control characteristics for all control deflections and angles of attack, flaps nested or extended.

Spoiler cross-sectional shape variations generally had modest influence on control characteristics. It is recommended that reflection plane tests be carried out to evaluate three-dimensional aerodynamic effects on hysteresis, and to determine factors which influence spoiler hinge moments.

A series of comparative tests of vortex generators applied to the GA(W)-1 airfoil show that triangular planform vortex generators are superior to square planform vortex generators of the same span, in providing increased $c_{\ell max}$ with minimum drag penalty.

Introduction

The present research is one component of NASA Langley Research Center sponsored activities particularly aimed at providing advanced aeronautical technology to general aviation. The research reported here was undertaken to develop a spoiler lateral control system for application to a high performance low speed airfoil (GA(W)-1) with a large Fowler flap. The project was undertaken in support of an Advanced Technology Light Twin (ATLIT) aircraft, a research vehicle designed to demonstrate advanced technology concepts. The ATLIT airplane (Ref. 1) features a spoiler only lateral control system to permit full-span flaps for high landing and takeoff performance. The research thus developed, of course, has potential applicability to any flight vehicle designed to operate at low Mach numbers. Two-dimensional airfoil and flap aerodynamic characteristics have been reported earlier (Refs. 2, 3, 4). The present report presents results of wind tunnel tests of more than twenty spoiler configurations applied to the GA(W)-1 airfoil.

Symbols

The force and moment data have been referred to the .25c location on the flap-nested airfoil. Dimensional quantities are given in both International (SI) Units and U. S. Customary Units. Measurements were made in U. S. Customary Units. Conversion factors between the various units may be found in Reference 5. The symbols used in the present report are defined as follows:

- c airfoil reference chord (flap nested)
- c_ℓ airfoil section lift coefficient, section lift/(dynamic pressure x chord).
- c_d airfoil section drag coefficient, section drag/(dynamic pressure x chord).
- c_m airfoil section pitching moment coefficient with respect to the .25c location, section moment/(dynamic pressure x chord^2).

c_p coefficient of pressure, $(P-P_\infty)$/dynamic pressure.

α angle of attack, degrees

Δ increment

δ rotation of surface from nested position, degrees

Subscripts

s Spoiler

EXPERIMENTAL INVESTIGATIONS

Wind Tunnel Models and Instrumentation

All tests were conducted using the GA(W)-1 airfoil with a 30% Fowler flap. Airfoil and flap geometry are shown in Figure 1. Testing was conducted in the WSU 2.13m x 3.05m (7' x 10') Low Speed tunnel, fitted with inserts to provide a 2.13 m x 0.91m (7' x 3') two-dimensional working section. Details of the model installation are given in Reference 2.

Early spoiler tests were conducted utilizing spoilers fabricated from 1.80 mm (.071") flat aluminum sheet stock supported by sets of 4 wedge-type mounting blocks 6.35 mm (.25") wide to provide the various spoiler deflections, as shown in Figure 2(a). The spoiler assemblies were retained by cloth adhesive tape applied along the spoiler leading edges and along the trailing edge of the wedge blocks. After these early tests indicated the need for venting of air from lower to upper surface, the wing aft section was modified as shown in Figure 2(b). This model utilizes a 15% trailing edge section mounted on 4 spanwise ribs. The spoilers are attached to hinged sectors located at the 70% chord location at each rib station. Spoiler deflections are obtained by rotating the sector and spoiler plate relative to the ribs. A small screw retains each sector at the proper deflection angle. Spoiler deflection angles from 0° to 60° are easily obtained with this setup. Various spoiler plates, internal flow fillers and fairings were fabricated and tested. Test Reynolds number was 2.3×10^6.

Three-component force measurements were obtained on all configurations utilizing the tunnel pyramidal balance system. The experimental setup utilizes large disk end plates which are attached directly to the wing spar. As a consequence, a fairly large drag dynamic tare is measured by the balance system. This tare drag has been determined by wake rake airfoil section drag measurements as reported in Reference 2. All data have been corrected for this effect as well as for the wind tunnel wall effects, as outlined in Reference 6.

For the purposes of the present tests, a special data reduction computer program was written to calculate directly the incremental effects of spoiler deflections. Thus most of the data is presented in the form of increments utilizing zero spoiler deflection as a base line. In certain instances, however, conventional c_ℓ versus α plots are presented to illustrate non-linear characteristics observed during these tests.

Spoiler Tests

The first series of spoiler tests were carried out with simple flat plate spoilers attached to the upper surface of the GA(W)-1 airfoil. These tests were carried out with the following configurations:

Table 1 - Flat Plate Spoiler Configurations

Angle of Attack	Chords	Deflections	Hingelines
-5° to +20°	7.5% and 15%	20°, 40°, 60°	60% and 70%

From this series of runs it was found that certain combinations of negative angle of attack and 40° flap resulted in zero change in lift coefficient with 20° spoiler deflection (zero control). With flap nested, on the other hand, no control problems were encountered. These results have been reported in Reference 2. Based upon these results, the present detailed studies of smaller spoiler deflections were carried out.

Figure 3 illustrates the performance of a simple 15% chord spoiler with hingeline at 70% and 85% chord. For the flap nested case, spoiler control is nearly linear, except for a "softening" or dead-band tendency for small deflections at high angles of attack. These tendencies, not unlike aileron control near stall, would probably be quite acceptable.

With 40° flap deflection and 70% hingeline, on the other hand, the present tests illustrate (Fig. 4) not only zero control for small deflections, but actually show regions of control reversal. Comparison of these data with spoiler control forces from reflection plane tests reported in Reference 7 reveals that the same characteristic trends are also present for other airfoils with large Fowler flaps.

Tuft studies of the upper surface flow with small spoiler deflections revealed that the flow was separating aft of the spoiler, but the flap was fully attached, even for spoiler deflections of 10°. This is not too surprising when it is realized that the projection heights of the spoiler trailing edge are much smaller than the flap slot gap. Under these conditions the spoiler evidently has the effect of adding a small amount of positive camber to the airfoil section. Since the Kutta condition is preserved by attached flow at the flap trailing edge, a positive increment in lift (negative spoiler control) results. The "added camber" theory is supported by the pitching moment data which show a nose-down tendency for small spoiler deflections.

The data in Figure 5 show that the addition of a 1.5% leading edge gap to the spoiler has no significant effect for spoiler deflections of 15° and greater.

Data from Reference 7 indicate that providing lower surface ventilation air through the spoiler cavity will improve control effectiveness at small deflections. To determine whether ventilation would help spoiler control at small deflections, a series of holes were bored through the model to crudely provide partial ventilation. Results of this test indicated that the control reversal could be eliminated.

The model was then modified as shown in Figure 2(b). The entire aft 30% of the wing was removed and a new trailing section was fabricated, with four ribs for structural support, sectors for positive spoiler position, and hinge-points at the 70% chord station at each rib.

With the modified model geometry, it was possible to shim the 15% chord trailing edge segment and obtain a series of spoiler effectiveness data for a "slot-lip" type spoiler (Figure 6). These data show positive control even for control surface deflections as small as 5°. Evidently opening the flap slot serves as a powerful lift regulating mechanism. The problem of designs utilizing the slot lip spoiler is the large hinge moment associated with zero spoiler deflection, flaps down. The magnitude of this moment can be calculated from the pressure distribution data of Reference 2, which show Δc_p values of 2.0 for 40° flap deflection.

Tests of a 15% chord spoiler with lower surface venting revealed that positive control could be provided at small spoiler deflections. At moderate deflections, however, it was discovered that a serious aerodynamic hysteresis problem was present. Figure 7 illustrates this effect: for fixed spoiler and flap settings, two distinct c_ℓ versus α curves are produced, differing in lift coefficient by about 0.4. The hysteresis band persists from -15° to +6° angle of attack. A small half dowel was fitted into the cavity in an attempt to relieve the hysteresis effect. It is seen that this modification eliminated the hysteresis for 15° spoiler deflection. For 20° spoiler deflection a narrow hysteresis band is observed, even with the cavity nose dowel in place (Figure 8).

The significant favorable benefits of lower surface venting are clearly illustrated by comparing Figure 8 with Figure 4. It is seen that the tendency for control reversal at low spoiler deflections has been eliminated. While the control effectiveness curves are highly non-linear, positive control response is provided throughout the angle of attack and spoiler deflection ranges. Effects of a 4% spoiler leading edge gap are shown in Figure 9.

Effects of Spoiler Chord

Effects of spoiler chord variations are illustrated by comparing Figures 8, 10 and 11 which show spoiler effectiveness for 15%, 7.5% and 10% spoiler chords, respectively. These data illustrate very similar characteristics when compared at the same $\Delta h/c$ rather than at the same δ_s. Thus the data illustrate that spoiler performance is much more strongly dependent upon maximum projection height than deflection angle and spoiler chord. It should be noted that this series of tests was carried out with a fixed (70%) hingeline location, so that the spoiler trailing edge chordwise location is different for each spoiler chord.

Effects of Flap Setting

Because the intent of the ATLIT airfoil development program was to attain the highest possible $c_{\ell max}$, every effort was made to obtain a spoiler configuration compatible with the flap setting for highest $c_{\ell max}$. This configuration, as determined in previous tests (Ref. 2) consists of 40° deflection of a 30% chord Fowler flap, and produces a maximum lift coefficient of 3.8. Under these conditions the flap produces a normal force coefficient of about 1.3 based upon flap chord. This value is derived from airfoil and flap pressure distributions as reported in Reference 2. Because of the high lifting condition of the flap, and the coupling between spoiler and flap aerodynamics, it seemed highly probable that the spoiler hysteresis effects and control ineffectiveness discussed earlier would be alleviated by operating with reduced flap settings. This was proven by the tests shown in Figures 12 and 13. These data for a 10% chord spoiler show that for 20° and 30° flap settings the adverse spoiler characteristics are much less severe than with 40° flap. A control reversal occurs for 5° spoiler at 8° angle of attack. This angle of attack is near $c_{\ell max}$ for the 20° and 30° flap settings, and the spoiler vent flow evidently delays the stall slightly, resulting in an increase in c_ℓ. As mentioned earlier, this tendency is not unlike aileron behavior, and is not viewed as a serious problem. These effects are shown in Figure 11(b), 12(b), and 13(b).

Effects of Spoiler Lower Surface Shape

A series of spoiler lower surface shapes were designed in order to evaluate effects of lower surface shape variations. These spoiler shapes (Figure 14) include:

a) flat plate
b) a cusped shape similar to the Mitsubishi MU-2 airplane spoilers
c) a triangular back face
d) a triangular back face with a thin metal edge added, designated "sharp triangle spoiler"
e) a spoiler with an angle fitted to the back side, designated "tee-spoiler"
f) a trapezoidal configuration, designated "thick flat plate"

Results of effectiveness tests of these spoilers are shown in Figures 15 to 19. These models all utilize 10% spoiler chord with 1.5% gap. These tests reveal that the differences between shapes are rather small. On several of the control curves, branches are indicated. These are a result of hysteresis in the c_ℓ versus angle of attack curves, as discussed earlier.

Following are a series of observations from this series of tests:

1) No configuration tested exhibited better control effectiveness than the simple thin flat plate spoiler. From a structural standpoint, however, the flat plate is an undesirable shape because of its lack of bending and torsional stiffness.
2) The triangle spoiler had been designed to provide good bending and torsional stiffness with minimum weight and fabrication expense, but this configuration shows slightly degraded performance relative to the flat plate. A thin metal strip was added to this spoiler to provide a sharp corner at the lower triangle apex. This spoiler has essentially the same performance as the simple triangle spoiler.
3) The cusped MU-2 spoiler is more susceptible to hysteresis than any other configuration tested.
4) The Tee-spoiler has a greater tendency toward hysteresis problems than the flat plate or triangle shapes, but less tendency than the MU-2 spoiler.

Because the triangle spoiler provided an adequately stiff structural design and had non-reversing (non-negative) control characteristics with 40° flap, this spoiler was evaluated with 30° flap setting (Figure 20). As indicated with the thin-flat-plate spoiler, reducing flap load reduces the non-linear tendency. With this flap setting, the triangle spoiler exhibits a control reversal for 5° spoiler at 8° angle of attack, similar to the trend observed with the flat plate spoiler. (See Figure 12(a) and page 8.) It is quite possible, of course, that the shape of the rear spoiler face has a significant influence on hinge-moment characteristics, which were not measured in the present investigation.

Effects of Cavity Shape

Since the early tests with lower surface venting had shown a significant effect of cavity shape on spoiler performance, a series of cavity modifications were designed for investigation.

These shapes are shown in Figure 21, and have been designated "Modification A, B, C," etc. as shown in the figure. The effects of these modifications are illustrated by a series of c_ℓ versus α curves for 0° and 15° spoiler deflections with 40° flap. Cavity shape evaluations were carried out for the flat plate, MU-2, and triangle type spoilers. The results of these tests are shown in Figures 22, 23 and 24.

For the flat plate spoiler, non-linearity in the control characteristics tends to be unchanged or slightly worsened by most cavity modifications. The exception is Mod C which provides significant improvement in control response at low angles of attack.

For the MU-2 type spoiler, the tests show that all lower surface modifications except Mod C tended to aggravate hysteresis tendencies, compared to the open vent path (unmodified). Mod C again provides substantially improved performance. Possibly this modification promotes lower surface air bleed through the spoiler leading edge gap at small deflections, enhancing loss of lift. Furthermore the effectiveness becomes much less dependent on angle of attack than for an "unmodified" vent path. Unfortunately this modification intrudes severely into the flap cavity space which is ordinarily used for actuators, flap tracks, etc.

Effects of cavity modification on triangle spoiler control effectiveness are shown in Figure 24. Figure 24(a) illustrates the combined effects of cavity mods C and D when compared to Figure 19. This comparison shows an apparent slight deterioration of control response with Mods C and D.

When compared to Figure 19, Figure 24(b) shows an improvement in control response for small deflections due to Mod E. This modification was designed to provide higher cavity pressure at low angles of attack.

Comparison of Figure 24(c) with Figure 20 illustrates that Mod D provides improved control response at small deflections with the 30° flap setting.

Effects of Gap Leakage

While lower surface venting is highly desirable from the standpoint of providing positive spoiler effectiveness at small deflections, the venting path tends to promote leakage of air around spoiler leading and trailing edges, even with spoilers at zero deflection. This leads to degradation of $c_{\ell max}$ performance. This is illustrated by Figure 25 which shows incremental effects of gap leakage on maximum lift coefficient with 40° flap. These data were obtained by successive adjustment and taping of spoiler leading and trailing edge gaps.

Vortex Generators

In earlier airfoil and flap development research, (Reference 2) limited testing had been carried out to determine the effectiveness of vortex generators on the GA(W)-1 airfoil. At that time only a single configuration of vortex generators was evaluated. As part of the present tests, a series of vortex generators were tested, to evaluate size, shape and location effects. The configurations tested are described in Table 2 and Figure 26.

Table 2 - Vortex Generators

Configuration	Planform	Generator Height / Wing Chord	Average Spacing / Generator Height
1	73.3° delta	.0125	3.67
2	73.3° delta	.0125	7.33
3	73.3° delta	.0250	3.67
4	73.3° delta	.00625	3.67
5	Square	.0125	3.67

To determine the optimum chordwise location for vortex generators, tests were conducted with the configuration #1 generators located at stations from 30% to 70% chord. These results (Figures 27(a) and 27(b)) show that the 30%, 40% and 50% locations produce the highest $c_{\ell max}$ values, and that all these locations produce essentially the same value for $c_{\ell max}$. The 30% location delays stalling by 2°, but has substantially higher drag than the 40% and 50% locations. Based upon these results, the 50% location was selected as being near-optimum for subsequent testing of the effects of vortex generator size and shape variations. Results of size and shape variations are shown in Figures 28(a) and 28(b). These data show that for a given height and spacing, the triangular planform generators are clearly superior to rectangular planform generators. The large (Configuration #3) generators provided the highest maximum lift coefficient, but also resulted in the greatest penalty in terms of increased drag at low lift coefficient. A good compromise seems to be the configuration #1 generators which provide an increase in $c_{\ell max}$ of 0.52 with a drag increase of 19% at low lift coefficient. While it is not presumed that the GA(W)-1 airfoil should only be fabricated with vortex generators, the data presented here are intended to provide the designer with guidance in alleviating problems which may occur in particular configurations, i.e. to increase aileron, spoiler or flap effectiveness, etc.

While no tests of vortex generators were carried out with flaps down in the present series, previous tests indicate (Ref. 2) that generators provide approximately the same increment in $c_{\ell max}$ flap down as with flap nested. Confirmation of this will have to await further testing.

Conclusions

1. Spoilers applied to the GA(W)-1 airfoil with flap nested presented no special problems.

2. Spoilers applied to the GA(W)-1 airfoil with large flap deployment may yield control reversals at small deflections, and highly non-linear control characteristics, including substantial aerodynamic hysteresis. These characteristics have appeared with applications of spoilers to other airfoils with large flaps, and are attributed to spoiler flap interactions rather than characteristics of the particular airfoil section. Control problems are alleviated by reducing flap deflection.

3. Various spoiler configuration options are available to the designer to alleviate possible unsatisfactory control tendencies. The present research indicates that careful venting of lower surface air as the spoiler opens can provide adequate, although still non-linear control characteristics, even with 40° flap. The shape of the cavity through which this venting air passes is important. Any venting results in some loss in $c_{\ell max}$.

4. A slot lip spoiler was found to have satisfactory control characteristics, although it may present design problems in terms of a large hinge moment at zero spoiler deflection.

5. Spoiler back face geometry did not have a large influence on control characteristics, although possible effects on hinge moments were not evaluated.

6. Tests of vortex generators applied to the GA(W)-1 airfoil show that substantial increases in $c_{\ell max}$ can be achieved, although with some penalty in drag at low lift coefficient conditions.

7. Tests to determine optimum vortex generator shape indicate that a triangular planform is substantially better than the more commonly used rectangular planform for a fixed vortex generator projection height.

Recommendations

1. The effects on hinge moments of the various geometric parameters involved in spoiler design should be evaluated.

2. Tests of Spoilers on a finite span model with a large Fowler flap should be carried out to evaluate three-dimensional effects.

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δ_f	GAP(%)	OVERLAP(%)
40°	2.7	- .7
35°	3.0	1.2
30°	2.5	2.2
20°	2.5	4.7
10°	2.5	7.1
5°	2.5	12.1
0°	0	30.0

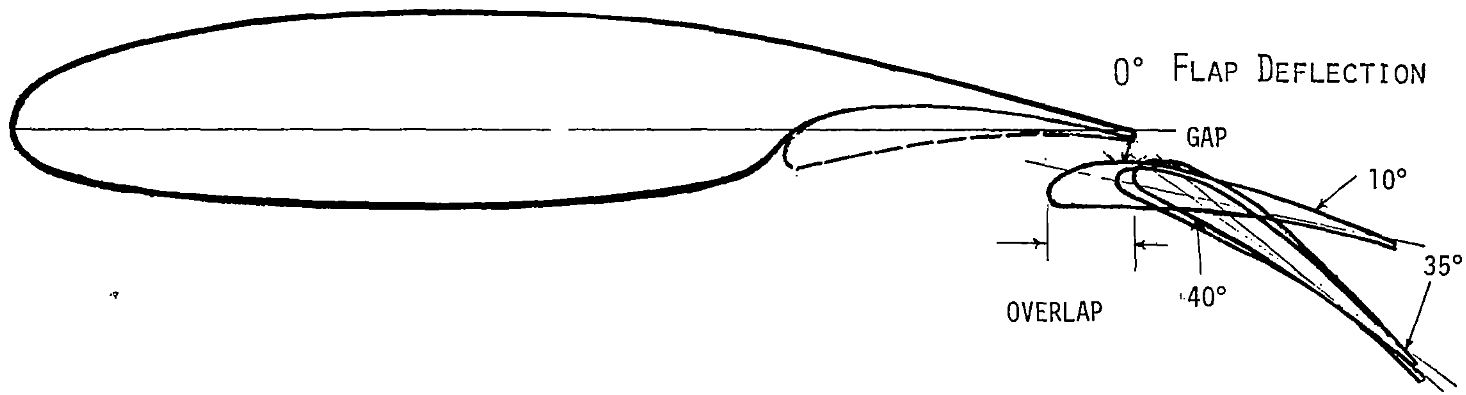
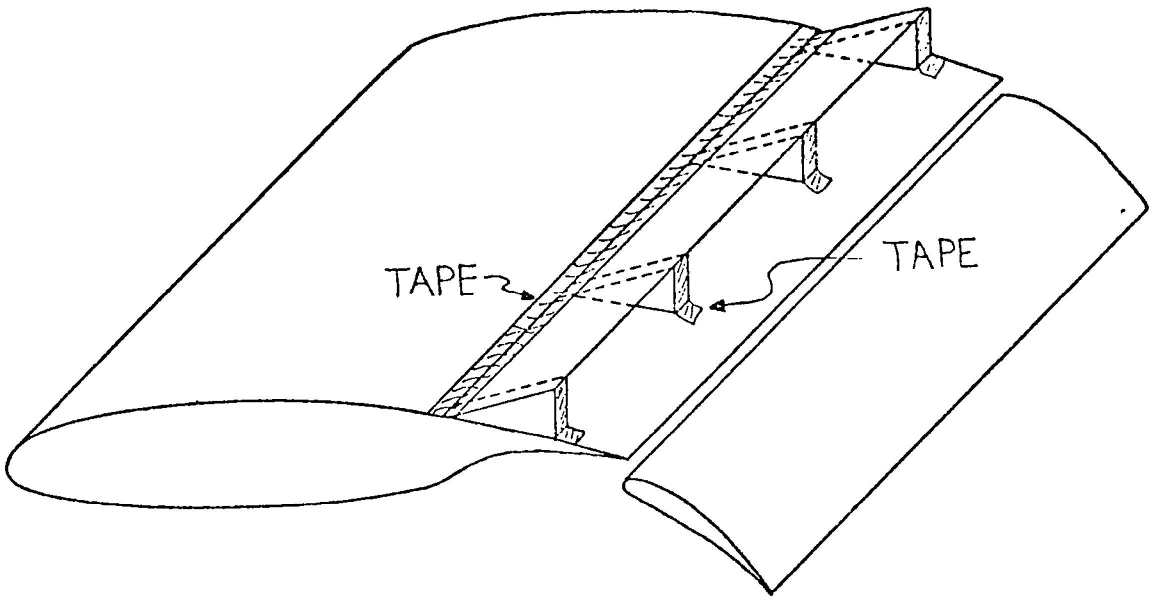
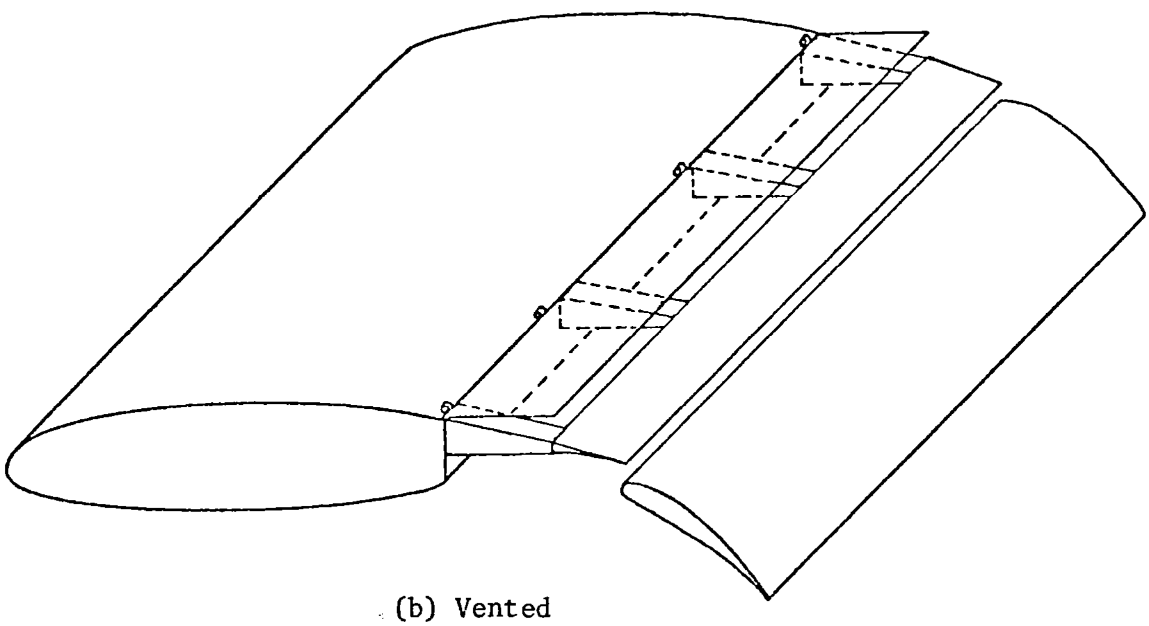


Figure 1 - Airfoil and Flap Geometry

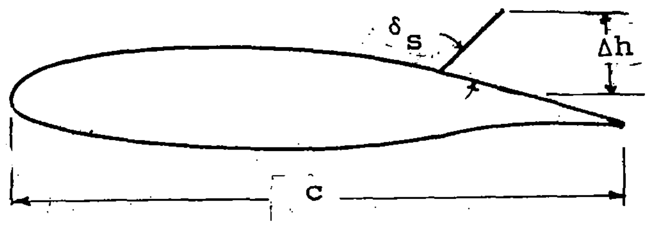


(a) Unvented



(b) Vented

Figure 2 - Model Geometry



Spoiler Chord 15%
Gap 0%
Hingeline 70%

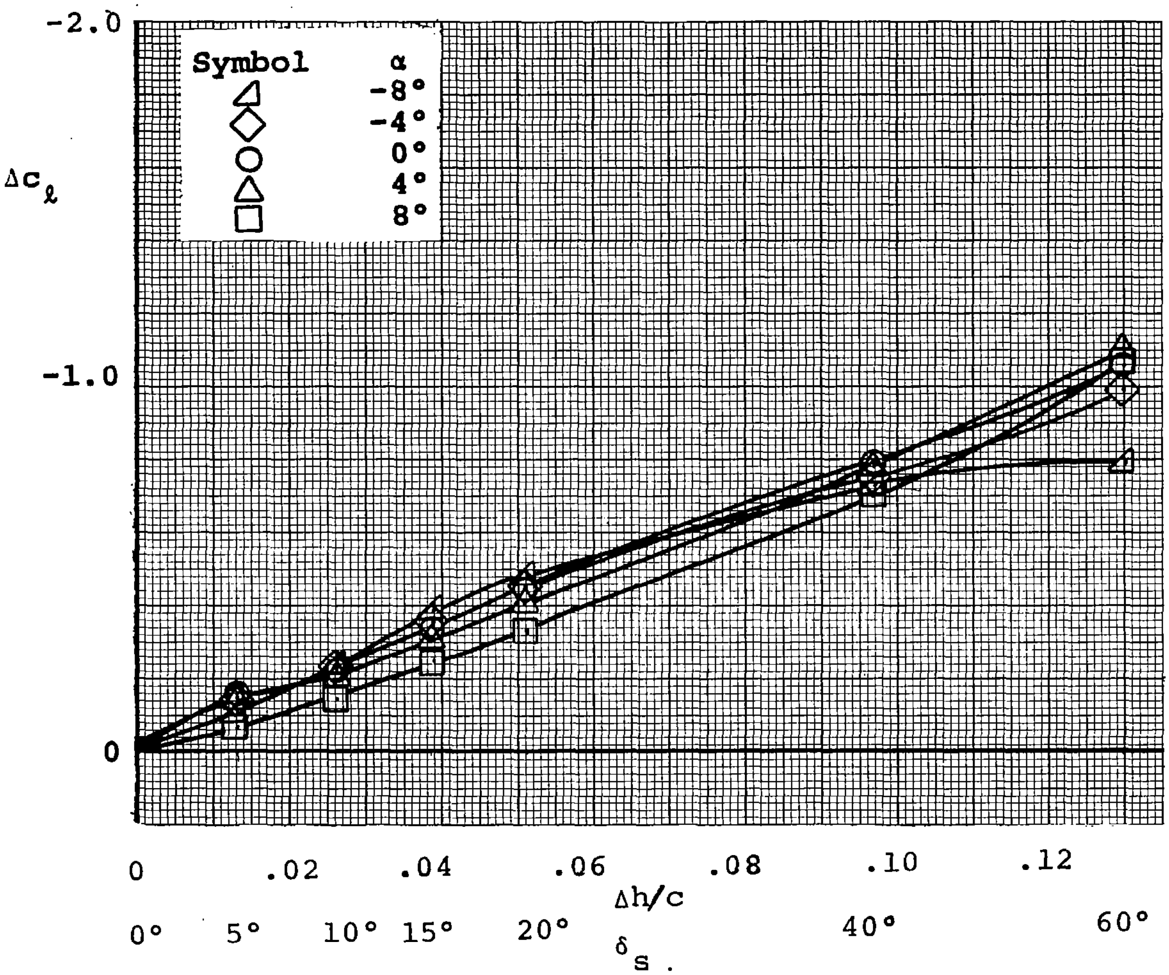


Figure 3(a) Effect of unvented 15%c spoiler on lift. Flap nested.

