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WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

V - THE USE OF A BEVELED TRAILING EDGE TO REDUCE THE HINGE MOMENT OF A CONTROL SURFACE

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SUMMARY

Wind-tunnel tests have been made to investigate the possibility of reducing the hinge moments of a control surface by beveling the trailing edge. The tests were made with a 9-percent-thick airfoil having a 30-percent-chord plain flap. A faired beveled shape, 5 percent of the airfoil chord in width and having a thickness of $2\frac{1}{2}$ percent of the airfoil chord, was found to give approximately 50-percent reduction in the hinge moment caused by a given deflection of the flap and 80-percent reduction in the hinge moment due to the angle of attack of this airfoil for a wide range of angles. A blunter beveled portion of the same thickness gave overbalance and reversal of the floating tendency over a small angular range. Elliptical trailing-edge shapes were also tried but were found to be somewhat less effective than the shapes ending in an acute angle. A semicircular trailing edge produced only a slight change in the hinge moments but caused a drag increment much greater than that of an efficient beveled shape.

INTRODUCTION

The hinge moments obtained in tests of airfoils with plain flaps have often been observed to fall considerably below the values predicted by the potential-flow theory. It has also been noted that the hinge moments obtained in different tests show wider discrepancies than do other airfoil characteristics.

Several years ago the NACA had occasion to test a flap with a particularly thin, sharp trailing edge. In this case the hinge moments were higher than usual and agreed better with the theory. Thus, it appeared that the discrepancies in the hinge moments obtained in the usual tests might have been due to minor differences in the shapes of the trailing edge. This phenomenon led to speculation concerning the nature of the flow near the trailing edge and the effect of small departures from the Kutta condition.

In the ideal flow, the Kutta condition requires that the air leaving the trailing edge maintain the direction of the mean camber for a short distance downstream. The velocities on the upper and lower surfaces approach the same value with the result that the pressure difference or lift vanishes at the trailing edge. The curve marked "a" in figure 1 shows the lift distribution over an airfoil section with the flow conforming perfectly to this condition. The guiding action of a slightly blunt or beveled trailing edge will not be perfect, however, and in such a case a relatively great negative lift will be developed across the edge, as shown by curve "b" in figure 1. A deliberate thickening of the airfoil, designed to permit further deviation from the Kutta condition, might therefore lead to the type of pressure distribution represented by curve "b" in figure 1. It was thought that the effect might be used to provide aerodynamic balance for a control surface and in order to test this theory a series of wind-tunnel experiments was planned. These tests have recently been made and form the subject of the present paper.

TESTS

Apparatus and Models

In figure 2 are shown the shapes tested. These shapes are of two types - beveled and elliptical. In the case of the beveled flap, the point at which the beveling of the flap began was faired into an arc in order to allow smooth flow. The portion of the flap extending from the center of this arc to the trailing edge will be referred to hereinafter as the "bevel." Because the action of the blunt trailing edge is in some ways similar to that of an automatic balancing tab (see fig. 3), the beveled shapes were designed to approximate the outline of such tabs in the balancing position. The 20-percent bevel corresponds to a 20-percent c_f tab deflected 10°. The elliptical shapes are of somewhat similar proportions. A flap having a bulged portion near the hinge was also tried. With the exception of the bulged flap, all shapes tested were obtained by interchanging trailing-edge blocks having these shapes on a standard 2-foot-chord by 4-foot-span model of laminated mahogany.

Table I gives the ordinates of the standard section (derived from the NACA 0009 airfoil by drawing straight lines from the 55-percent station back to the removable tail block). The dimensions of the removable tail portions are shown in figure 2 and the ordinates of the bulged flap are given in table II. As shown in figure 2, the flap was of the plain unbalanced type, 30 percent of the airfoil chord in width. The tests were made with the gap both sealed and open.

The procedure of the tests was similar to that followed in reference 1. They were made in the NACA 4-foot by 6-foot vertical tunnel, modified as described in reference 2. The lift, the drag, and the pitching moments were measured on a three-component balance. The hinge moments were measured electrically with a calibrated torque rod built into the model. The model extended completely across the closed test section of the tunnel, so that the flow was very nearly two-dimensional. The tests were made at a dynamic pressure of 15 pounds per square foot, corresponding to a velocity of about 76 miles per hour and a test Reynolds number of 1,430,000. The flap deflection was varied in 5° increments from 0° to 30°. In some cases check points at $\pm 2^\circ$ from neutral were obtained. Lift, drag, airfoil pitching moment, and flap hinge moments were measured throughout the angle-of-attack range, from positive to negative stall of the airfoil, at 2° intervals of angle of attack.

Precision

The maximum error in the angle of attack or in flap setting appears to be about $\pm 0.2^\circ$. An experimentally determined correction has been applied to the lift but not to the hinge moments. The hinge moments are probably slightly higher than would be obtained in free air. It should be noted that the drag of the basic 0009 airfoil is somewhat higher than is obtained in other tests at the same Reynolds number.

RESULTS AND DISCUSSION

Symbols

c_l airfoil section lift coefficient (l/qc)

c_{d_o} airfoil section profile-drag coefficient (d_o/qc)

c_m airfoil section pitching-moment coefficient (m/qc^2)

c_h flap section hinge-moment coefficient (h/qc_f^2)

α_o angle of attack of infinite aspect ratio

δ_f flap angle with respect to airfoil

l airfoil section lift

d_o airfoil section profile drag

m airfoil section pitching moment about quarter-chord point of airfoil

h flap section hinge moment

c chord of airfoil with flaps neutral

c_f flap chord

c_b chord of beveled portion of flap

Section data are plotted in figure 4. Figures 5 and 6, cross-plotted from the section data, show typical variations of lift and hinge moment and illustrate the magnitude of the effect obtainable with a moderate and with an extremely blunt bevel. It will be noted that the reduction in hinge moment outweighs the loss in lift and also that the reduction in $\partial c_h/\partial \alpha_o$ is greater than the reduction in $\partial c_h/\partial \delta_f$. The lift of the airfoil with the control free is therefore actually greater for the blunt trailing edge than for the plain flap. The results for the plain flap are taken from reference 1, part I.

The results given for the flap with beveled trailing edge are for the gap-sealed condition. The data obtained from the tests with the gap open are presented in reference 3.

Table III summarizes several important characteristics of the shapes tested. The values given in the table apply to a fairly wide angular range. An idea of the deviations from linearity may be obtained by inspection of figure 4.

The results show an interesting difference in the behavior of the elliptical and the beveled trailing edges. The bluntest elliptical shape, which was simply a circular rounding, increased the floating tendency and the drag but had no appreciable effect on $\partial c_h/\partial \delta_f$ or $\partial c_l/\partial \alpha_0$. In this case the curvature of the surface is so great that the flow apparently leaves the airfoil as if the end had been cut off square. The increment of drag coefficient in this case is approximately 0.0028. The moderately beveled or tapered shapes, the 0.20 c_f and 0.15 c_f bevels, on the other hand, showed less than 0.0004 increase in drag coefficient, indicating fairly complete closure of the flow behind the airfoil. This small drag increase, together with the regularity of the hinge-moment variation, indicates that the balancing action of the moderate shapes does not depend on a pronounced separation of flow but on more or less progressive changes in the boundary-layer thickness on the two sides of the bevel. As the angle of the bevel becomes steeper, the closure of the flow becomes less complete and the balancing action becomes more pronounced, though somewhat irregular, and may involve complete separation on one side or the other. The critical angle in the present tests was that of the 0.13 c_f bevel.

As will be noted in table III, the airfoil pitching moments follow the variation that might be expected from the hinge moments. In the most extreme case (0.10 c_f bevel), the aerodynamic center was shifted 0.051c ahead of the quarter-chord point.

