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RESEARCH MEMORANDUM

WIND-TUNNEL INVESTIGATION AT LOW SPEED OF A TWISTED AND CAMBERED WING SWEPT BACK 63° WITH VORTEX GENERATORS AND FENCES

By James A. Weiberg and George B. McCullough

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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WIND-TUNNEL INVESTIGATION AT LOW SPEED OF A TWISTED AND CAMBERED WING SWEPT BACK 63° WITH VORTEX GENERATORS AND FENCES

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SUMMARY

The low-speed characteristics of a twisted and cambered 63° swept-back wing with boundary-layer-control fences and with vortex-generating devices are presented. The data include force, pressure-distribution, and boundary-layer measurements.

Using either fences or vortex generators, sufficient improvement was obtained in the flow over the wing to eliminate the large variations of longitudinal stability with lift coefficient. The maximum lift-drag ratio of the wing with fences was greater than with vortex generators for the same improvement in stability. At lift coefficients above that for maximum lift-drag ratio, the lift-drag ratio was nearly the same for the wing with either fences or vortex generators.

INTRODUCTION

Low-speed tests of a wing with the leading edge swept back 63° showed large movements of the aerodynamic center for lift coefficients greater than about 0.3 (references 1 and 2). In reference 1, the deficient stability characteristics of this 63° swept wing were attributed to flow separation near the leading edge of sections near the wing tip and to the subsequent progression of the stalled area over the upper surface of the wing. Attempts to reduce the flow separation by twisting and cambering the wing were successful in delaying the leading-edge separation, but the stability characteristics were not greatly improved because of excessive thickening and separation of the boundary layer over the rear portion of the wing (references 3, 4, and 5). The presence of a large spanwise component in the boundary-layer flow may have aggravated this condition and accelerated the occurrence of turbulent separation

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near the wing tip. Because of the nature of the flow over the twisted and cambered 63° swept wing it was reasoned that separation of the boundary layer could be delayed by the use of vortex generators. These devices, which consist of small, low-aspect-ratio airfoils mounted on the surface of the wing, have been shown to delay separation of the turbulent boundary layer of a two-dimensional wing model (reference 6); consequently low-speed tests were made of vortex generators on the twisted and cambered wing described in reference 5.

The previous investigations of the twisted and cambered 63° swept wing (references 4 and 5) showed that rectangular boundary-layer fences produced considerable improvement in the stability of the wing. In the present investigation, additional tests of fences were made to determine if the size of the fences could be reduced without significantly altering their effectiveness.

The results of the tests with the vortex generators and the boundary-layer-control fences are presented and compared herein.

The tests were made for a Reynolds number of 3.7 million and a Mach number of 0.16 in one of the Ames 7- by 10-foot wind tunnels, and include force, pressure distribution, and boundary-layer measurements.

NOTATION

All data are presented as NACA coefficients corrected for tunnel-wall effects. Forces and moments (referred to the moment center shown in fig. 1) are those for a semispan model. Coefficients and symbols used are defined as follows:

b span of complete wing perpendicular to the plane of symmetry (twice span of semispan wing), feet

c' wing chord (fig. 2), feet

c projection of wing chord in wing reference plane ($c' \cos \epsilon$, fig. 2), feet

$\bar{c}$ mean aerodynamic chord $\left(\dfrac{\int_0^{b/2} c^2 dy}{\int_0^{b/2} c\, dy}\right)$, feet

C_D drag coefficient $\left[\dfrac{\text{drag}}{q(S/2)}\right]$

$C_{D_{min}}$	minimum drag coefficient
C_L	lift coefficient $\left[\frac{\text{lift}}{q(S/2)}\right]$
c_l	section lift coefficient as determined from measured pressure distributions
C_m	pitching-moment coefficient about $\bar{c}/4$ $\left[\frac{\text{pitching moment}}{q\bar{c}(S/2)}\right]$
h	height of fence, inches
$\frac{L}{D}$	lift-drag ratio
P	pressure coefficient $\left(\frac{p_l-p}{q}\right)$
p	free-stream static pressure, pounds per square foot
p_l	local static pressure on the surface, pounds per square foot
q	free-stream dynamic pressure $\left(\frac{\rho V^2}{2}\right)$, pounds per square foot
S	area of complete wing (twice area of semispan model), square feet
t	maximum thickness of the section at the station of the fence, inches
u,v	velocities within the boundary layer (fig. 3), feet per second
V	free-stream velocity, feet per second
x	distance measured parallel to X axis (fig. 2), feet
y	distance measured perpendicular to plane of symmetry, feet
x',y',z'	orthogonal coordinates used for boundary-layer data (x' perpendicular to the leading edge, y' parallel to the leading edge, and the x'y' plane tangent to the surface at the point of measurement, fig. 3), feet
$y_{c_{max}}$	maximum camber (fig. 2), percent chord (c')
α	angle of attack of wing reference plane,[1] degrees

[1]The wing reference plane contains the wing leading edge and the X and Y axes (fig. 2).

ϵ angle of twist (fig. 2), degrees

ρ free-stream mass density, slugs per cubic foot

CORRECTIONS

Tunnel-wall corrections were applied to the angle of attack and to the lift, drag, and pitching-moment coefficients using methods similar to those of references 7 and 8. The corrections were applied as follows:

$$C_L = 0.991\ C_{L_u}$$

$$\alpha = \alpha_u + 1.548\ C_{L_u}$$

$$C_m = C_{m_u} + 0.001\ C_{L_u}$$

$$C_D = C_{D_u} + 0.0319\ C_{L_u}$$

where the subscript u denotes the uncorrected values.

DESIGN OF BOUNDARY-LAYER-CONTROL DEVICES

Vortex Generators

The principle of the vortex generators, as discussed in reference 6, depends on the action of trailing vortices shed from the tips of the small airfoils (vortex generators) mounted on the surface of the main airfoil to produce an exchange of energy between the boundary layer and the stream outside the boundary layer. It was shown that when applied to a two-dimensional wing model, better results were obtained with adjacent generators set to produce vortices of opposite sense (counter-rotating) than with generators set to produce vortices rotating in the same sense (corotating). For an application to the swept wing it was anticipated that, in addition to the mixing action of the vortex generators, a further benefit possibly could be realized by setting the generators to produce vortices rotating in the sense which would tend to induce an inward component to the flow next to the surface of the wing, and oppose the natural spanwise flow of the boundary layer.

The design of the vortex generators employed in this investigation was based on the data presented in reference 6. The geometry, spacing, and chordwise location of the vortex generators were expressed in relation to the thickness of the boundary layer of a two-dimensional wing at the location of the vortex generators and to the turbulent separation point.

For application to the swept wing, the vortex generators were made of one size and shape which was based on the estimated boundary-layer thickness at 0.3 of the chord at 0.5 semispan of the wing at a lift coefficient of 0.4. This design undoubtedly was not optimum for all sections of the swept wing, especially for differing chordwise locations of the generators, but the simplification of the design was considered justifiable because the results of reference 6 indicated that a fairly wide latitude in the design of vortex generators is permissible. At any rate, it was believed that the design chosen would give an adequate indication of the effectiveness of vortex generators as boundary-layer-control devices on the swept wing of the present investigation.

Variables which might be expected to govern the effectiveness of vortex generators in these tests are:

1. Chordwise location
2. Spanwise extent
3. Spacing
4. Sense of adjacent generators
5. Angular deflection
6. Generator size and design

In the following discussion, only the effects of the first five variables for a given generator size and shape are considered. The effects of variations of generator size and design or the benefits of more than one row of vortex generators were not investigated.

Fences

The investigation reported in reference 5 showed that the unsatisfactory stability characteristics of the 63° swept wing were primarily the result of flow separation and spanwise flow of the boundary layer, particularly over the aft portion of the wing. It was reasoned, therefore, that the full-chord, rectangular, boundary-layer-control fences employed in that investigation could be shortened and reduced in size without markedly impairing the improvement in the stability of the wing produced by the fences.

MODEL AND APPARATUS

The model used was the one described in detail in reference 5 and consisted of a swept-back wing-fuselage combination designed to be mounted in the wind tunnel as a reflection-plane model (fig. 1). The geometry and dimensions of the wing and fuselage are given in figure 1 and in tables I and II. The twist, camber, and thickness of wing sections parallel to the plane of symmetry are shown in figure 4. The salient dimensions of the wing are as follows: sweepback of the leading edge, 63°; aspect ratio, 3.5; ratio of tip chord to root chord, 0.25. A photograph of the model installed in the wind tunnel is shown in figure 5. Pressure orifices were installed in the wing along sections parallel to the plane of symmetry at 0.200, 0.383, 0.707, and 0.924 semispan.

Dimensions of the vortex generators are shown in figure 6, and photographs of the generators installed on the model are shown in figure 7. Dimensions of the boundary-layer-control fences tested on the model are given in figure 6 and in table III.

For the boundary-layer measurements a multiple-pronged rake was used. A photograph of this rake is shown in figure 8.

RESULTS AND DISCUSSION

Force Measurements

Tests with vortex generators.- A comparison of the most effective of the arrangements which employed generators producing counter-rotating vortices (deflection angles of 30° and -10°) with the most nearly equivalent arrangement of generators producing corotating vortices that was tested (deflection angle 35°) is shown in figure 9. The arrangement employing corotating vortices provided considerably greater improvement in the stability of the wing above a lift coefficient of 0.4. Hence the remainder of the investigation of vortex generators is devoted exclusively to the type of arrangement which gave corotating vortices. Representative data showing the over-all effects of the variables investigated are shown in figure 10. In general, the generators reduced by varying amounts the large variation in stability of the plain wing (i.e., the twisted and cambered wing without vortex generators) for lift coefficients greater than 0.4, but had no effect at lower lift coefficients. Since the greatest improvement in the stability of the wing due to the vortex generators was in the range of lift coefficients immediately above 0.4, the slope of the pitching-moment curve $C_{m_{C_L}}$ at a lift coefficient of 0.5 was chosen as a parameter to show the effects of variations of the chordwise location, spanwise extent, and spacing of the generators. Summary plots showing the effects of these variables on $C_{m_{C_L}}$ at a lift coefficient of 0.5 and on the minimum drag $C_{D_{min}}$ and the maximum lift-drag ratio $(L/D)_{max}$ are presented in figure 11. Insofar as the improvement of stability is concerned the following generalizations can be made:

1. For a generator deflection of 20°, the amount of stability $C_{m_{C_L}}$ at a lift of 0.5 increased as the generators were moved back from the 10-percent-chord station to the 60-percent-chord station. For larger angular deflections, the stability increase was relatively independent of the chordwise location. The more forward locations, however, increased the upper limit of the range of lift coefficients for positive stability (figs. 10(a) and (b)).

2. The amount of stability increase was greatest with the generators extending over the major portion of the span to the tip of the wing (figs. 11(b) and (c)). For less than full-span arrangements, considerably greater improvement in the amount of stability was produced when the generators were located over the outer portion of the span than with the same extent of generators over the inner portion of the span.

3. The effectiveness increased with closer spacing at least up to 8 generators per foot (1.5-inch spacing), but the amount of improvement was not in direct proportion to the spacing (fig. 11(d)).

4. The effectiveness increased with increasing deflection of the generators at least up to about 50°, as may be seen by inspection of figures 11(a), (b), and (c).

From stability considerations, the best arrangement found for the twisted and cambered 63° swept wing of the present investigation was with the vortex generators extending from 0.1 semispan to the tip along the 0.20-chord station, 1.5-inch spacing, and deflection angle of 50° (fig. 11(b)).

The increment of minimum drag above that of the plain wing for the wing with vortex generators set at a given deflection was nearly in proportion to the number of generators, as is shown by the tendency of the curves of drag against the number of generators per foot of span in figure 11(d) to form straight lines radiating from the value of minimum drag of the plain wing (no generators). The drag of the wing is also shown to be a function of the number of generators in figures 11(b) and (c), which also show that variations of the spanwise location of a given number of generators had no perceptible effect on drag. The drag of the wing with vortex generators tended to decrease slightly as the generators were moved back along the chord (fig. 11(a)), but increased rapidly with increasing angular deflection. The minimum drag coefficient increment due to the vortex generators extending from 0.1 semispan to the tip along the 0.2 chord with 1.5-inch spacing and deflected 50° was approximately 0.017 (fig. 11(b)).

Flight tests of straight- and swept-wing airplanes (references 9 and 10) have shown that at full-scale Reynolds numbers and at high speeds vortex generators are beneficial, at least in two cases, in extending the limits of pitch-up, wing dropping, and buffeting to higher lift coefficients with little detrimental effects on the performance. It should be pointed out that, for these flight tests, the deflection of the generators with respect to the free-stream velocity was 20°. On the wing of the present investigation with vortex generators set at 20° deflection (10° to 15° angle of attack with respect to free-stream velocity) and extending from 0.1 semispan to the tip along the 0.2 chord with 1.5-inch spacing, the minimum-drag coefficient increment due to the generators is of the order of 0.004 (fig. 11(b)).

Tests with fences.- The effects of variations of the shape and size of a single fence at 0.6 semispan are shown in figures 12 and 13. In these figures, the relative effectiveness of a full-chord rectangular fence ($h = 5t$) and triangular fences with heights varying from $h = 0.5t$ to $h = 5t$ are compared. Reducing the fence size from a full-chord rectangular fence ($h = 5t$) to a triangular fence with height approximately the thickness of the wing did not markedly impair the improvement in the stability of the wing produced by the fences.

The results of tests made with a single triangular fence ($h = t$) located at different spanwise stations and with multiple fences are shown in figure 14. The greatest improvement in stability of the wing was produced with fences at 0.3, 0.6, and 0.8 semispan. A comparison of the result obtained with this arrangement of fences with the results obtained with three different vortex-generator arrangements is shown in figure 15. The three vortex-generator arrangements chosen for comparison with the fences employed generators extending from 0.3 semispan to the tip with 3-inch spacing, and were selected from considerations of improvement of stability without excessive drag. The stability of the wing with fences was about the same as with either of the two vortex-generator arrangements with the generators deflected 40°, but the maximum lift-drag ratio of the wing with generators was generally lower. The maximum lift-drag ratio of the wing with vortex generators deflected 20° was about the same as for the wing with the three fences, but the stability, indicated by $C_{m_{C_L}}$, at high lift coefficient was slightly less. At a lift coefficient of 0.6 (above that for maximum lift-drag ratio), the lift-drag ratio was nearly the same for the wing with either fences or vortex generators.

Pressure-Distribution Measurements

The pressure distributions measured at four spanwise stations on the wing have been integrated to ascertain the various section lift coefficients. The variations of the section lift coefficients with wing angle of attack are shown in figure 16. Included in this figure are the wing pitching-moment coefficients obtained from force tests. The data are presented for the plain wing, for the wing with three triangular fences (h = t), and for the wing with vortex generators at 0.4 chord extending from 0.3 semispan to the tip with 3-inch spacing, and 20° deflection. The addition of either fences or vortex generators increased the maximum lift of the section near the tip (0.924 semispan) approximately the same amount (fig. 16).

The effect of the fences and of the vortex generators on the chordwise distribution of pressure at 0.924 semispan is illustrated in figure 17. For an angle of attack of 11°, the pressure distribution of the plain wing was suggestive of the pressure distribution of a thin airfoil section near the angle of attack for maximum lift in two-dimensional flow. The addition of either the fences or the vortex generators increased the pressures on the upper wing surface without greatly changing the distribution. The greater area enclosed by the pressure distribution for the wing with fences or with vortex generators accounts, of course, for its greater section lift coefficient.

For an angle of attack of 15.2° (beyond that for maximum lift of the section either with or without fences), the three pressure distributions for the 0.924 semispan station are similar but do not resemble the pressure distributions of stalled thin airfoil sections in two-dimensional flow. Instead they are more reminiscent of airfoil sections which stall from the trailing edge and develop a long extent of turbulent separated flow over the rear portion without separation from the leading edge.

Boundary-Layer Measurements

The effect of the vortex generators on the boundary-layer flow over the wing was ascertained by direct measurements using the directional rake shown in figure 8. The flow velocity and direction at several distances above the surface of the wing were measured and resolved into components perpendicular and parallel to the leading edge as shown in figure 3. The data are presented as ratios of the u and v components of the local velocity to the free-stream velocity V, and the flow direction through the boundary layer. The boundary-layer characteristics measured at four stations near the trailing edge of the outer portion of the plain wing are shown in figure 18 for several angles of attack. Similar measurements for the wing with vortex generators are shown in figure 19. Comparison of the two figures shows that the effect of the vortex generators was to increase the chordwise component of the flow and to reduce the thickness of the boundary layer at high angles of attack.

The effect of differences in the arrangement of vortex generators on the boundary layer measured at 0.95 semispan and 0.80 chord is shown in figure 20 for two angles of attack. The two arrangements with

40° deflection produced the greatest effect on the flow direction. For the higher angle of attack (11°), all generator arrangements reduced the thickness of the boundary layer below that on the plain wing.