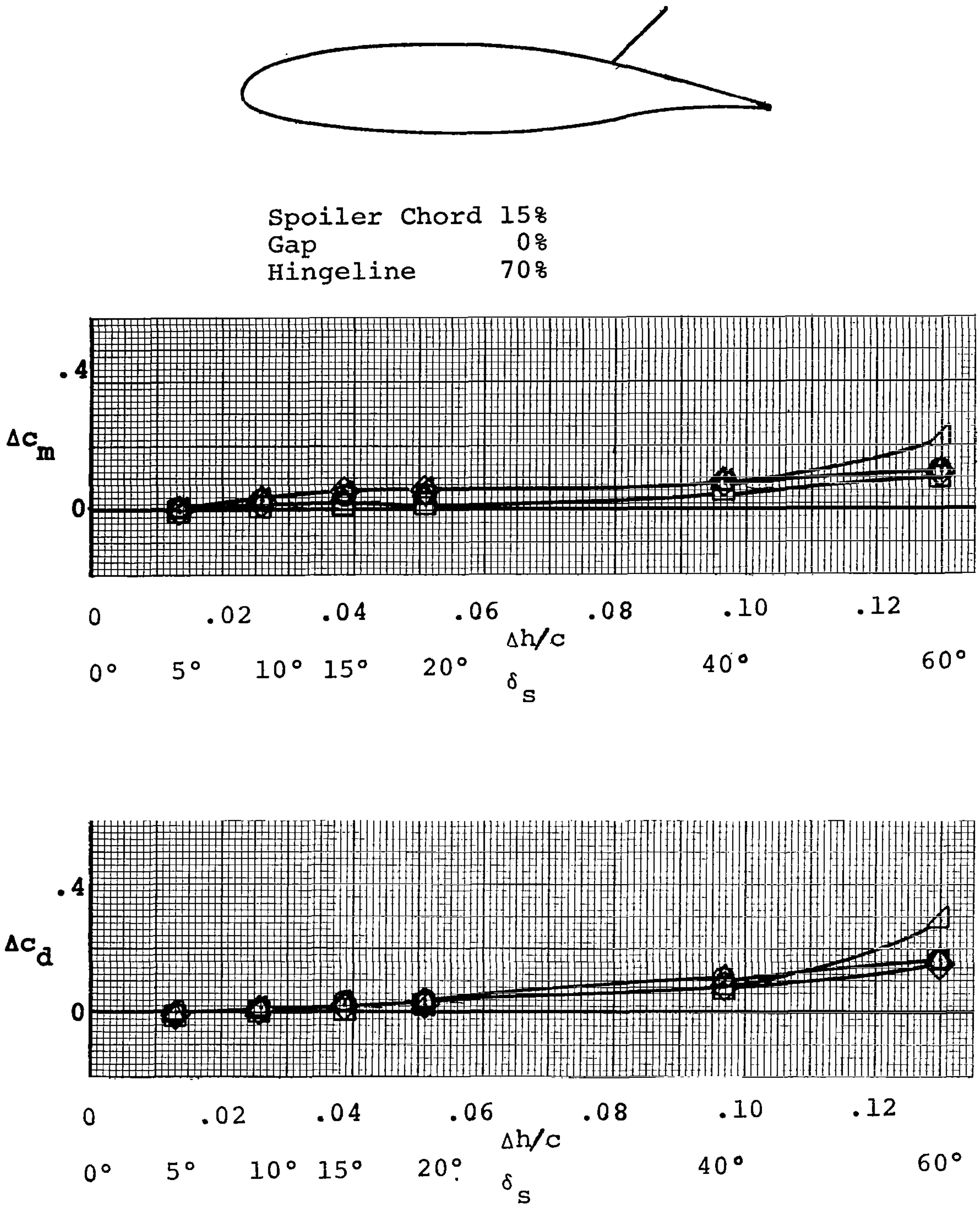
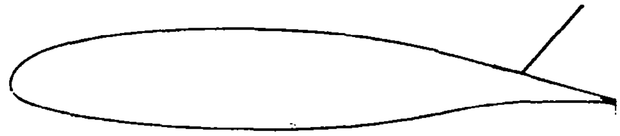


Figure 3(b) - Effect of unvented 15%c spoiler on drag and pitching moment. Flap nested.



Spoiler Chord 15%
Gap 0%
Hingline 85%

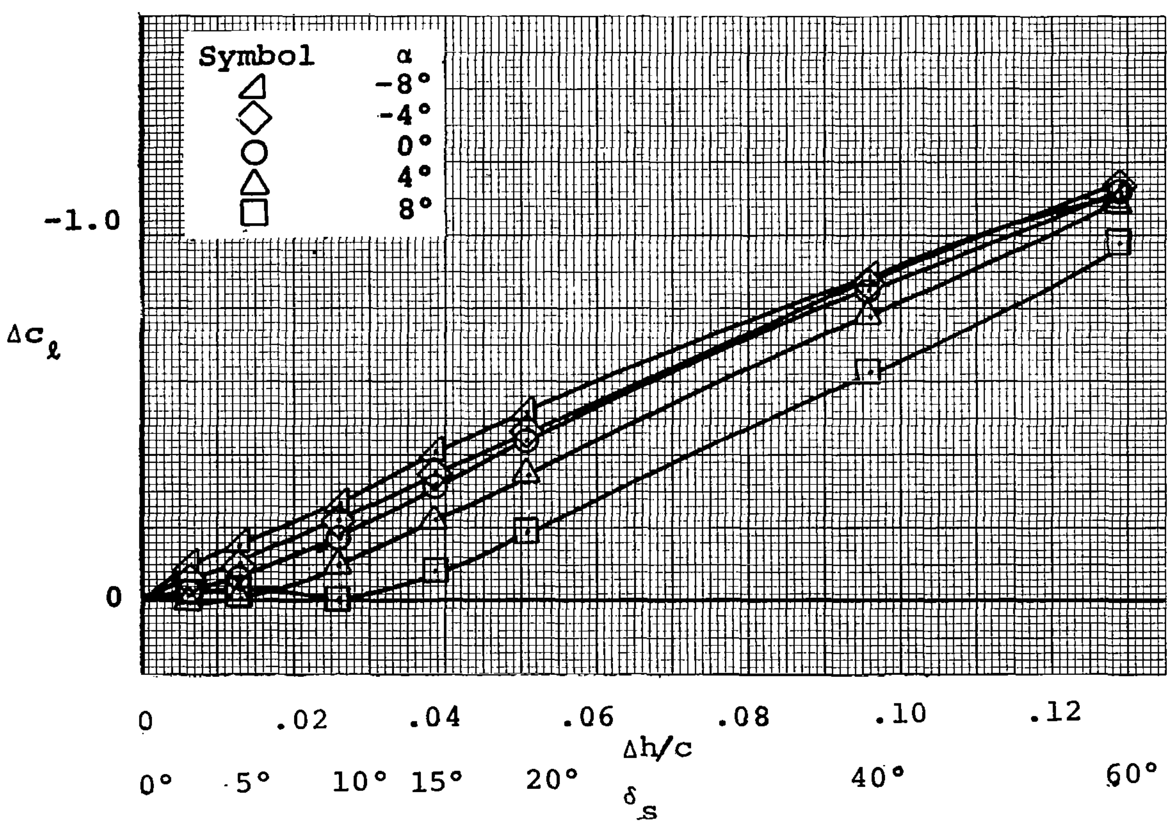


Figure 3(c) - Effect of unvented 15%c spoiler on lift. Flap nested.

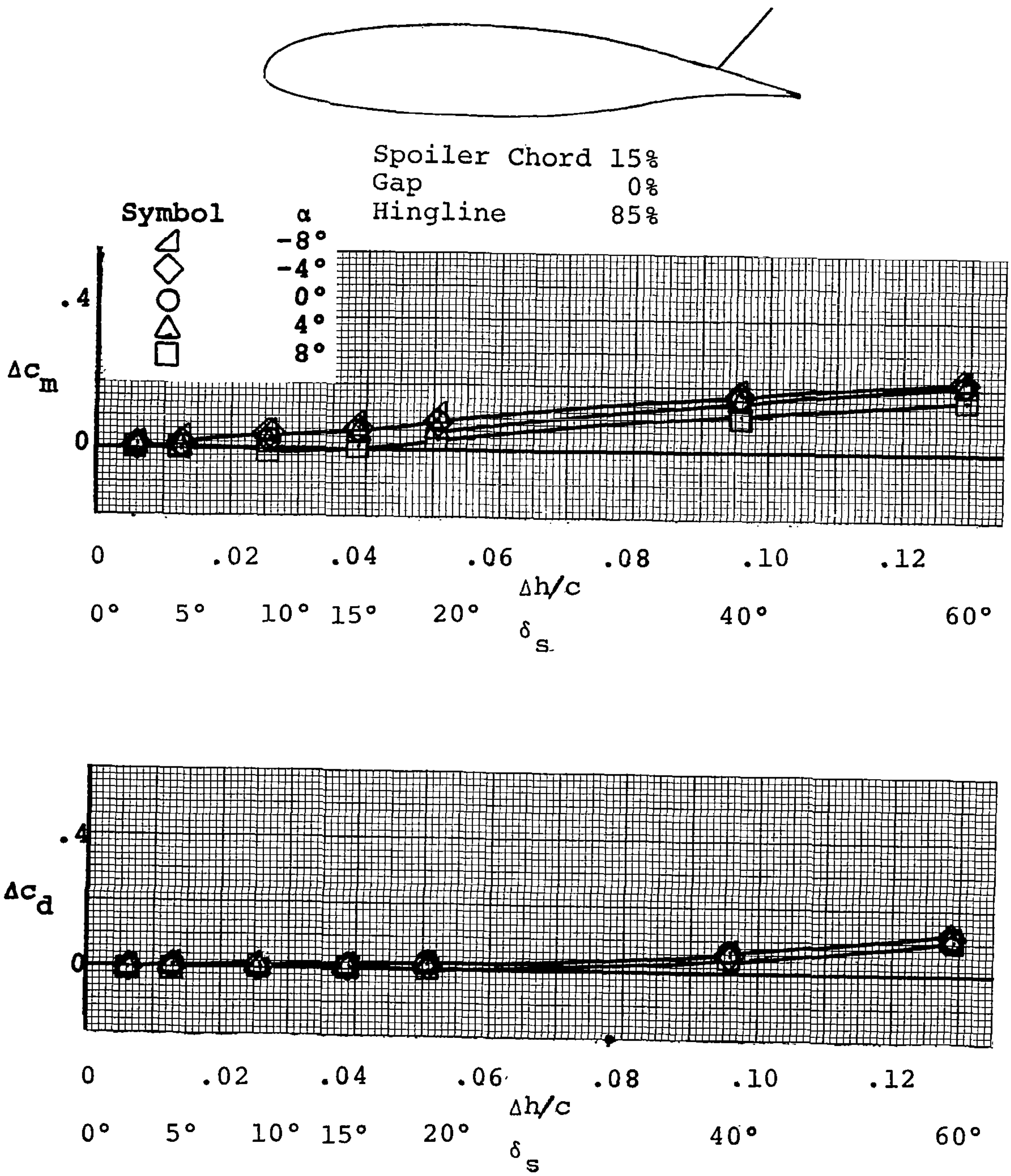
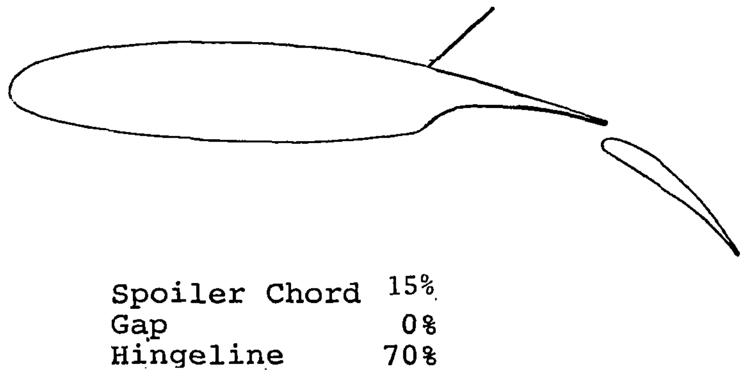


Figure 3(d) - Effect of unvented 15%c spoiler on pitching moment and drag. Flap nested.



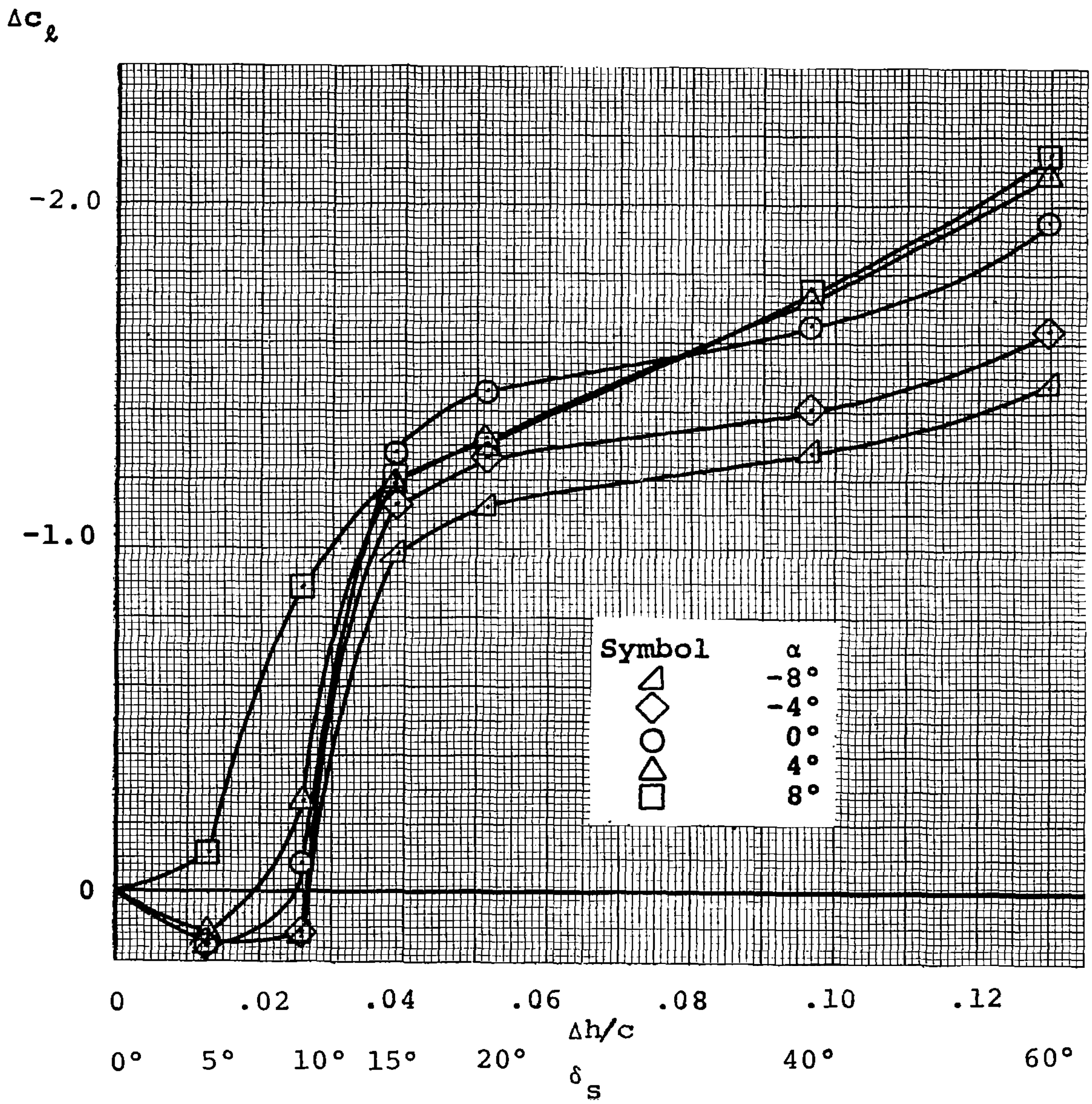


Figure 4(a) - Effect of unvented spoiler on lift. Flap 40°.

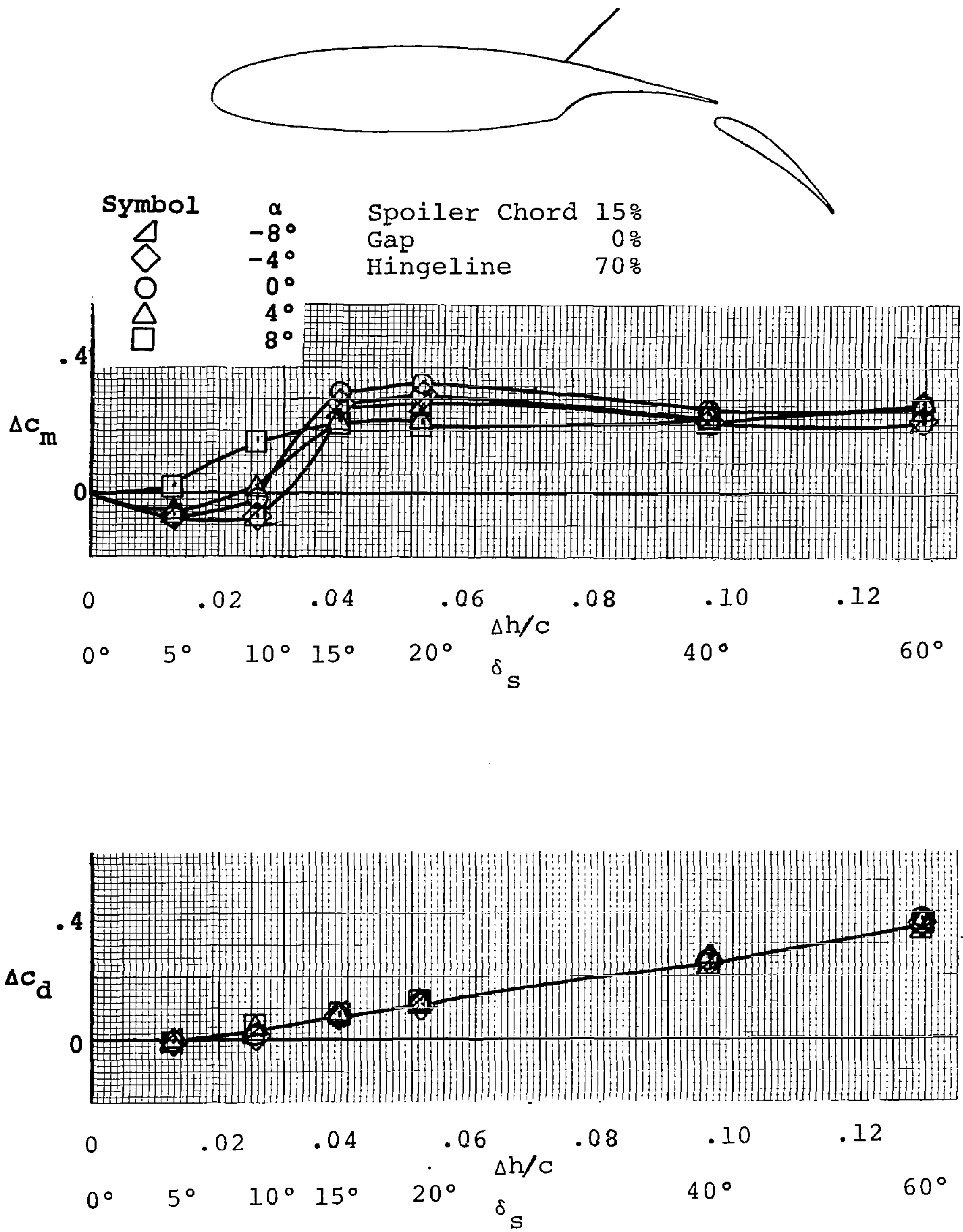


Figure 4(b) - Effect of unvented 15%c spoiler on pitching moment and drag. Flap 40°.

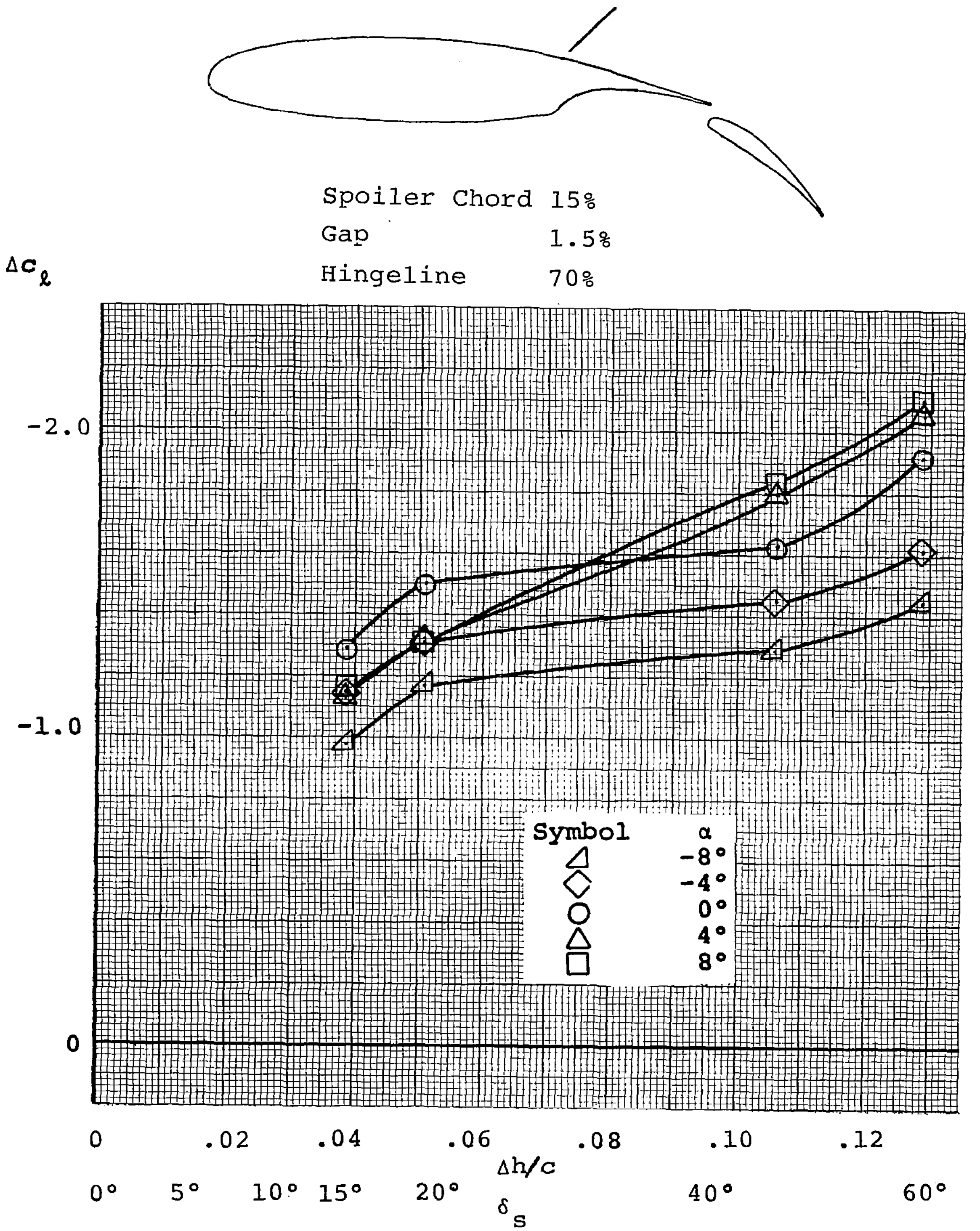


Figure 5(a) - Effects of unvented 15%c spoiler with gap on lift. Flap 40°.

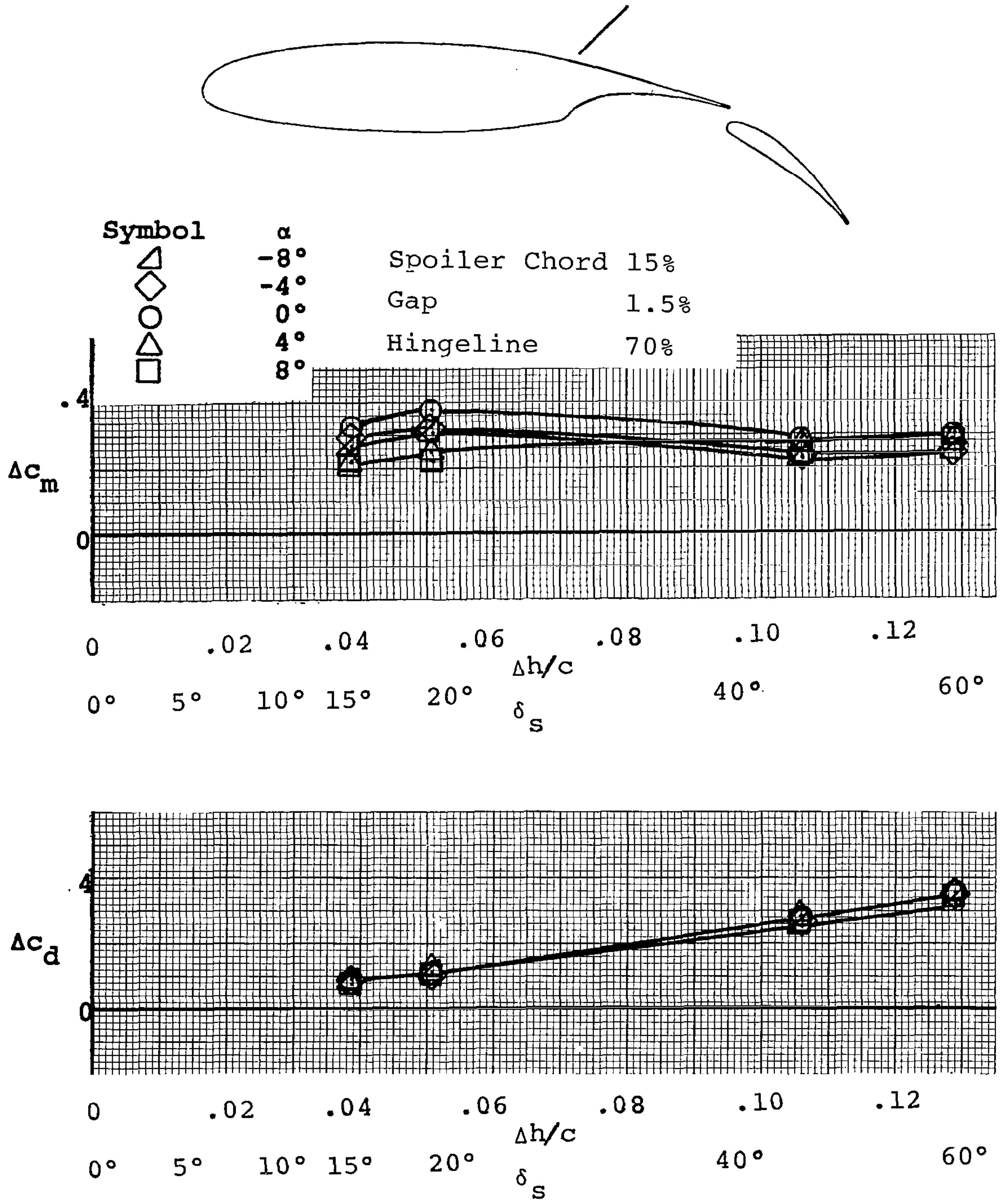


Figure 5(b) - Effects of unvented 15%c spoiler with gap on pitching moment and drag. Flap 40°.