From a practical standpoint the most interesting results are those obtained with the moderately beveled and elliptical shapes (0.15 c_f to 0.20 c_f bevels). Thus the 0.20 c_f bevel shows nearly 50-percent reduction in $\partial c_h/\partial \delta_f$ and more than 50-percent reduction in $\partial c_h/\partial \alpha_0$, as compared with the plain flap. The drag increments are not so great as those obtained in comparable tests (reference 1) of the conventional inset-hinge balance with the medium or tapered nose but are greater than those obtained with the blunt nose balance. Inasmuch as the beveled trailing edge is effective in reducing the floating moment, the lift of the airfoil is greater with the control free than with the plain or the inset-hinge flap.

It is frequently found that full balance cannot be obtained in a satisfactory manner by the use of a single device; for example, a large degree of balance with the inset-hinge type of control surface requires such a long overhang that the permissible deflection of the flap is limited. The use of a large horn balance introduces structural difficulties. It is helpful, therefore, to have available several independent means of reducing hinge moments. The beveled trailing edge should be especially useful in combination with other types of balance, because it involves no additional linkages. Also, it is occasionally found desirable to increase the hinge moments slightly as a final adjustment during flight tests. Such an adjustment might be provided by the addition of a thin, sharp edge.

The present tests are too limited to furnish more than very general information on the effects of trailing-edge shape. Thus, the variations with flap chord, Reynolds number, or airfoil section have not been explored. In any event, it is to be expected that the effect of trailing-edge shape will be greatly magnified as the chord of the flap is reduced - a fact that makes it necessary to employ a certain amount of care in the construction of the trailing edge.

CONCLUSIONS

The beveled trailing edge provides a convenient means of reducing the hinge moments of control surfaces. In the present tests, a moderate bevel on a 30-percent-chord flap produced a 50-percent reduction in the hinge moment caused by a given deflection of the flap. This balancing effect extended over a wide angular range and showed a smooth variation with angle of attack and with flap deflection. The profile-drag coefficient showed an increase of 0.0004.

Overbalance and reversal of the floating tendency over a small angular range were obtained when rather blunt bevels were tested. The effect of trailing-edge shape is expected to be even more pronounced as the chord of the flap is reduced, indicating the necessity for careful construction of narrow flaps.

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2. Ames, Milton B. Jr. and Sears, Richard I.: Pressure-Distribution Investigation of an N.A.C.A. 0009 Airfoil with a 30-Percent-Chord Plain Flap and Three Tabs. T. N. No. 759, NACA, 1940.

3. Sears, Richard I.: Wind-Tunnel Data on the Aerodynamic Characteristics of Airplane Control Surfaces. NACA ACR No. 3L08, 1943.

TABLE I

ORDINATES OF MODIFIED NACA 0009 AIRFOIL

[Stations and ordinates in percent airfoil chord]

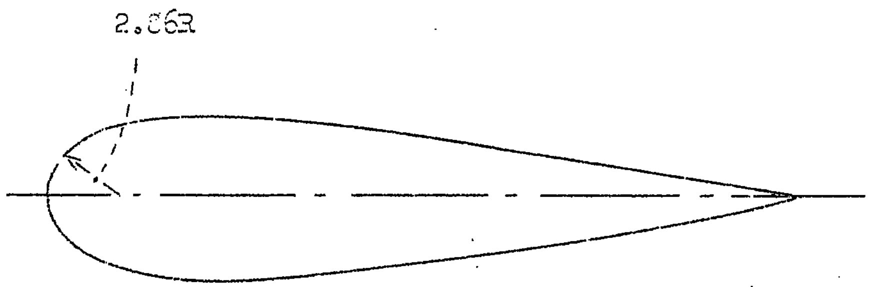
	Stations	Ordinates
NACA 0009 airfoil section	0	0
	1.25	±1.42
	2.5	±1.96
	5.0	±2.67
	7.5	±3.15
	10	±3.51
	15	±4.01
	20	±4.30
	25	±4.46
	30	±4.50
	40	±4.35
	50	±3.97
Straight portion	60	±3.42
	70	±2.83
	80	±2.25
	90	±1.67
	100	±1.08

L. E. radius: 0.89

TABLE II

ORDINATES OF BULGED FLAP

[Stations and ordinates in percent airfoil chord]



Stations (from hinge axis)	Ordinates
0	±2.96
1.94	±3.38
4.82	±3.62
7.85	±3.43
10.80	±3.03
15.25	±2.37
19.70	±1.69
25.15	±1.02
30.00	±0.10

TABLE III.- SUMMARY OF CHARACTERISTICS OF TRAILING-EDGE SHAPES TESTED

Modifications	$\left(\frac{\partial c_h}{\partial \delta_f}\right)$	$\left(\frac{\partial c_h}{\partial \alpha_o}\right)_{\delta_f}$	$\left(\frac{\partial c_l}{\partial \alpha_o}\right)_{\delta_f}$ (Control fixed)	$\left(\frac{\partial c_l}{\partial \alpha_o}\right)_{c_h=0}$ (Control free)	$\left(\frac{\partial \alpha_o}{\partial \delta_f}\right)_{c_l}$	$\left(\frac{\partial c_m}{\partial \delta_l}\right)_{\delta_f}$	$\left(\frac{\partial c_m}{\partial \delta_f}\right)_{c_l}$	$c_{d_{o_{min}}}$ (Uncorrected)
Plain	-0.012	-0.006	0.098	0.066	0.57	0.001	-0.010	0.0096
0.20c_f bevel	-.007	-.003	.092	.070	.56	.033	-.009	.0100
0.15c_f bevel	-.005	-.001	.091	.080	.56	.038	-.008	.0100
0.13c_f bevel	-.003	.001	.090	.106	.54	.048	-.008	.0105
0.10c_f bevel	.000	.002	.088	Unstable	.50	.051	-.007	.0110
0.20c_f elliptical	-.006	-.003	.091	.068	.50	.036	-.008	.0105
0.10c_f elliptical	-.011	-.008	.099	.060	.54	.011	-.008	.0118
Semicircular	-.012	-.009	.101	.059	.56	.002	-.010	.0124
Bulged	-.010	-.005	.095	.071	.50	.016	-.010	.0102