CONCLUDING REMARKS

Force, pressure-distribution, and boundary-layer measurements at low speed on a twisted and cambered 63° swept-back wing showed that the addition of boundary-layer-control fences or vortex-generating devices could alleviate considerably the large variations in longitudinal stability which characterized the wing without boundary-layer-control devices.

For this wing, it was found that of the fence arrangements tested the best arrangement for maximum improvement in stability characteristics consisted of three 0.65-chord fences extending forward from the trailing edge at 0.3, 0.6, and 0.8 semispan.

The effectiveness of the vortex generators varied with deflection, spanwise extent, and spacing but was relatively independent of chordwise position. However, the more forward locations increased the upper limit of the range of lift coefficients for positive stability. Generators over the outer portion of the span were more effective than the same extent of generators over the inner portion of the wing. The generators provided about the same improvement in stability of the wing as the fences, but the maximum lift-drag ratio was lower. At lift coefficients, above that for maximum lift-drag ratio, the lift-drag ratio was nearly the same for the wing with either fences or vortex generators. The size of the vortex generators, however, was not necessarily optimum for this application.

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TABLE I.- COORDINATES OF THE FUSELAGE

[All dimensions given in inches]

Station	Diameter	Station	Diameter
0	0	81.6	16.32
4	2.84	91.8	16.20
8	5.34	102.0	15.82
12	7.50	112.2	15.20
16	9.30	122.4	14.28
20	10.80	132.6	13.26
24	11.98	142.8	11.68
28	12.88	153.0	9.86
30.6	13.26	163.2	7.58
40.8	14.28	164.4	7.16
51.0	15.20	166.4	5.82
61.2	15.82	168.4	3.58
71.4	16.20	170.4	0
Fineness ratio, $\frac{\text{length}}{\text{max diam}} = 10.4$			

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TABLE II.- DIMENSIONS OF THE SEMISPAN MODEL

Wing	
Area, square feet	14.26[a]
Span, feet	5.00
Mean aerodynamic chord, feet	3.20
Aspect ratio	3.5[b]
Taper ratio	0.25
Sweepback of leading edge, degrees	63
Sweepback of 1/4-chord line, degrees	60.8
Geometric twist, degrees	20.5
Dihedral, degrees	0
Fuselage	
Length, feet	14.20
Maximum diameter, feet	1.36
Fineness ratio	10.4

[a]Area to projected tip was 14.29 square feet.
[b]Based on 10-foot span and area (to projected tip) of 28.57 square feet.

TABLE III.- GEOMETRY OF THE TRIANGULAR FENCES

Fence height	Fence chord, percent wing chord
0.5t	30
1t	65
3t	85
5t	95

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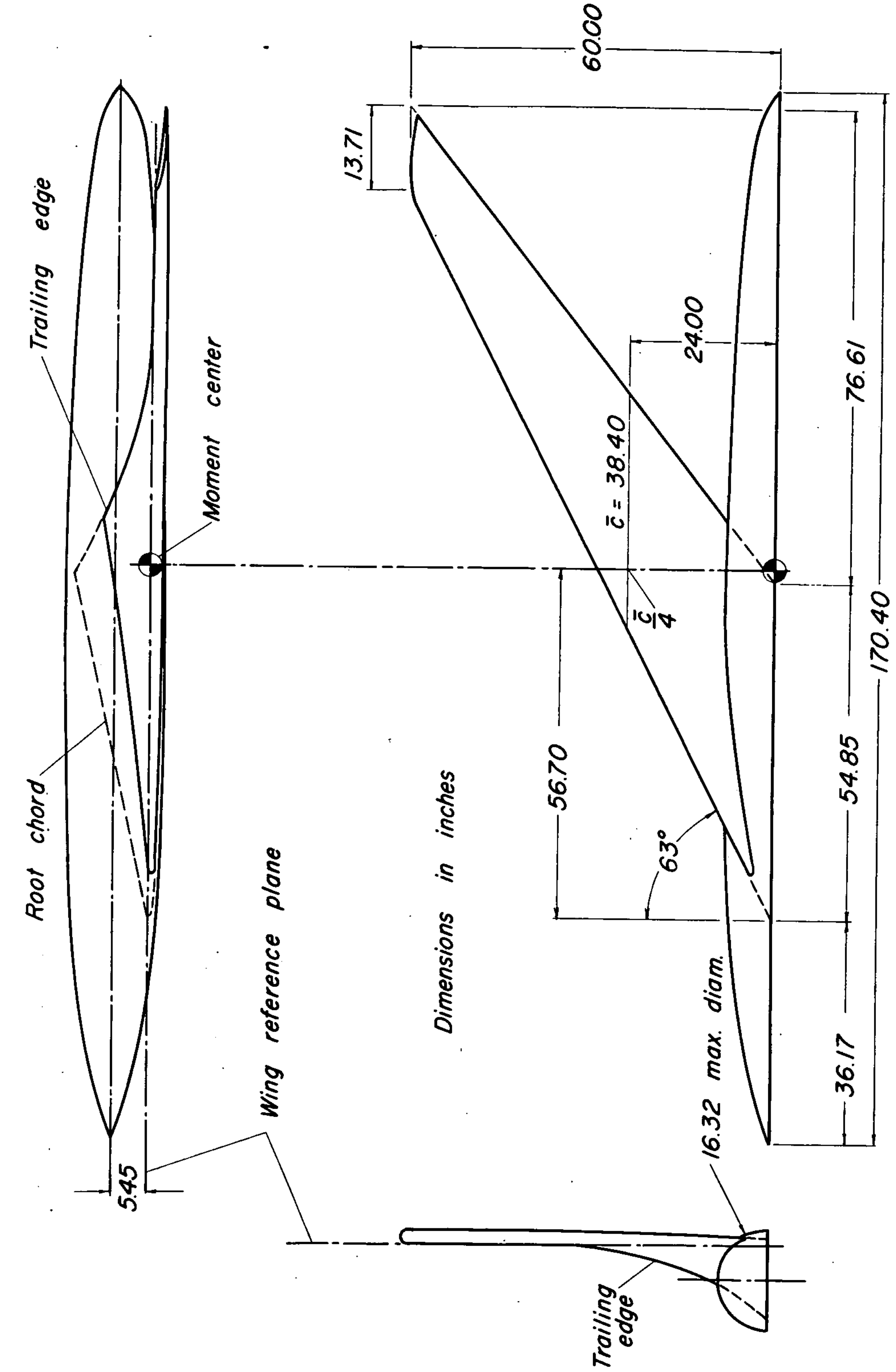

Figure 1.- Diagram of the model.

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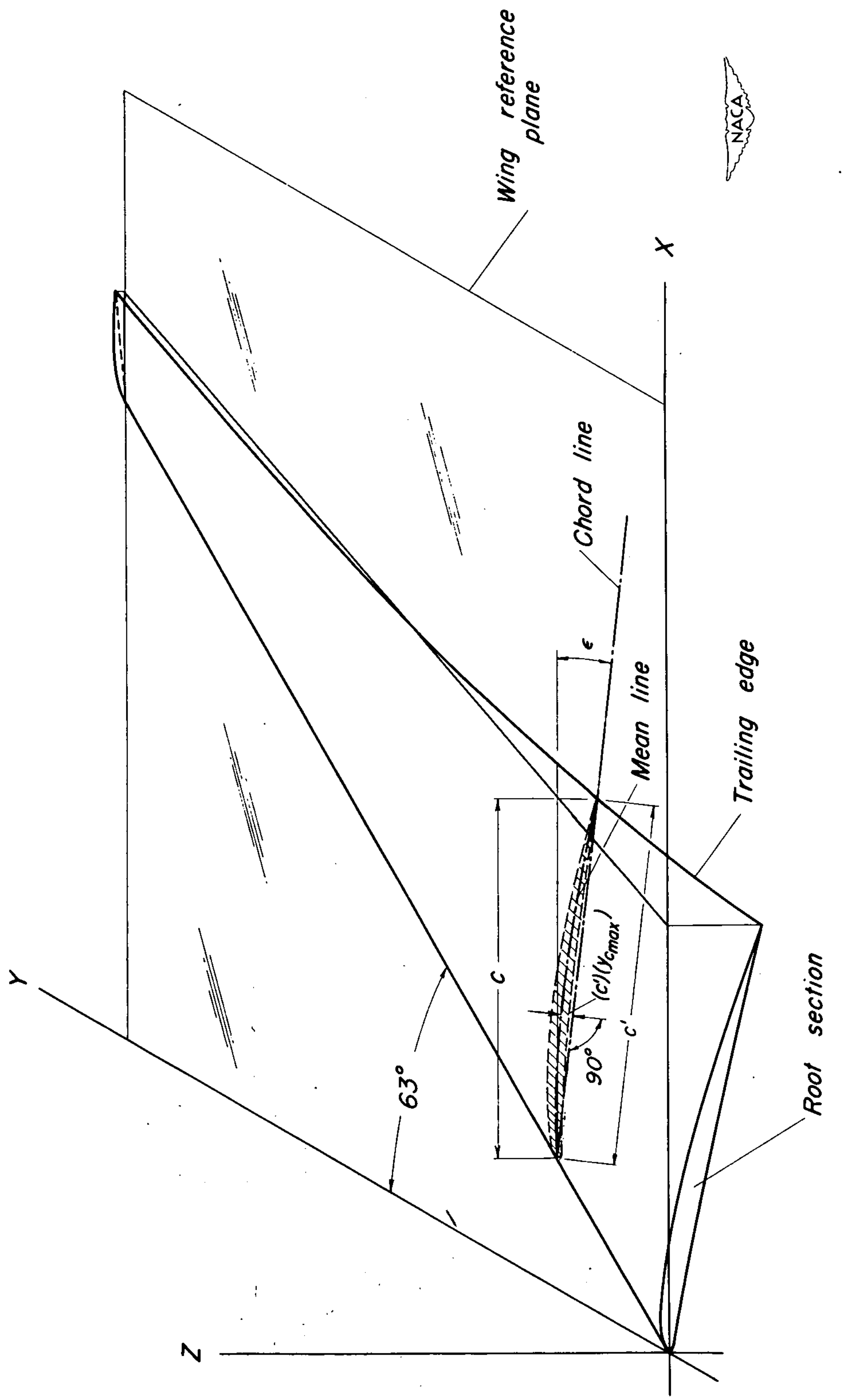

Figure 2.— Relationship between the wing geometry and the coordinate axes.

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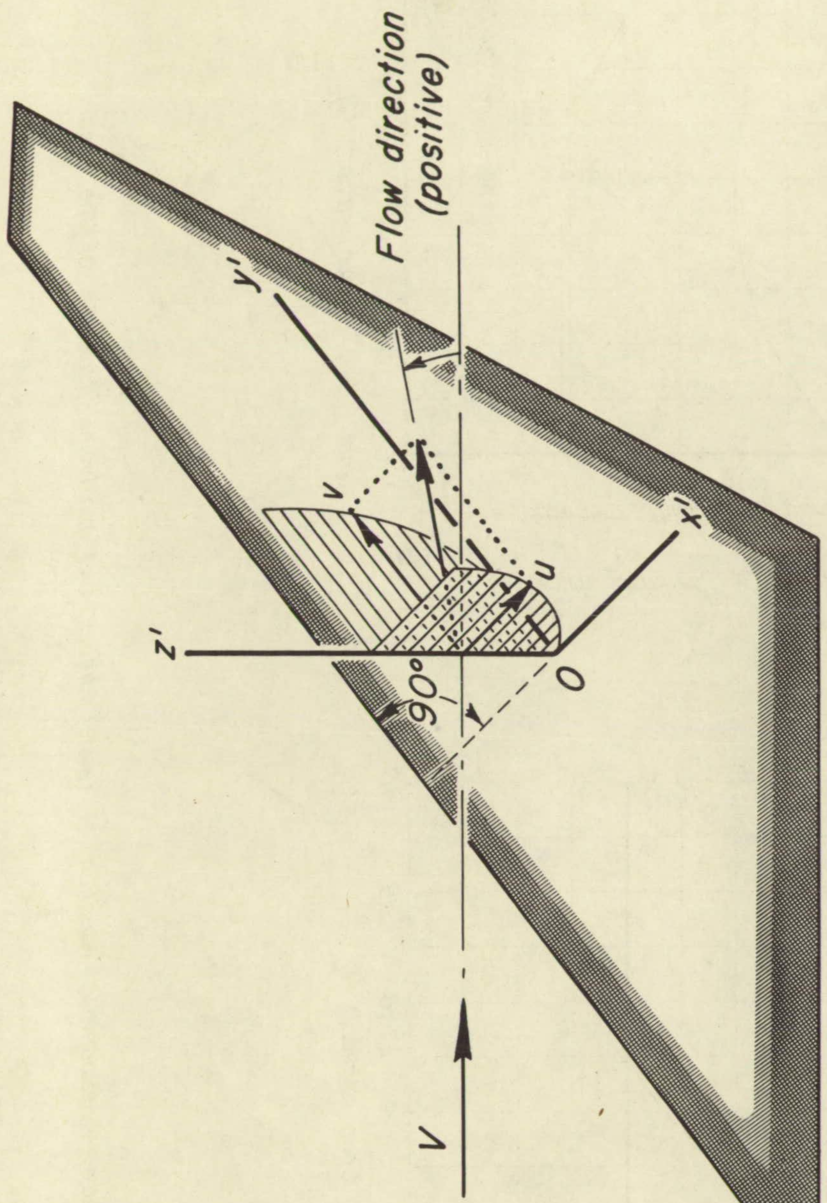

Figure 3.– Coordinate system used for boundary–layer measurements.

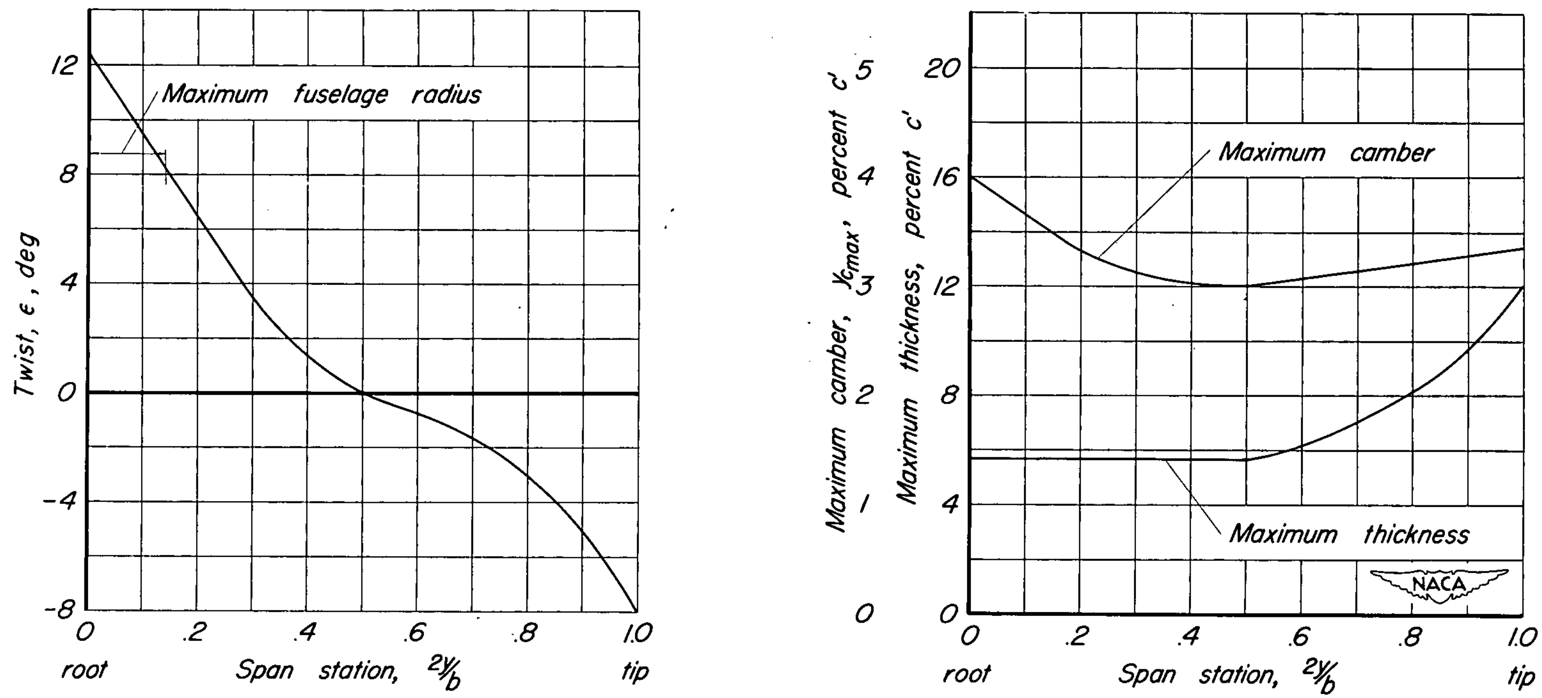

Figure 4.—Spanwise variation of twist, camber, and maximum thickness of the model.