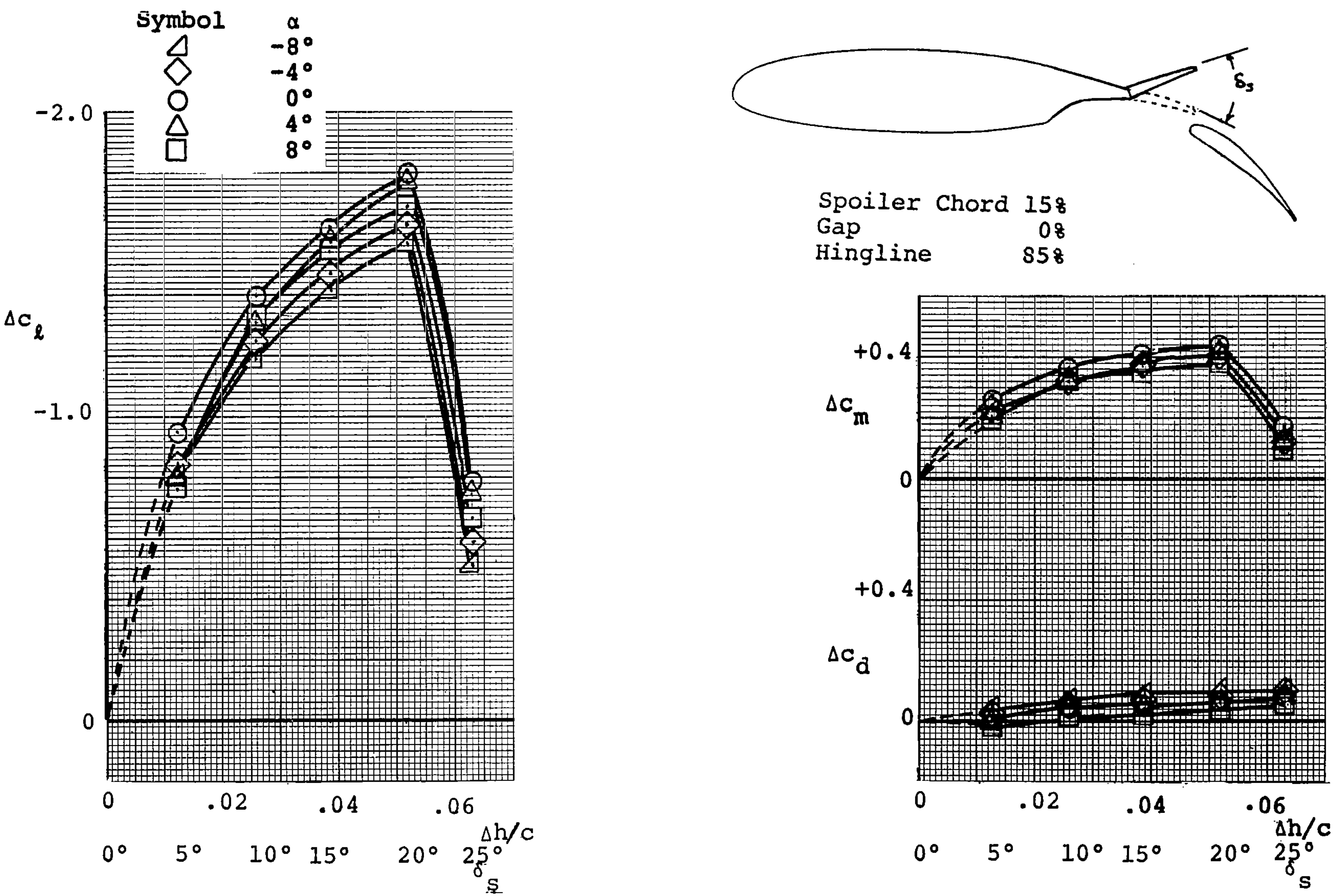


Figure 6 - Effects of slot lip spoiler on lift, pitching moment and drag. Flap 40°.

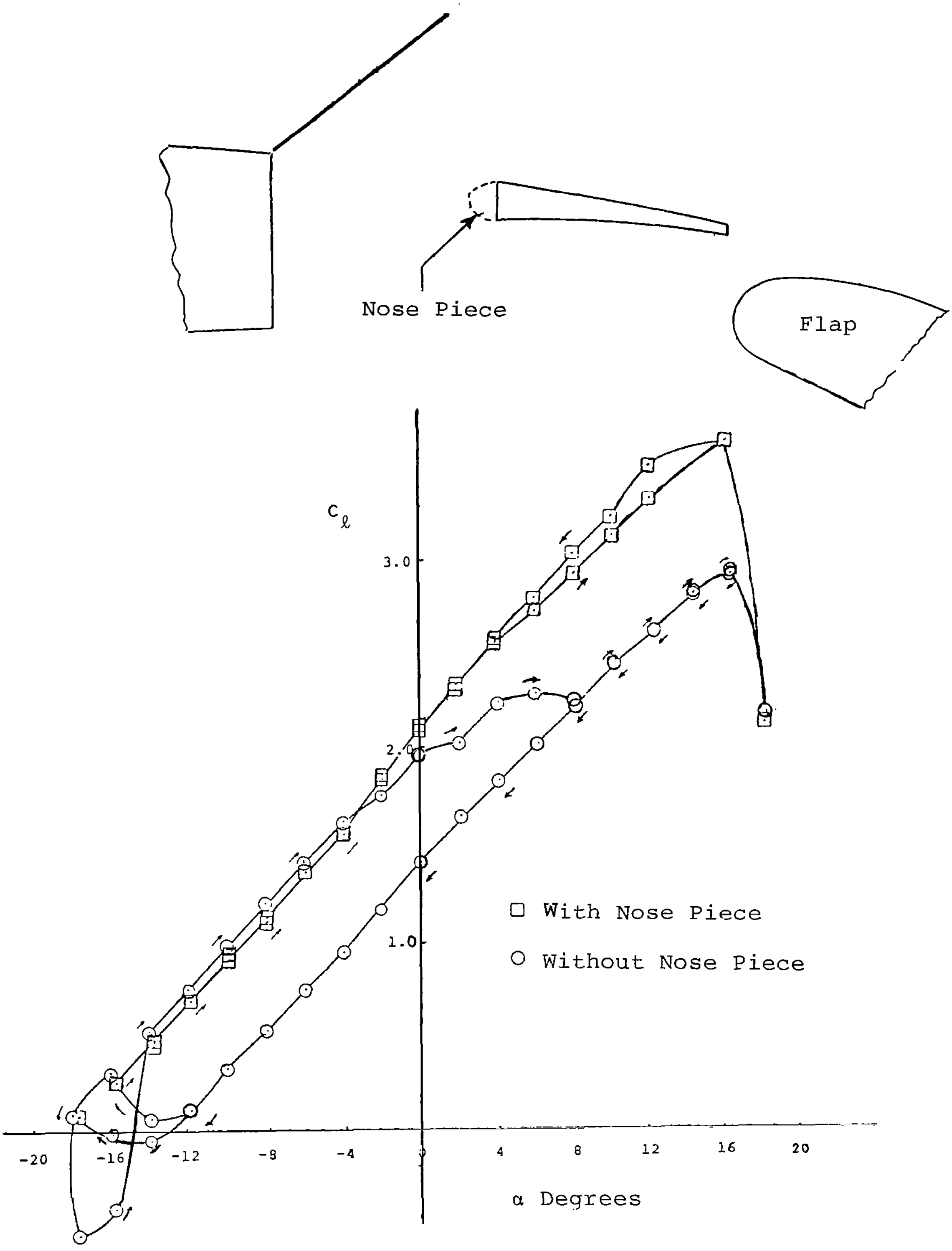


Figure 7 - Effect of cavity nose shape on hysteresis.
40° flap, 15° spoiler.

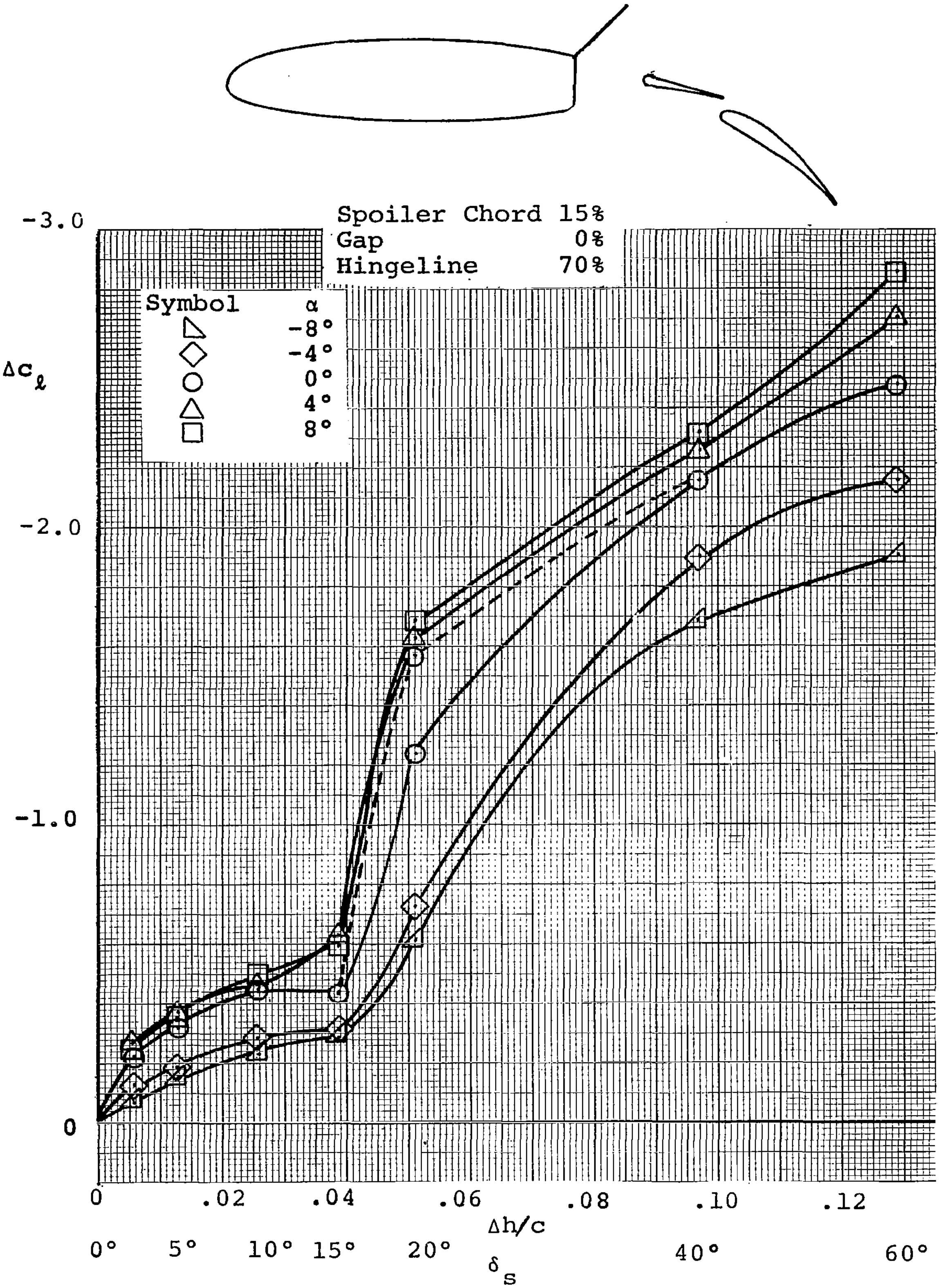


Figure 8(a) - Effect of venting on lift. Flap 40°.
(Compare with Figure 4(a).)

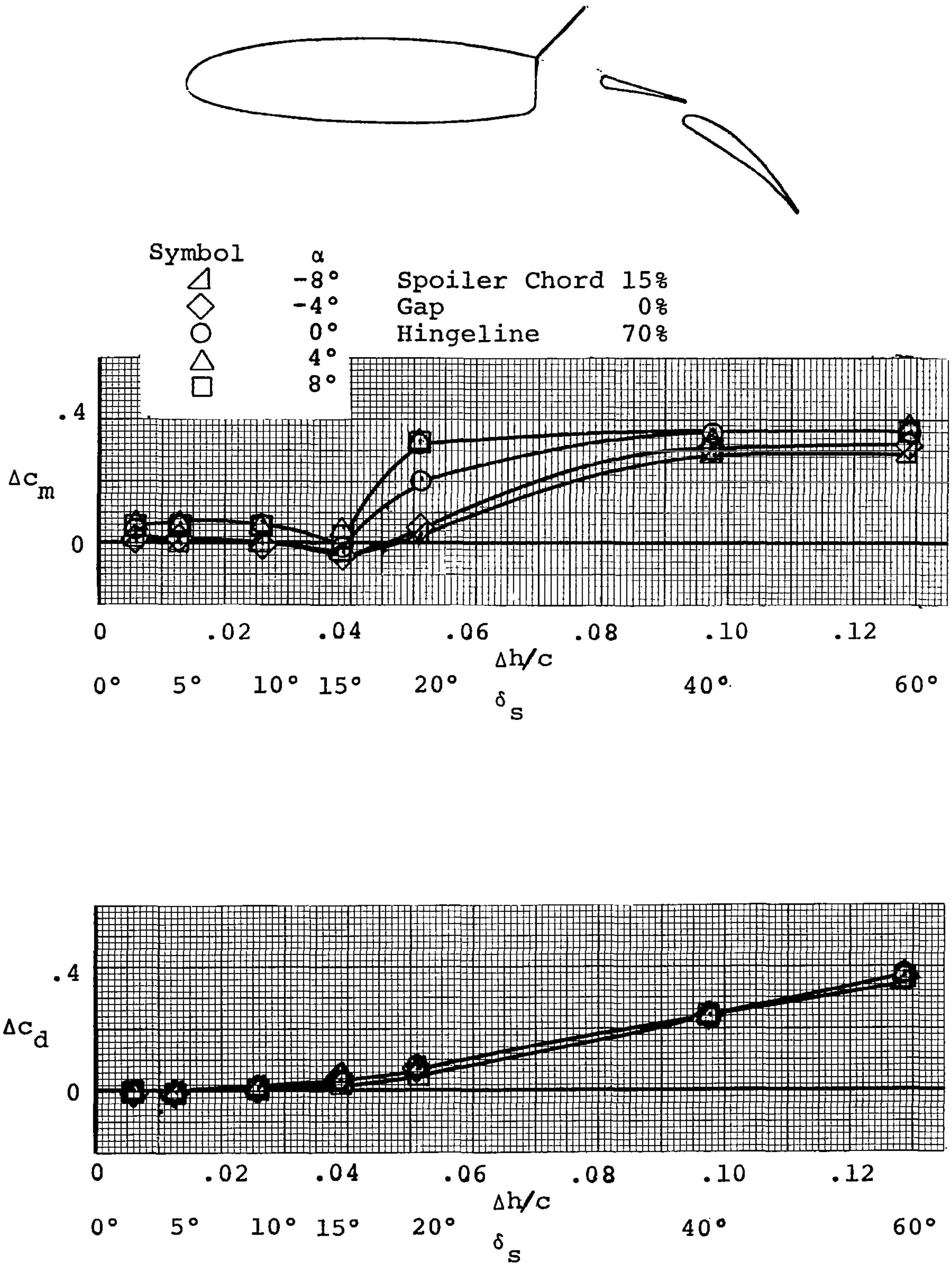


Figure 8(b) - Effects of venting on pitching moment and drag. Flap 40°. (Compare with Figure 4(b).)

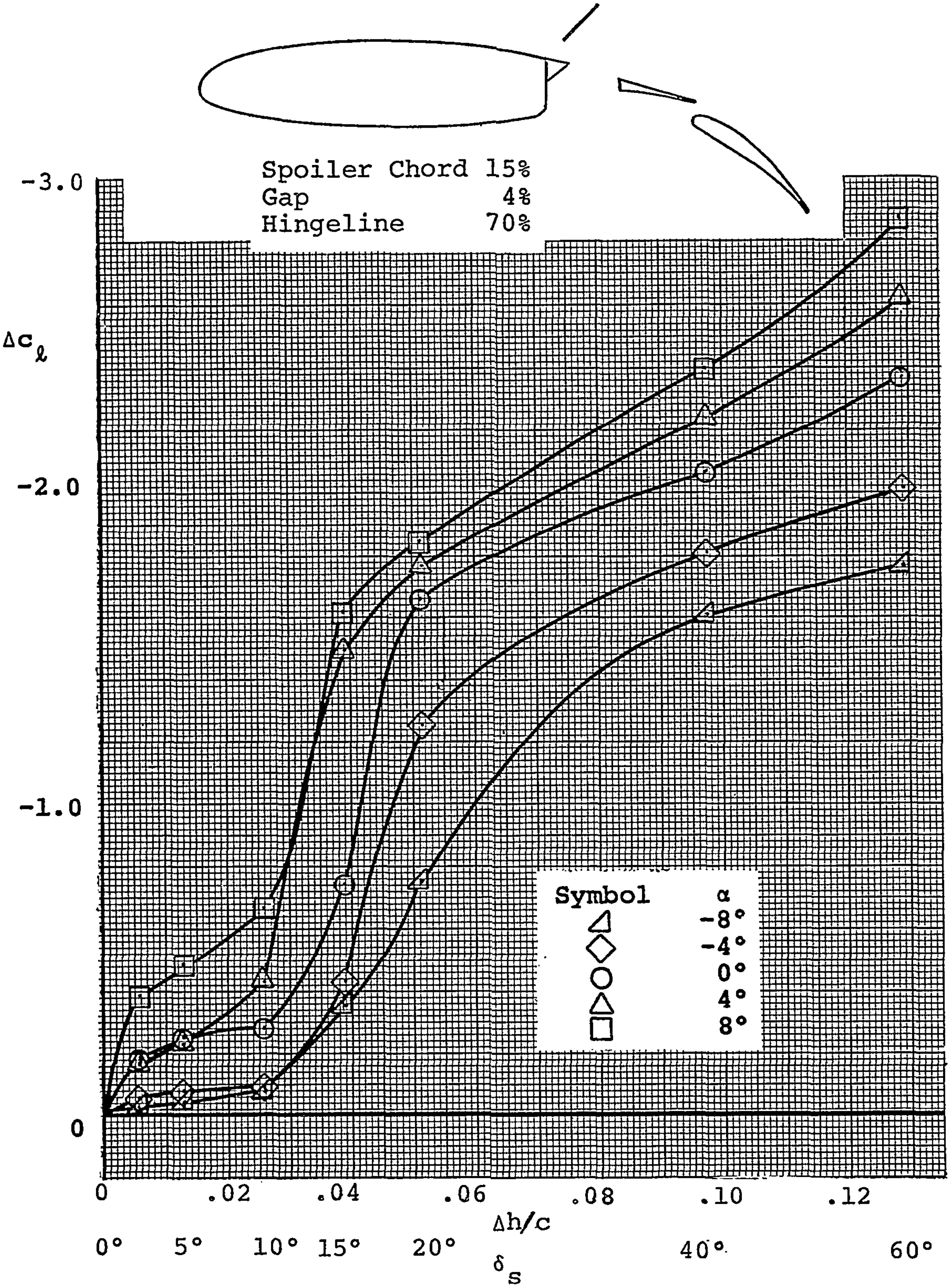


Figure 9(a) - Effect of spoiler gap on lift. Flap 40°. (Compare with Figure 8(a).)

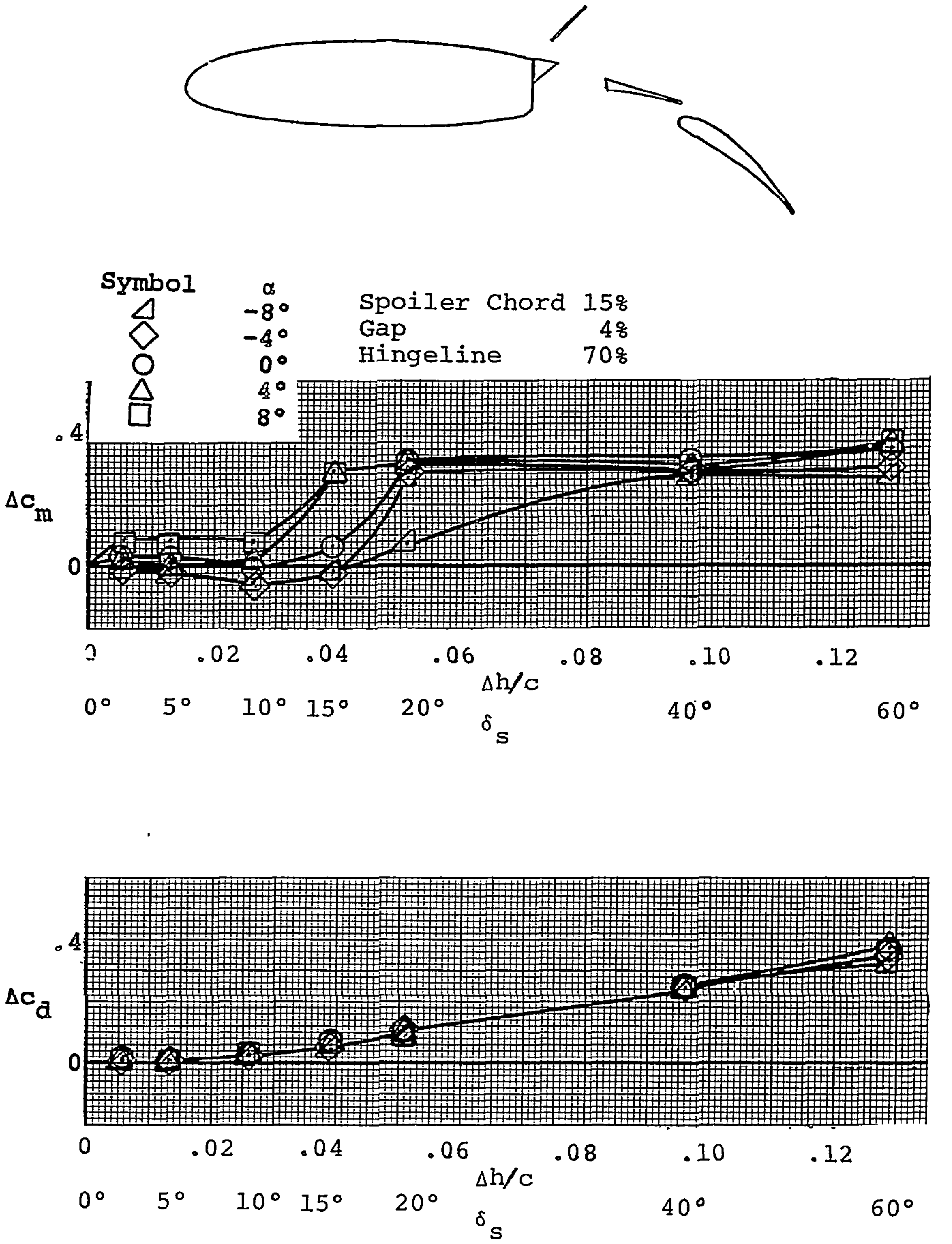


Figure 9(b) - Effect of spoiler gap on pitching moment and drag. Flap 40°. (Compare with Figure 8(b).)

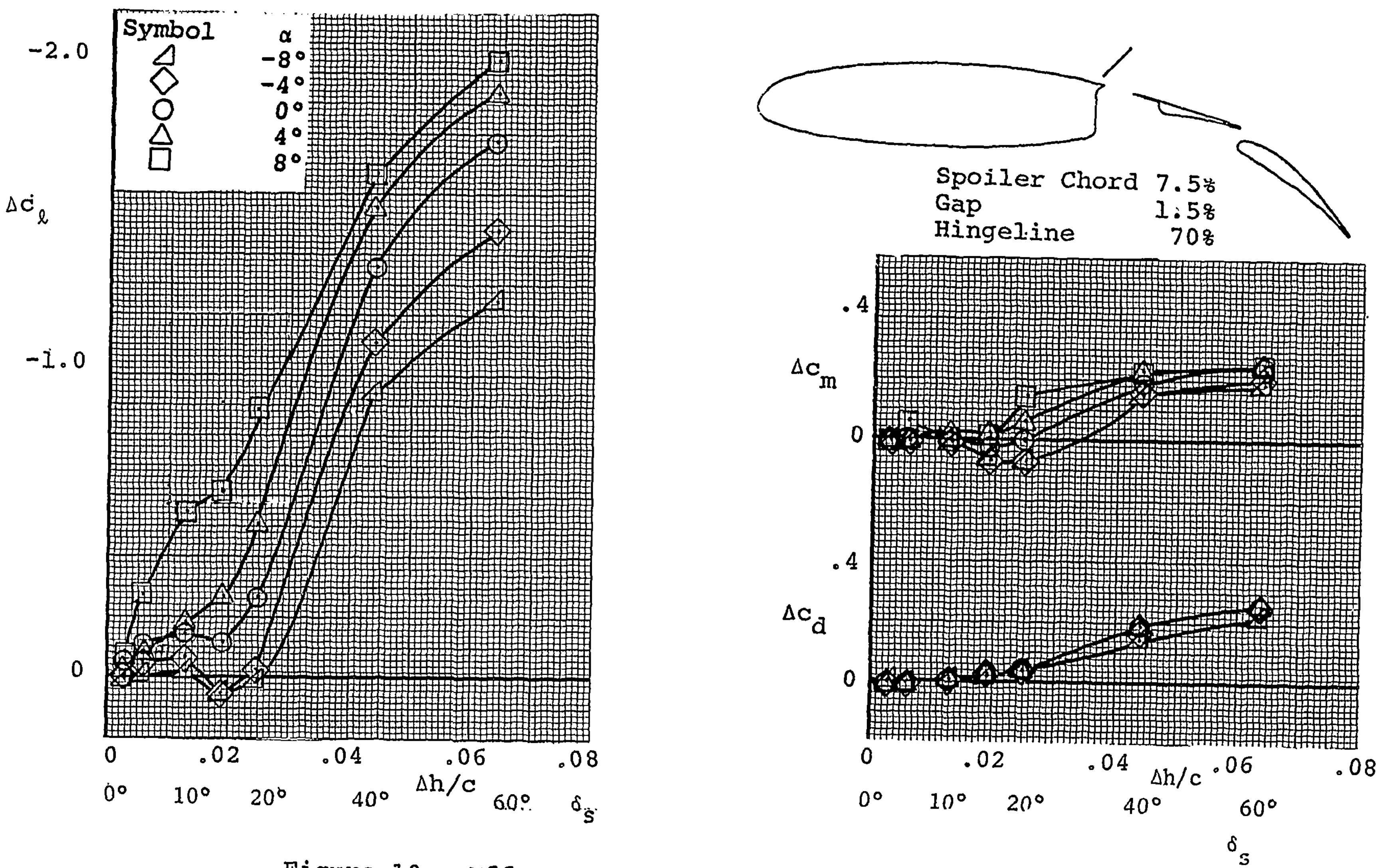


Figure 10 - Effect of 7.5%c spoiler on lift, pitching moment and drag. Flap 40°. (Compare with Figure 11.)