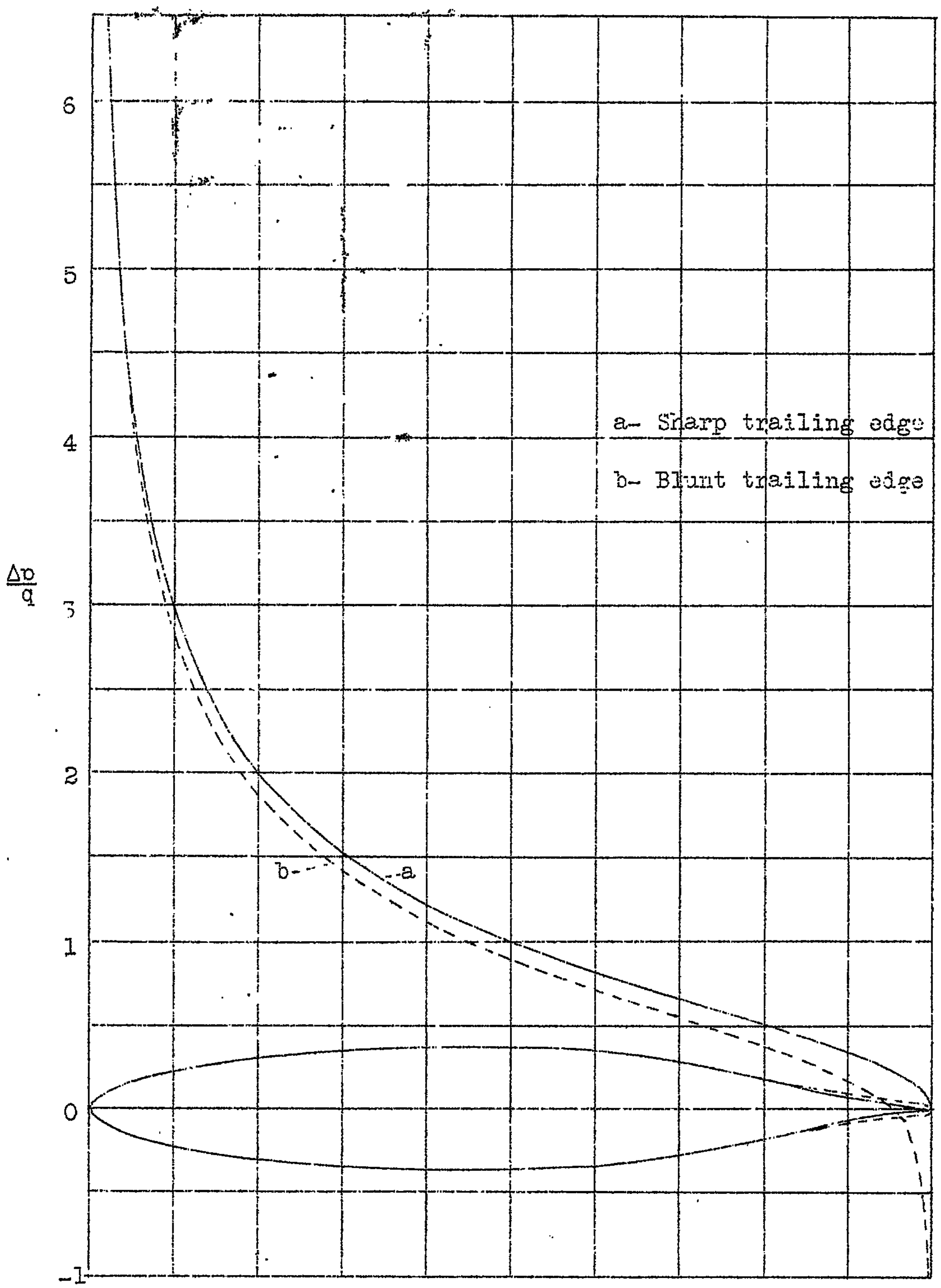


Figure 1.- The effect of flow around the trailing edge on the lift distribution.

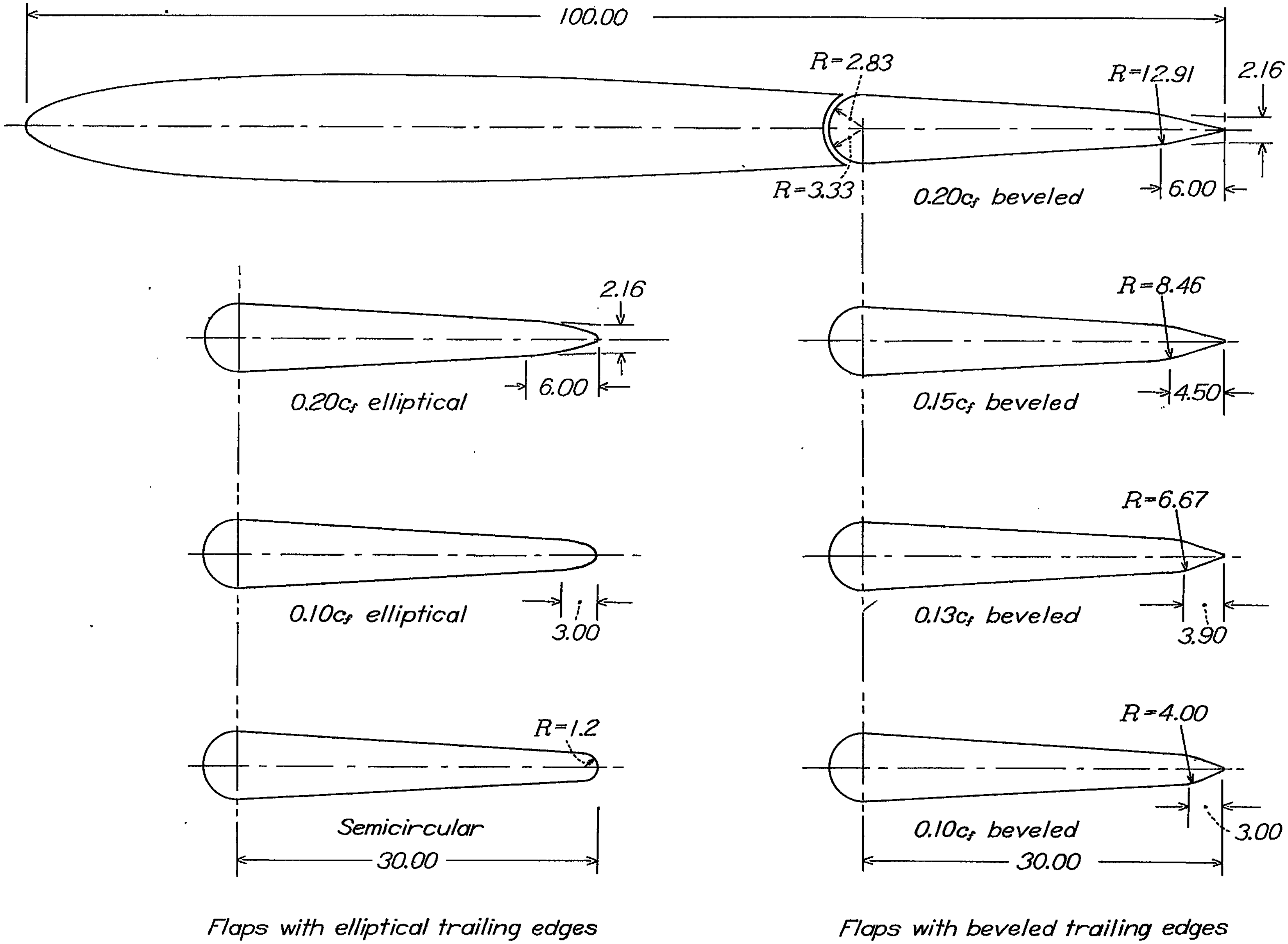


Figure 2.- Trailing-edge modifications. Dimensions are in percent of airfoil chord.

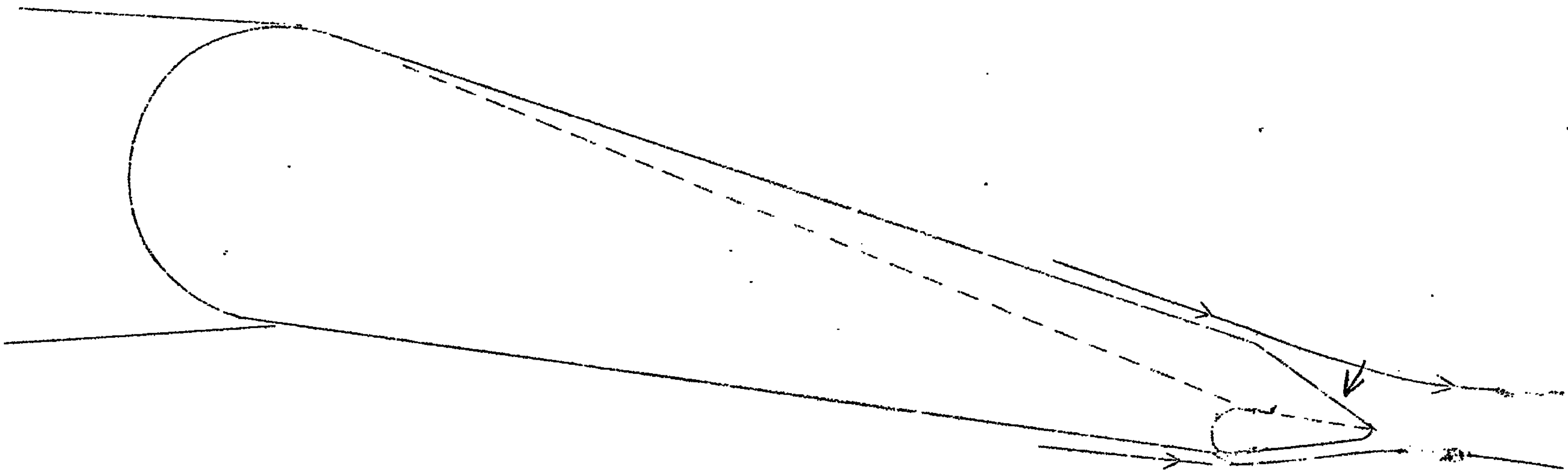


Figure 3.- Flow around beveled trailing edge showing similarity to the effect of a balancing tab.