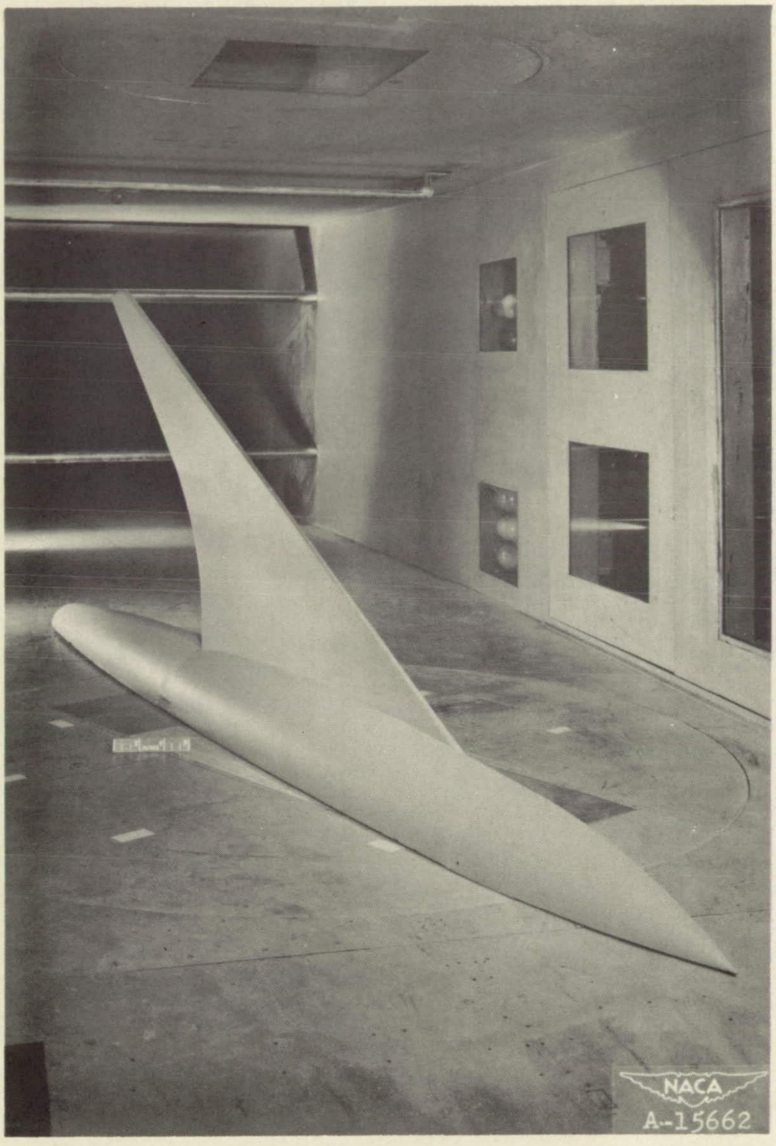

Figure 5.- The cambered and twisted 63° swept-wing model mounted in the wind tunnel.

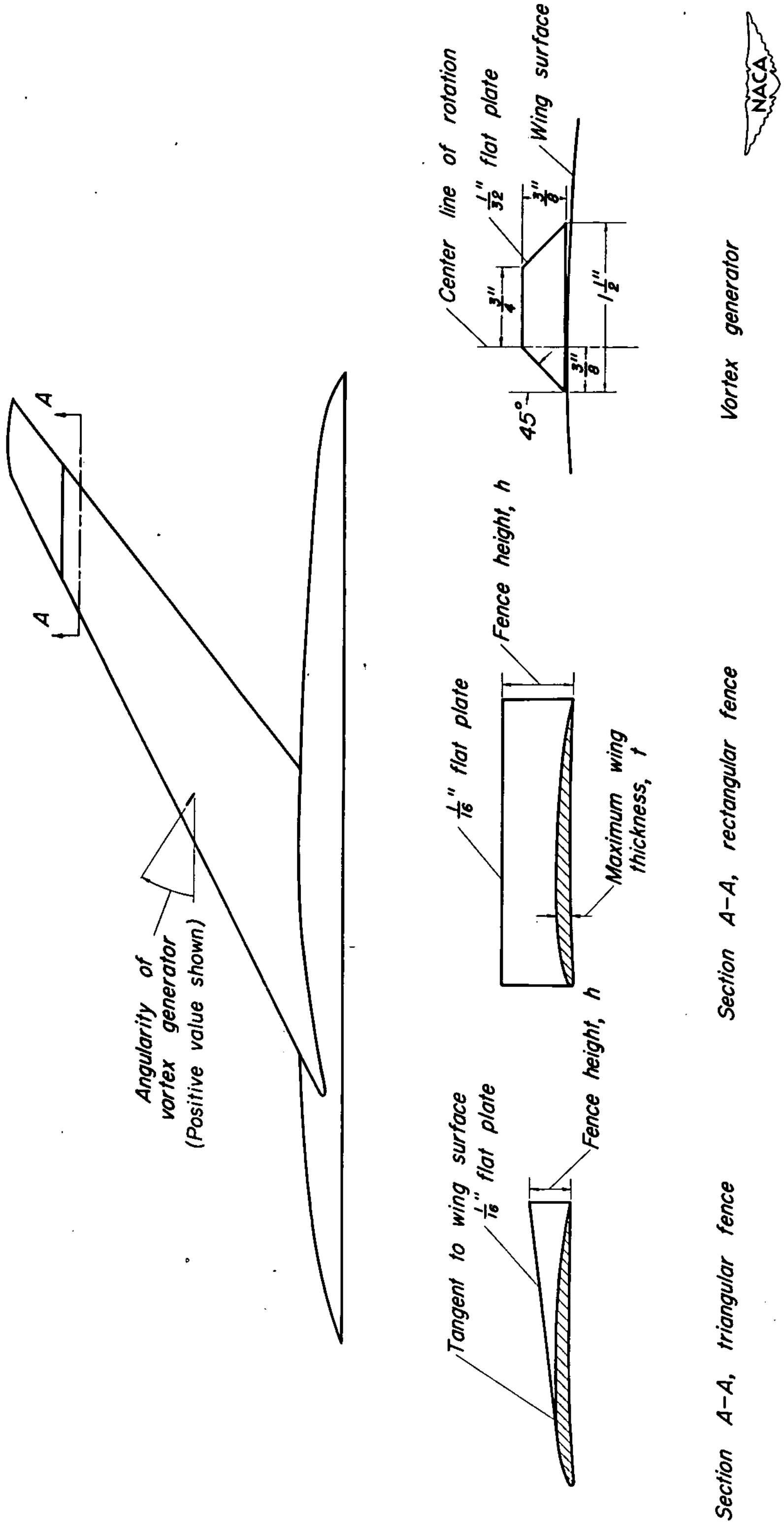

Figure 6.–Geometry of the fences and vortex generators.

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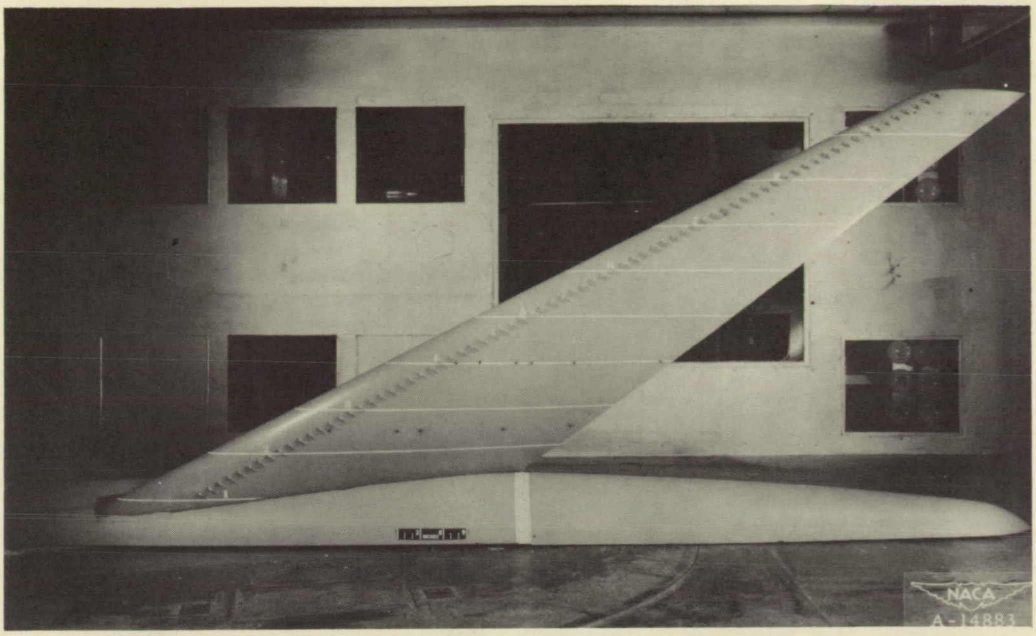
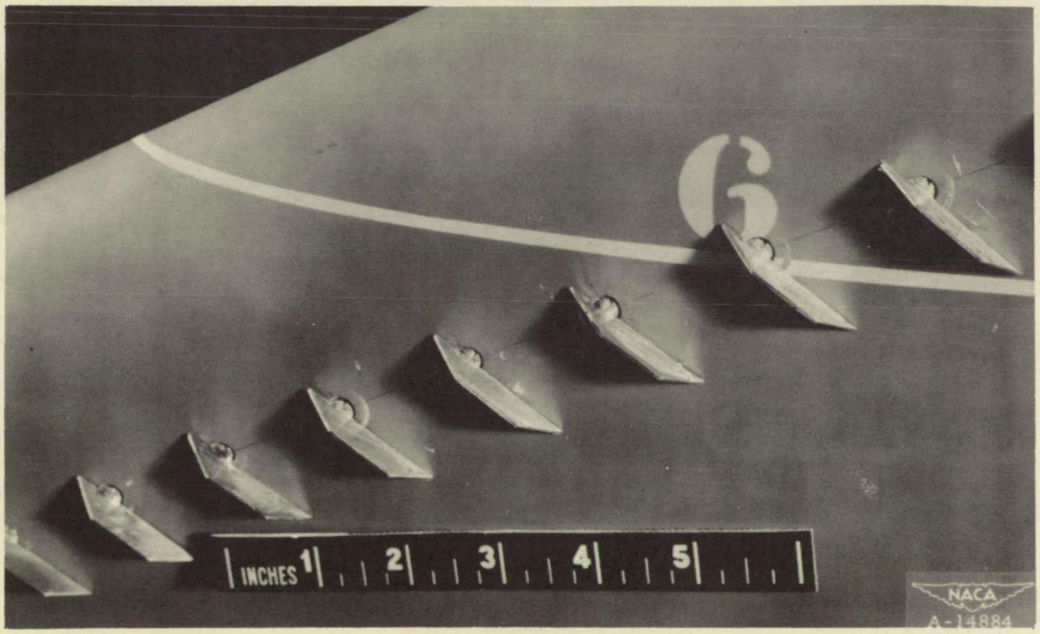


(a) Side view of the model.



(b) Detail of the generators.

Figure 7.- The vortex generators on the 63° swept-back-wing model.

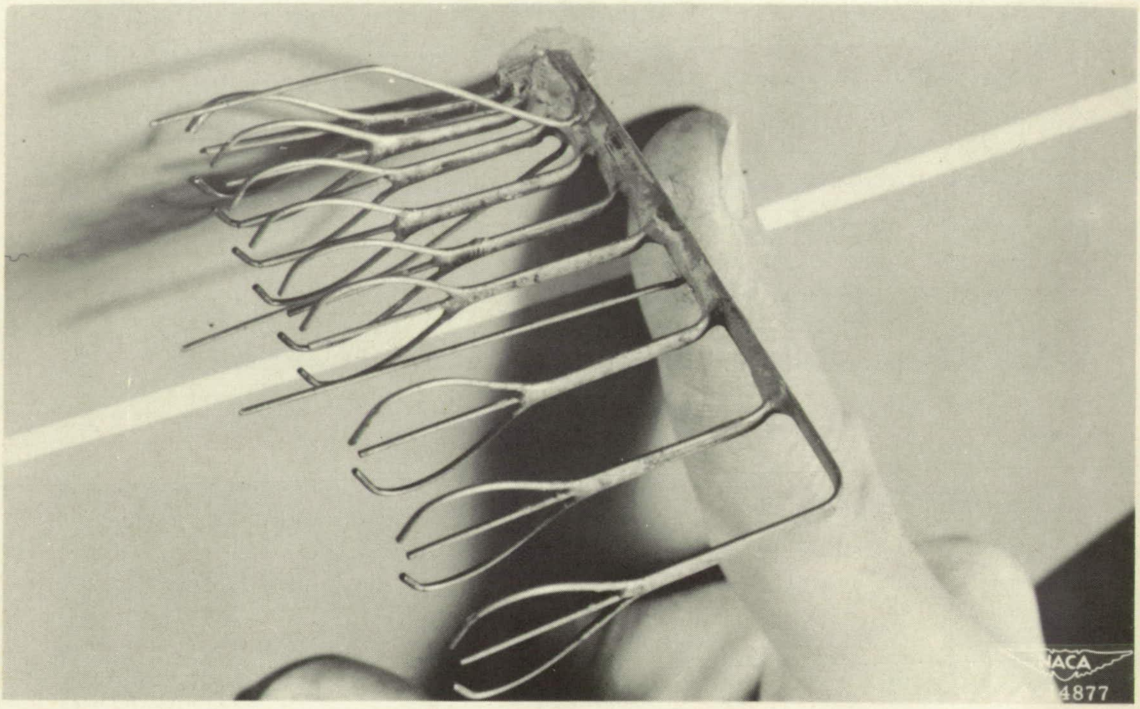


Figure 8.- Detail of the boundary-layer rake.

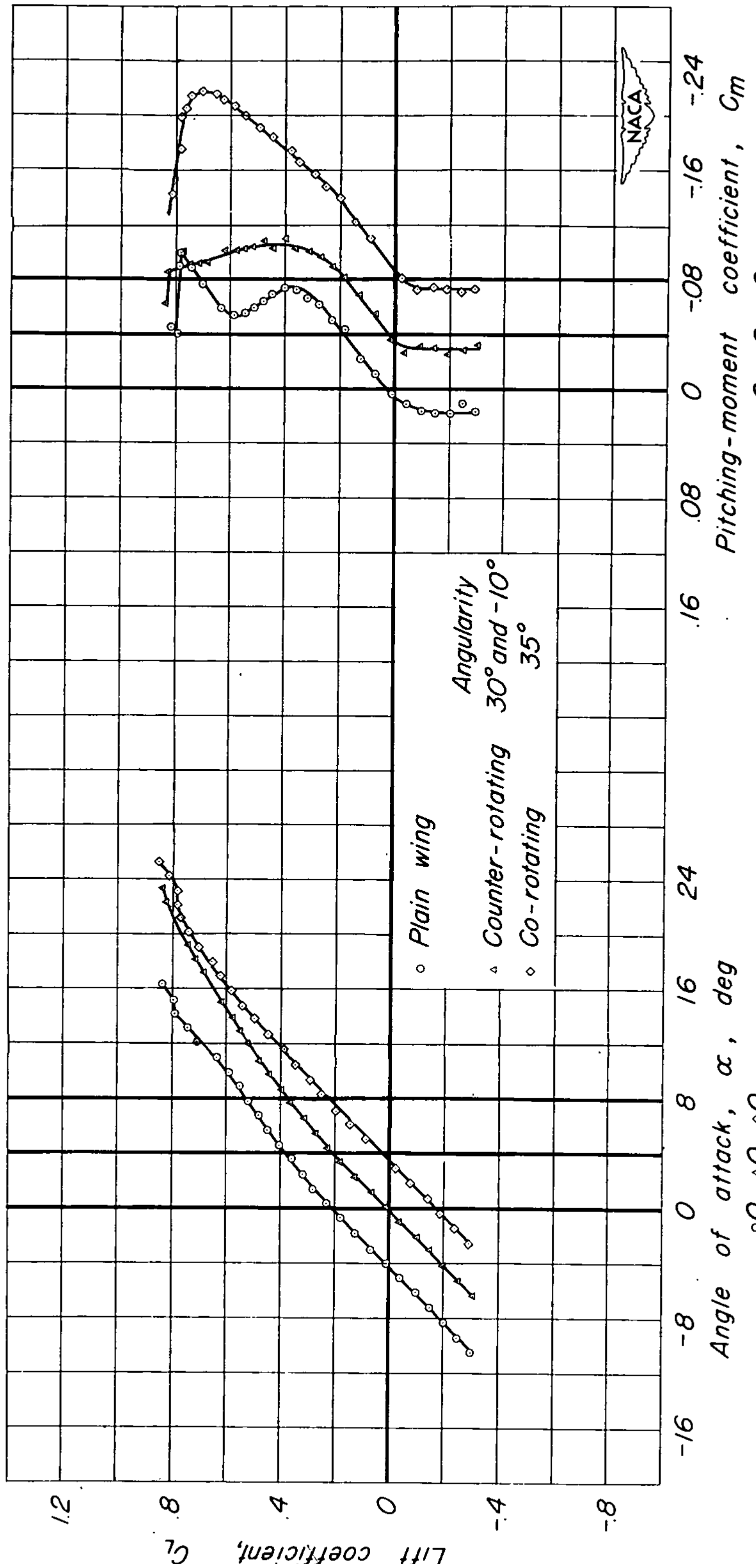


Figure 9.- Comparison of the effectiveness of vortex generators set to produce counter- and co-rotating vortices. Generators extend from 0.1 to 1.0 semispan at 0.2 chord with 1.5-inch spacing.