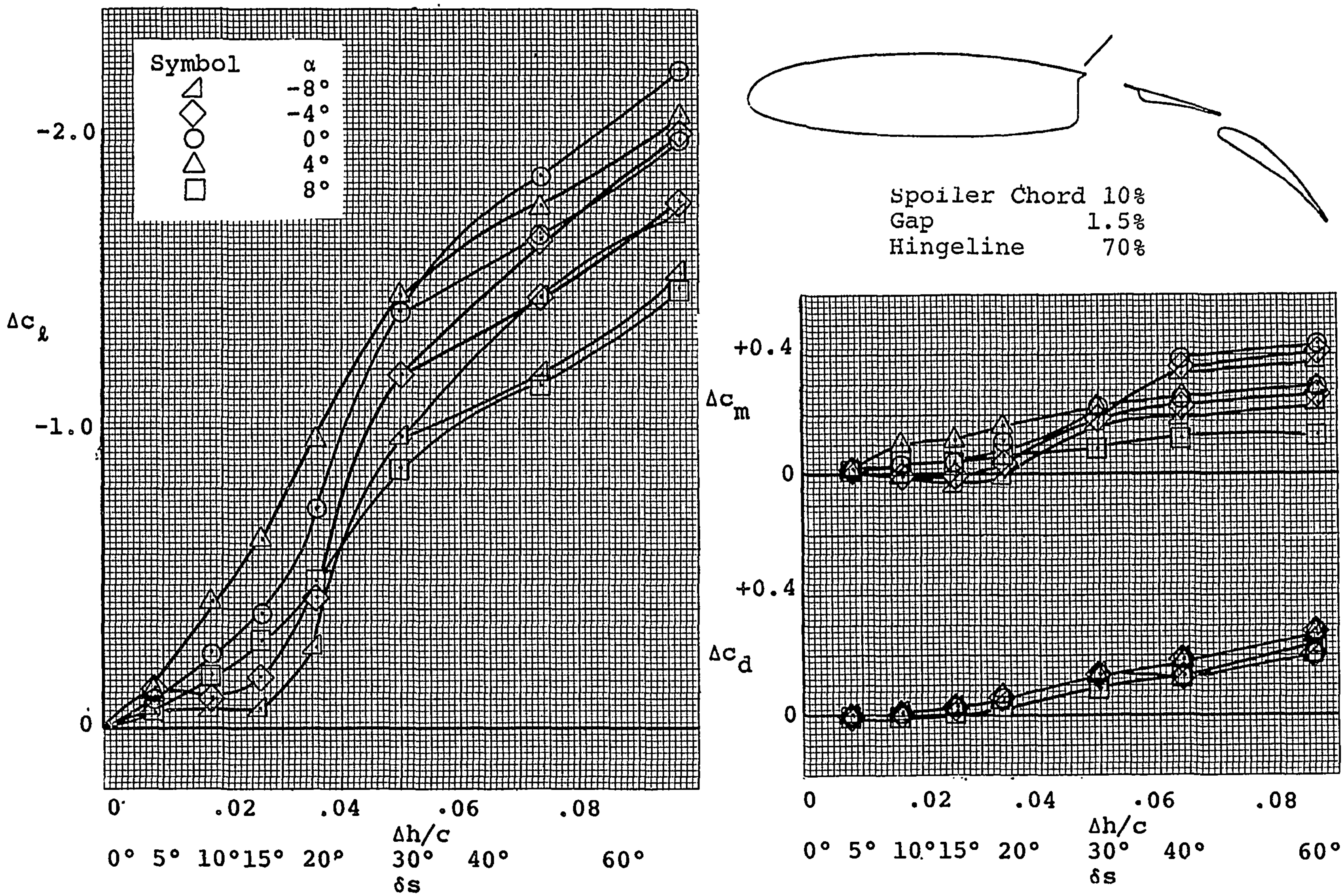


Figure 11(a) - Effect of 10% flat plate spoiler on lift, drag, and pitching moment. Flap 40°. (Compare with Figure 10.)

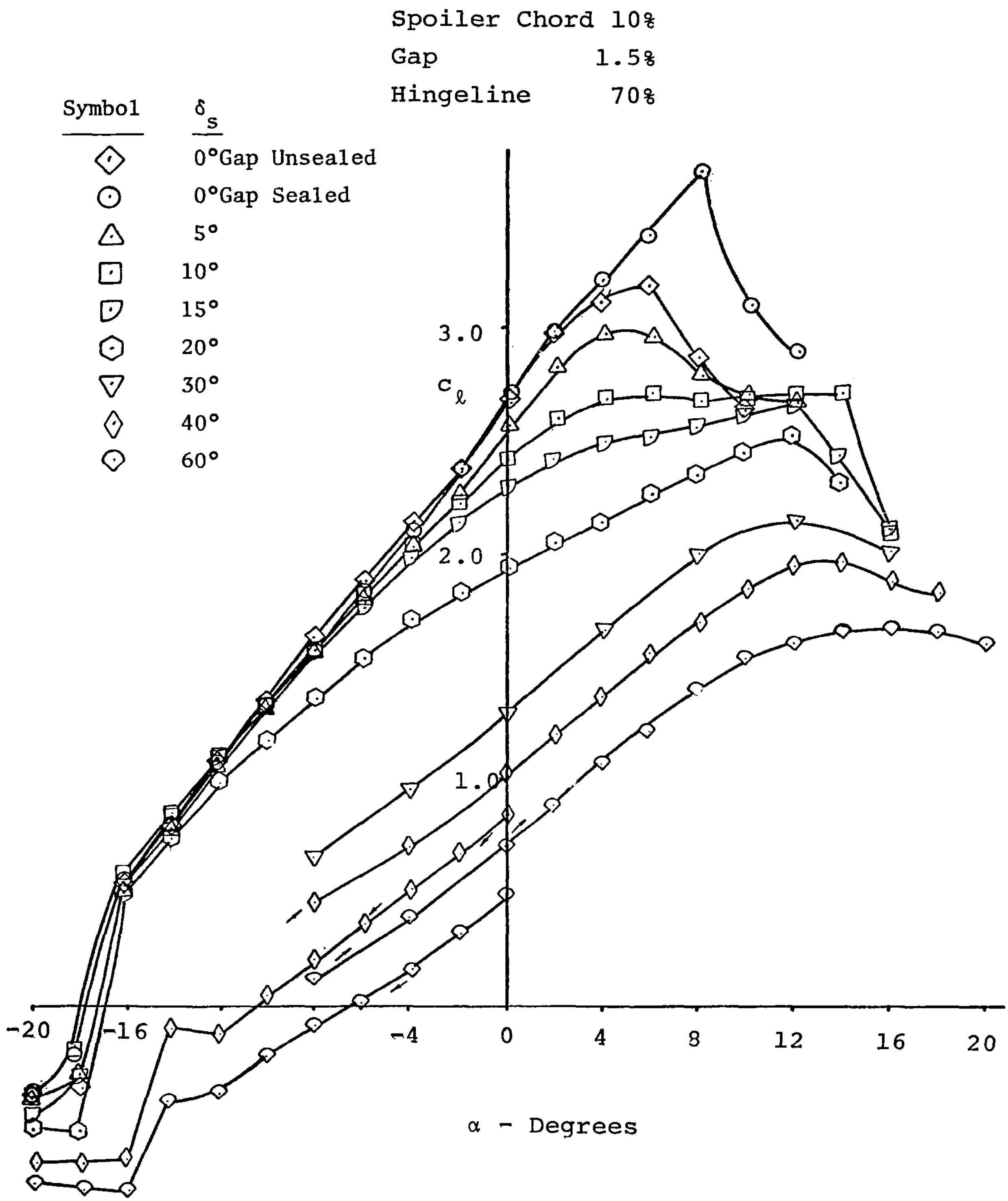


Figure 11(b) - Effect of spoiler on lift, Flap 40°. (Compare with Figure 12(b).)

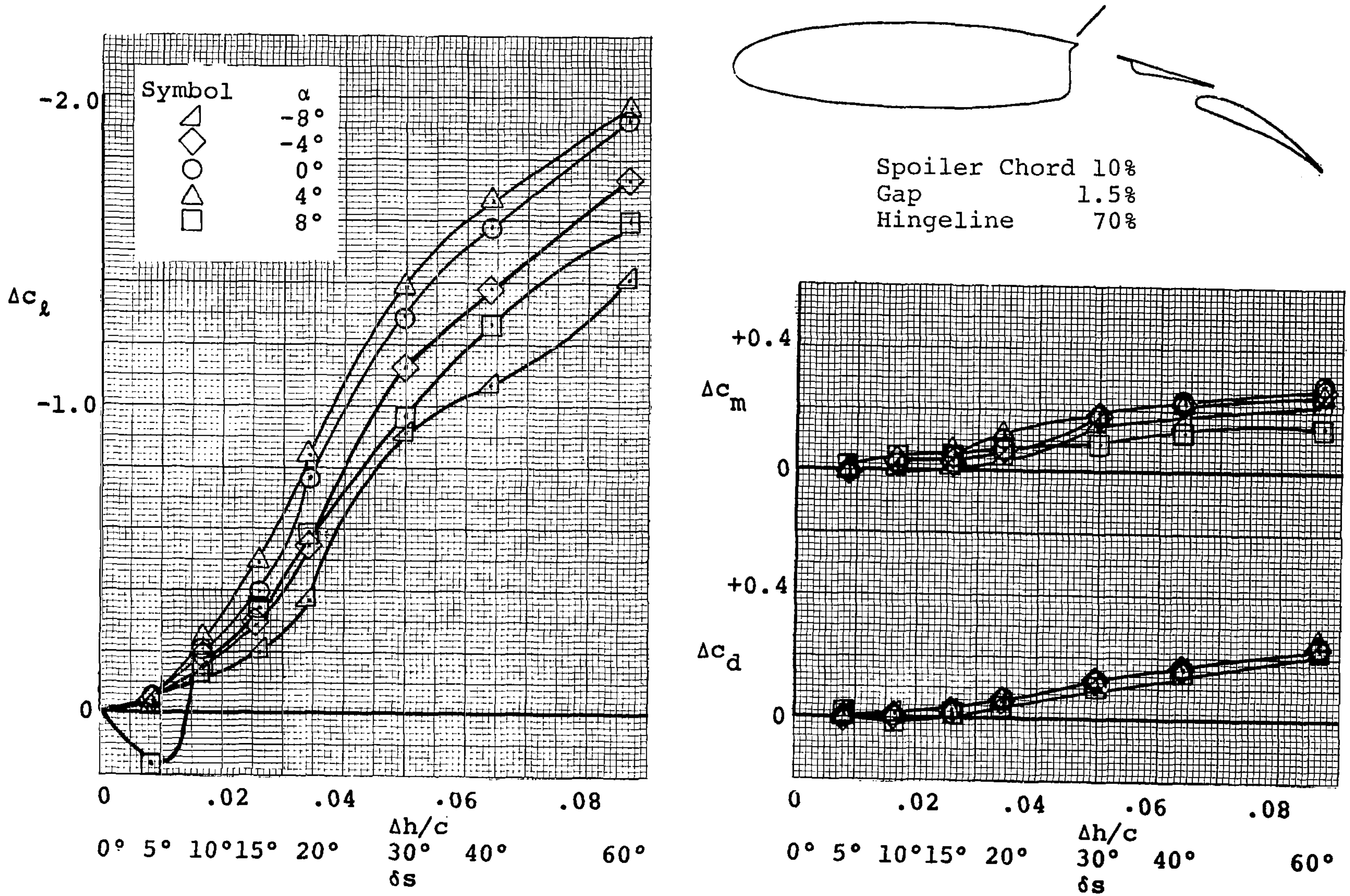


Figure 12(a) - Effect of flat plate spoiler on lift, pitching moment and drag. Flap 30°. (Compare with Figure 11.)

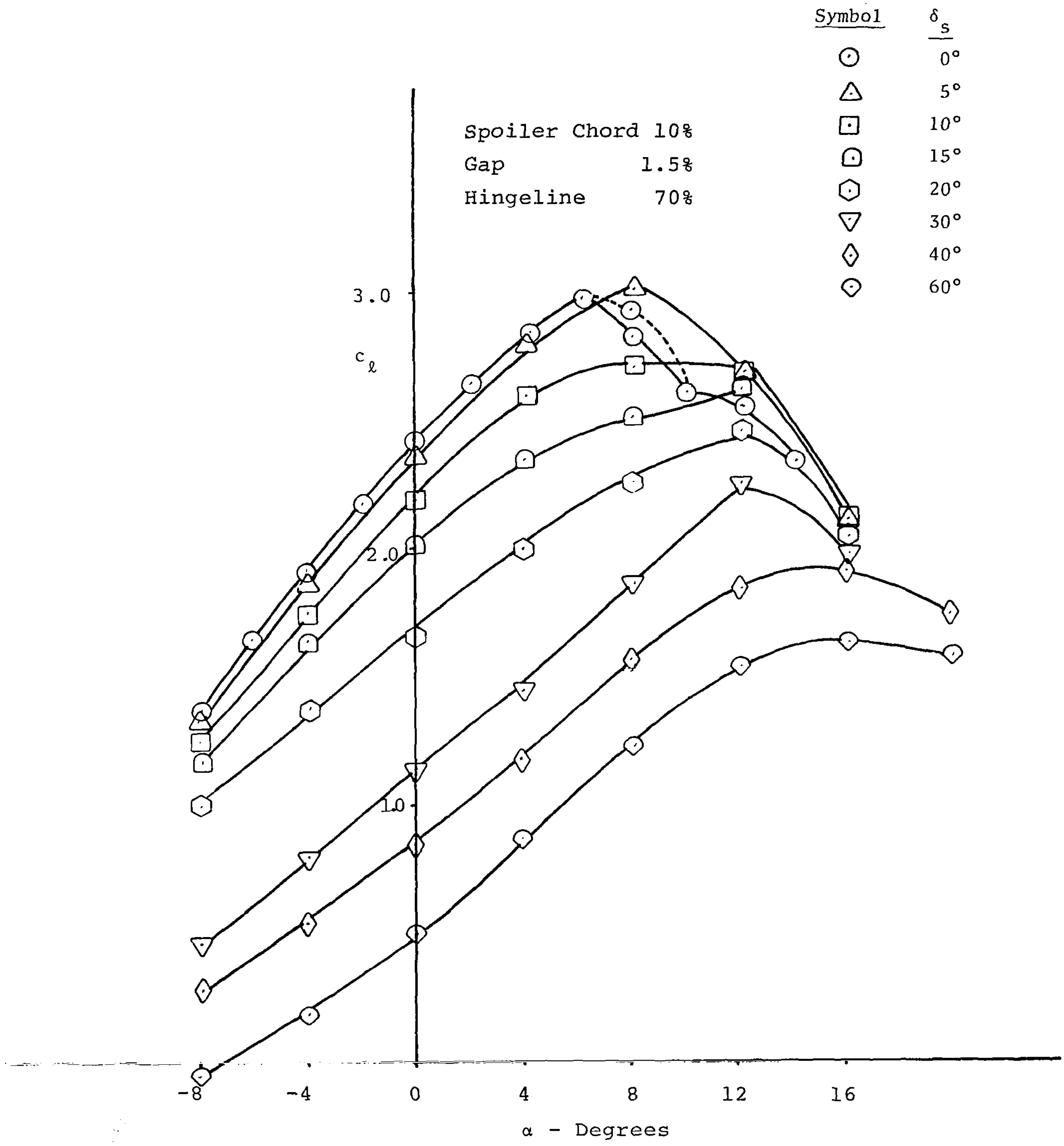


Figure 12(b) - Effect of spoiler on lift, Flap 30°.
(Compare with Figure 11(b).)

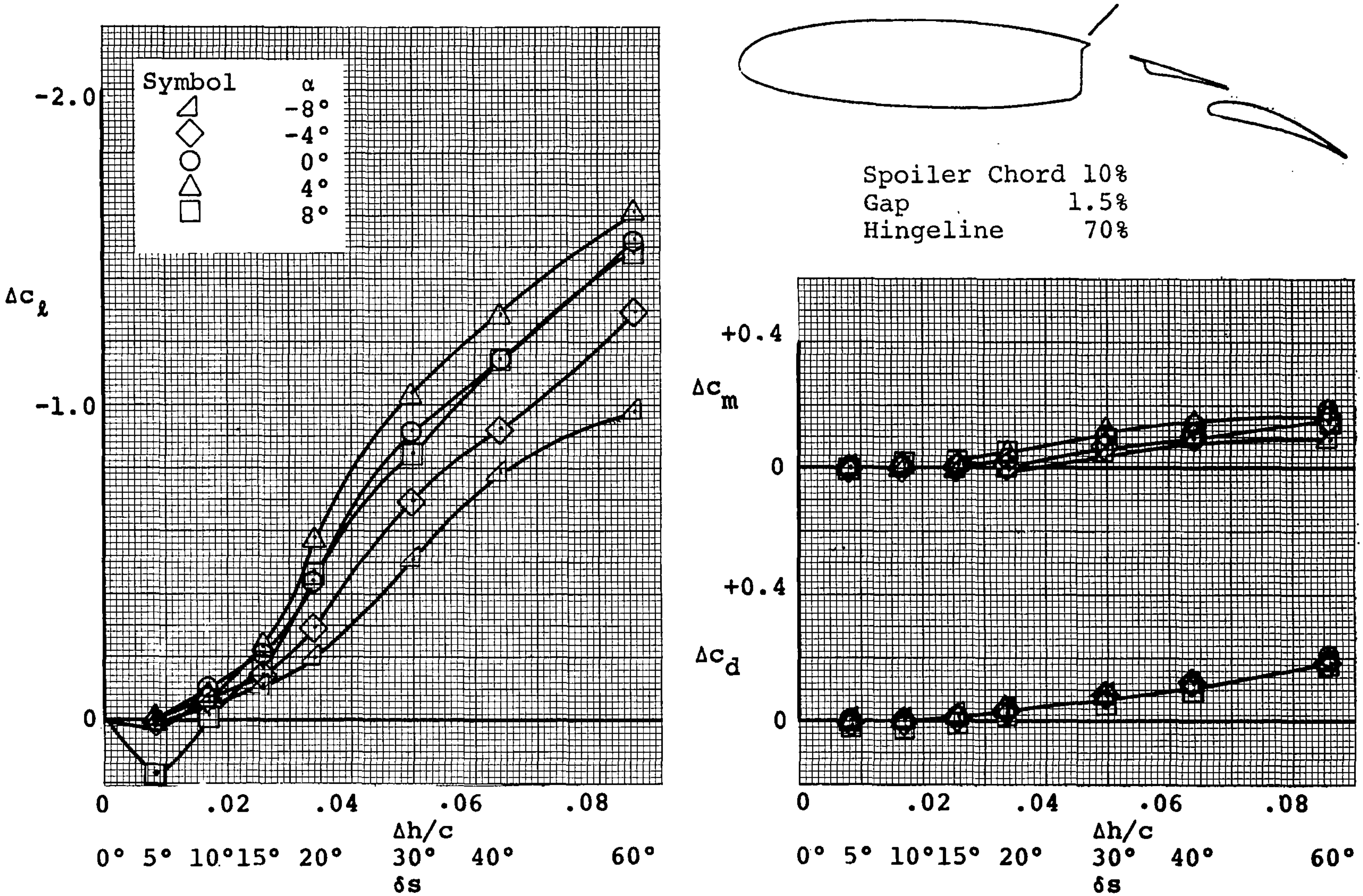


Figure 13(a) - Effect of flat plate spoiler on lift, drag and pitching moment. Flap 20°. (Compare with Figures 11 and 12).

Spoiler Chord 10%
Gap 1.5%
Hingeline 70%

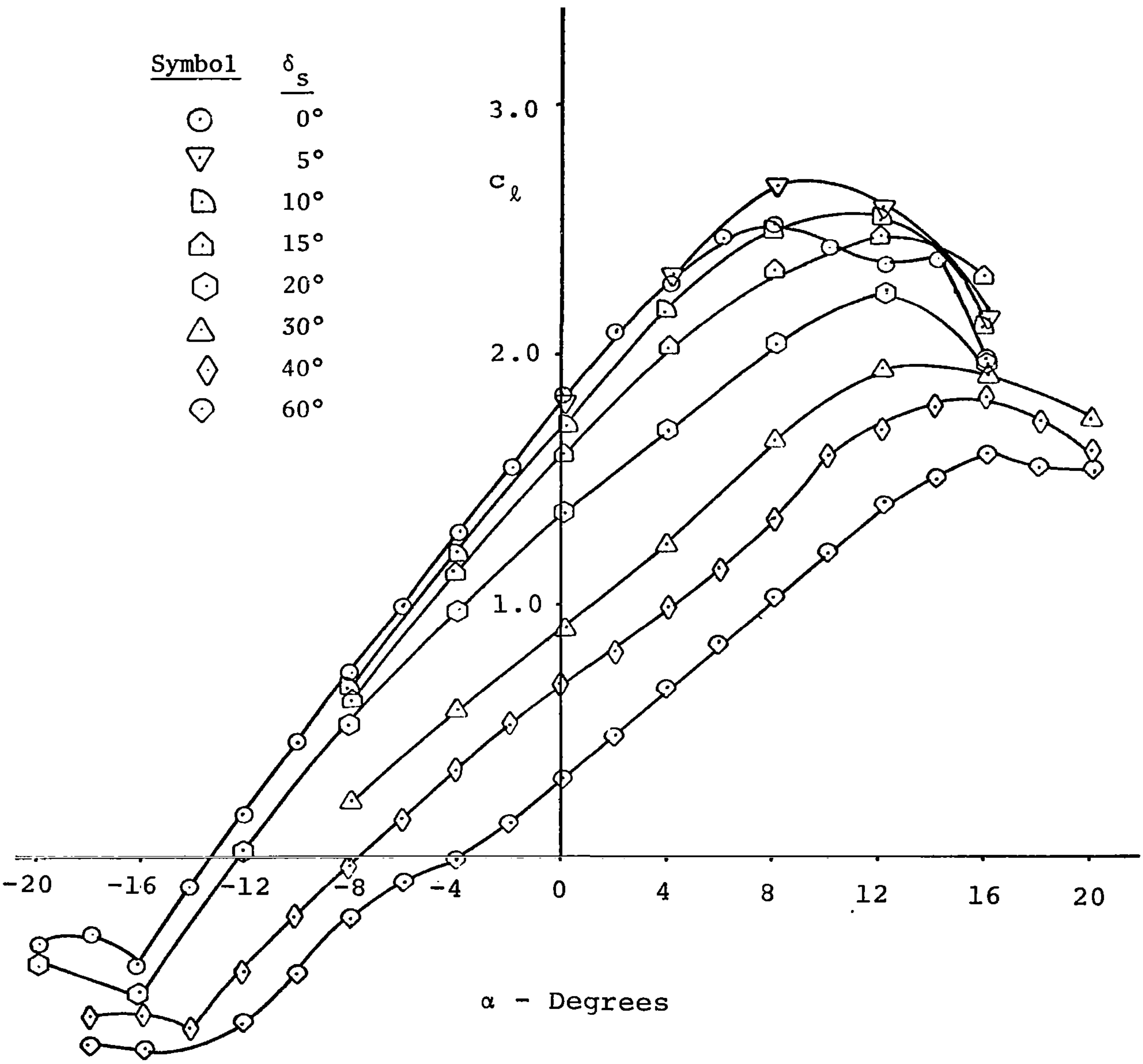
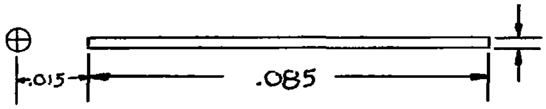
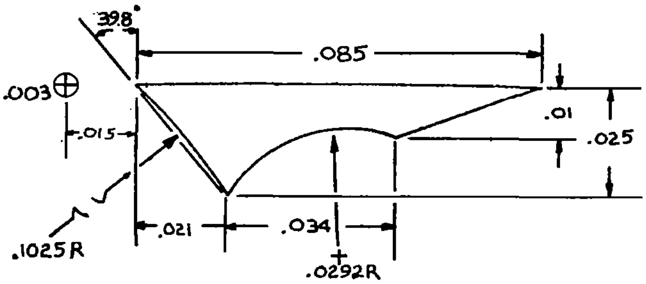


Figure 13(b) - Effect of spoiler on lift, Flap 20°. (Compare with Figures 11(b) and 12(b).)

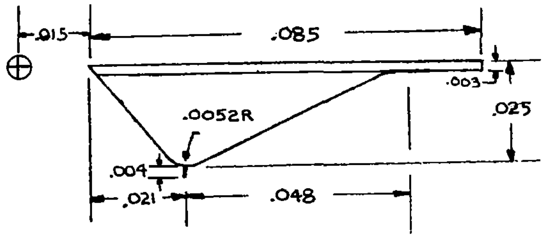


Flat plate

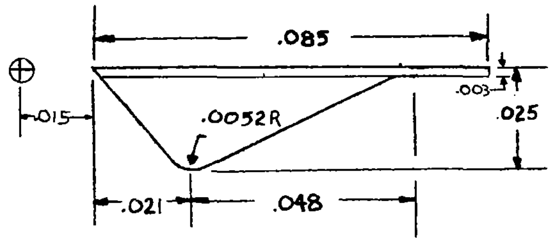


MU-2

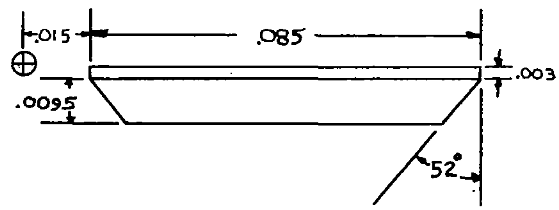
⊕—Hingeline



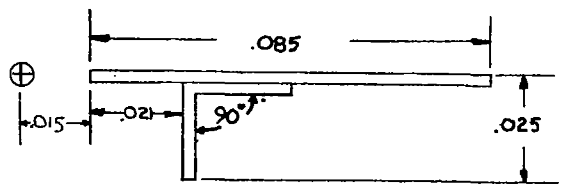
Triangle with shim



Triangle



Thick flat plate



Tee

Note: All lengths are non-dimensionalized with respect to wing chord

Figure 14 - Spoiler Geometry

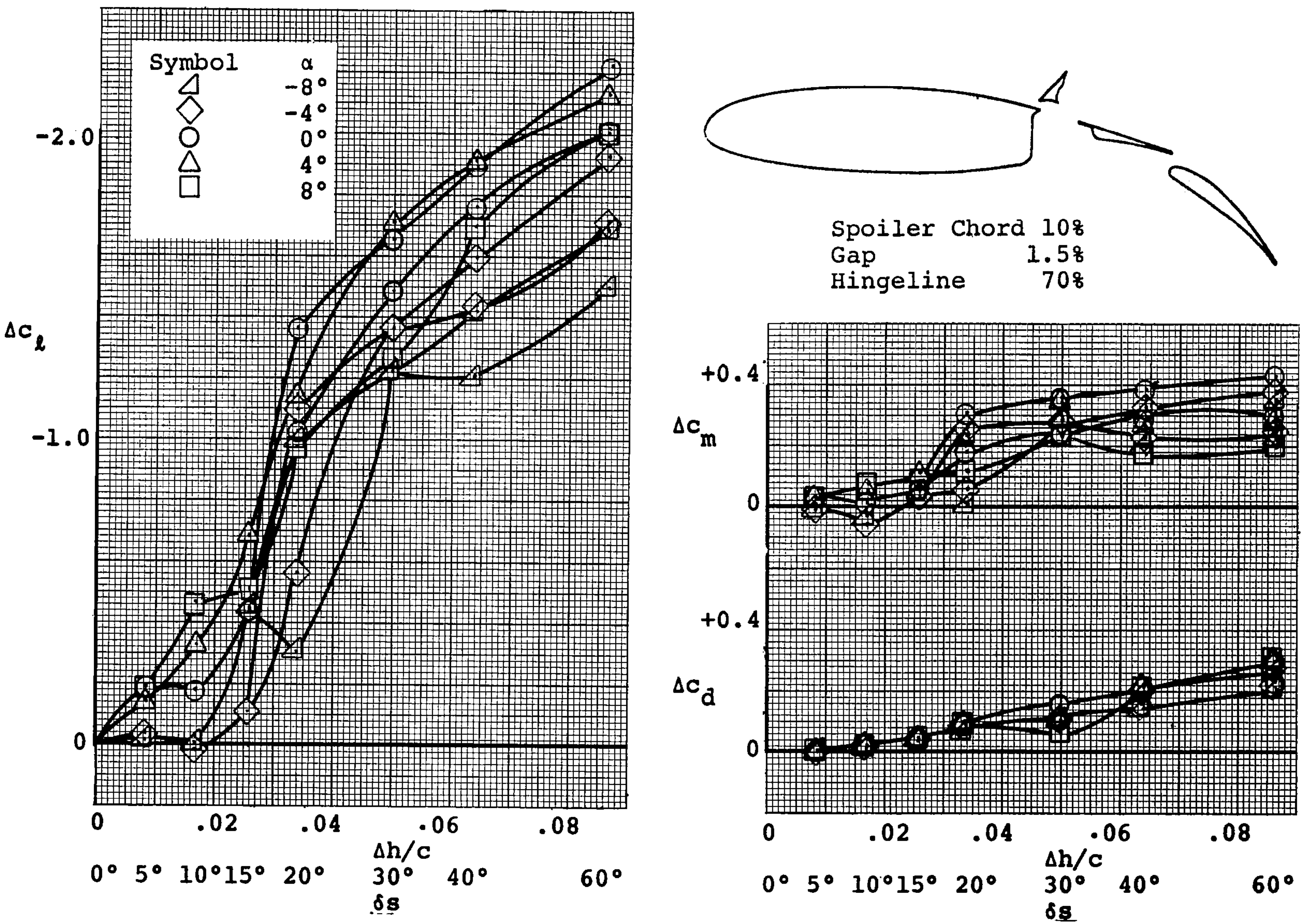


Figure 15 - Effect of 10%c MU-2 type spoiler on lift, pitching moment, and drag. Flap 40°.