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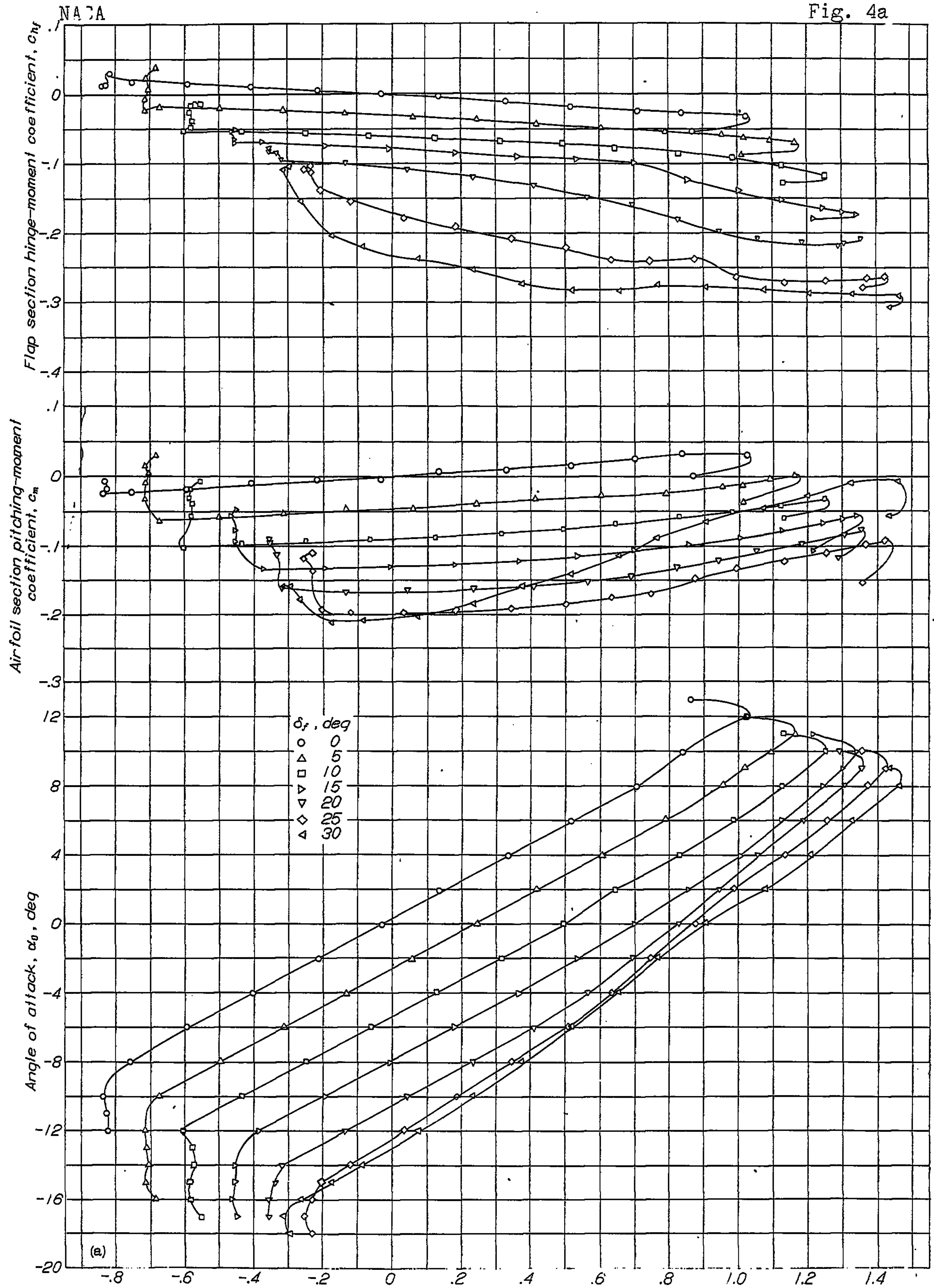

(a) Trailing-edge bevel, 0.20cf.

Figure 4(a to h).- Aerodynamic section characterisitics of airfoil and 0.20c flap.

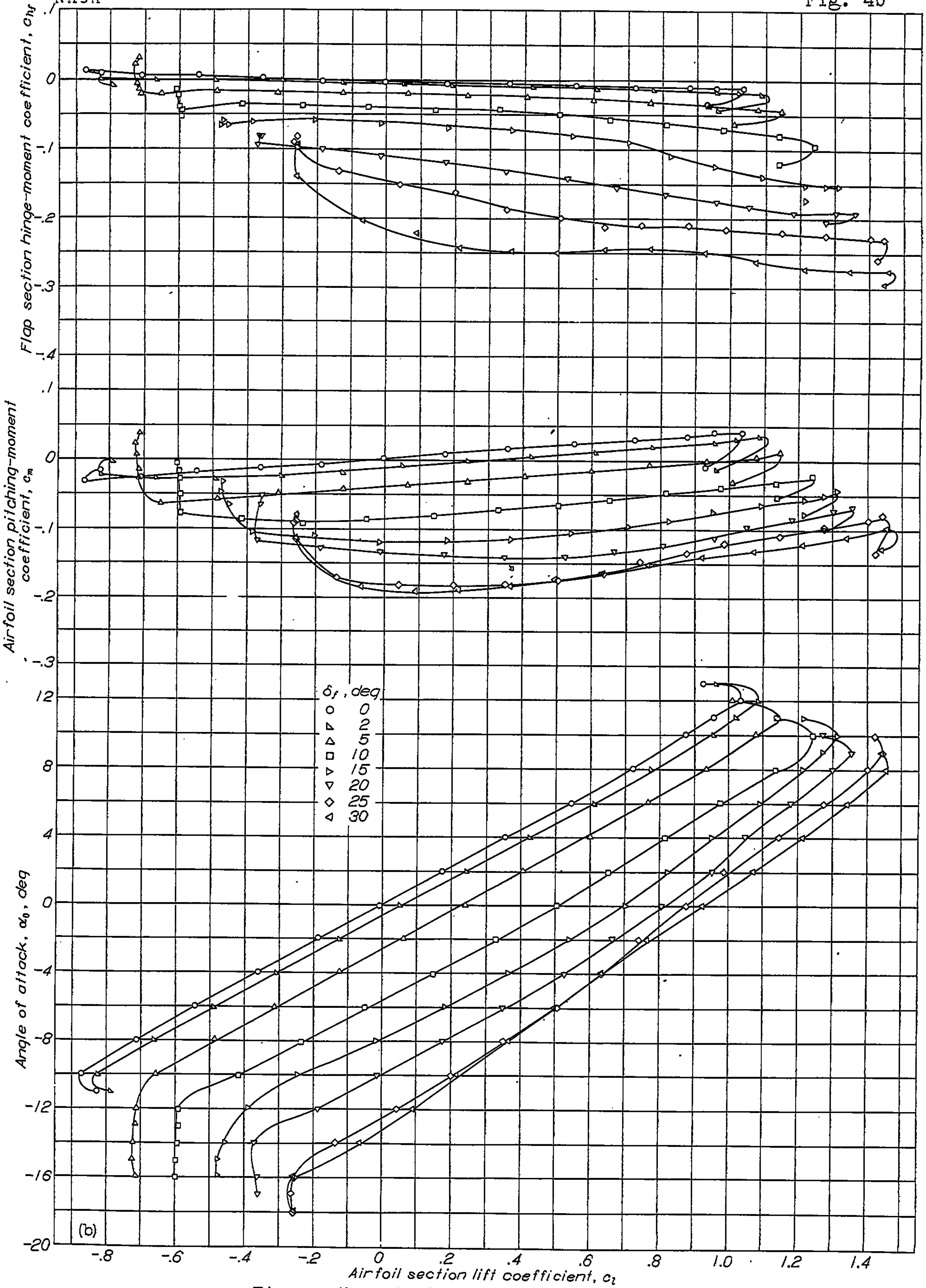

Figure 4b.- Trailing-edge bevel, $0.15c_f$.