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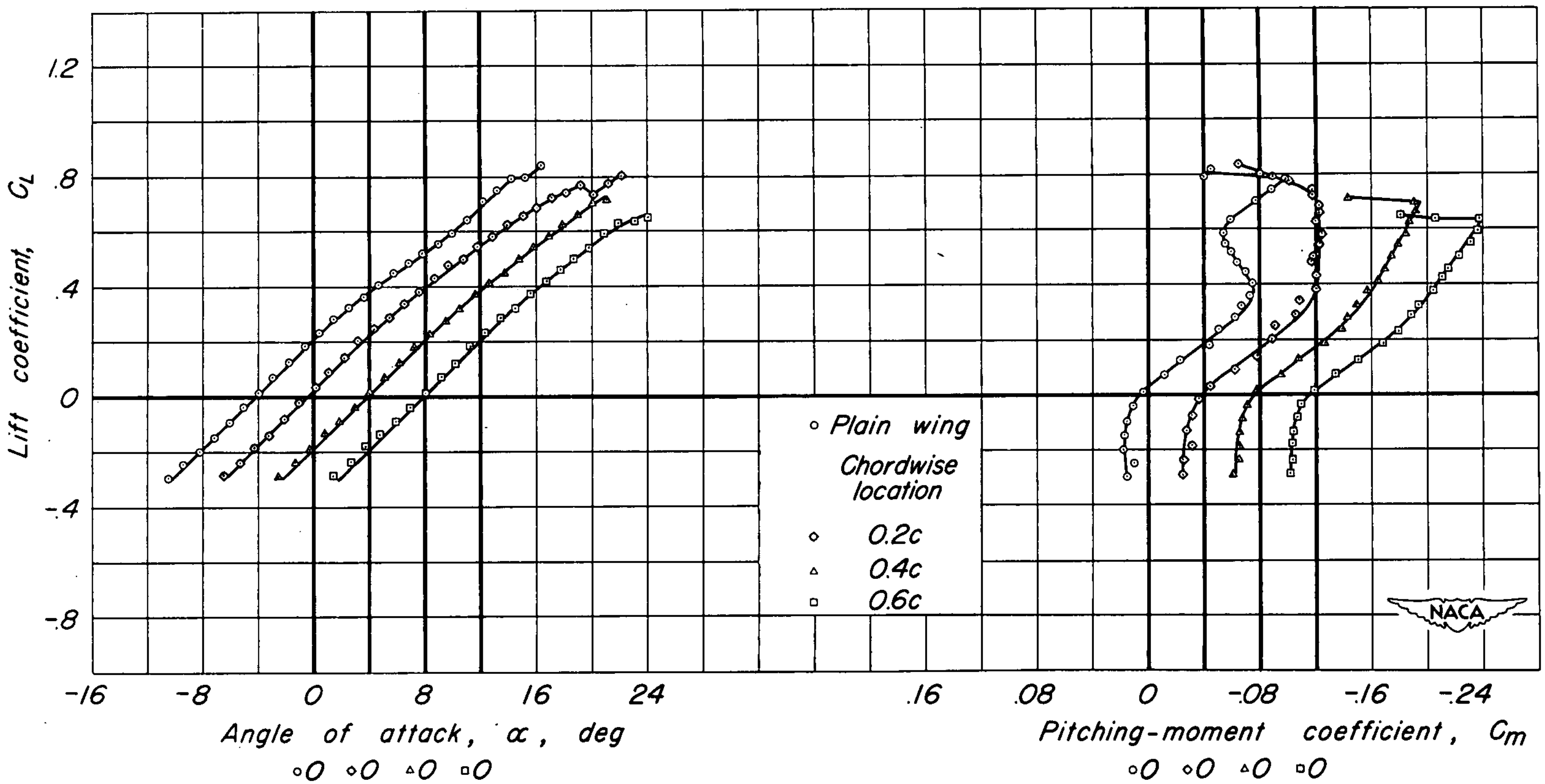
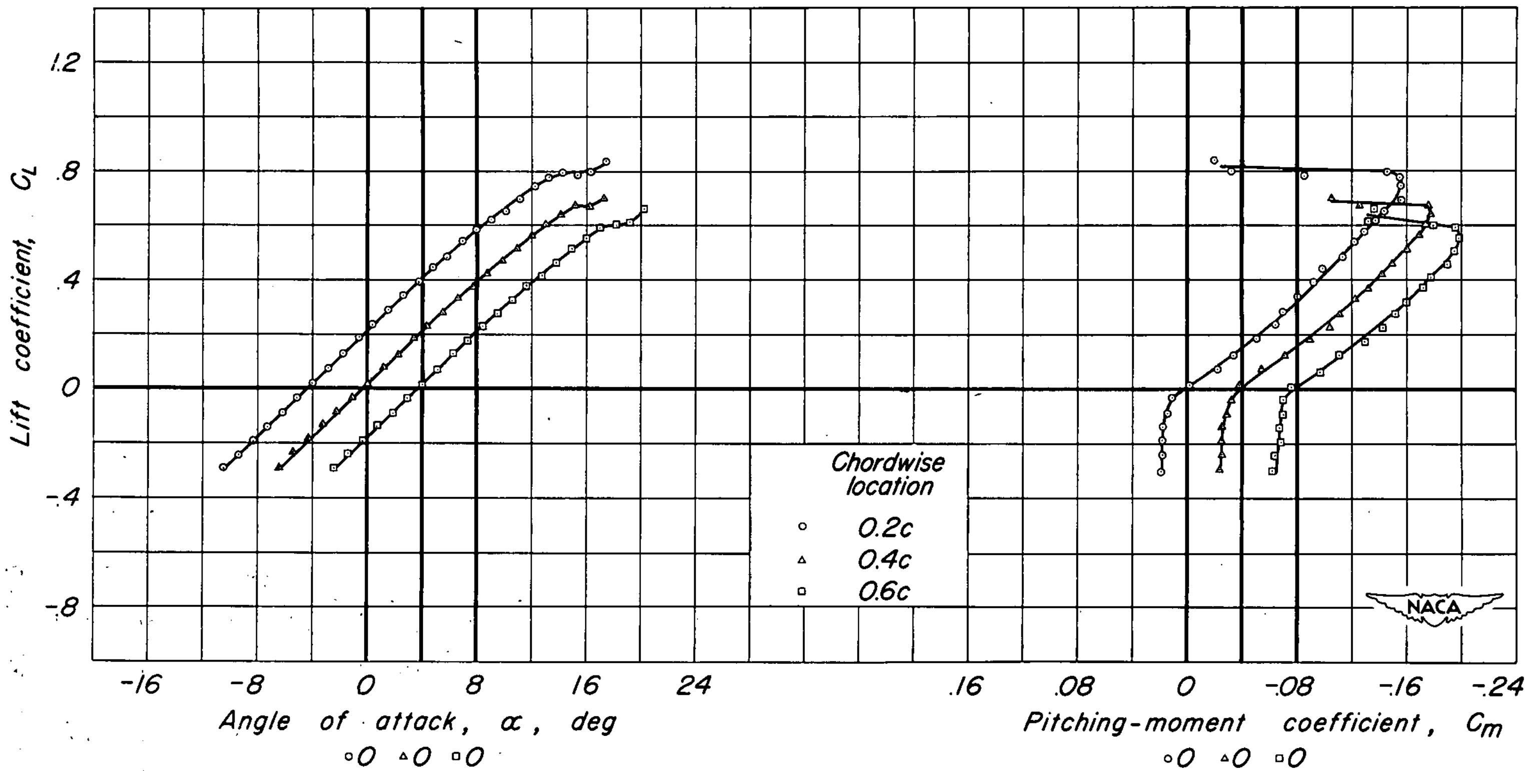


(a) Effect of chordwise location of vortex generators extending from 0.1 to 1.0 semispan with 3-inch spacing and 20° deflection.

Figure 10.— Lift and pitching-moment characteristics of the model with vortex generators.



(b) Effect of chordwise location of vortex generators extending from 0.1 to 1.0 semispan with 3-inch spacing and 50° deflection.

Figure 10.–Continued.

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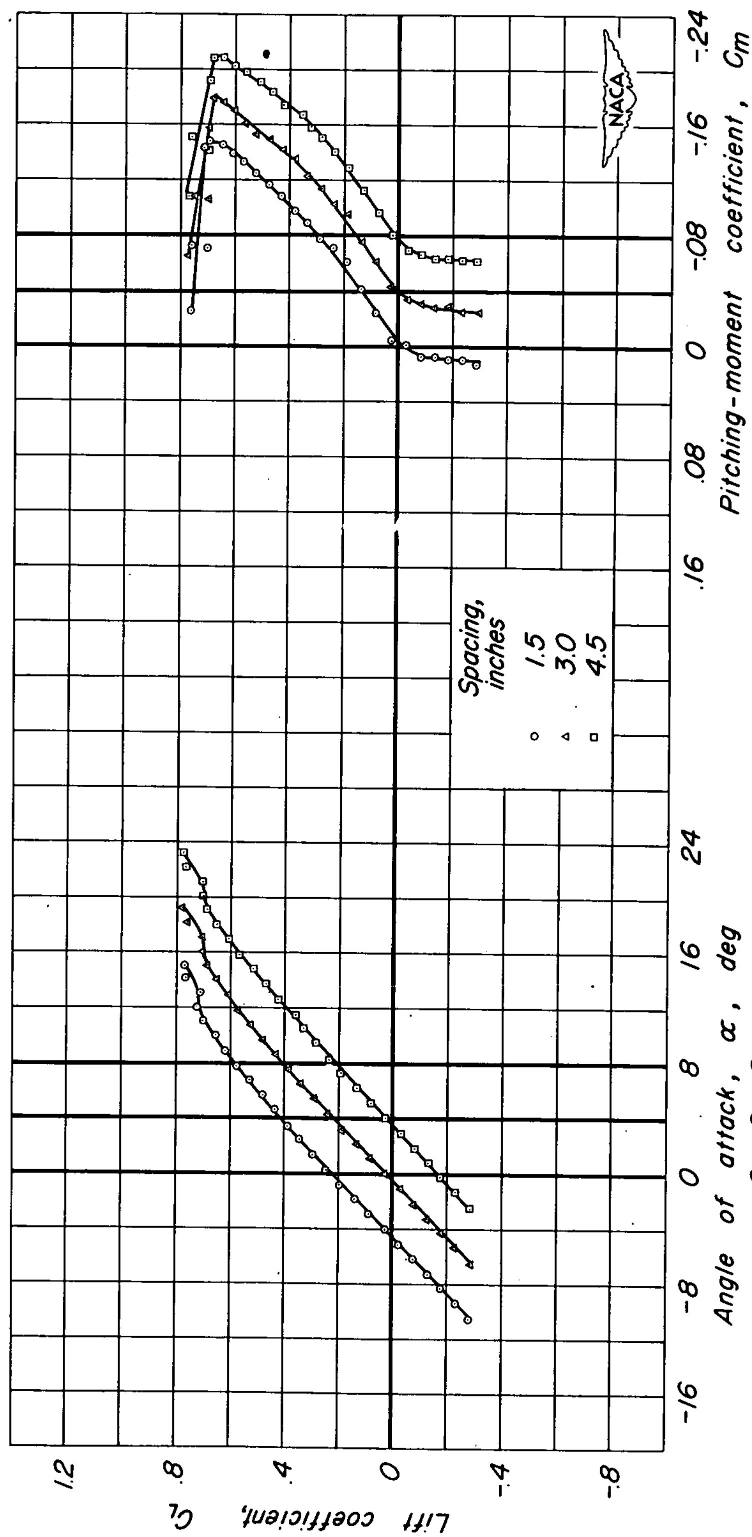
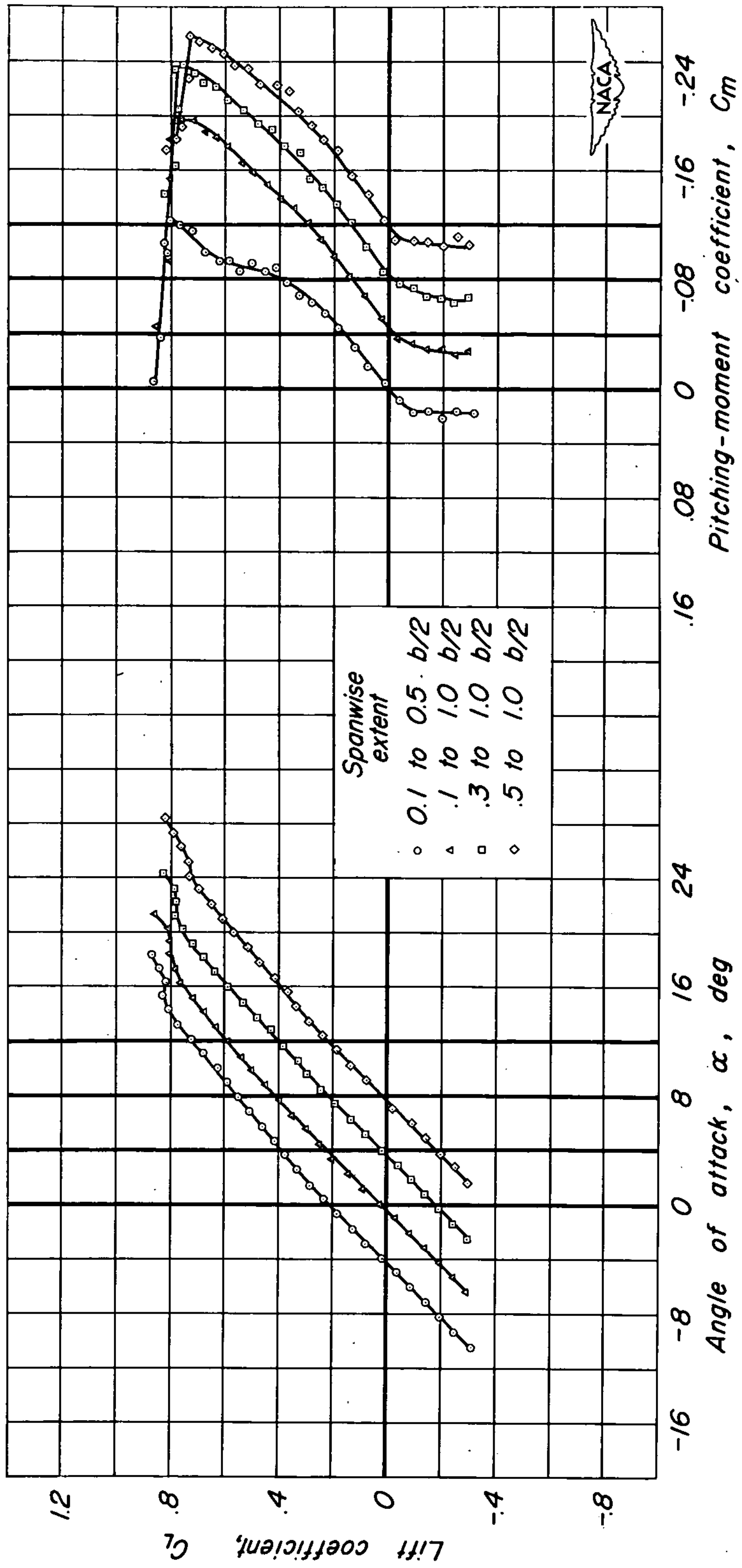