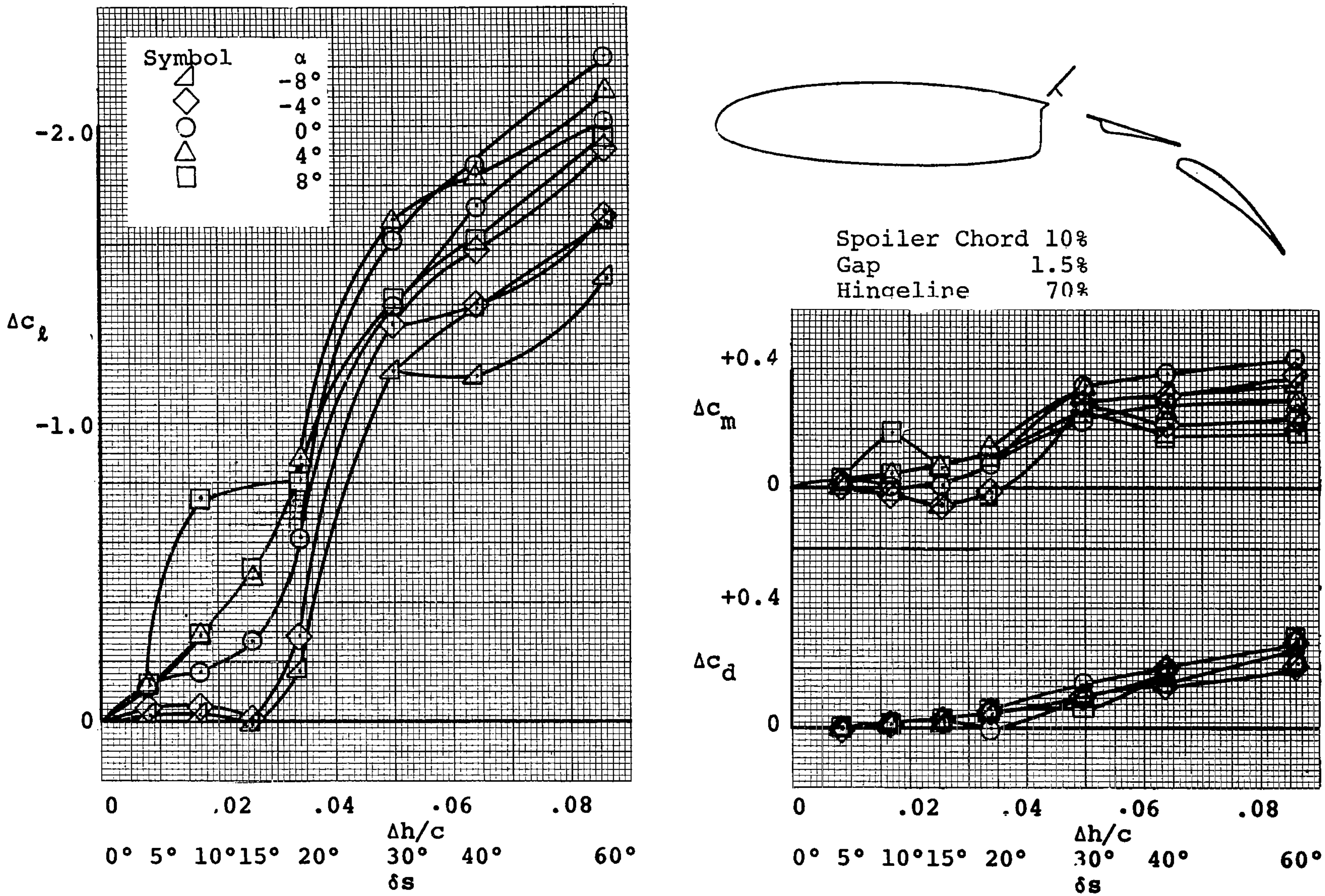


Figure 16 - Effect of 10%c T-type spoiler on lift, pitching moment, and drag. Flap 40°.

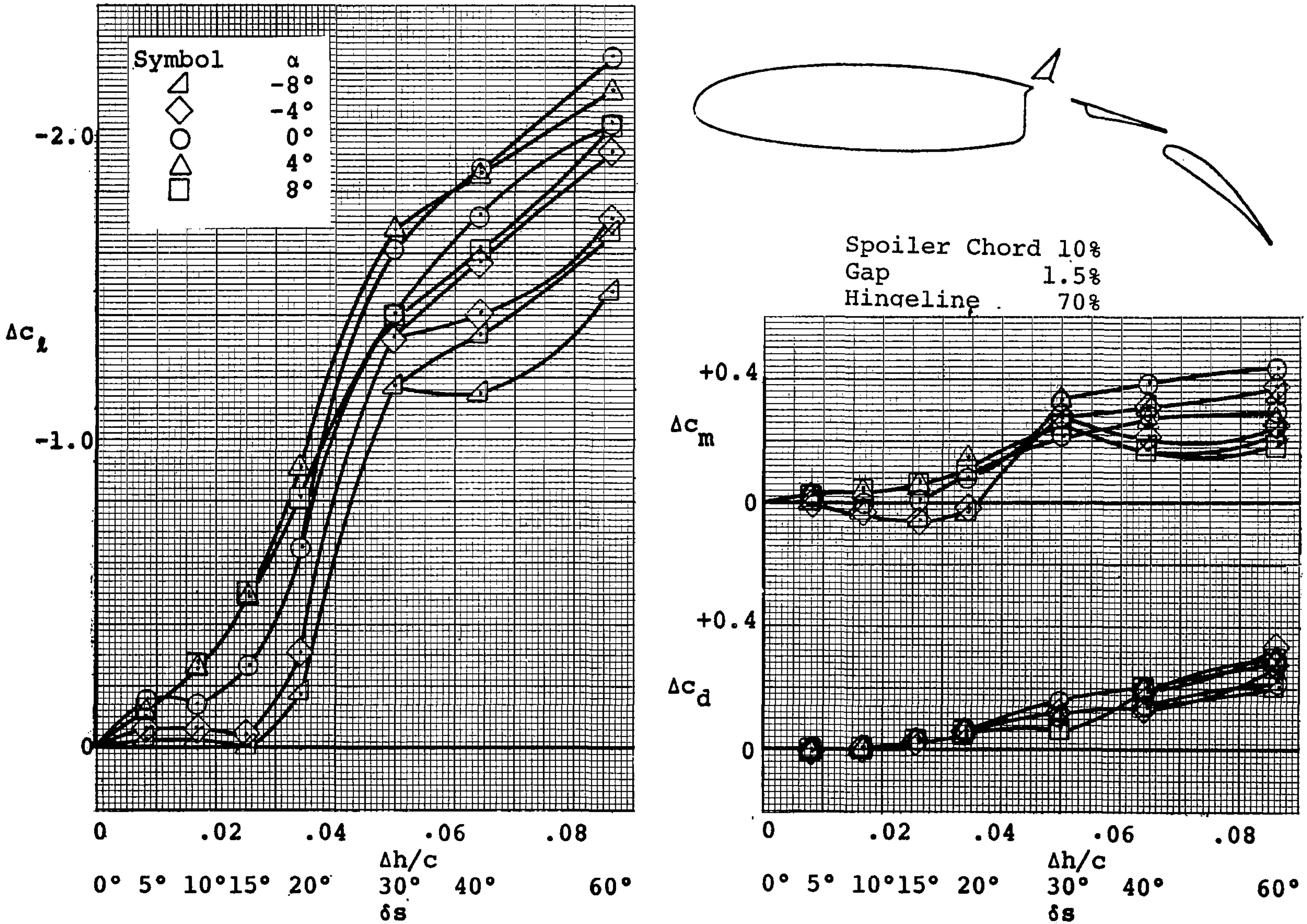


Figure 17 - Effect of 10%c sharp triangle spoiler on lift, pitching moment, and drag. Flap 40°.

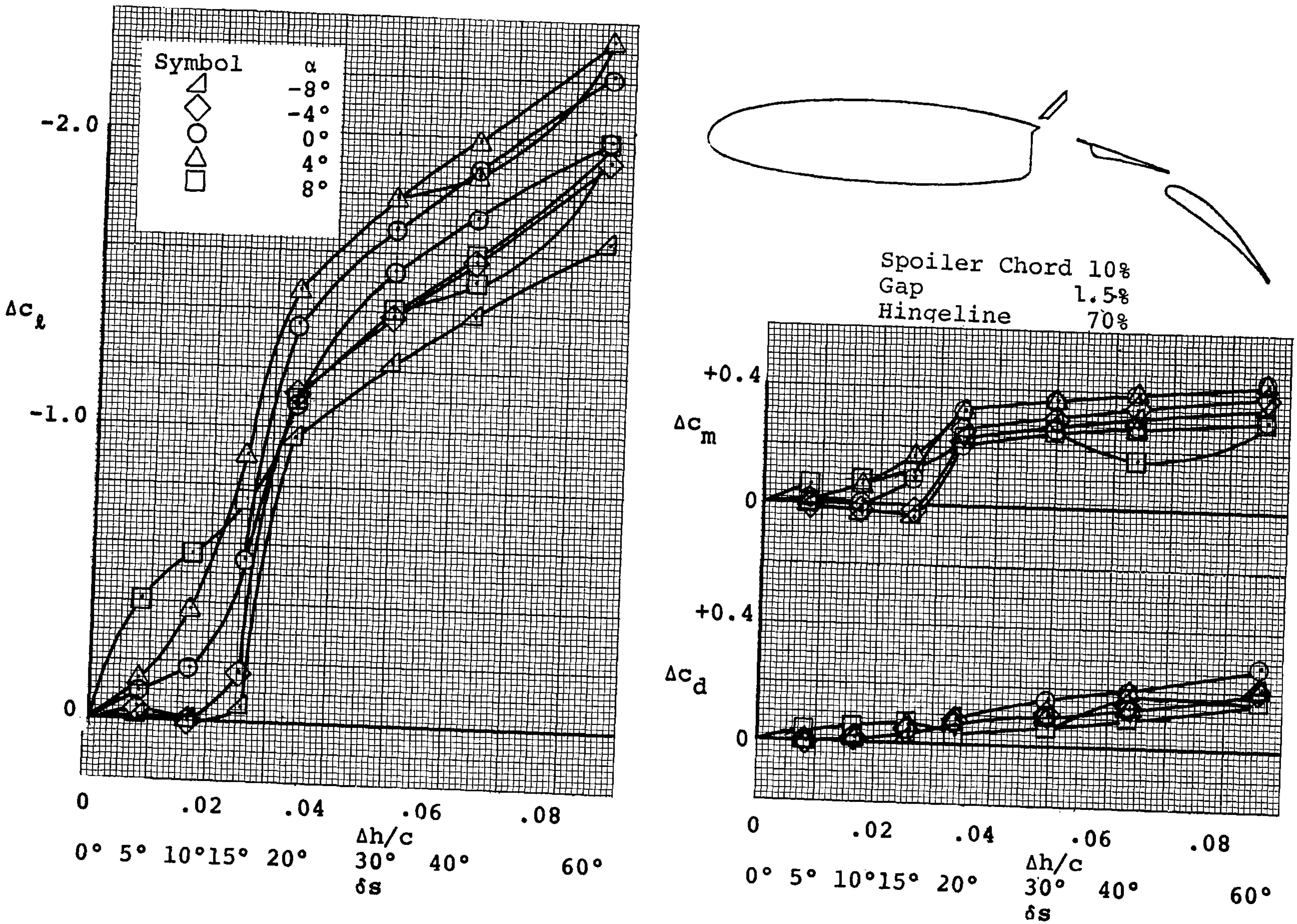


Figure 18 - Effect of 10%c thick flat plate spoiler on lift, pitching moment, and drag. Flap 40°.

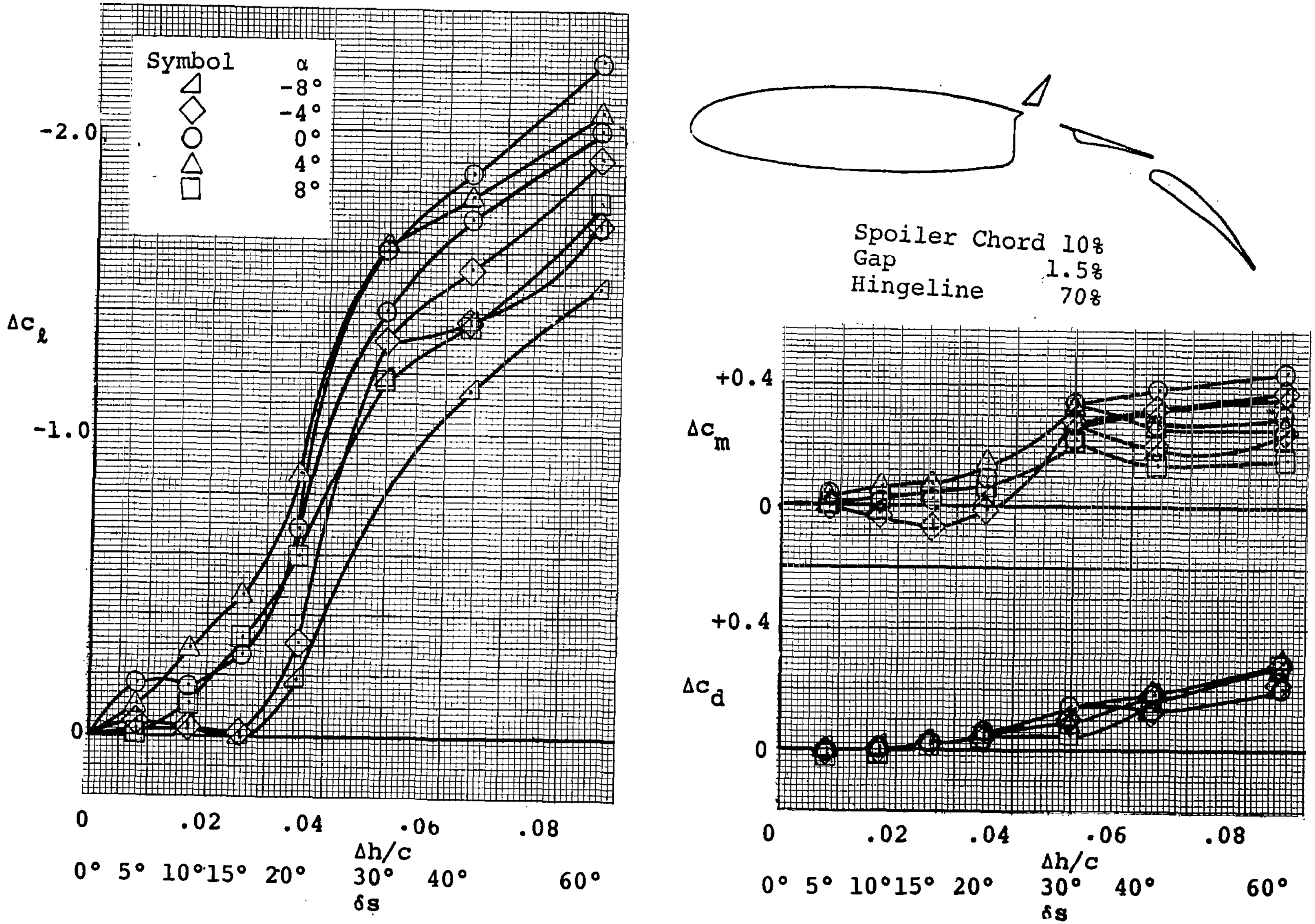


Figure 19 - Effect of 10%c triangle spoiler on lift, pitching moment, and drag. Flap 40°.

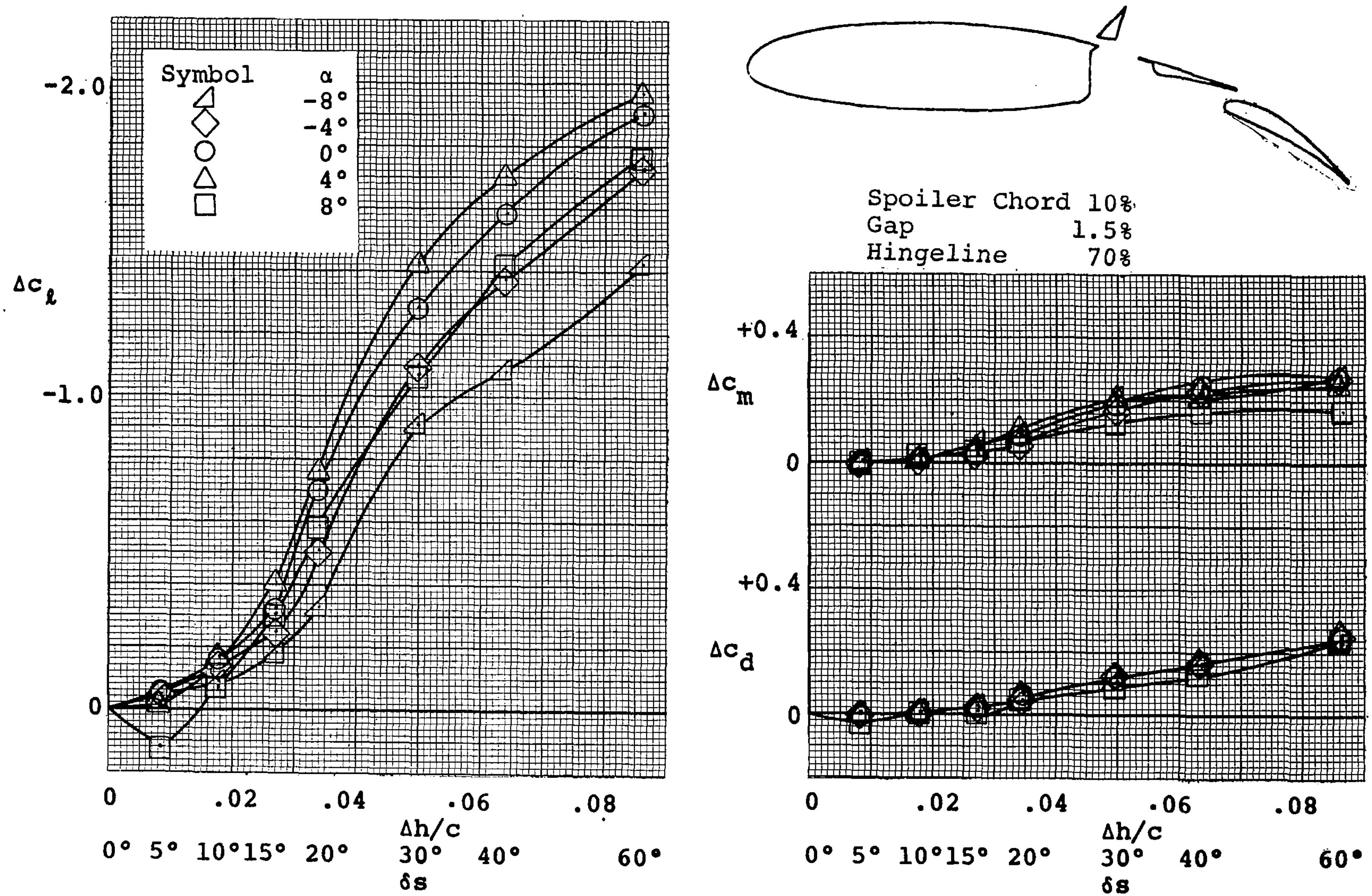
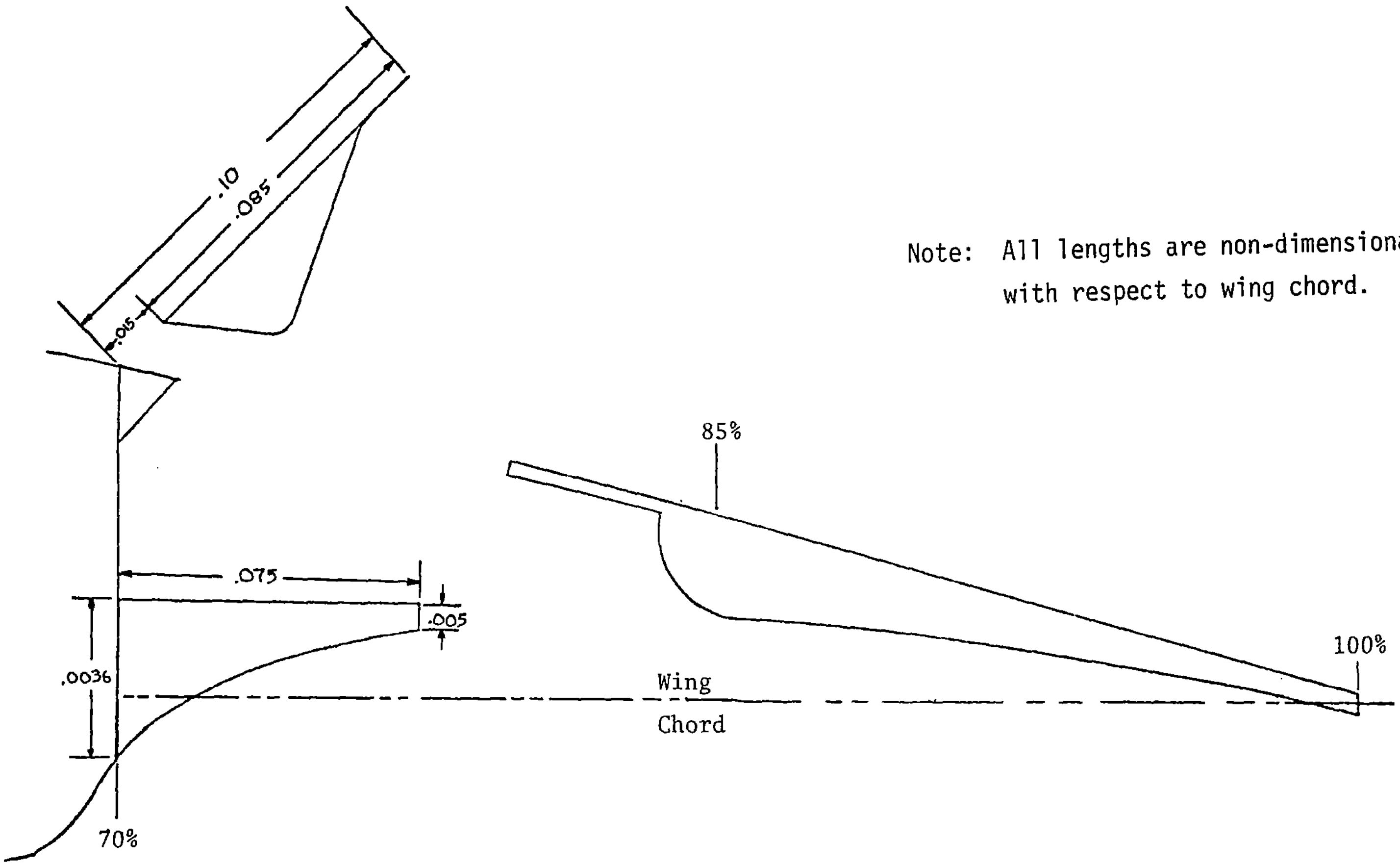
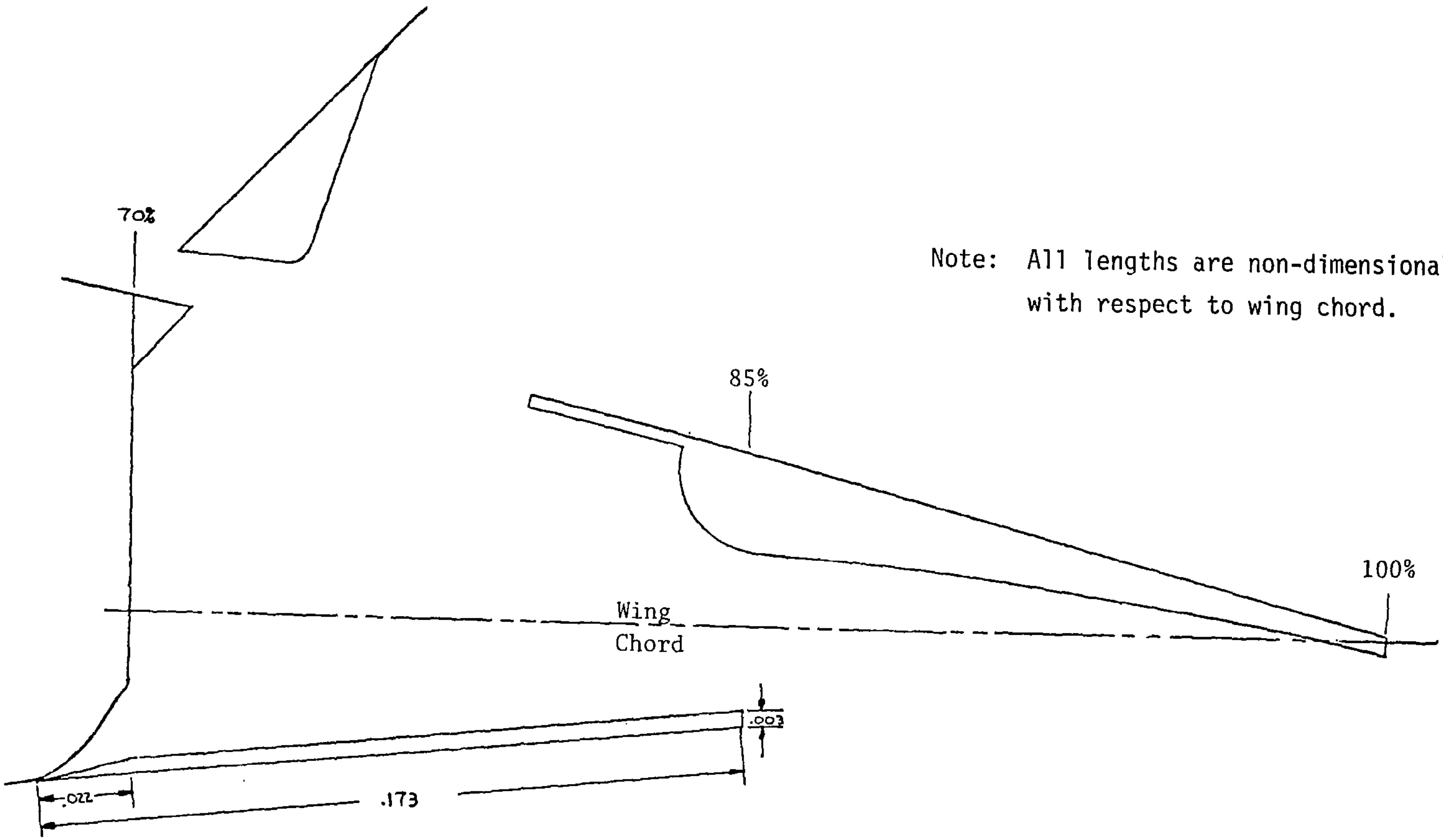


Figure 20 - Effect of 10%c triangle spoiler on lift, pitching moment, and drag. Flap 30°



Note: All lengths are non-dimensionalized with respect to wing chord.