NACA Fig. 4c

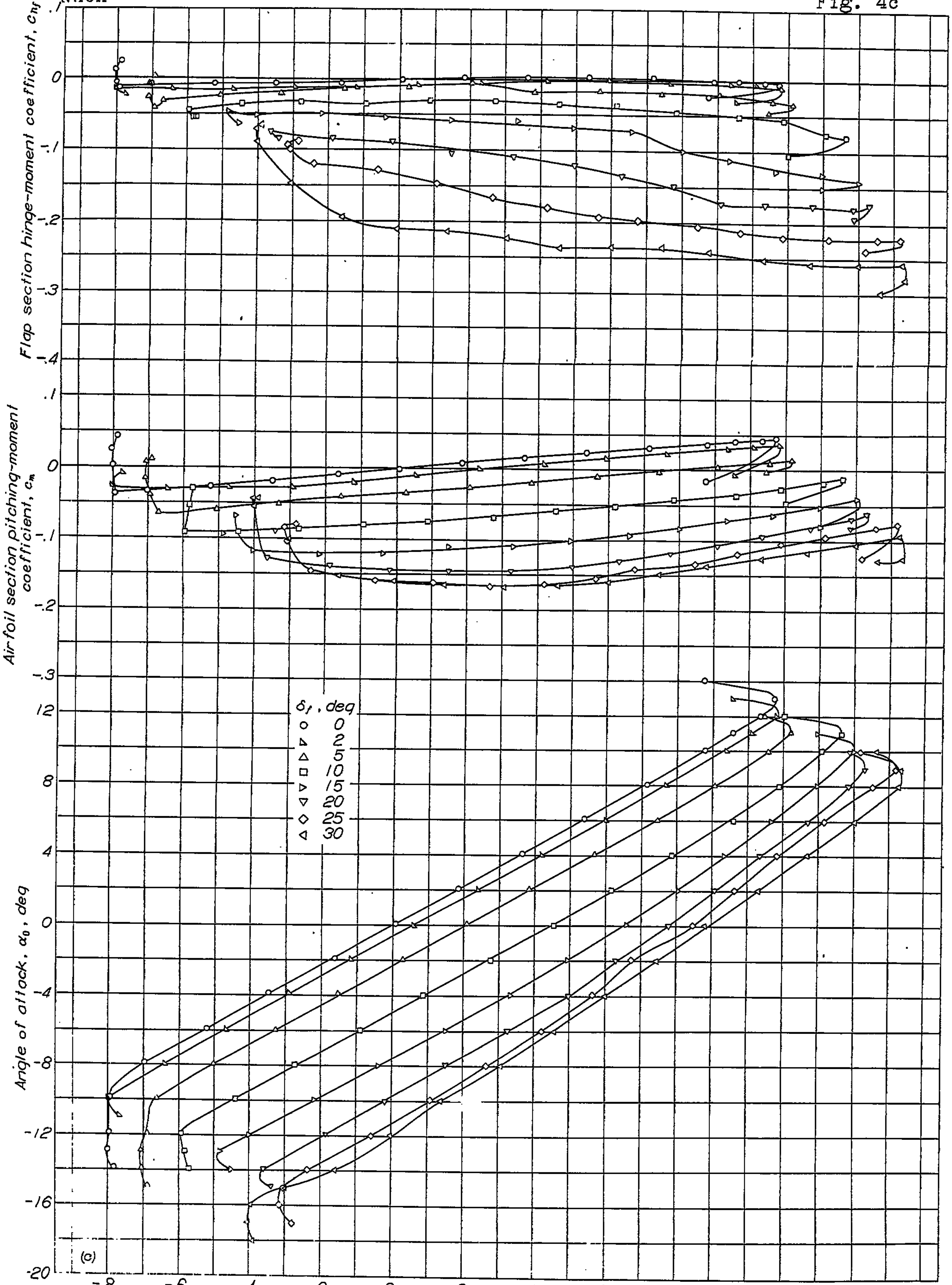

Figure 4c.- Trailing-edge bevel, 0.13c_f.

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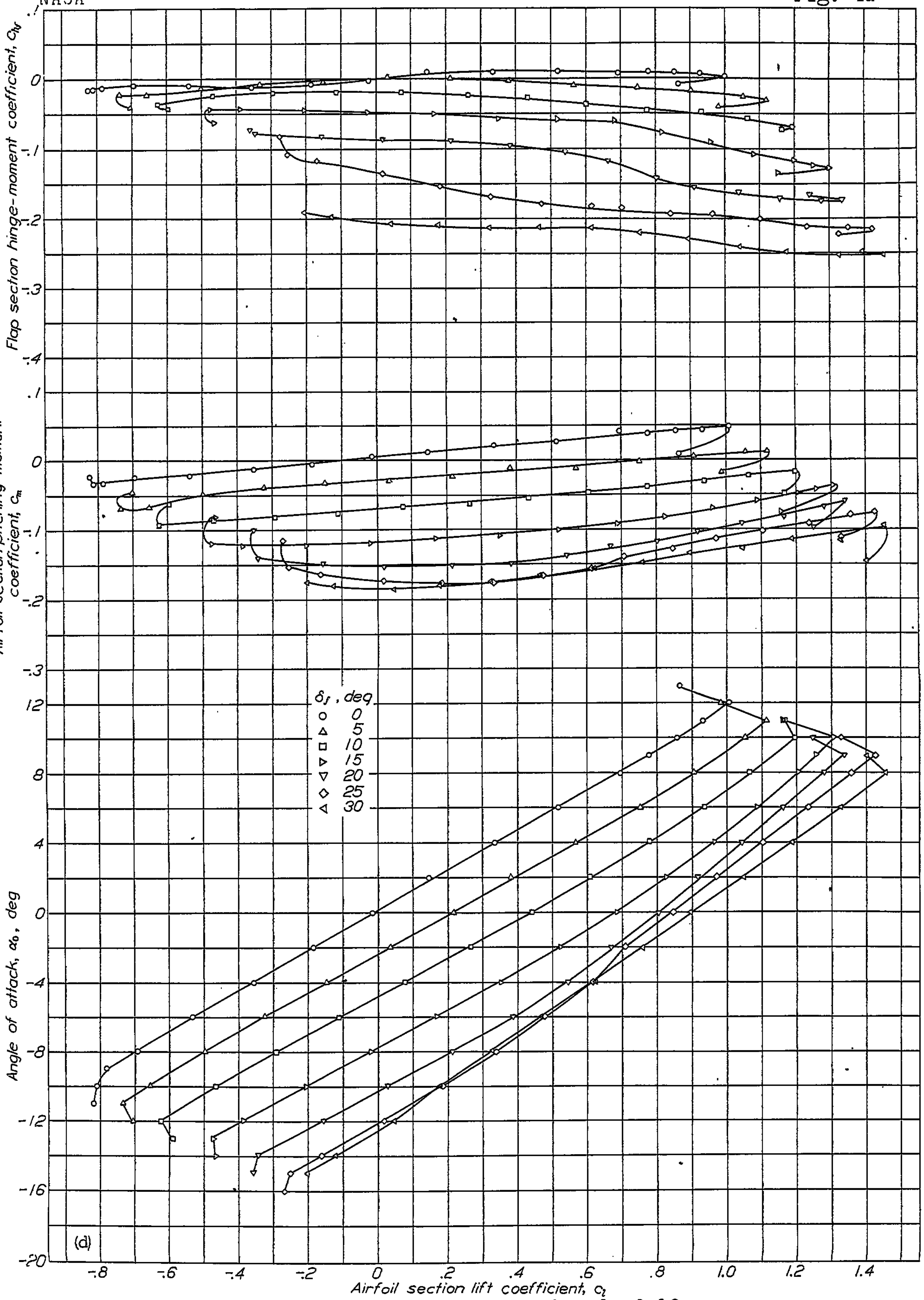

Figure 4d.- Trailing-edge bevel, 0.10c_f.