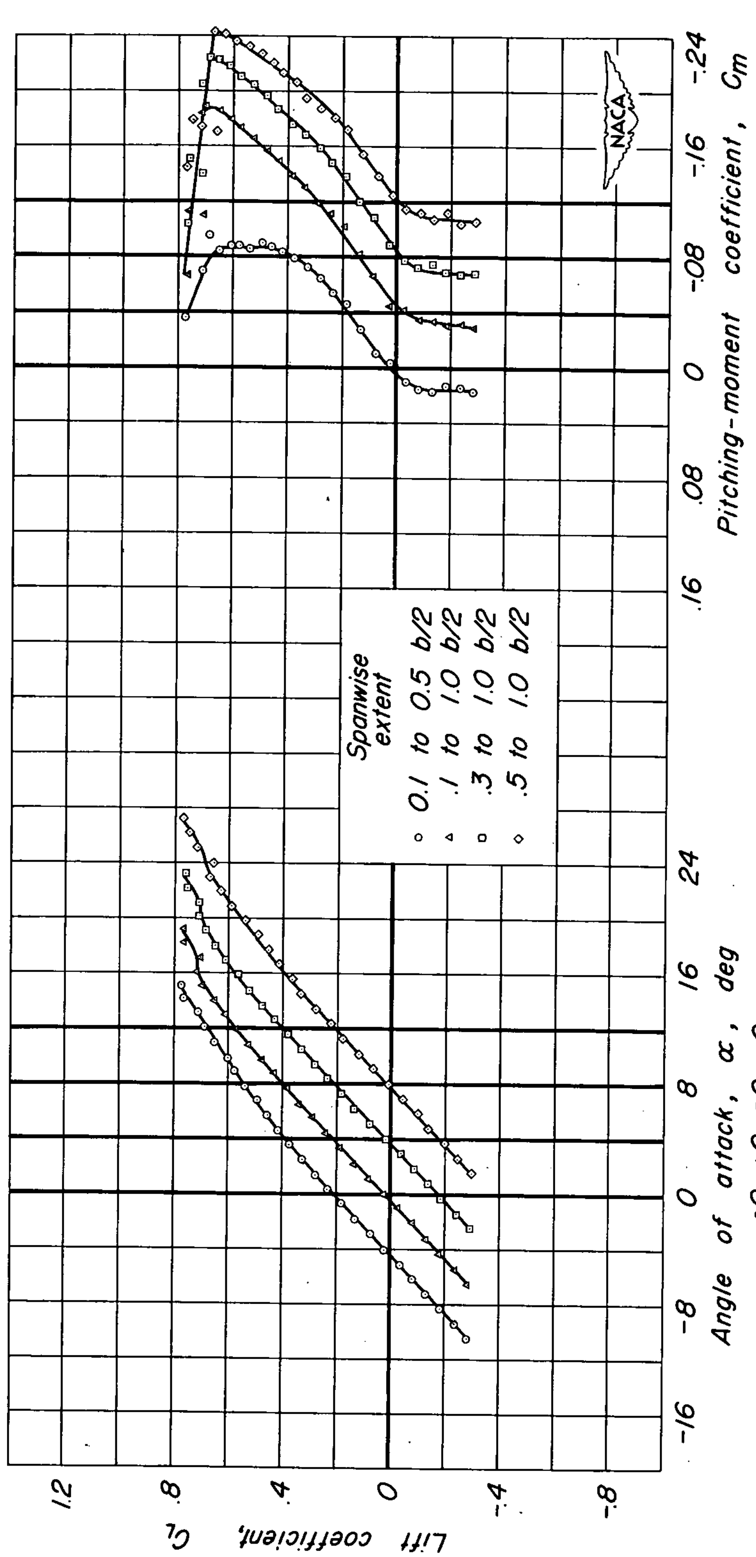
(c) Effect of spacing of vortex generators extending from 0.1 to 1.0 semispan at 0.4 chord with 40° deflection.

Figure 10.—Continued.



(d) Effect of spanwise extent of vortex generators along 0.2 chord with 1.5-inch spacing and 40° deflection.

Figure 10.–Continued.



(e) Effect of spanwise extent of vortex generators along 0.4 chord with 1.5-inch spacing and 40° deflection.

Figure 10.—Concluded.

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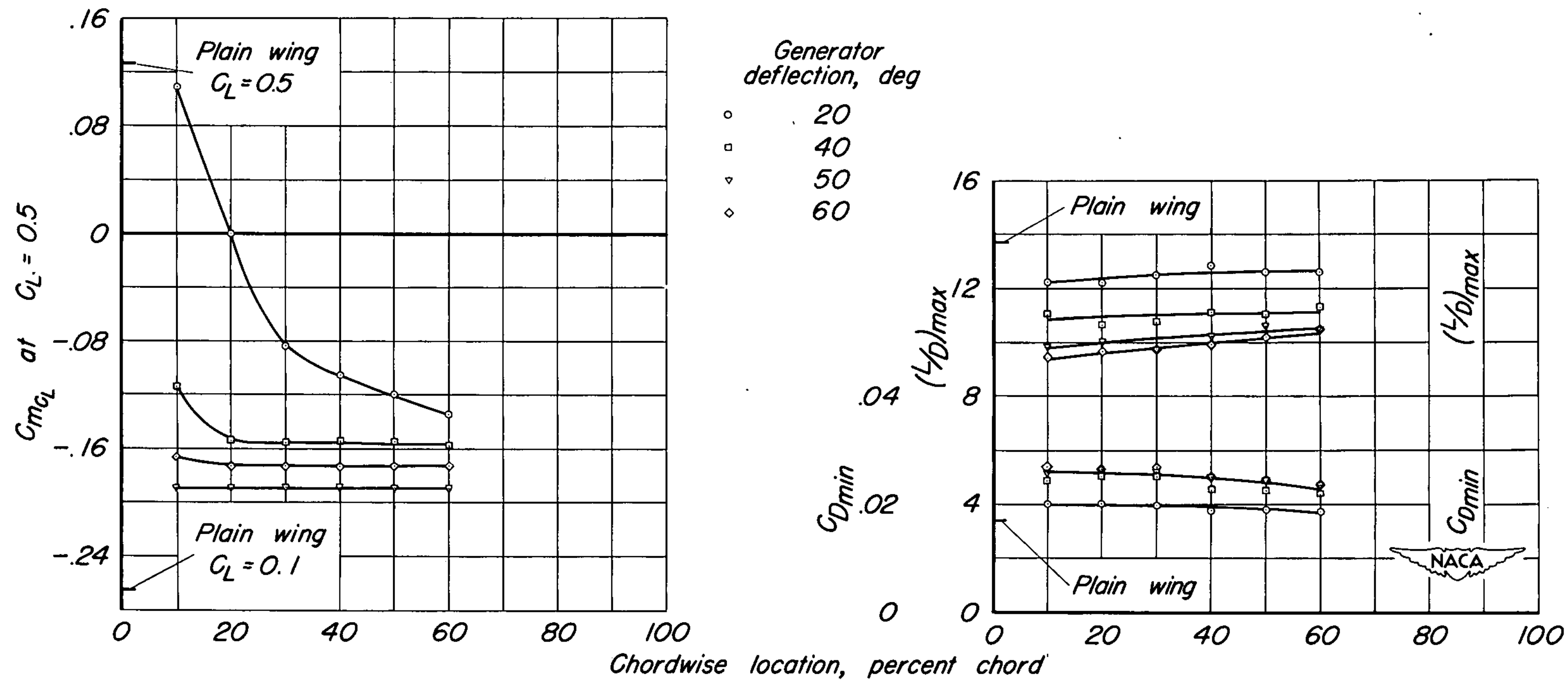
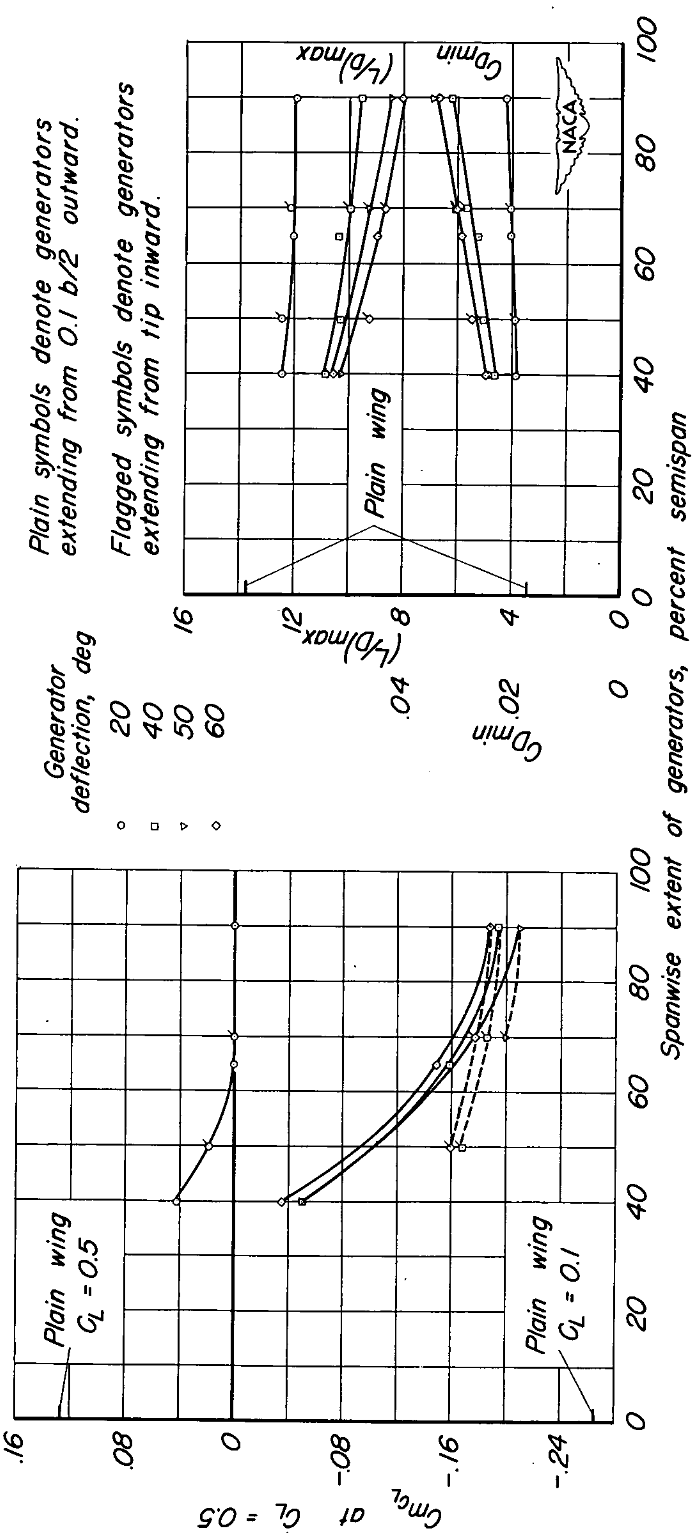


(a) Variation with chordwise location of generators extending from 0.1 to 1.0 semispan with 3-inch spacing.

Figure 11.—Variation of stability and drag characteristics of the model for various vortex generator arrangements.

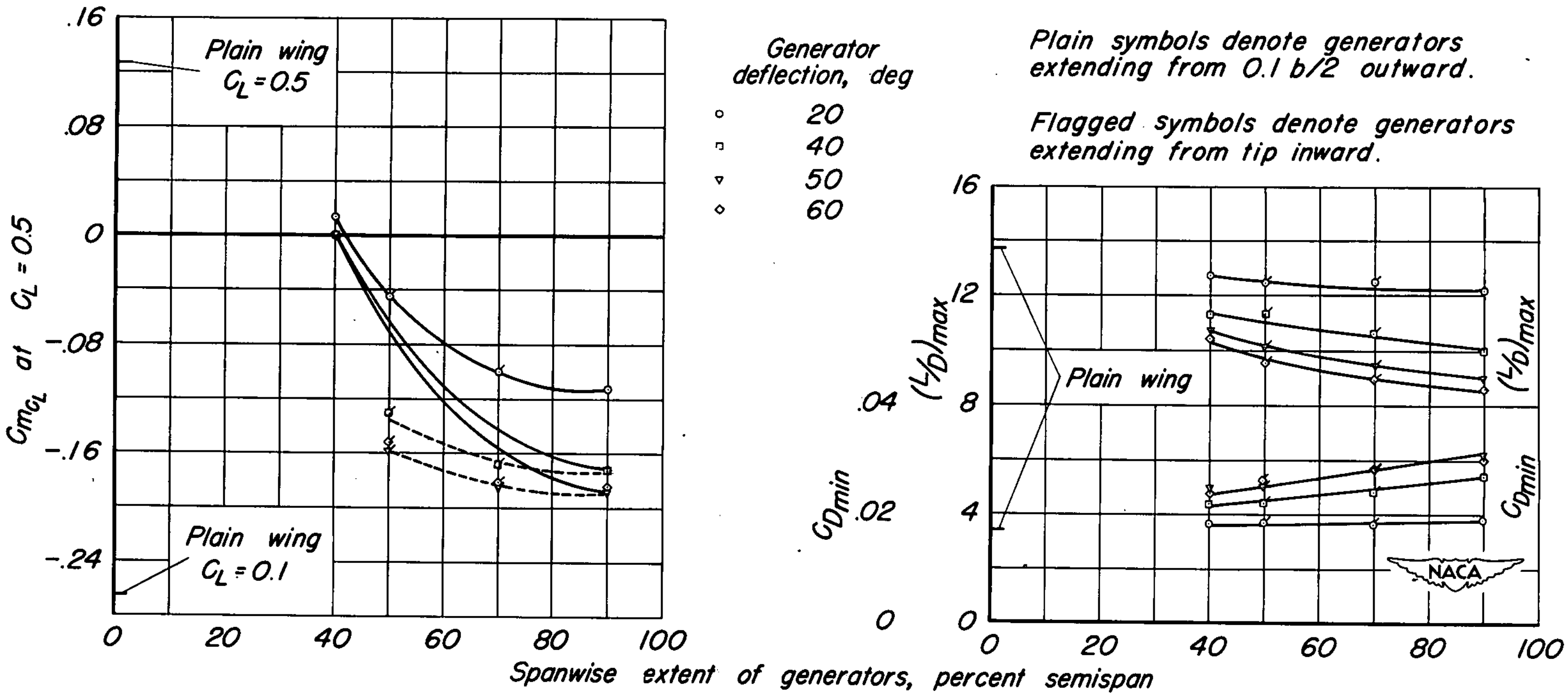
[redacted]



(b) Variation with spanwise extent of generators with 1.5-inch spacing along 0.2chord.

Figure 11.—Continued.

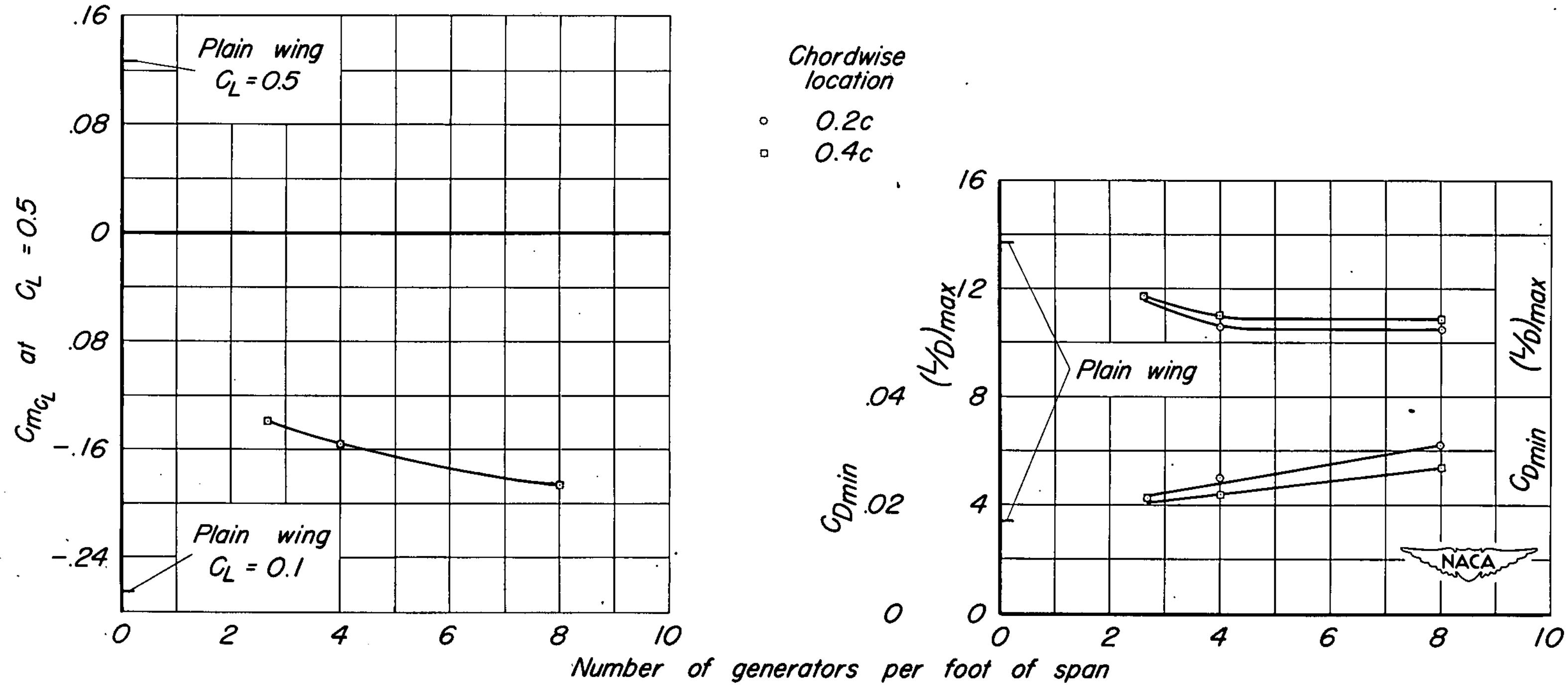
[redacted]



(c) Variation with spanwise extent of generators with 1.5-inch spacing along 0.4chord.