Figure 21(a) - Cavity modification A. Spoiler deflection 60° shown.



Note: All lengths are non-dimensionalized with respect to wing chord.

Figure 21(b) - Cavity modification B. Spoiler deflection 60° shown.

Note: All lengths are non-dimensionalized with respect to wing chord.

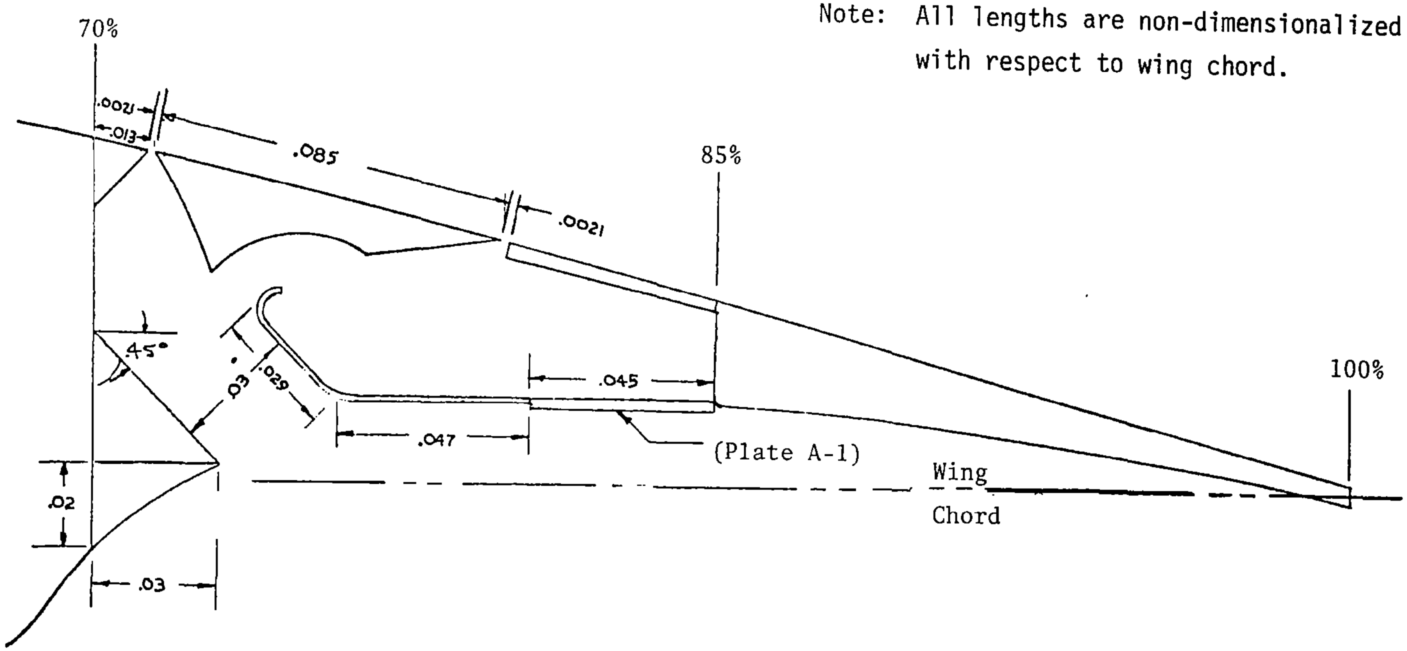


Figure 21(c) - Cavity modification C. Spoiler deflection 0° shown.

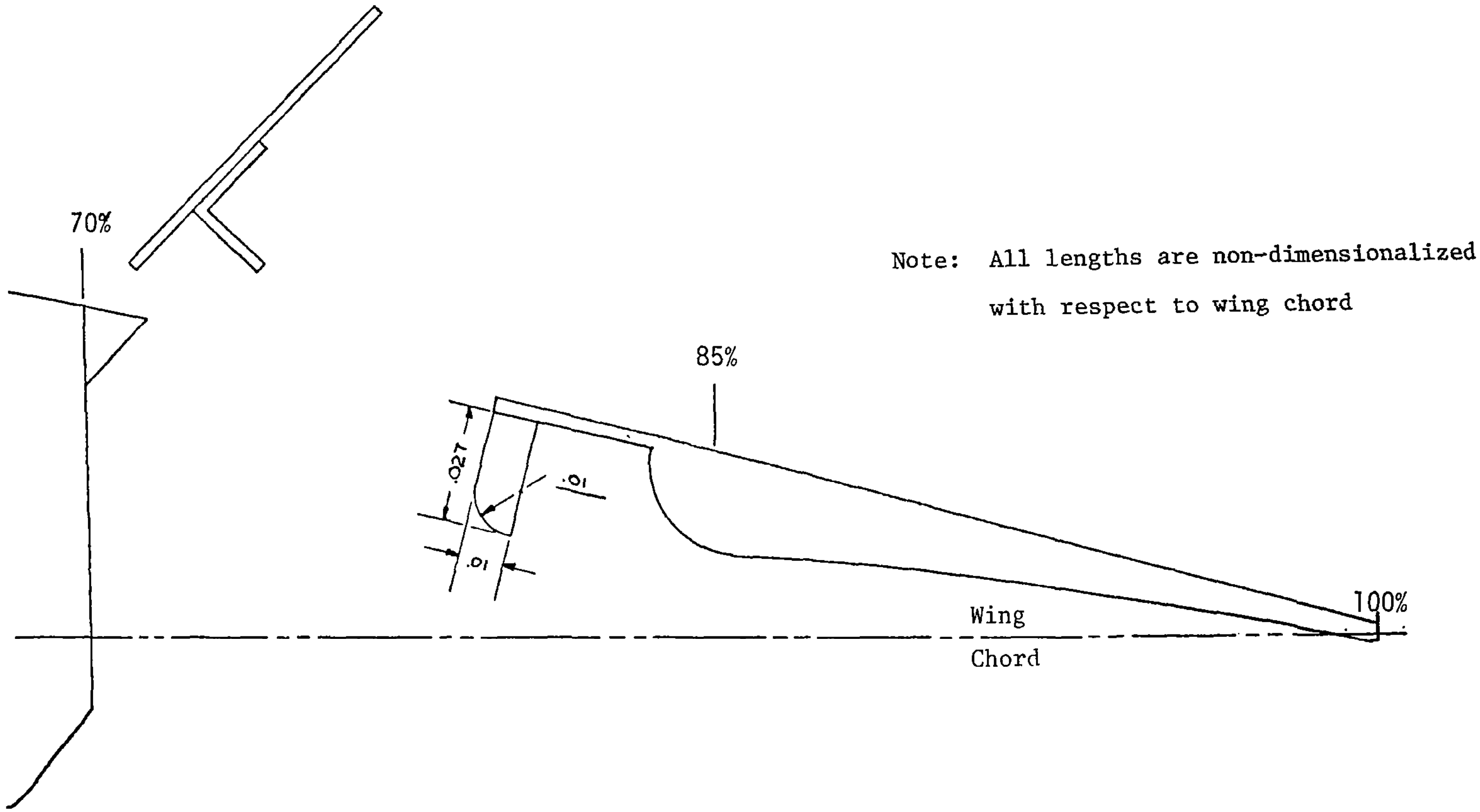


Figure 21(d) - Cavity modification D. Spoiler deflection 60° shown.

Note: All lengths are non-dimensionalized with respect to wing chord

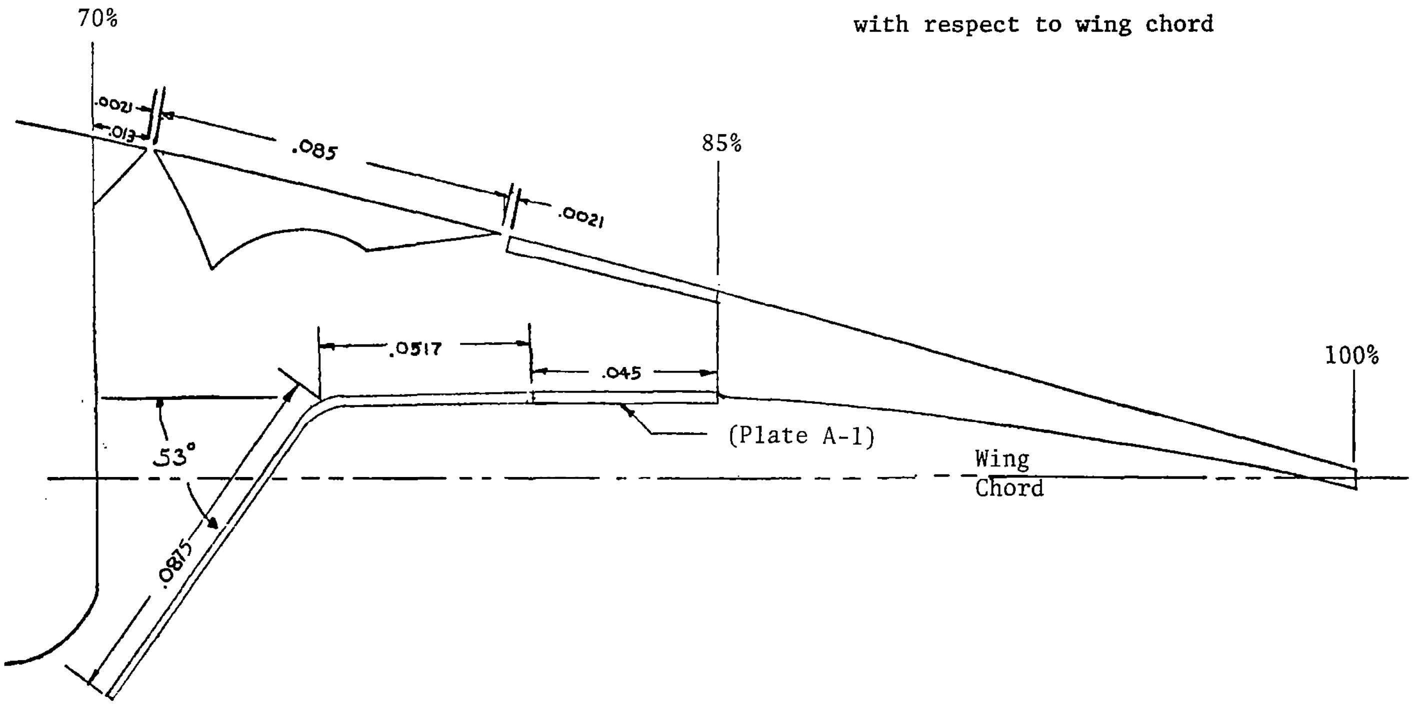


Figure 21(e) - Cavity modification E. Spoiler deflection 0°.

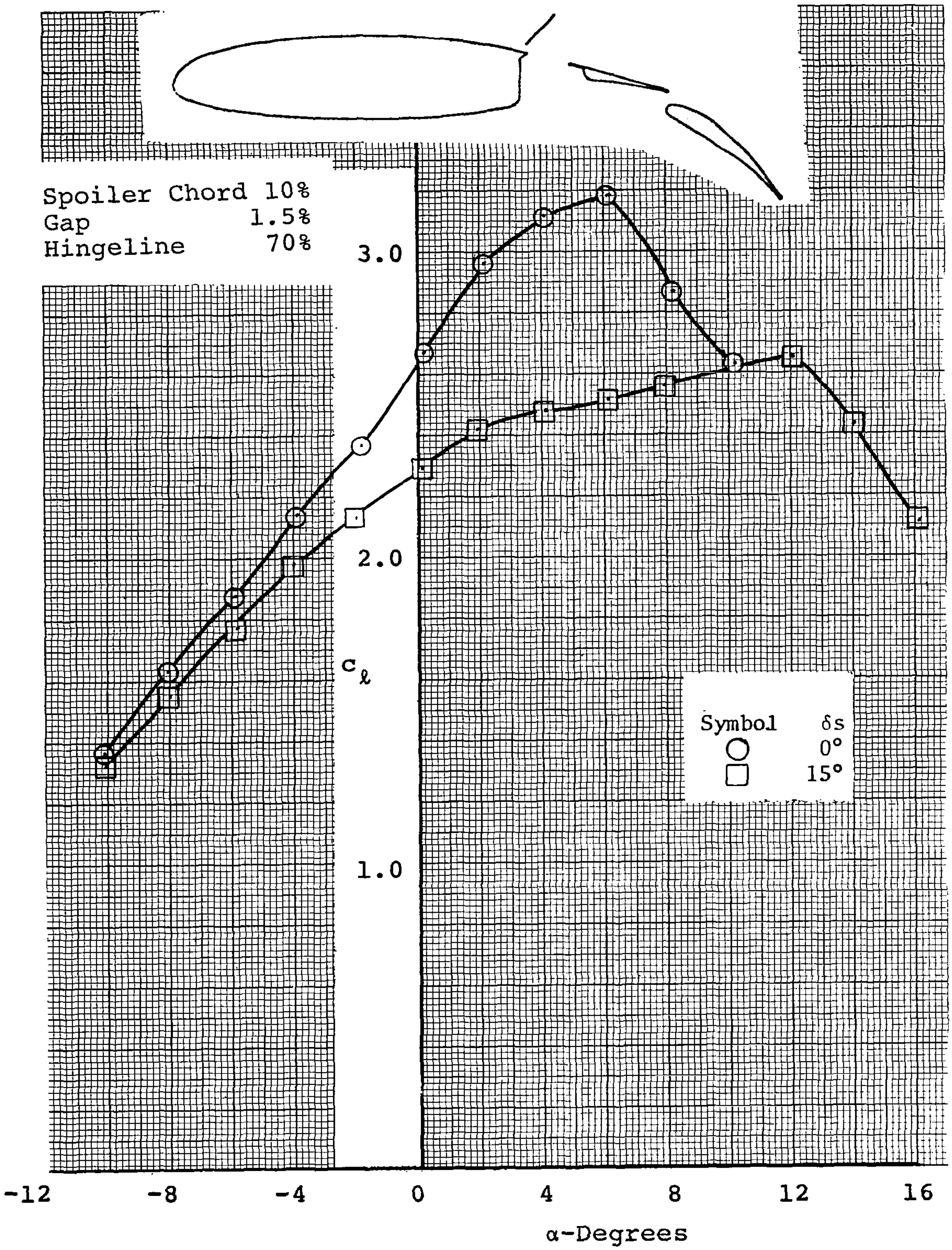


Figure 22(a) - Effect of cavity shape on lift, flat-plate spoiler, Flap 40°, unmodified cavity.

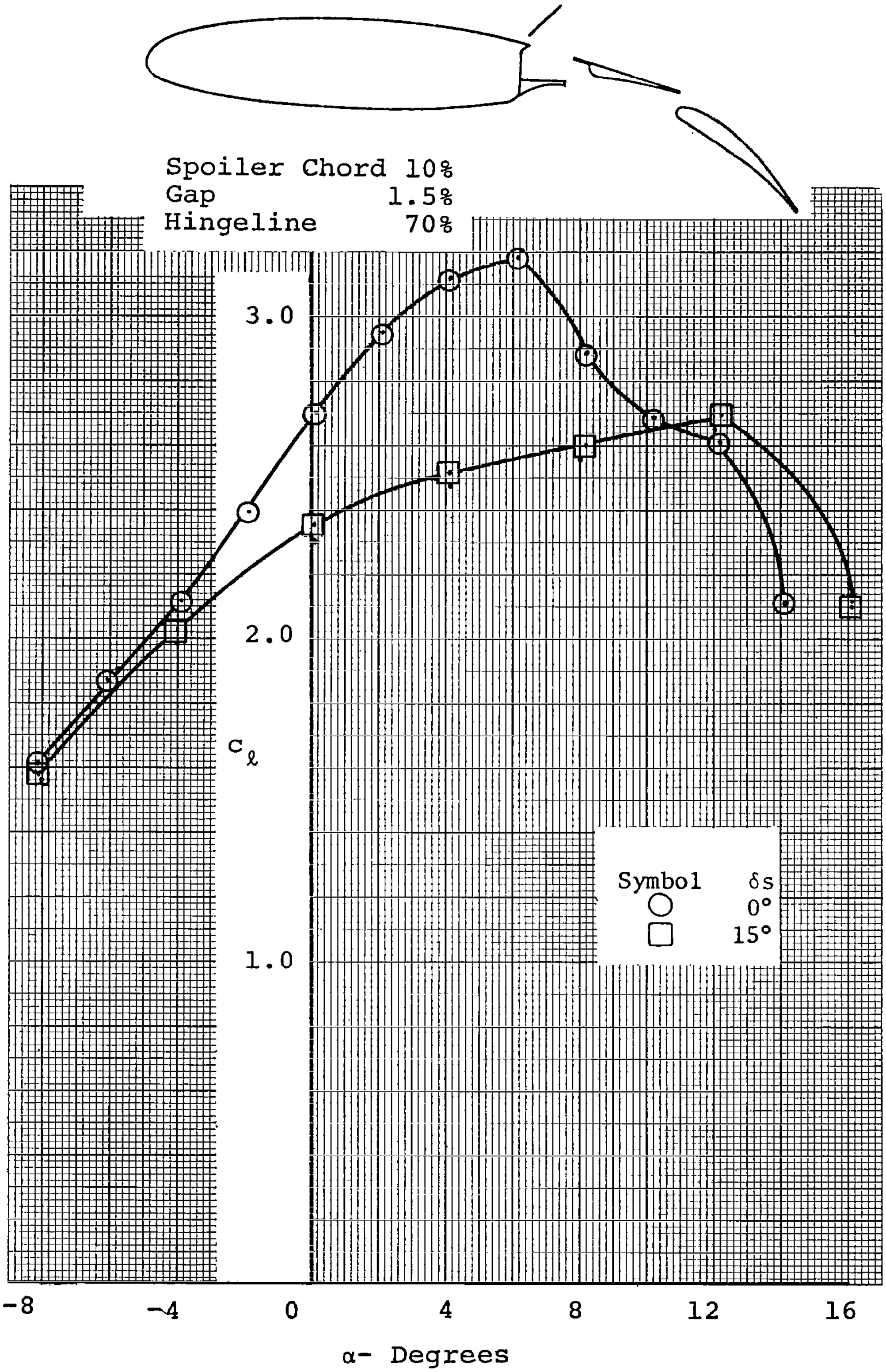


Figure 22(b) - Continued, cavity modification A.

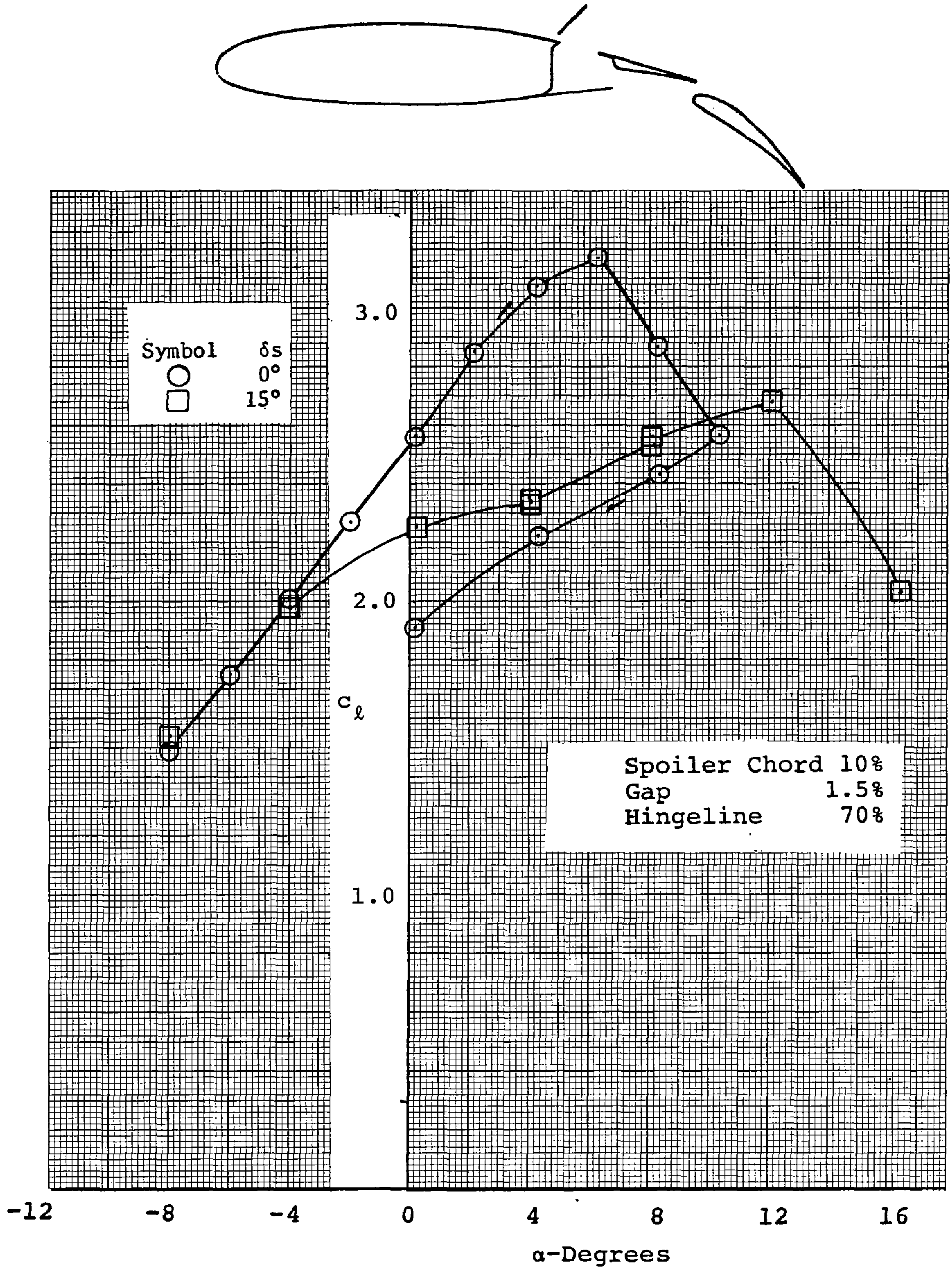


Figure 22(c) - Continued, cavity modification B.

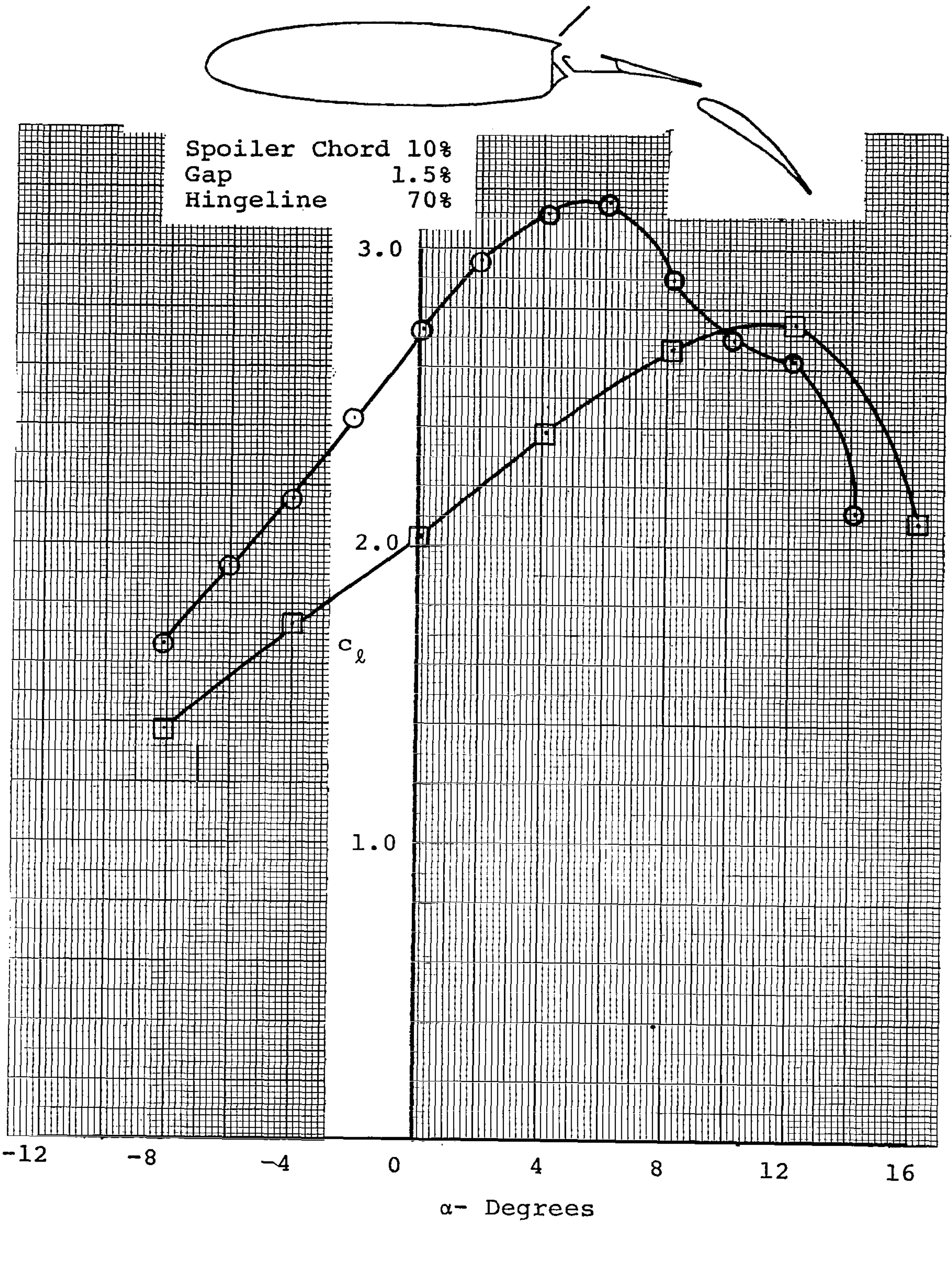


Figure 22(d) - Continued, cavity modification C.