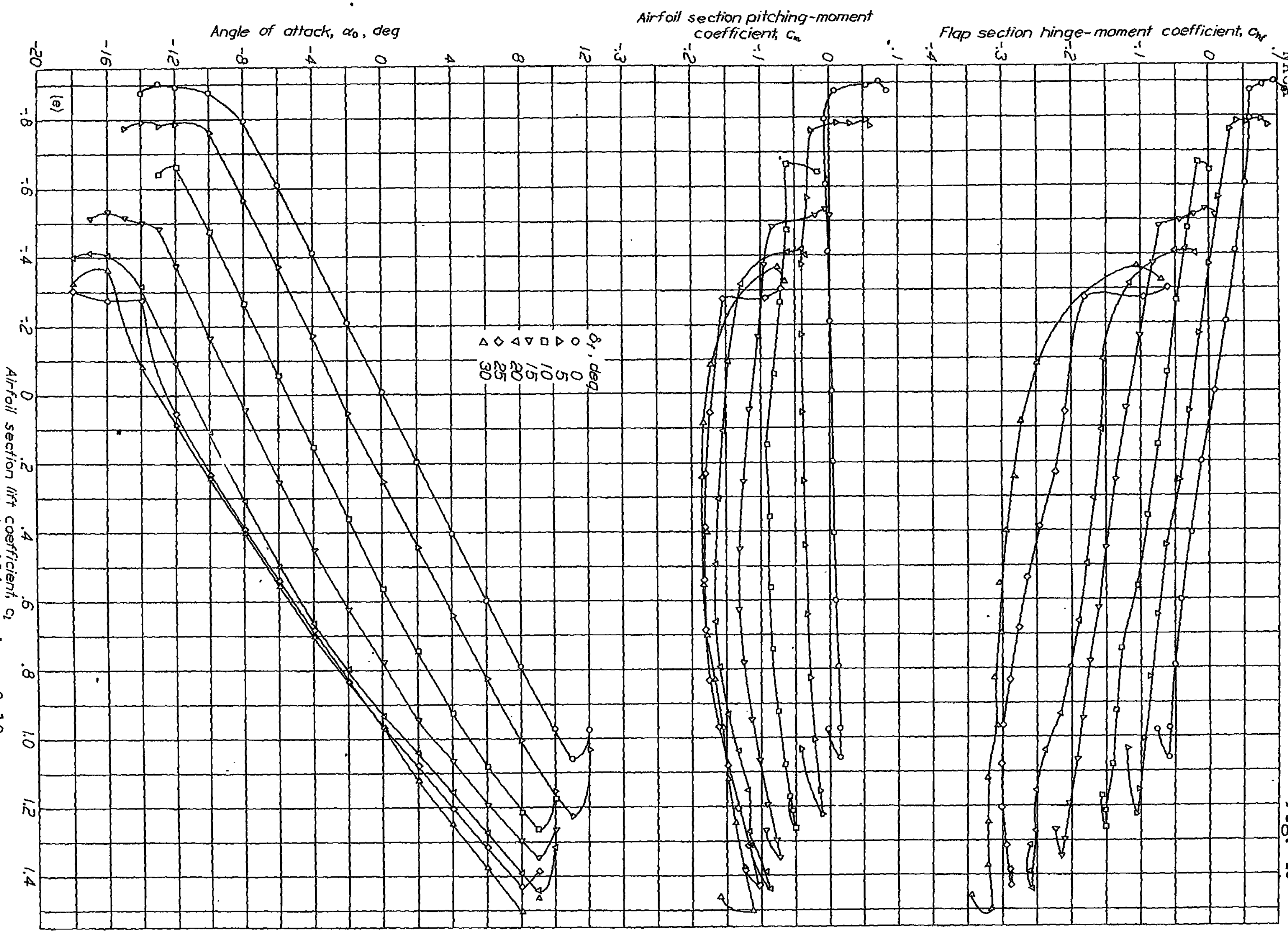

Figure 4e. - Elliptical trailing edge, 0.10cf.

Fig. 4e

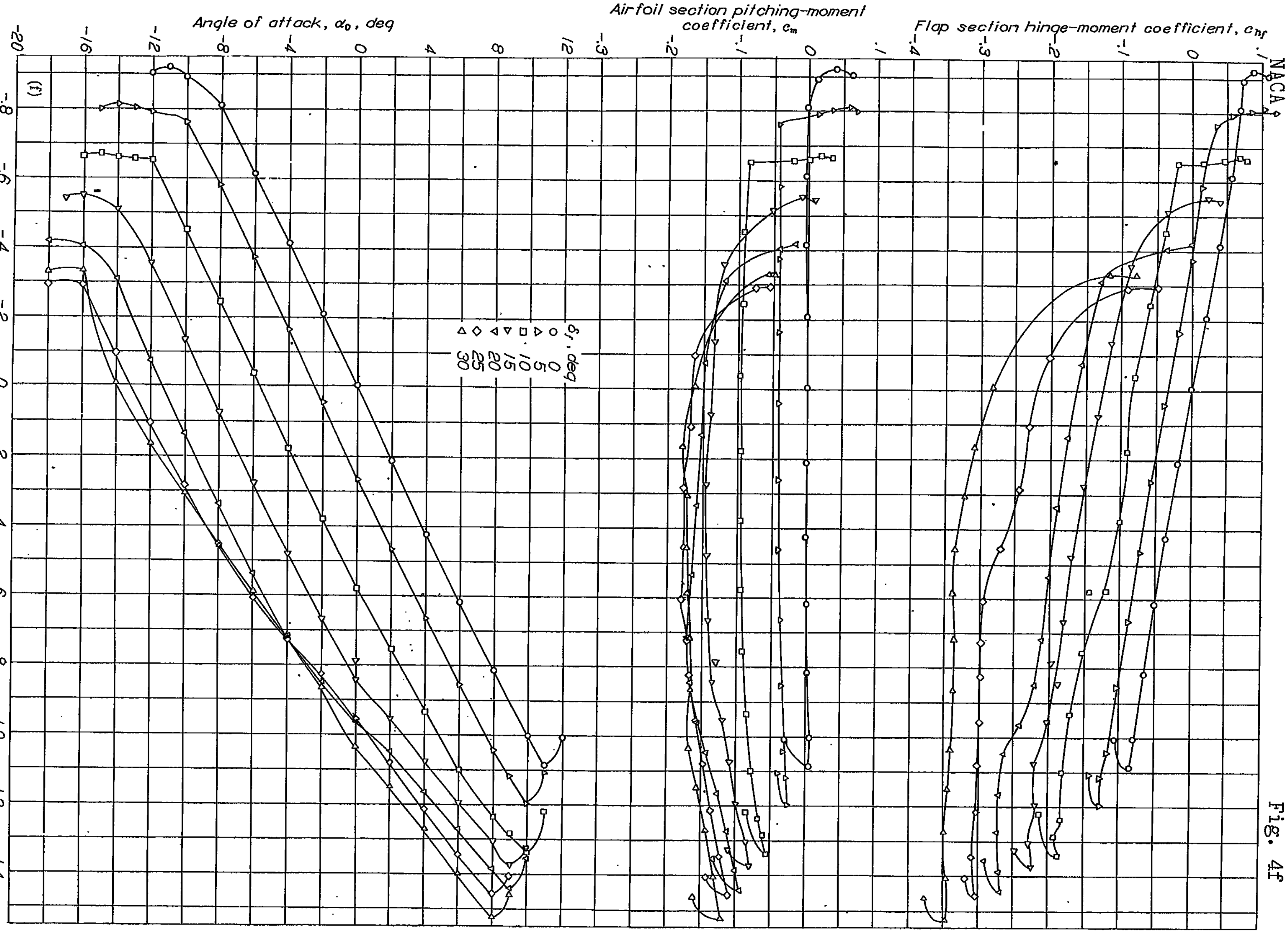

Figure 4f. - Semicircular trailing edge; radius, 0.036c.