Figure 11.—Continued.

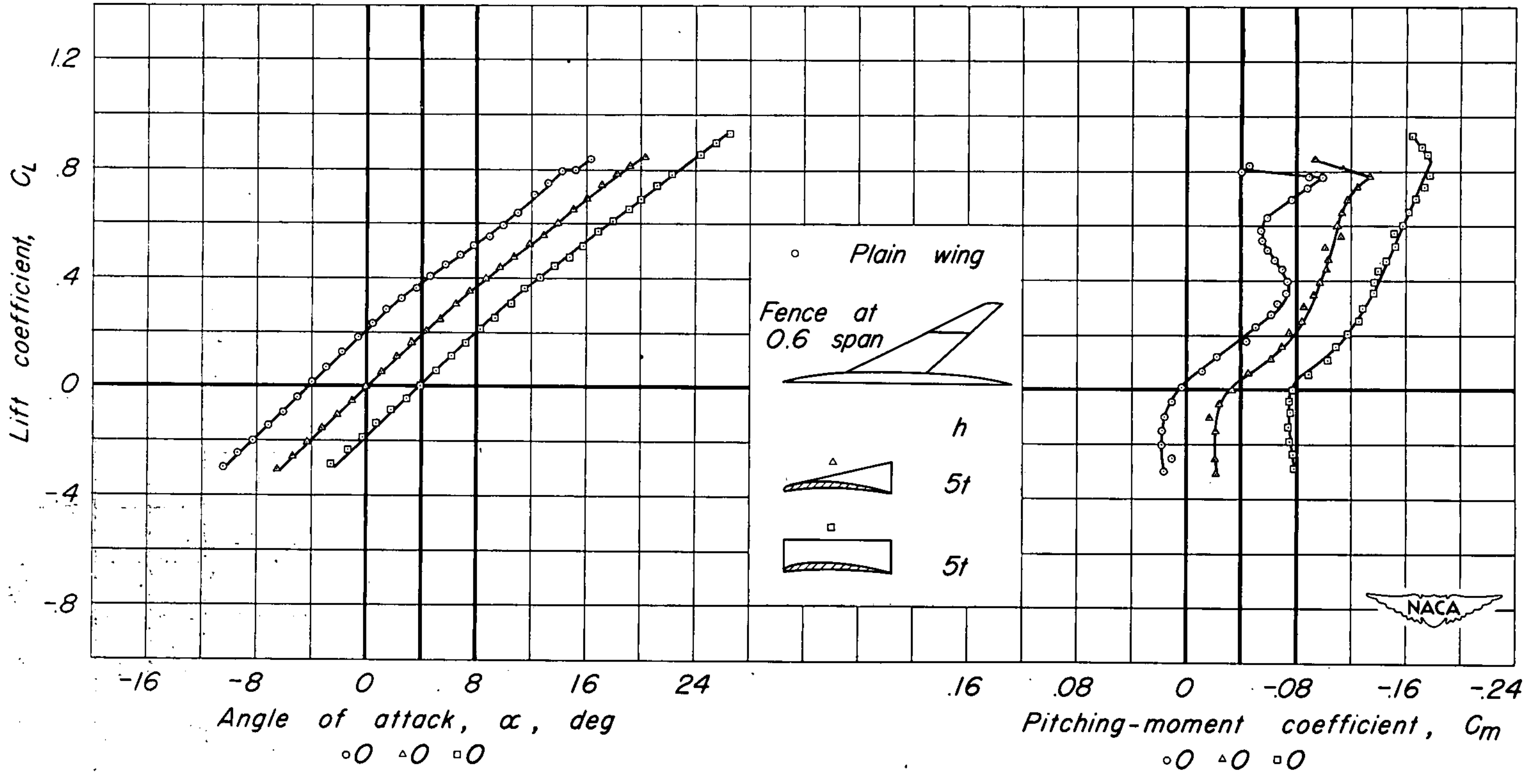
[redacted]



(d) Variation with spacing of generators extending from 0.1 to 1.0 semispan with 40° deflection.

Figure 11.—Concluded.

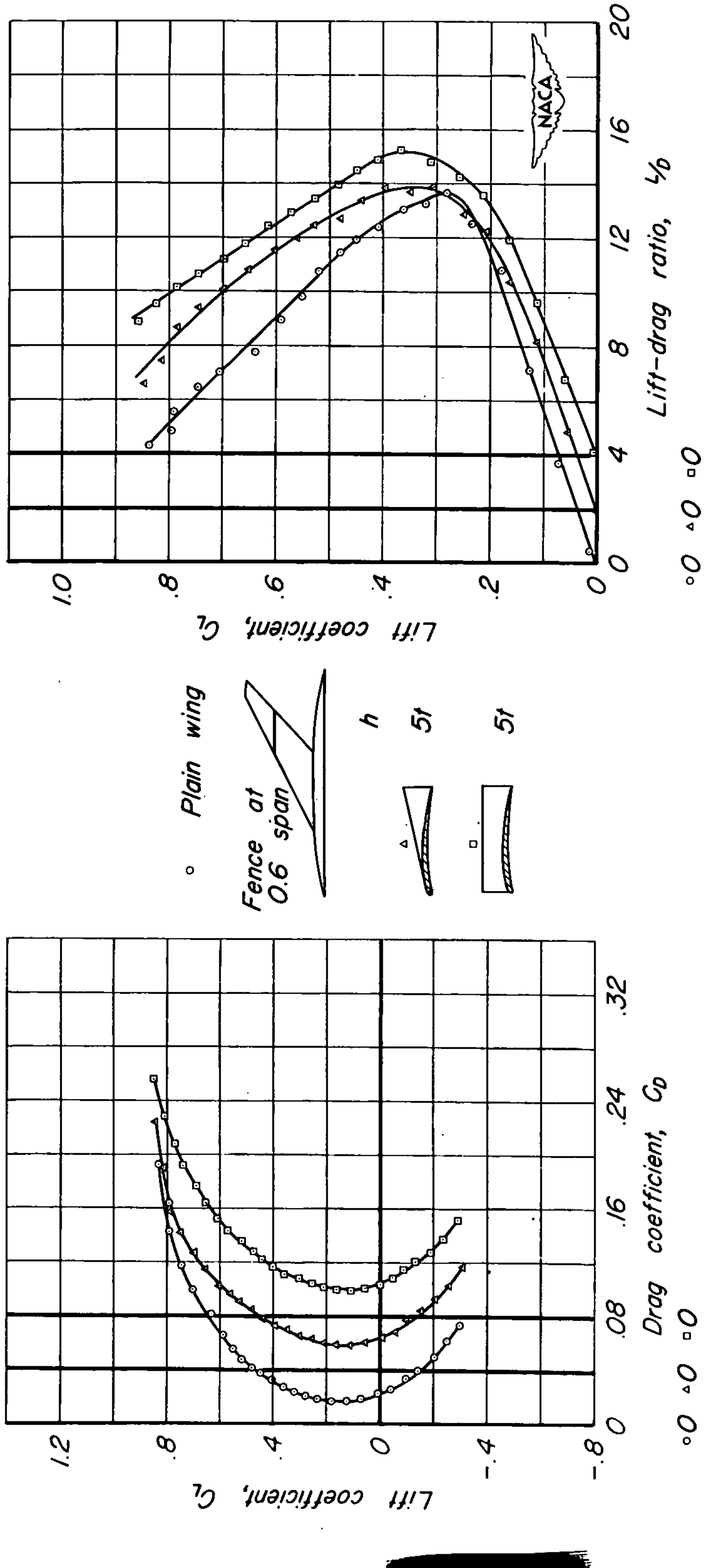
[redacted]



(a) Lift and pitching moment.

Figure 12.-Comparison of the effectiveness of a triangular and a rectangular fence.

[redacted]



(b) Drag and lift-drag ratio.

Figure 12.-Concluded.

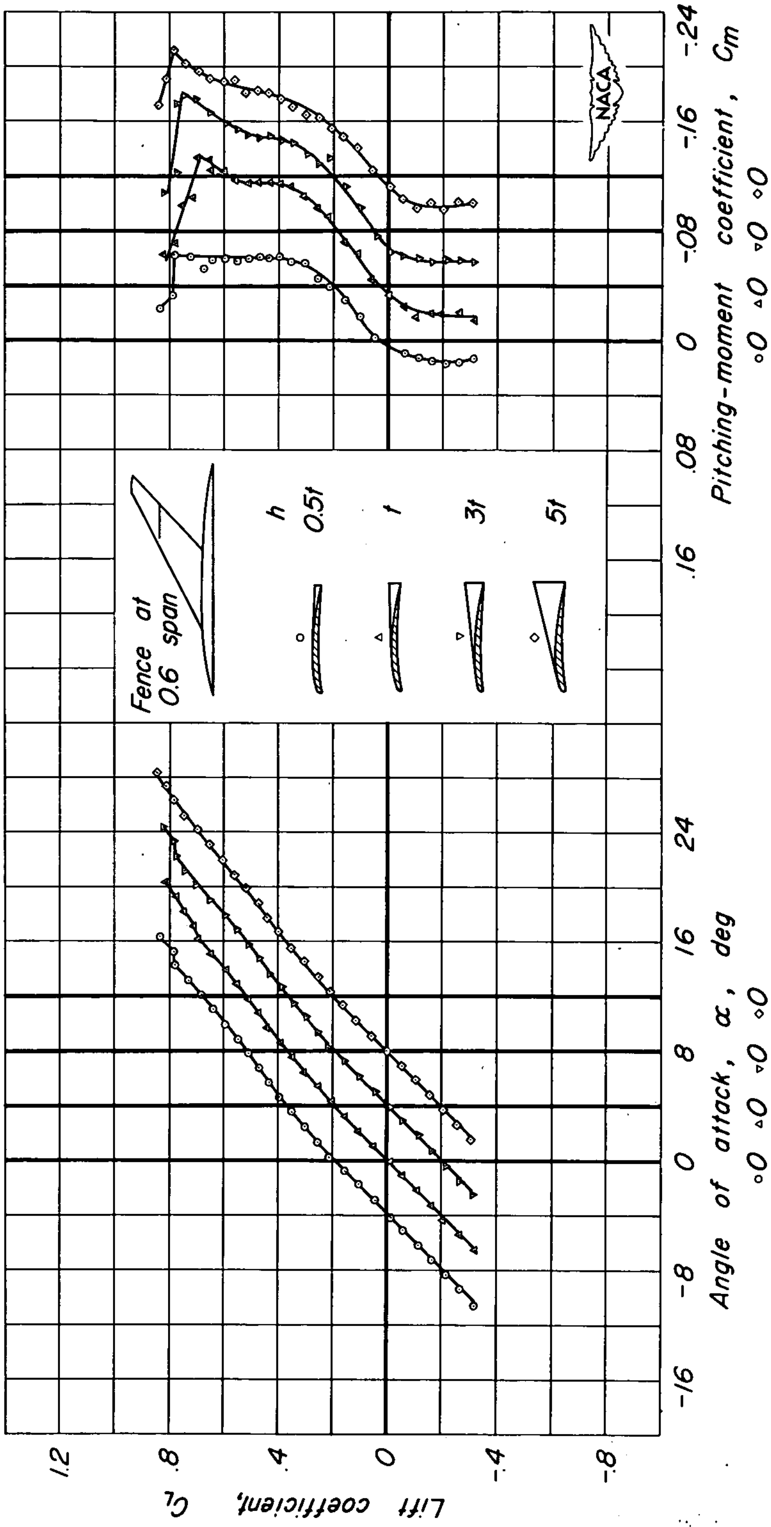


Figure 13.—Effect of height of the triangular fences.

[redacted]

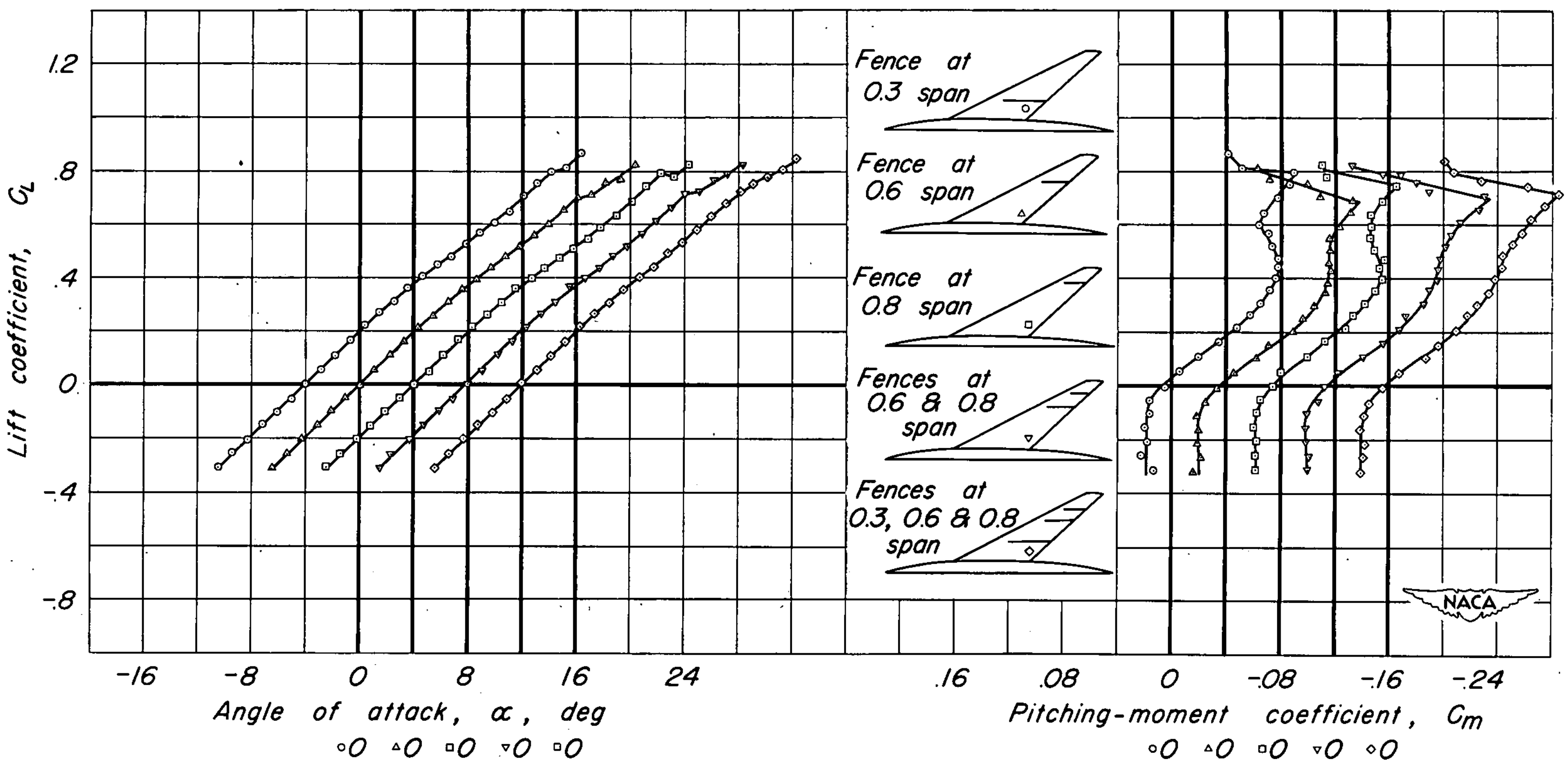
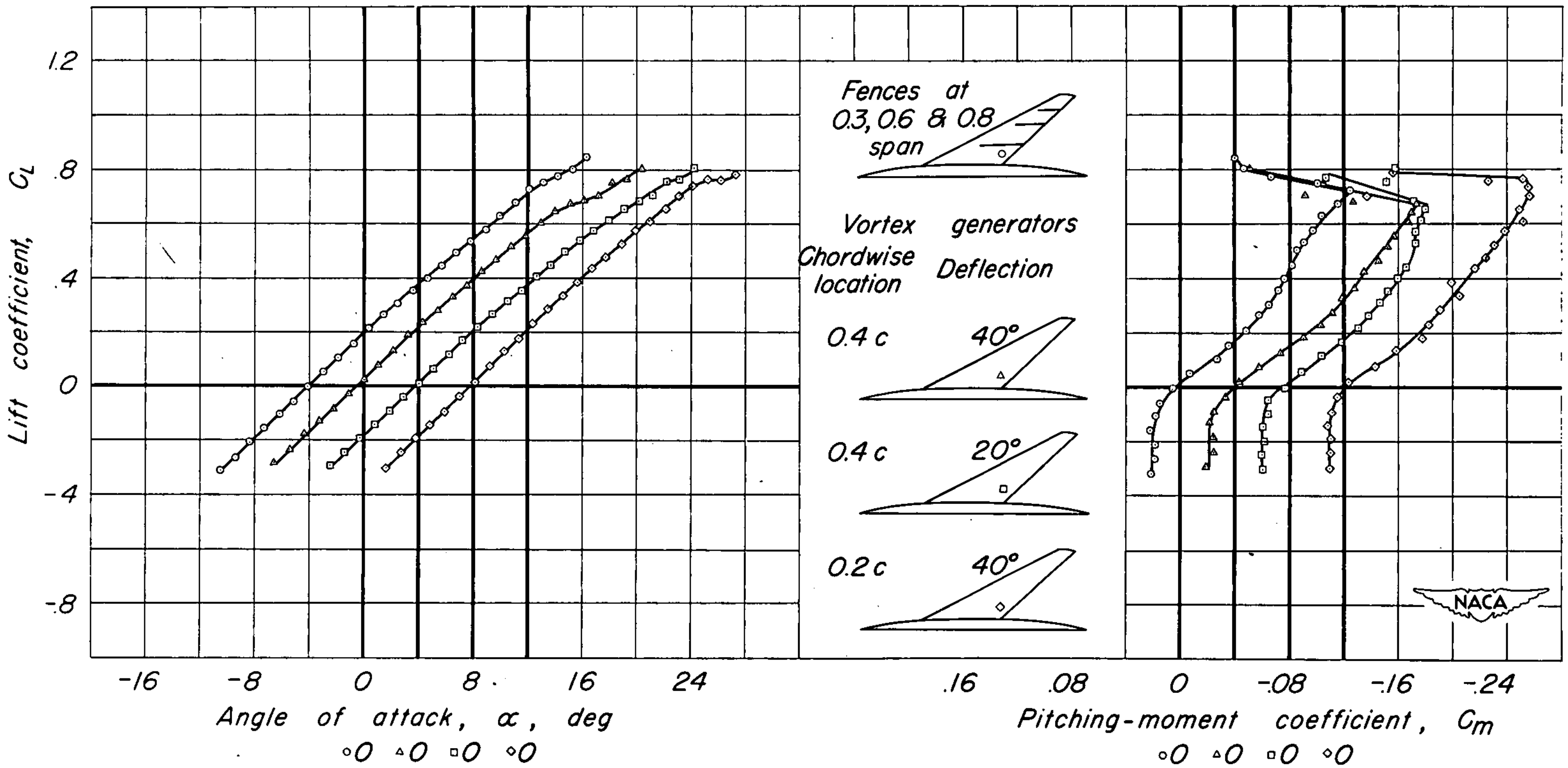