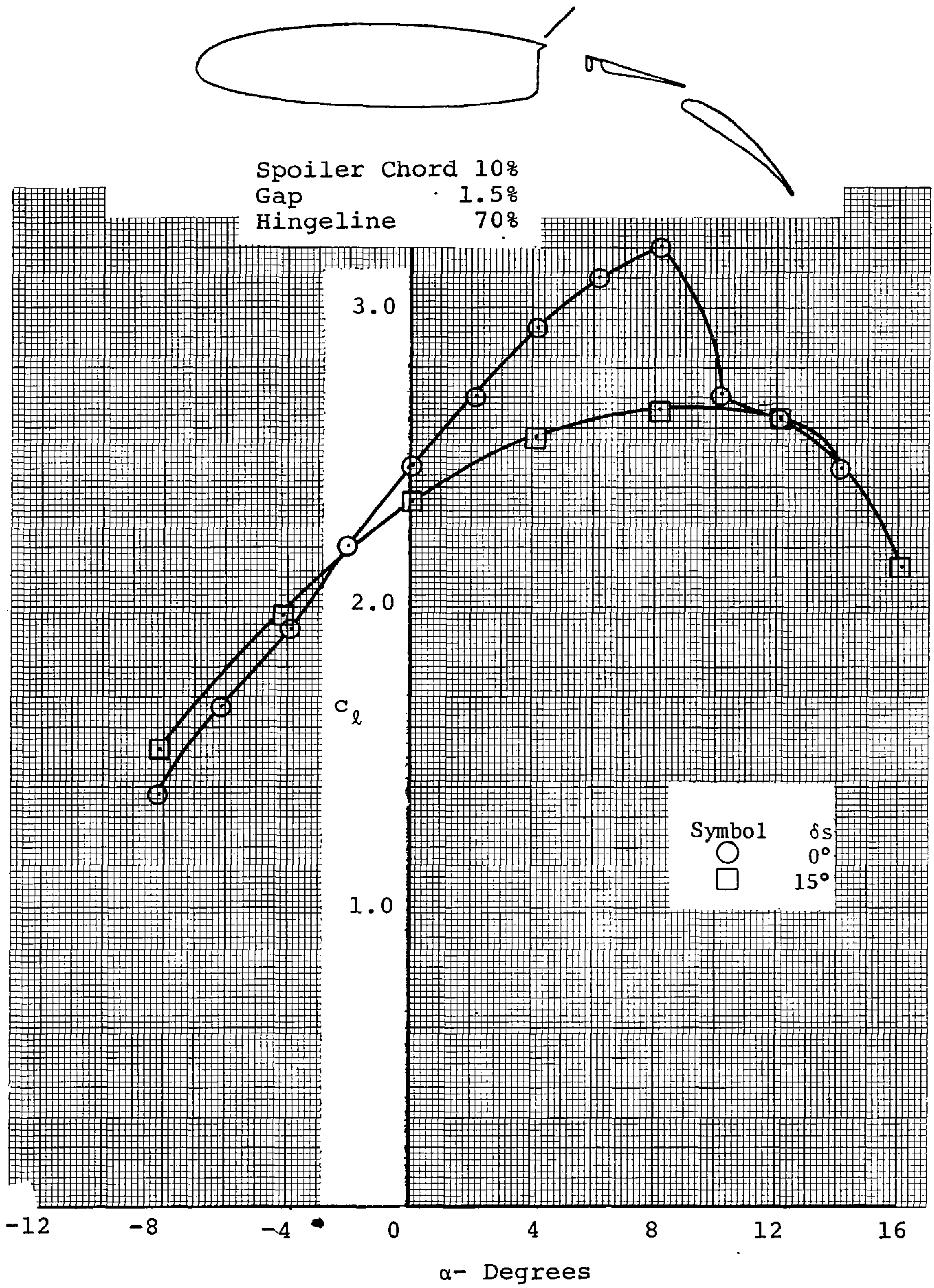


Figure 22.(e) - Concluded, Cavity modification D.

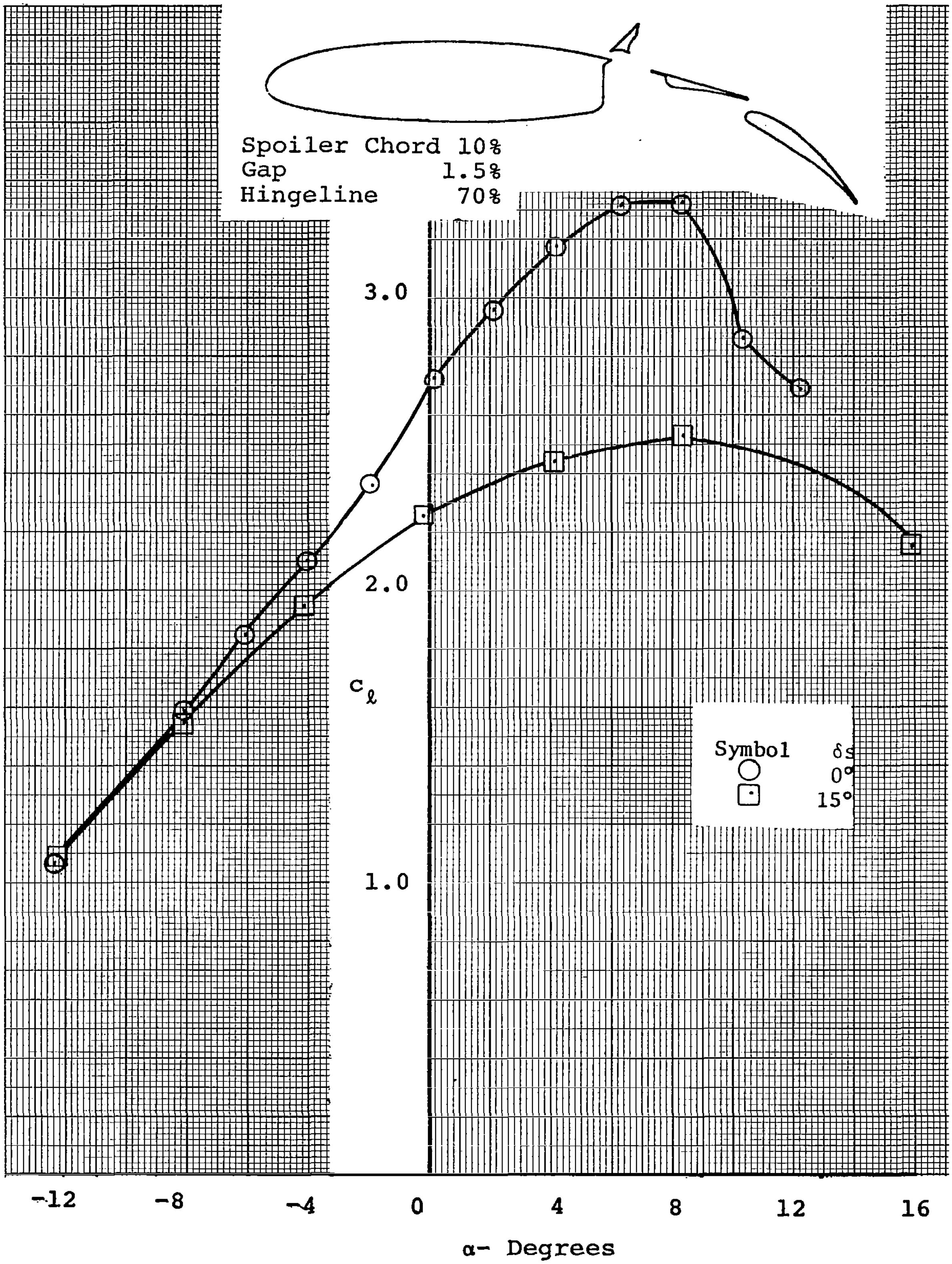


Figure 23(a) - Effect of cavity shape on lift, MU-2 spoiler, Flap 40°, unmodified cavity.

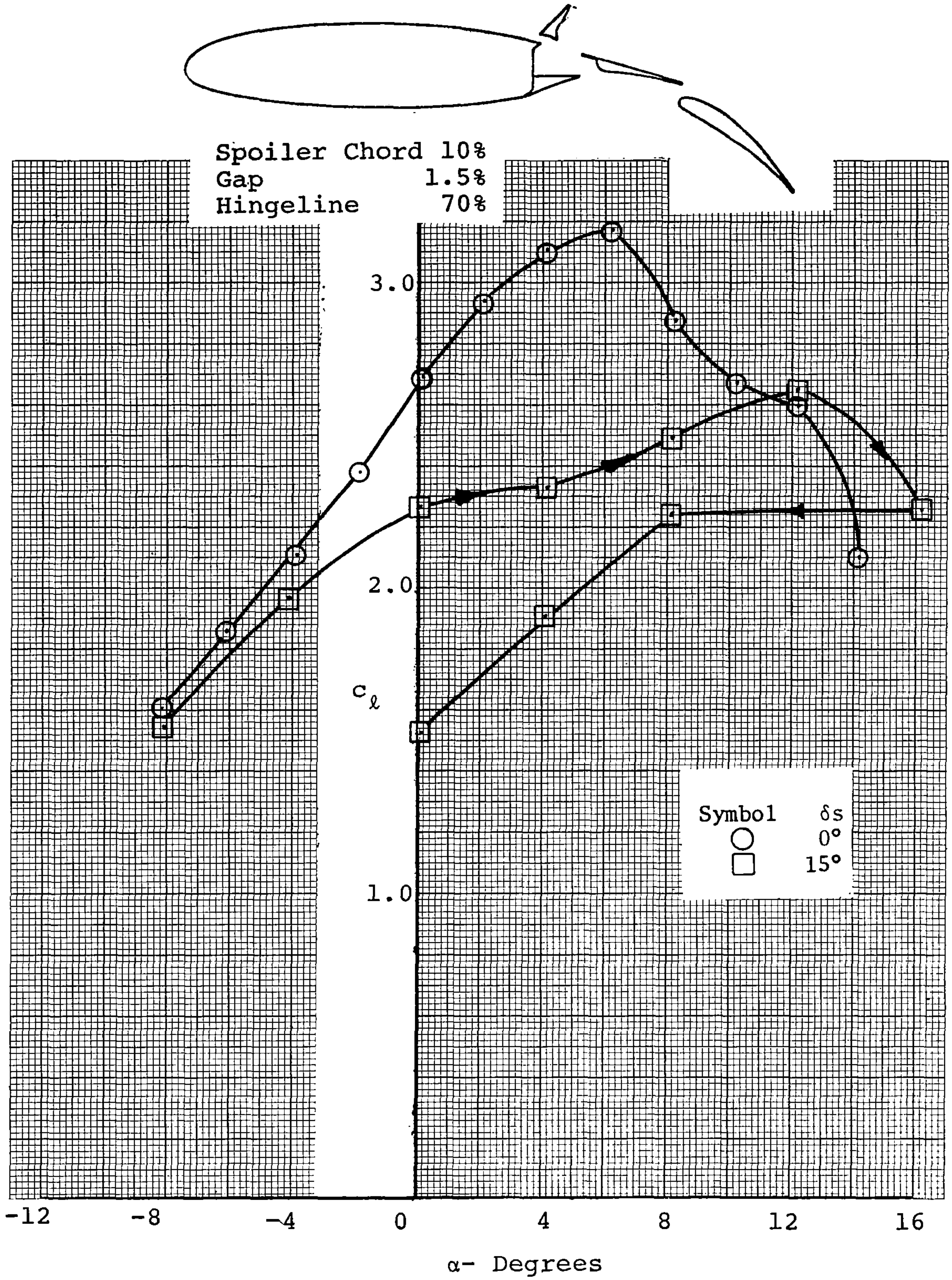
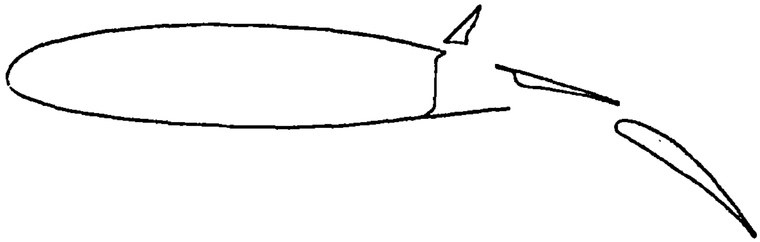


Figure 23(b) - Continued, cavity modification A.



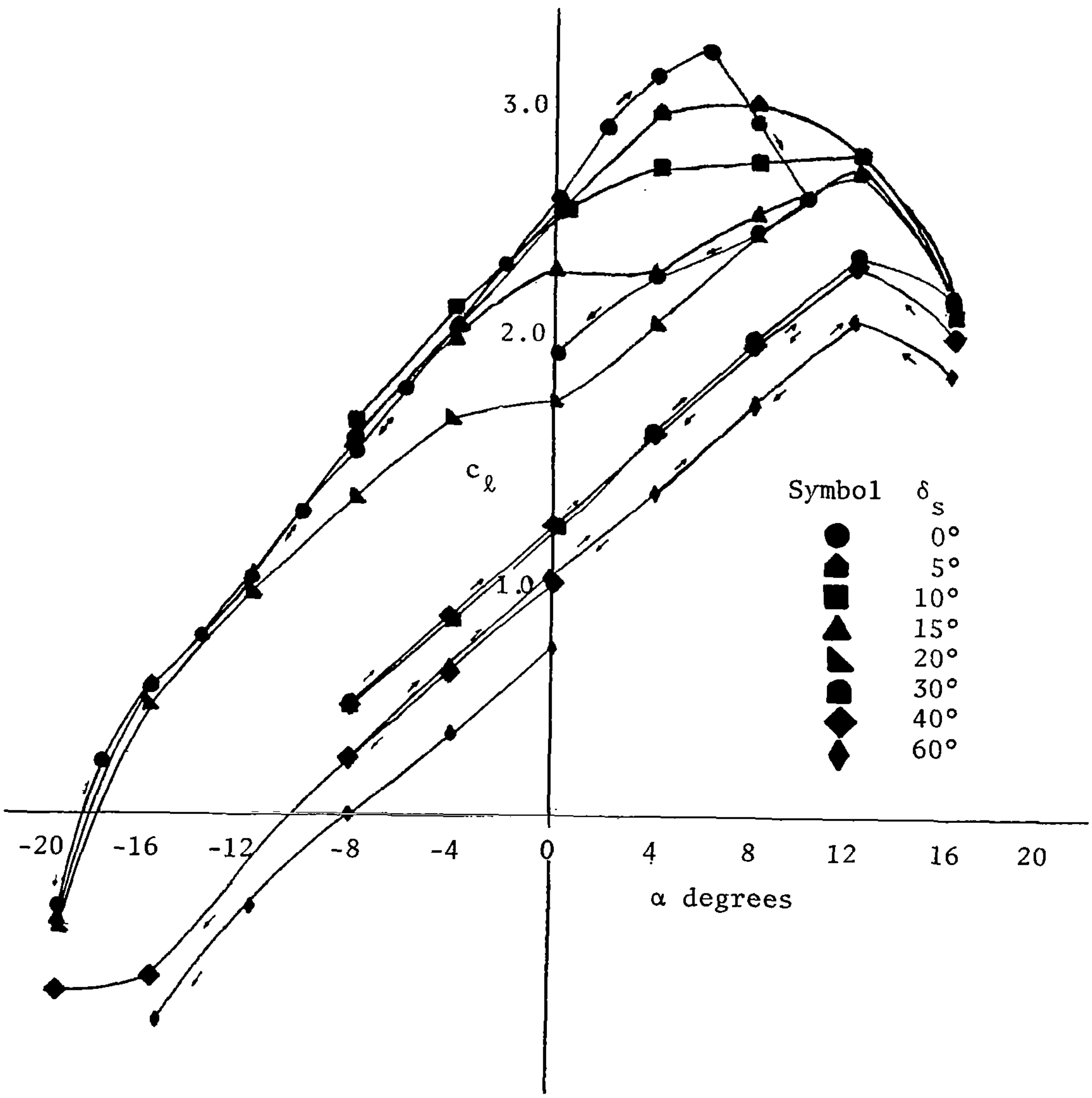


Figure 23(c) - Continued, cavity modification B.

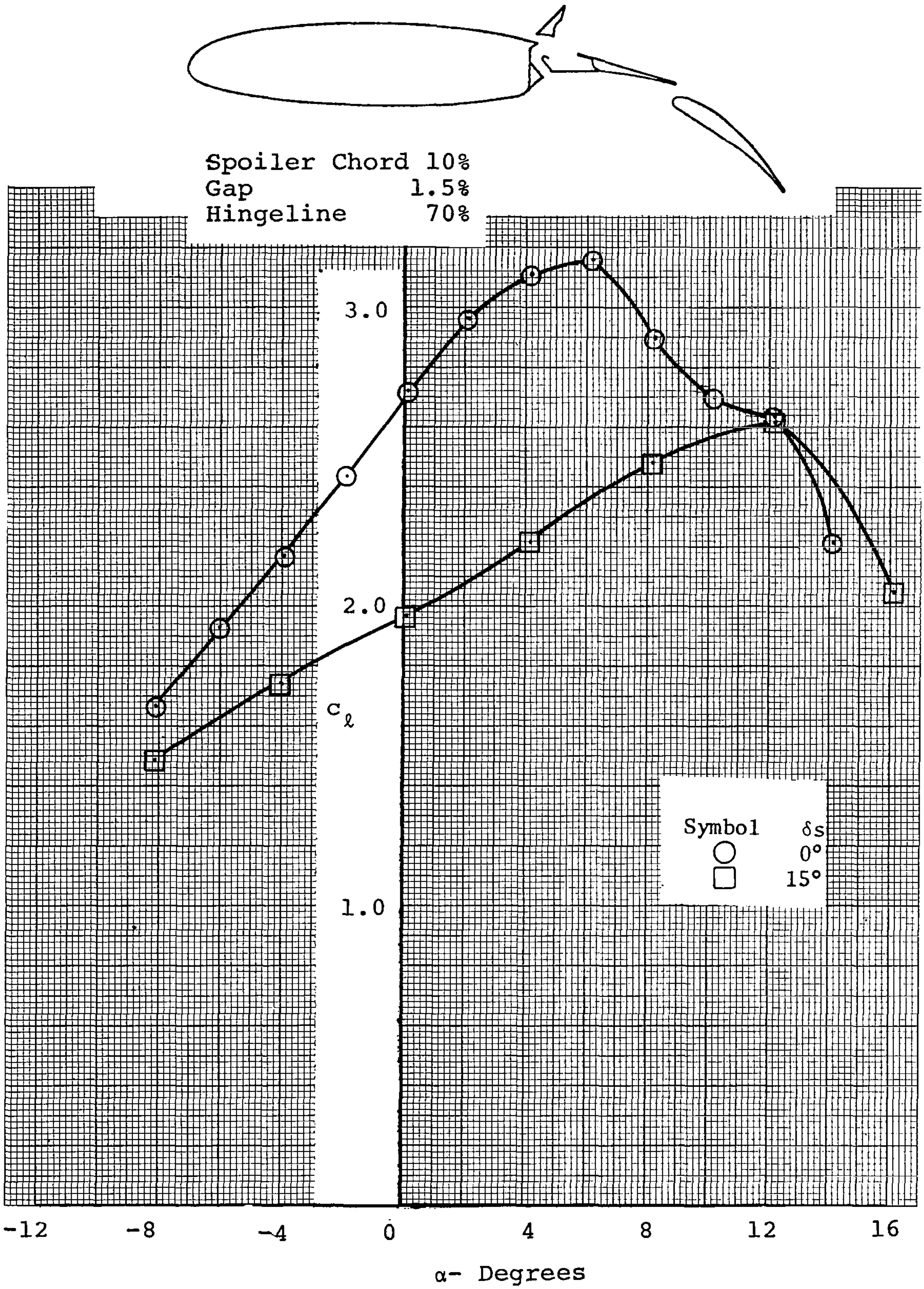


Figure 23(d) - Continued, cavity modification C.

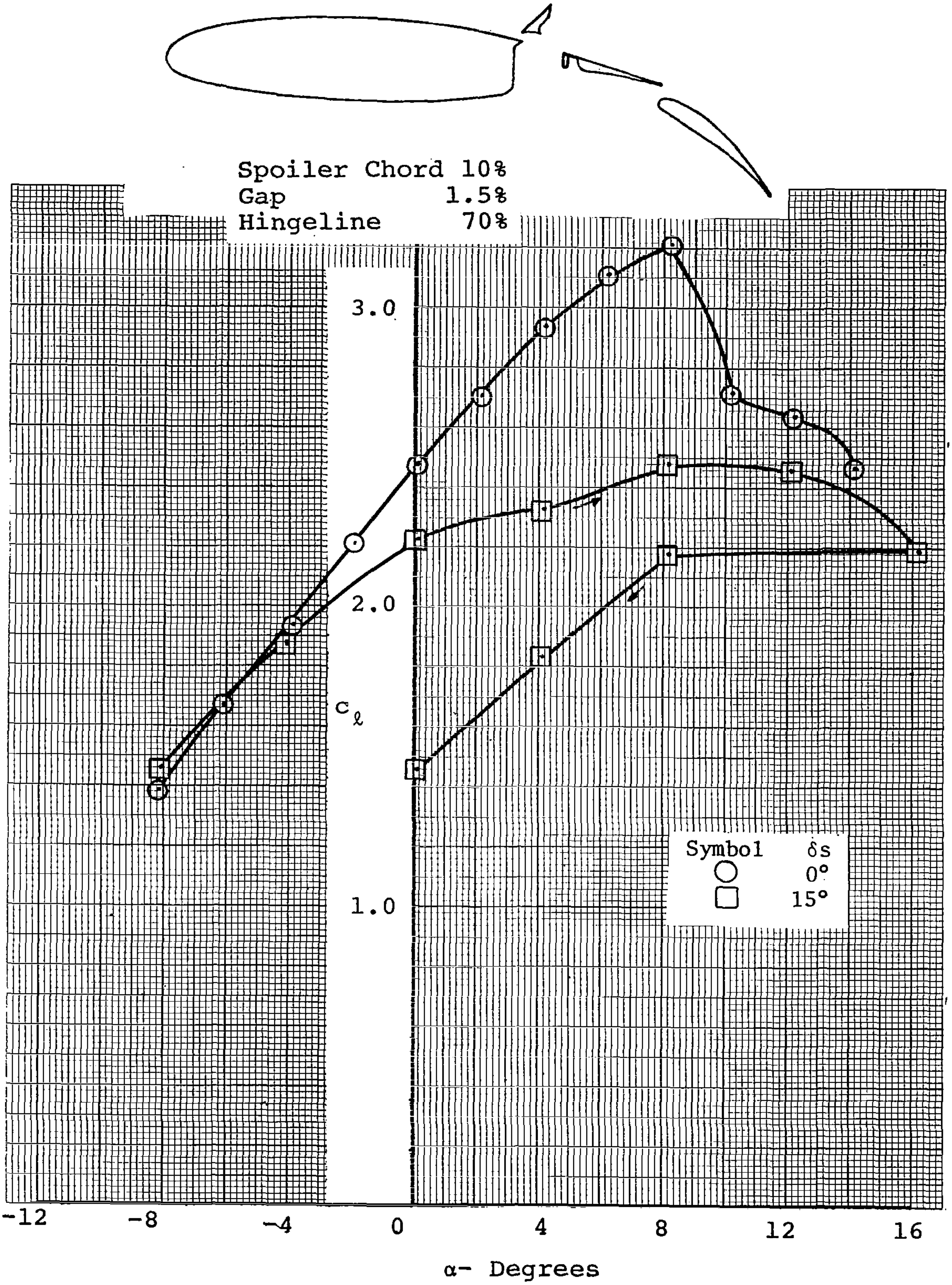


Figure 23(e) - Concluded, cavity modification D.

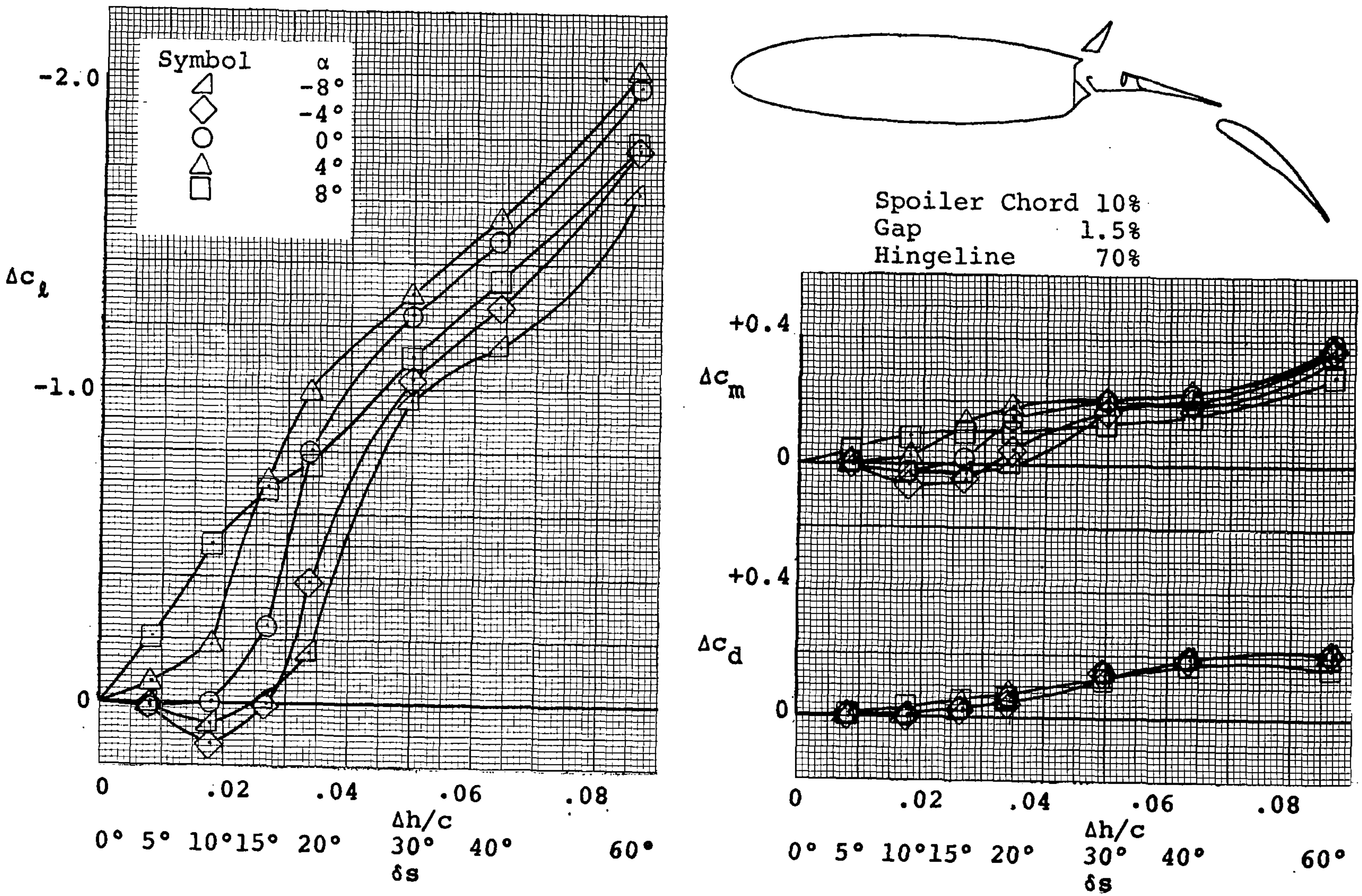


Figure 24(a) - Effect of cavity shape on lift, drag, and pitching moment, triangle spoiler (a) modifications C and D, Flap 40°

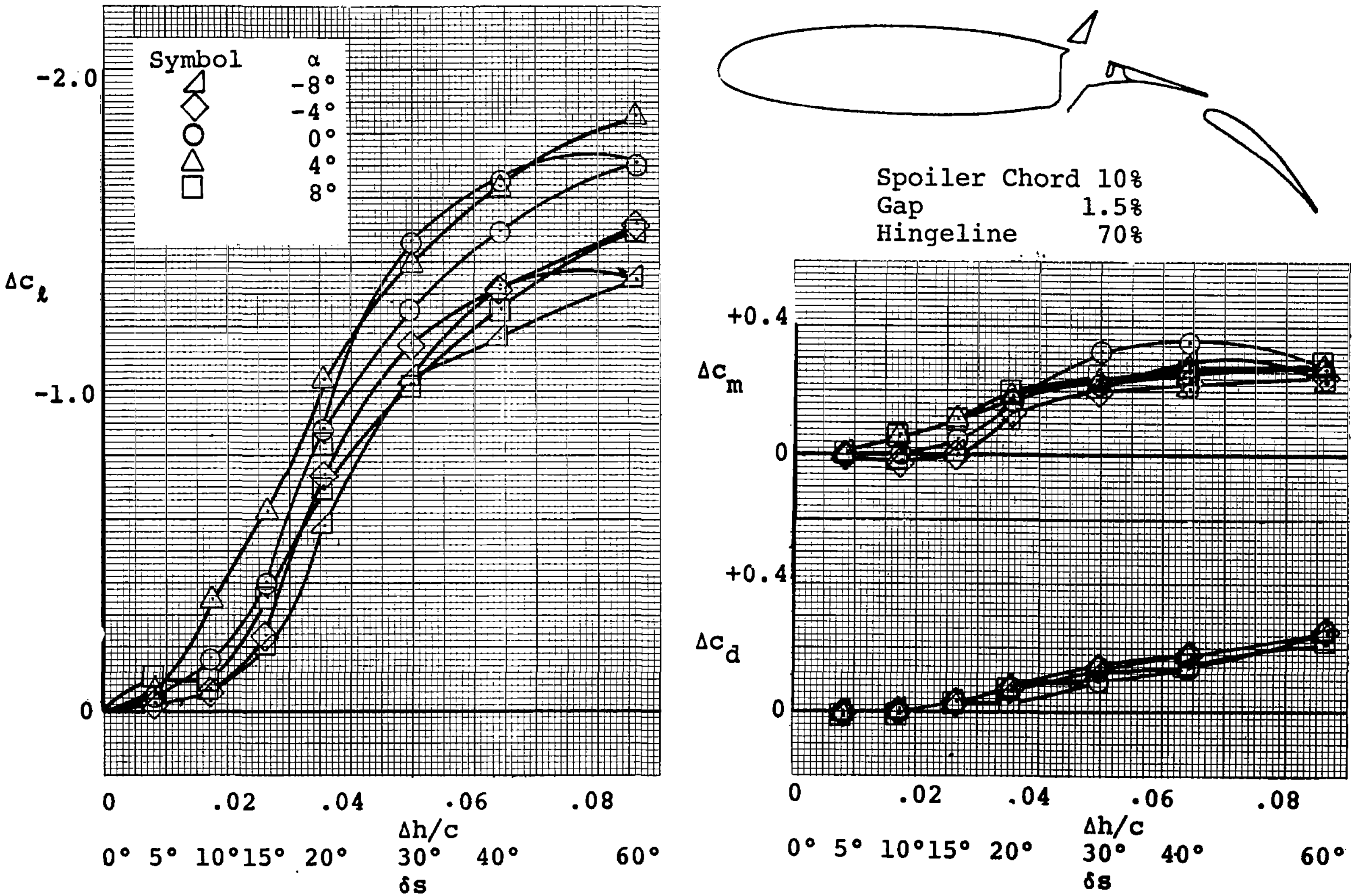


Figure 24(b) - Modifications D and E, Flap 40°.