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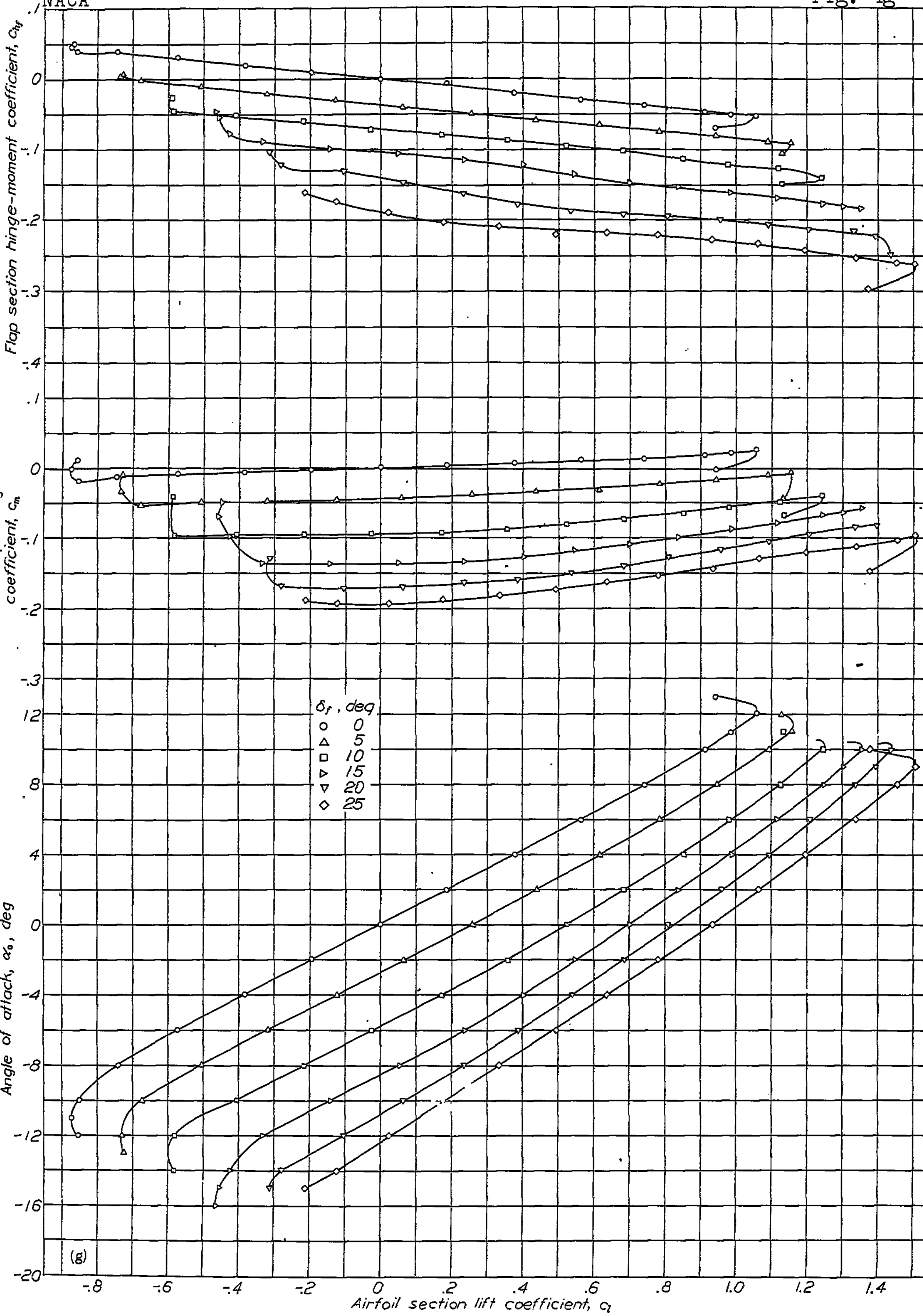

Figure 4g.- Bulged flap.

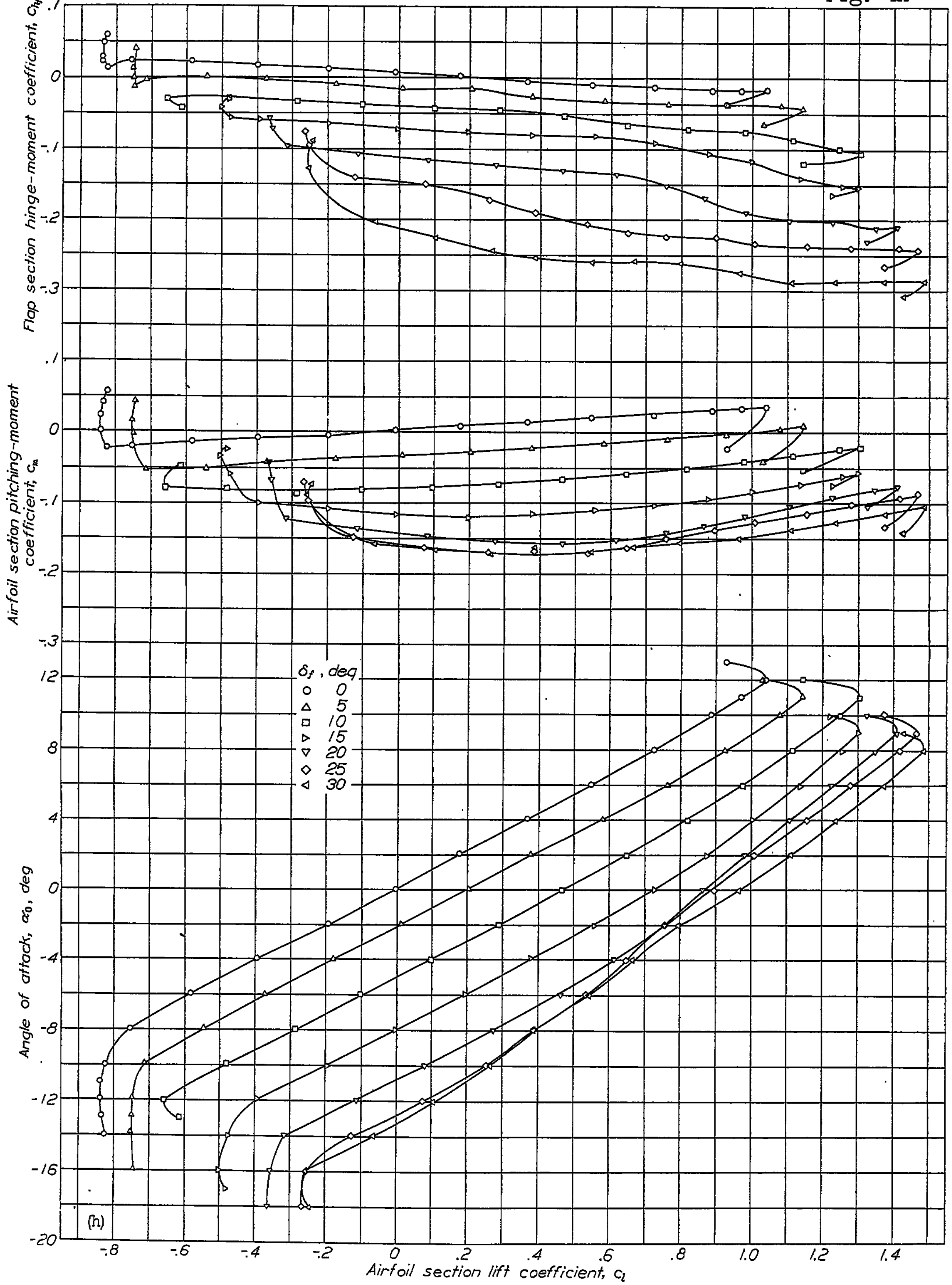

Figure 4h.-Elliptical trailing edge, 0.20c_f.