Figure 14.—Comparison of single and multiple triangular fences (h=t).

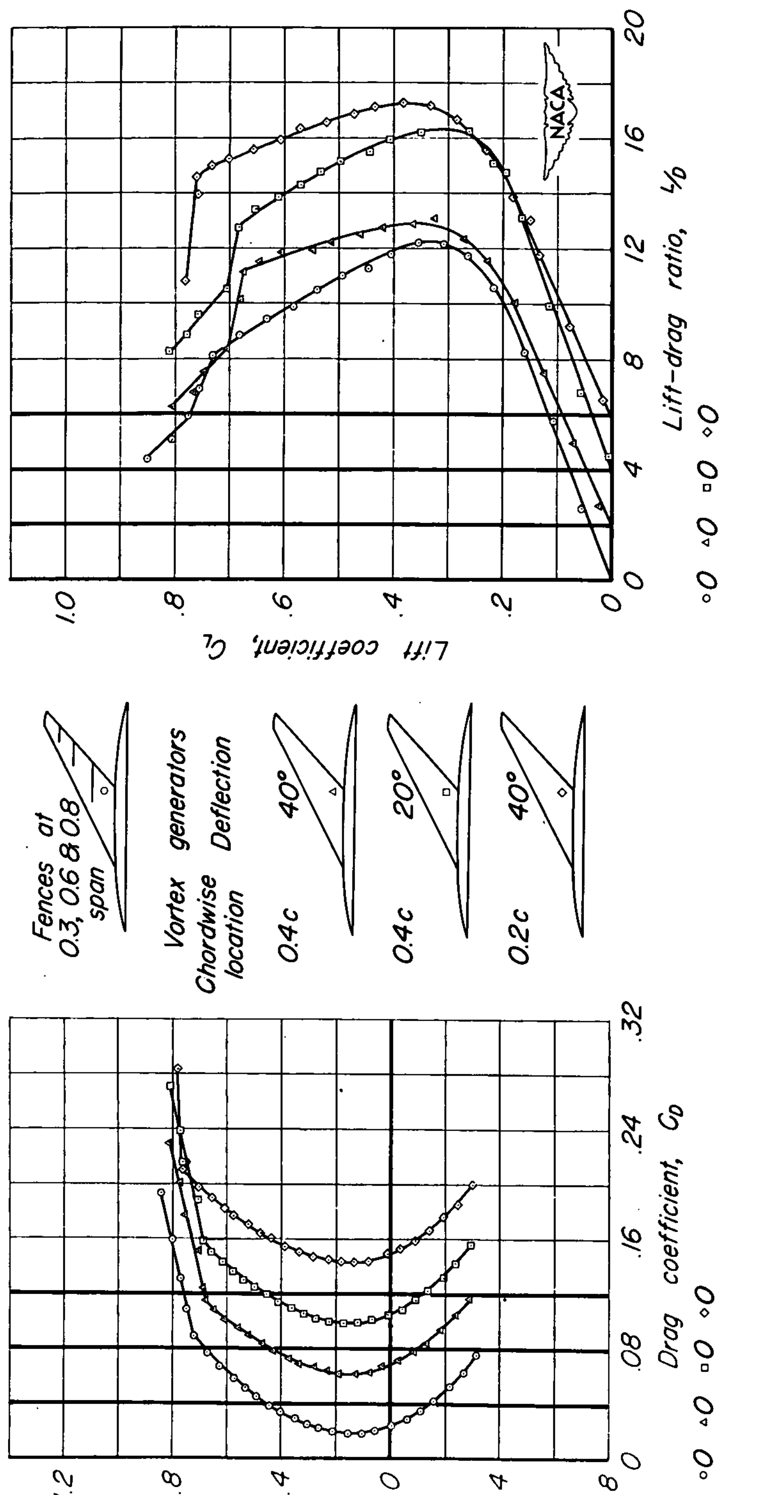
[redacted]



(a) Lift and pitching moment.

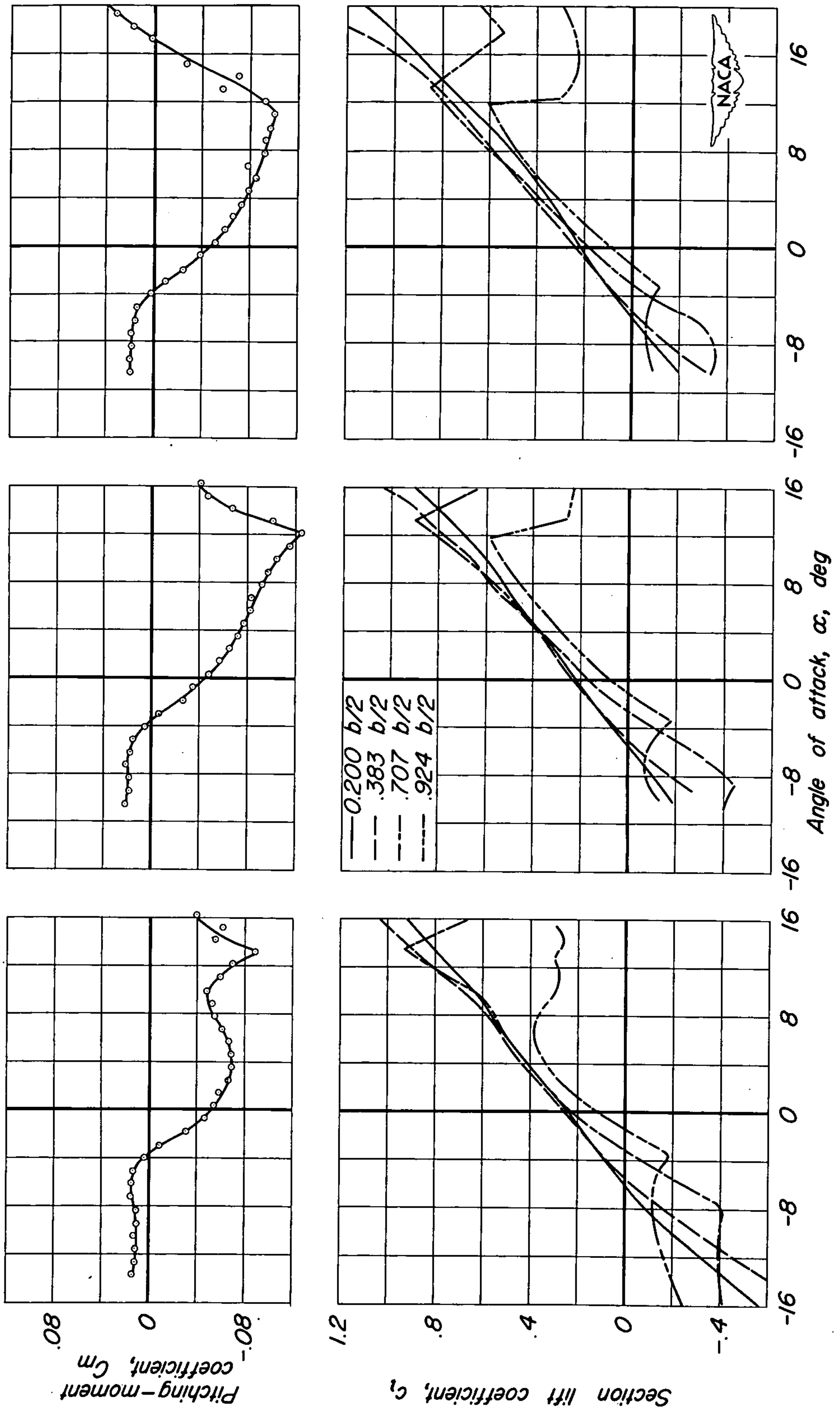
Figure 15.—Comparison of the effectiveness of triangular fences (h=t) and vortex generators extending from 0.3 to 1.0 semispan with 3-inch spacing.

[redacted]



(b) Drag and lift-drag ratio.

Figure 15.—Concluded.



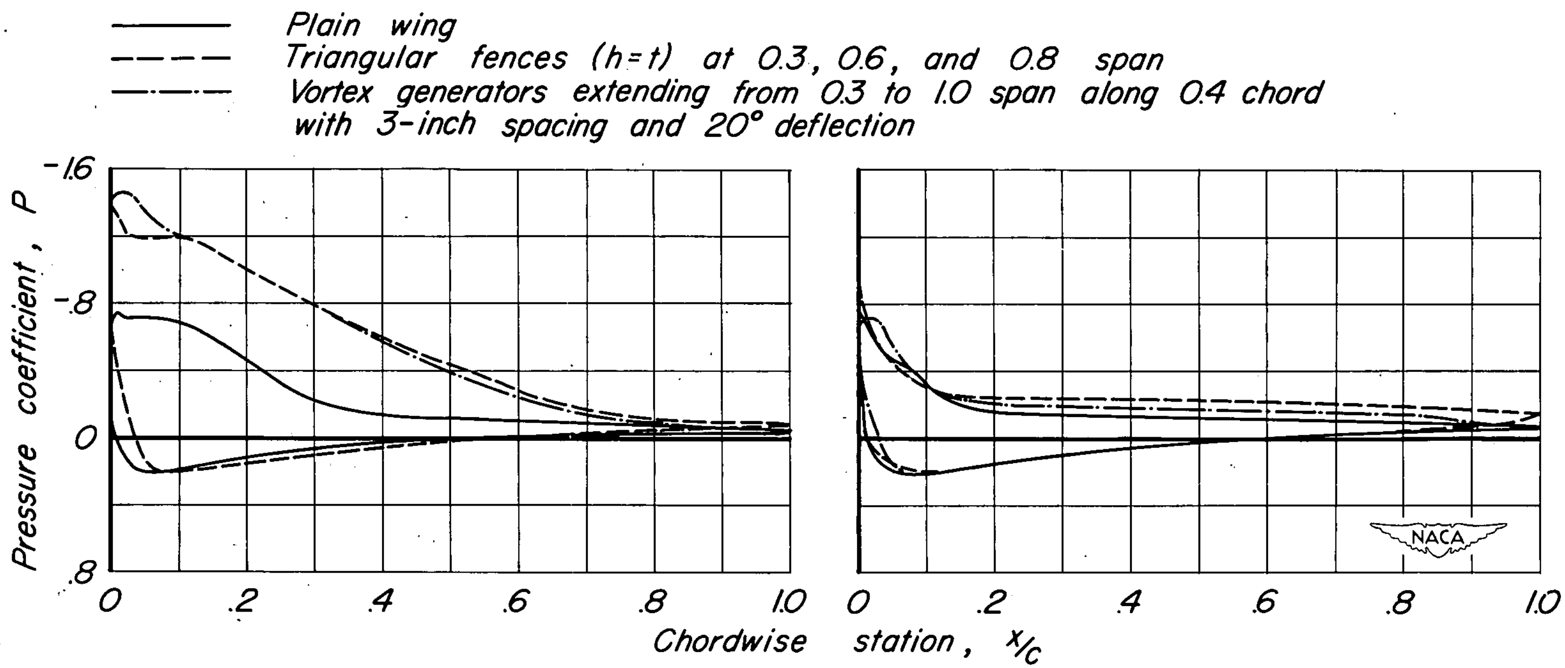
(a) Plain wing.

(b) Wing with triangular fences (h=1) at 0.3, 0.6, and 0.8 span.

(c) Wing with vortex generators extending from 0.3 to 1.0 span along 0.4 chord with 3-inch spacing and 20° deflection.

Figure 16.—Variation of pitching-moment and section lift coefficients with angle of attack.

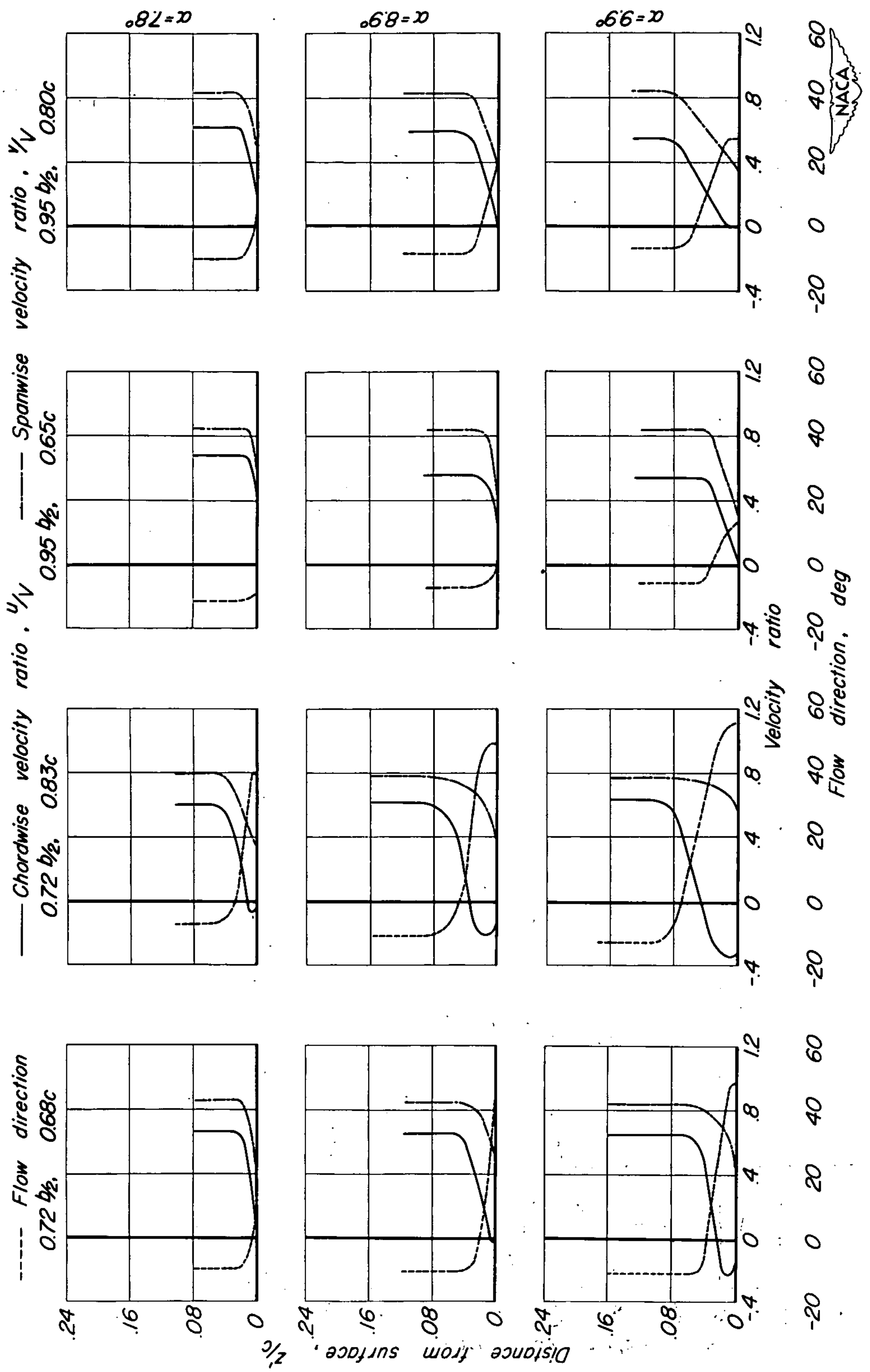
[redacted]