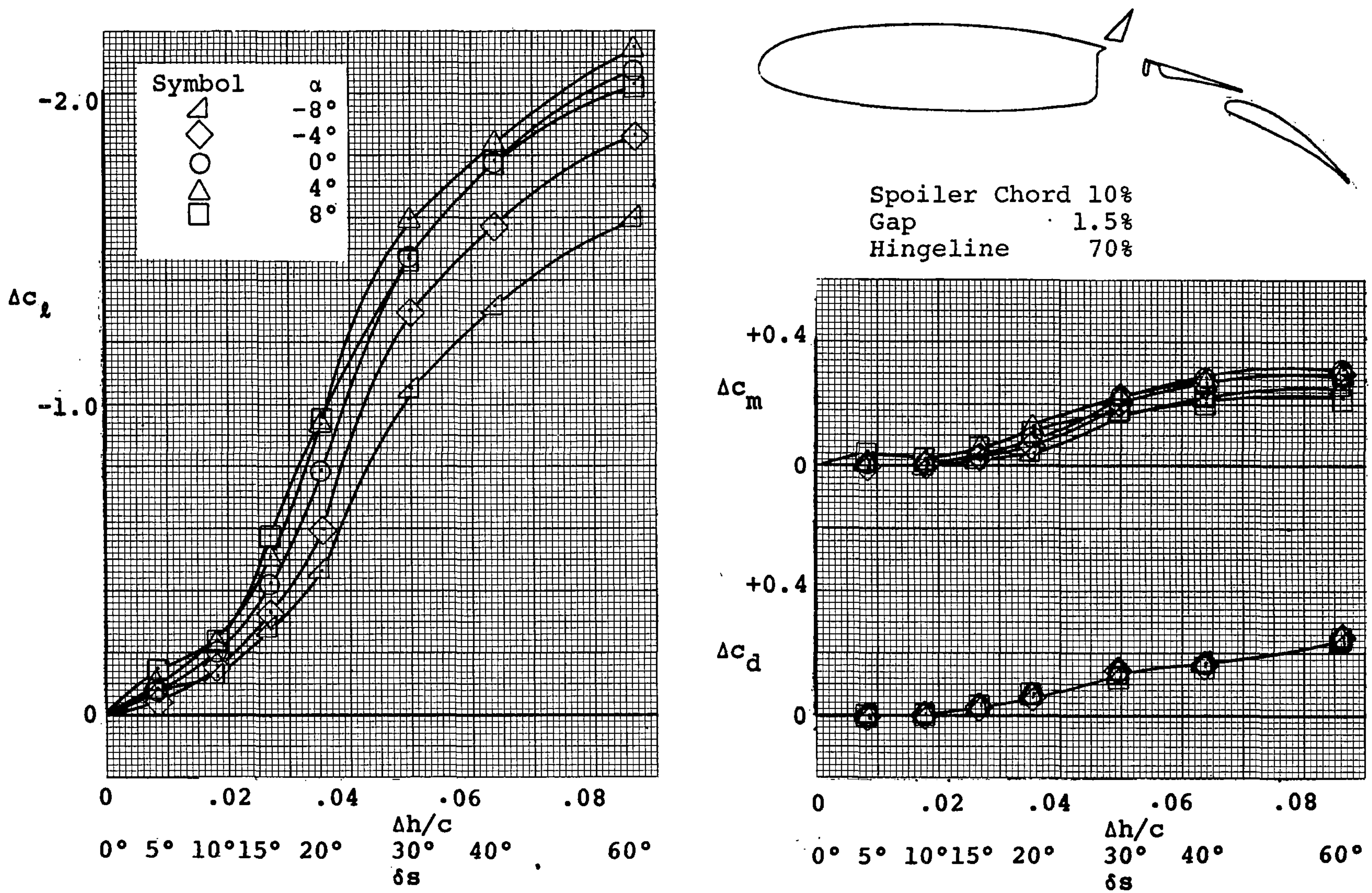
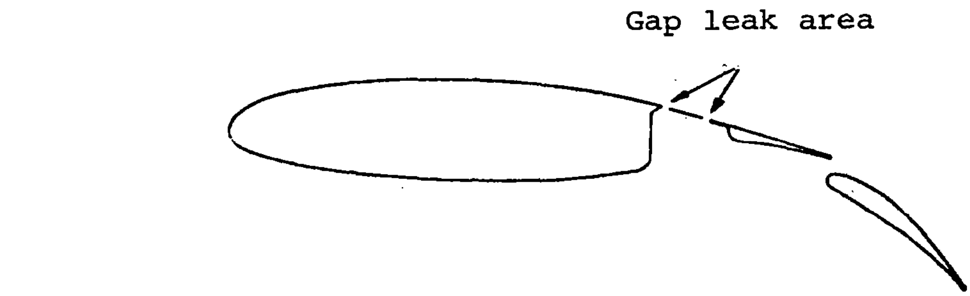


Figure 24(c) - Modification D, Flap 30°.



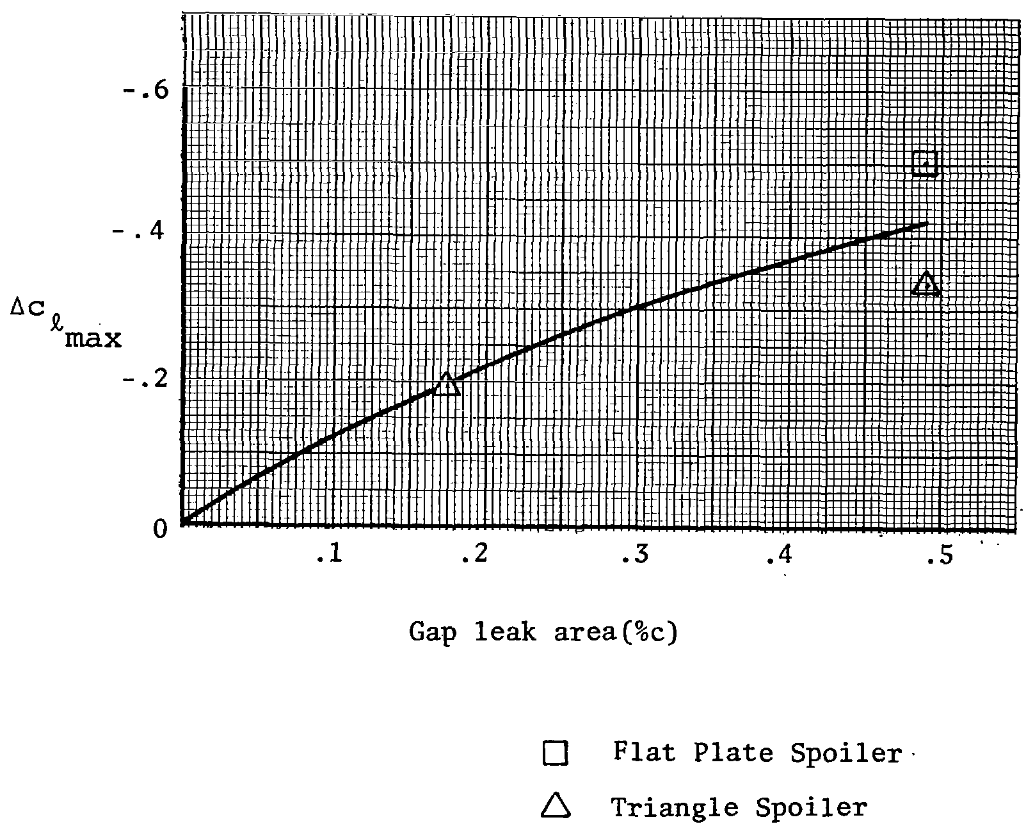
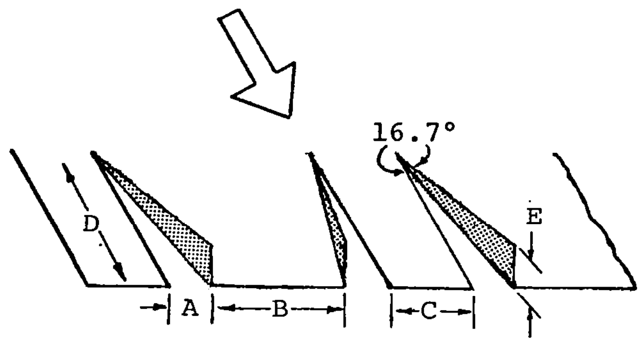


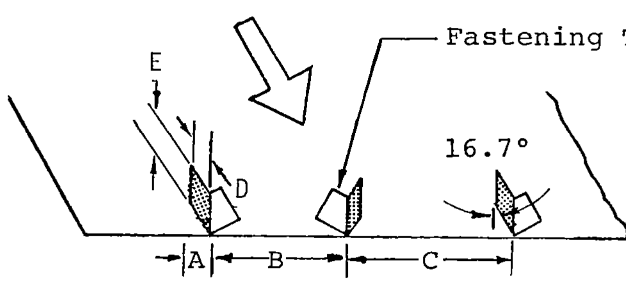
Figure 25 - Effect of spoiler gap leak area on c_ℓ max. Flap 40°.



Delta Vortex Generators

Generator Number	A	B	C	D	E
1	.0125	.0417	.0250	.0417	.0125
2	.0125	.0833	.0500	.0417	.0125
3	.0250	.0833	.0500	.0833	.0250
4	.0063	.0208	.0125	.0208	.0063

Note: All dimensions are fractions of chord.



Square Vortex Generators

Generator Number	A	B	C	D	E
5	.0036	.0417	.0492	.0125	.0125

Note: All dimensions are fractions of chord.

Figure 26 - Vortex Generator Details

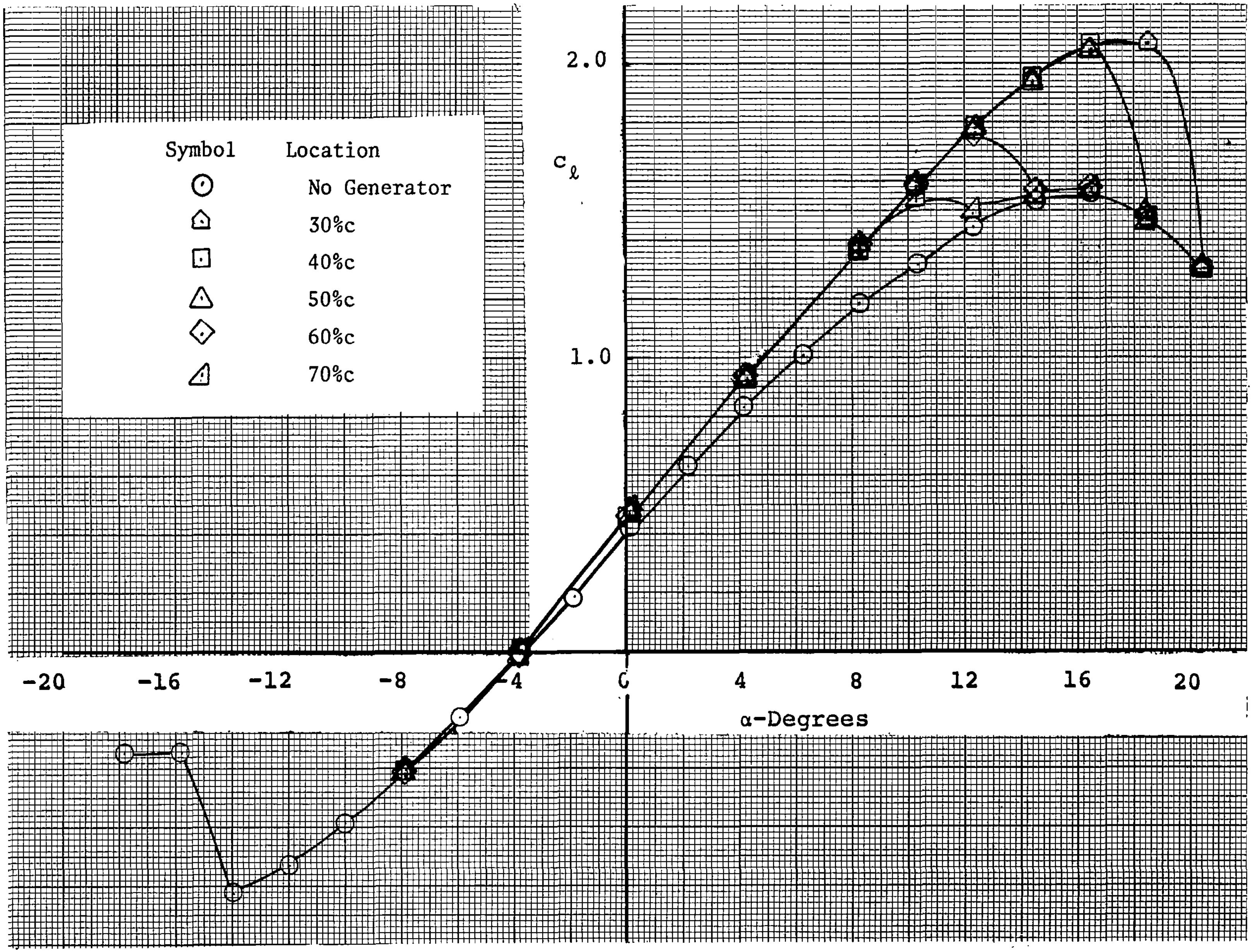


Figure 27(a) - Effect of Vortex Generator Location on Lift.

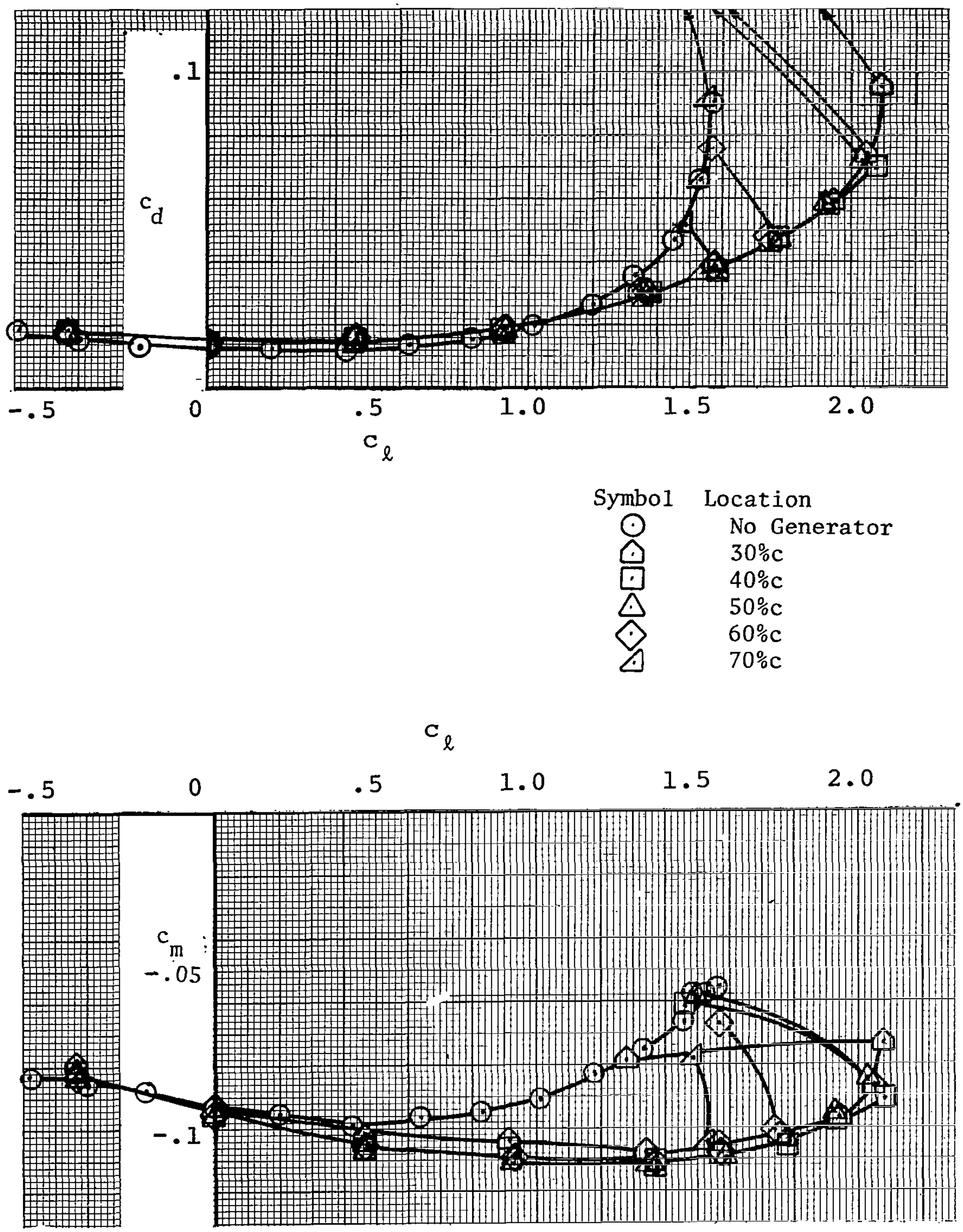


Figure 27(b) - Effects of Vortex Generator Location on Drag and Pitching Moment.

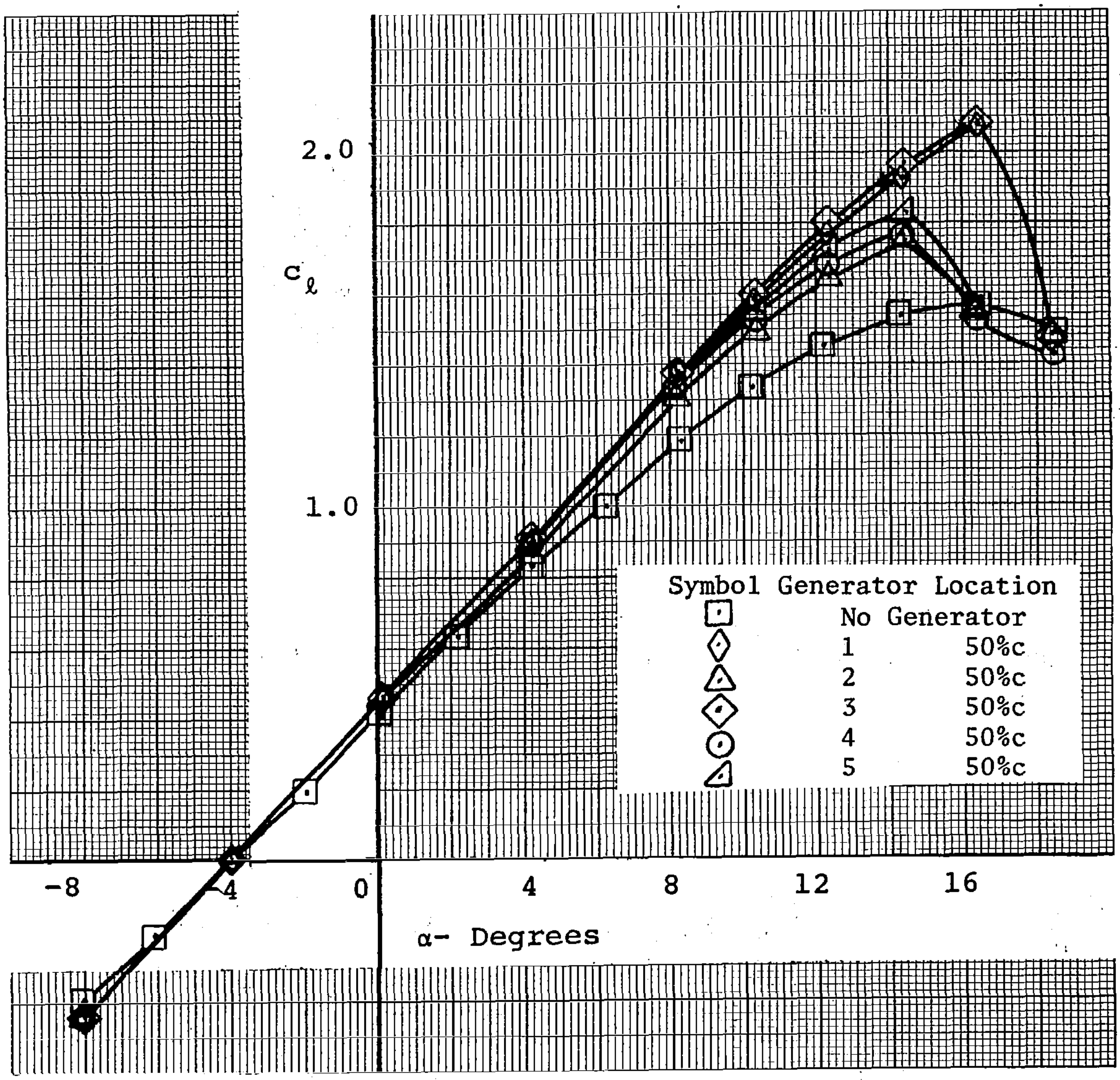


Figure 28(a) - Effects of Vortex Generator Size and Shape on Lift.

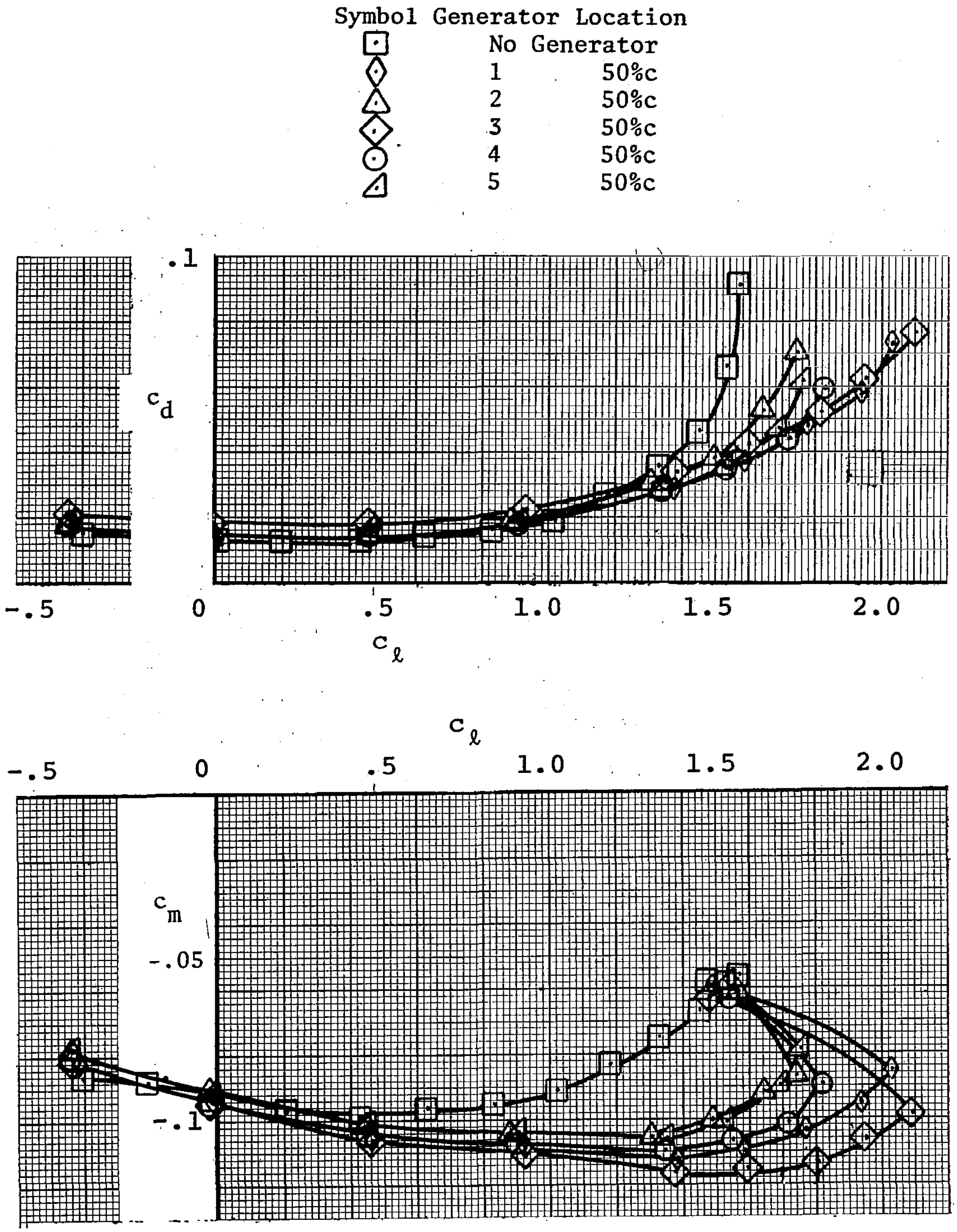


Figure 28(b) - Effects of Vortex Generator Size and Shape on Drag and Pitching Moment.

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