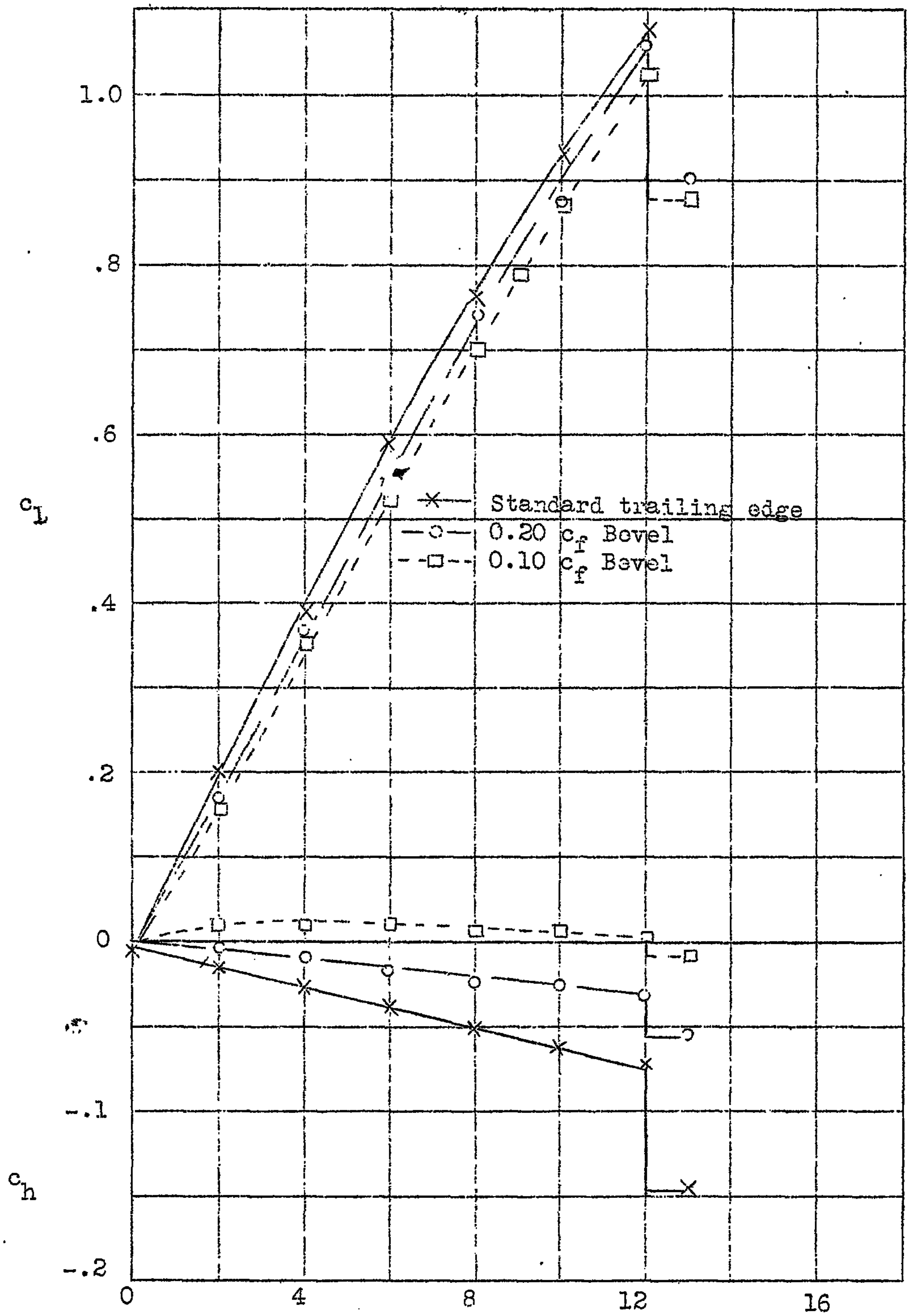

Figure 5.- Typical variations of lift and hinge moment with angle of attack. δ_f=0°.

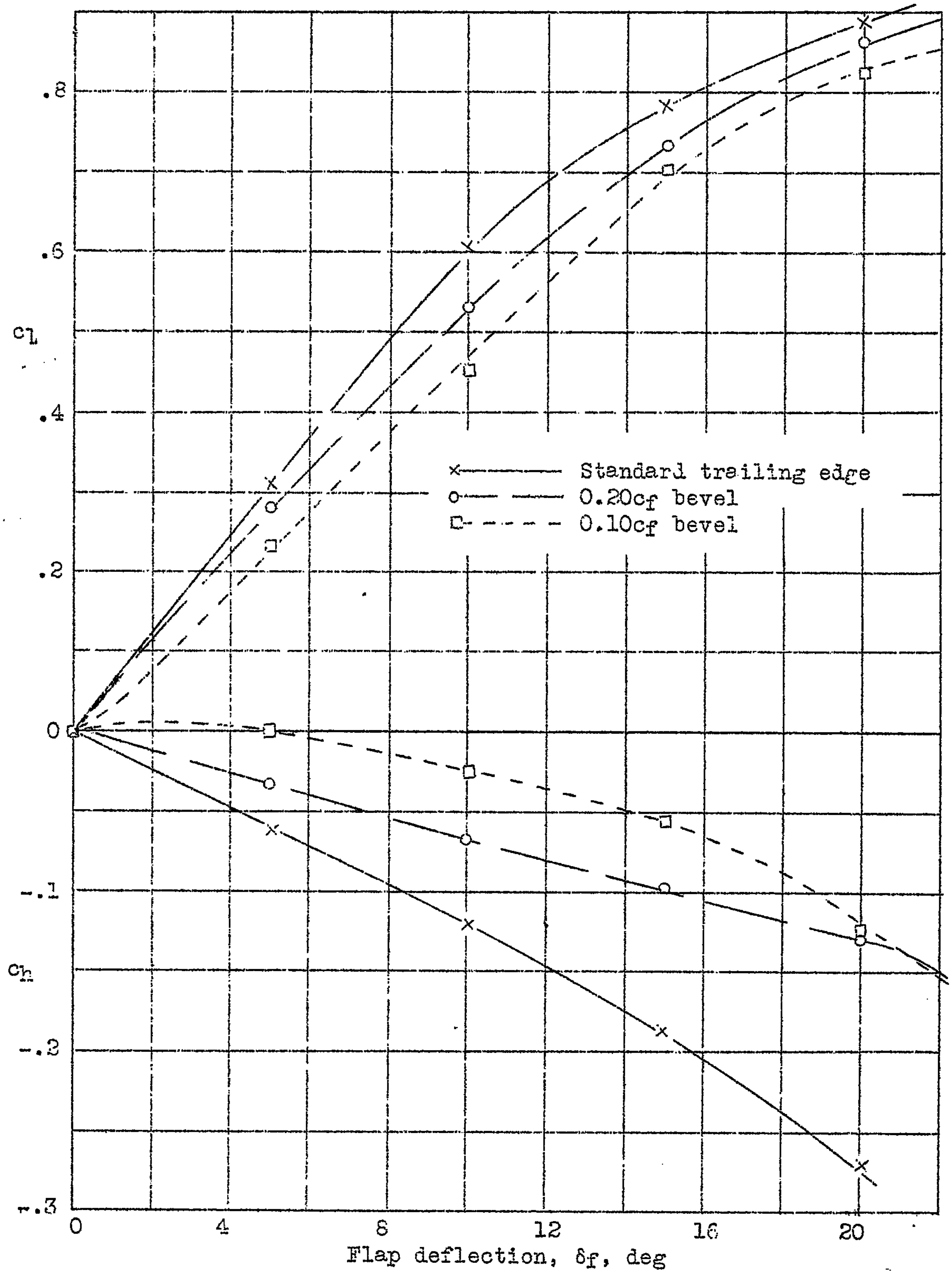

Figure 6.- Typical variations of lift and hinge moment with flap deflection. $\alpha = 0^\circ$.