(a) $\alpha = 11°$

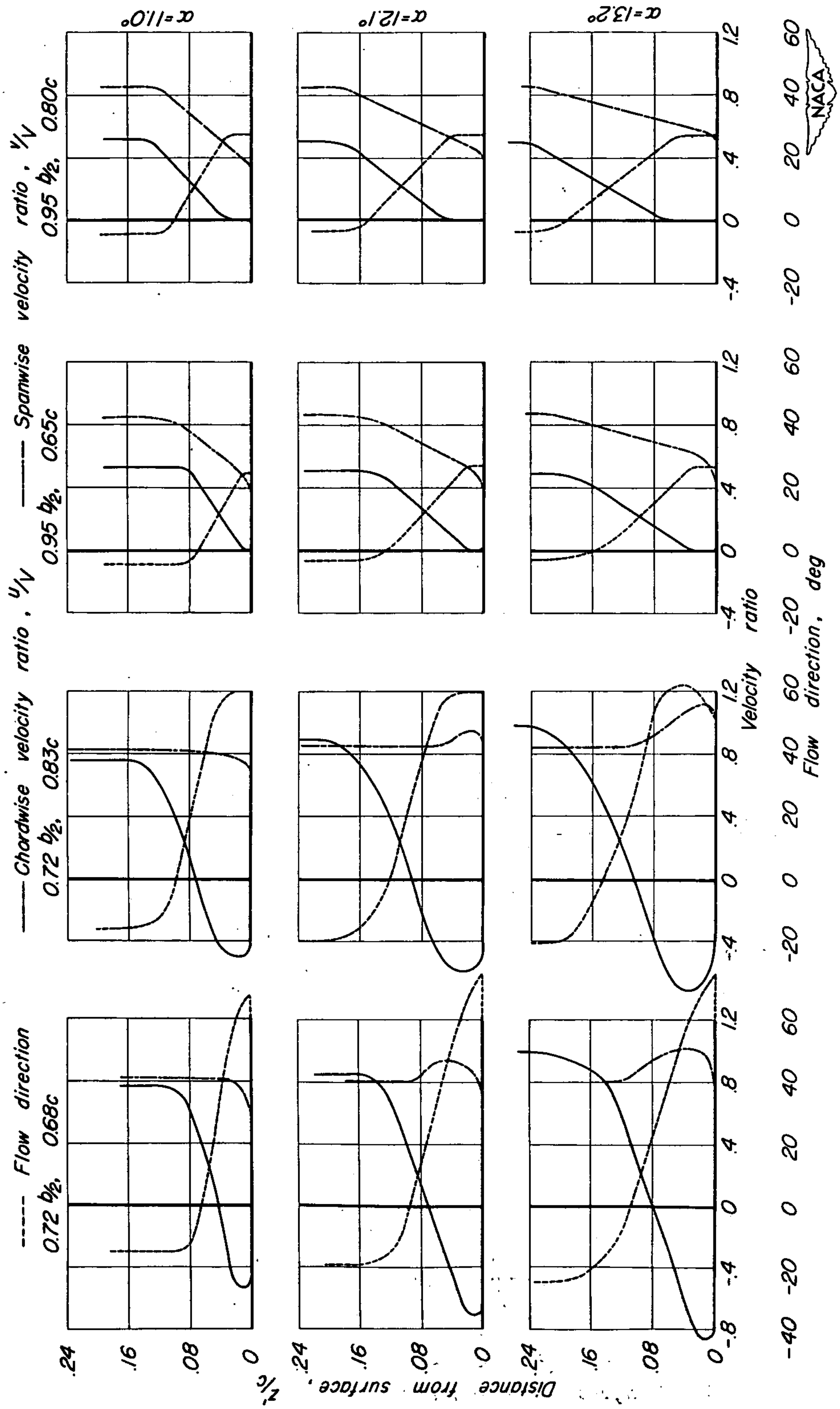
(b) $\alpha = 15.2°$

Figure 17.— Effect of fences on the pressure distribution at 0.924 semispan.



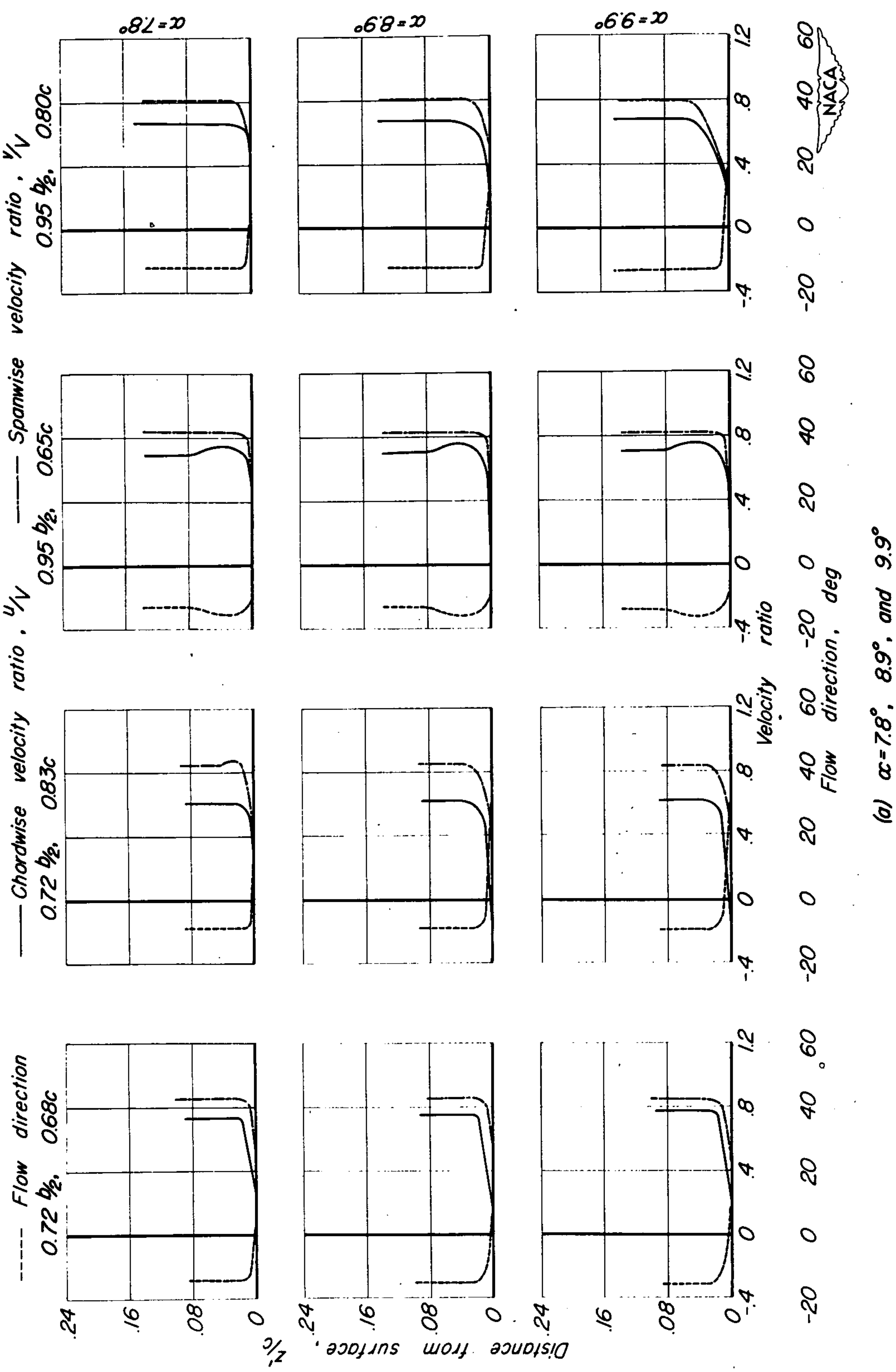
(a) α = 7.8°, 8.9°, and 9.9°

Figure 18.- Velocity and direction of the flow in the boundary layer on the plain wing.



(b) α=11.0°, 12.1°, and 13.2°

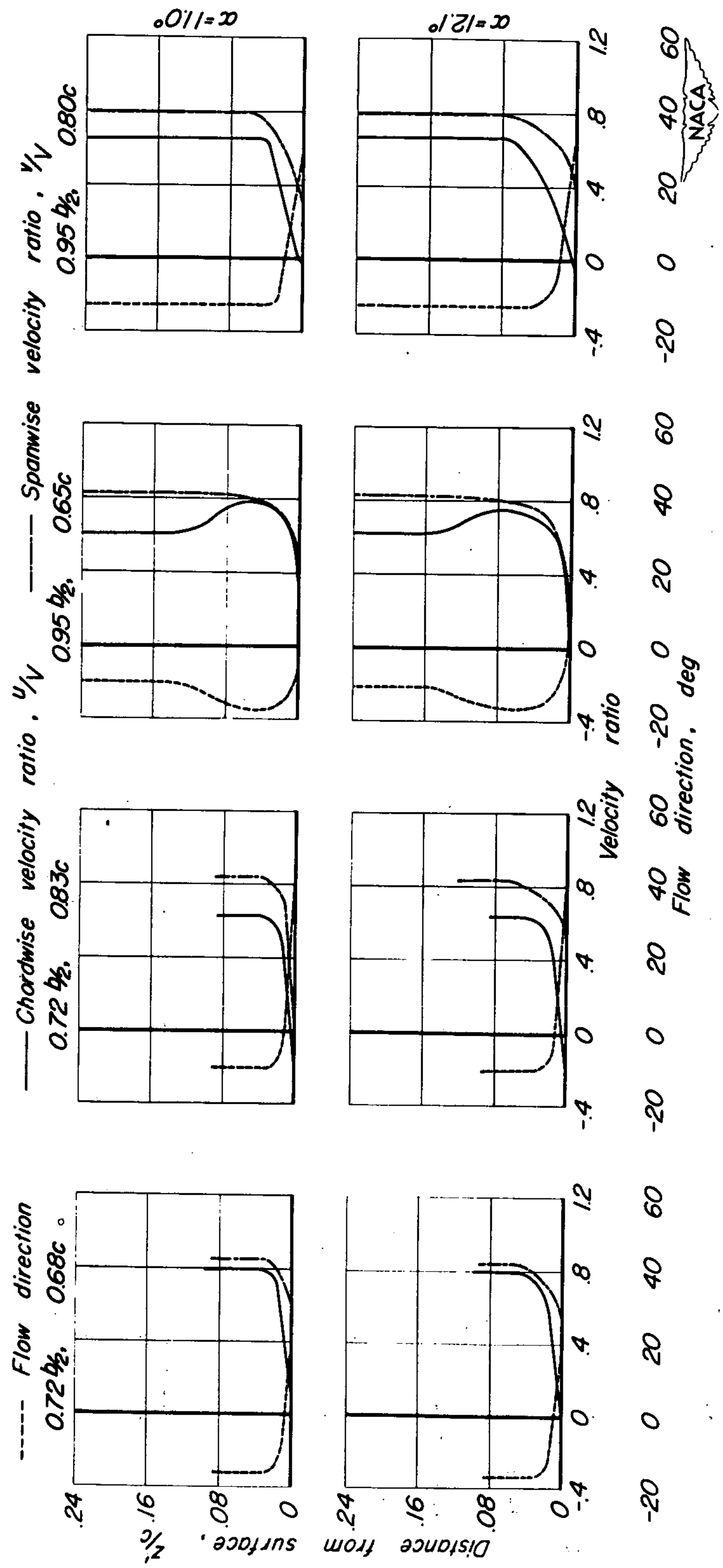
Figure 18.—Concluded.



(a) α=7.8°, 8.9°, and 9.9°

Figure 19.– Velocity and direction of the flow in the boundary layer on the wing with vortex generators extending from 0.3 to 1.0 semispan along 0.4c with 3-inch spacing and deflected 20°.

[redacted]



(b) α=11.0° and 12.1°

Figure 19.—Concluded.

[redacted]

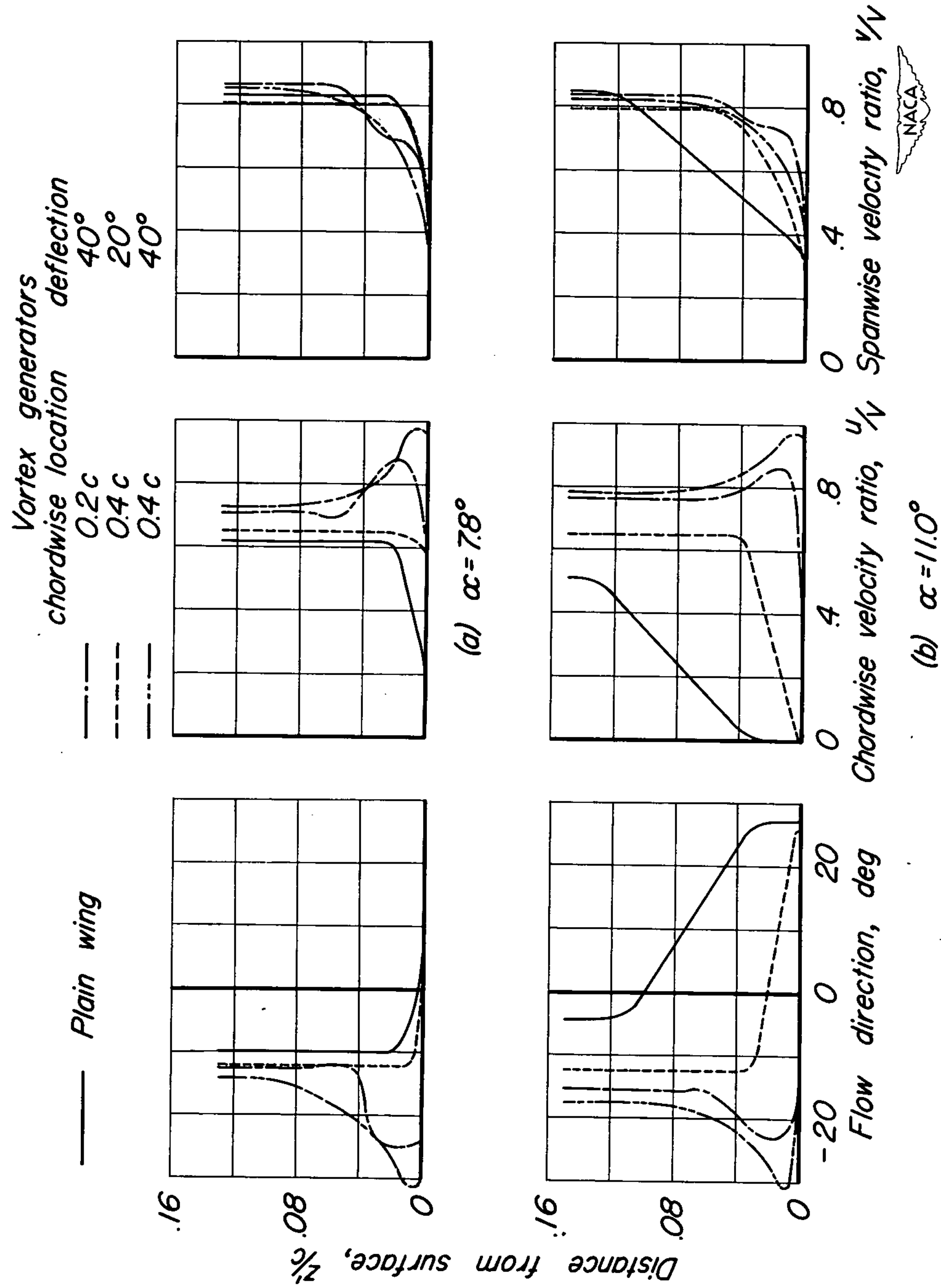


Figure 20.- Effect of chordwise location and deflection of vortex generators on boundary-layer characteristics at 0.95 semispan and 0.80 chord. Generators extending from 0.3 to 1.0 semispan with 3-inch spacing.

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