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WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

VI - A 30-PERCENT-CHORD PLAIN FLAP ON THE NACA 0015 AIRFOIL

By Richard I. Sears and Robert B. Liddell

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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ADVANCE RESTRICTED REPORT

WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

VI - A 30-PERCENT-CHORD PLAIN FLAP ON THE NACA 0015 AIRFOIL

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SUMMARY

Force-test measurements in two-dimensional flow have been made in the NACA 4- by 6-foot vertical tunnel of the characteristics of an NACA 0015 airfoil equipped with a plain flap having a chord 30 percent of the airfoil chord and a plain tab having a chord 20 percent of the flap chord. The results are presented in the form of aerodynamic section characteristics for several flap and tab deflections and for a sealed and an unsealed gap at the flap nose.

The slope of the lift curve of the NACA 0015 airfoil was slightly less than the slope of the corresponding curve for the previously tested NACA 0009 airfoil, but the effectiveness of the plain flap in producing increments of lift was practically the same for both airfoils. For the thicker airfoil the variation of flap hinge moment with angle of attack was about one-third and with flap deflection about one-half of that for the similar flap on the thinner airfoil. Unsealing the gap at the flap hinge axis had a greater effect on the characteristics of the 15-percent-thick airfoil than on those of the 9-percent-thick airfoil.

INTRODUCTION

The NACA has instituted an extensive investigation of the aerodynamic characteristics of control surfaces in an effort to determine the types of flap arrangement best suited for use as control surfaces and to supply experimental data for design purposes. The first phase of this investigation consisted of the experimental determination of the pressure distribution on the NACA 0009 airfoil with many sizes of plain flaps and tabs. The results of these tests have been summarized in reference 1, which presents parameters for determining some of the characteristics of a thin symmetrical airfoil with a plain flap of any chord.

The second phase of the investigation consisted of force-test measurements in two-dimensional flow of the characteristics of an NACA 0009 airfoil with a 0.30c flap having variations in aerodynamic balance, in the shape of the flap nose, in the size of the gap at the flap nose, and in the trailing-edge shape of a flap of thickened profile. The results of these tests are reported in references 2 and 3 and in the papers listed in the bibliography.

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As a continuation of the investigation, tests have been made to provide data for the NACA 0015 airfoil with flap arrangements similar to those already tested on the NACA 0009 airfoil. The present paper presents the aerodynamic section characteristics of an NACA 0015 airfoil with a 0.30c plain flap and a $0.20c_f$ plain tab.

APPARATUS AND MODELS

The tests were made in the NACA 4- by 6-foot vertical tunnel described in reference 4. The test section of this tunnel has been converted from the original open, circular, 5-foot-diameter jet to a closed, rectangular, 4- by 6-foot throat for force tests of models in two-dimensional flow. A three-component balance system has been installed in the tunnel in order that force-test measurements of lift, drag, and pitching moment may be made. The hinge moments of the flap and the tab were measured with special torque-rod balances built into the model.

The 2-foot-chord by 4-foot-span model (fig. 1) was made of laminated mahogany (except for a metal tab) to the NACA 0015 profile. (See table I.) For the present tests, the model was equipped with a 0.30c plain flap and a $0.20c_f$ plain tab. The nose radii of the flap and the tab were approximately one-half the airfoil thickness at the respective hinge axes. The flap gap was 0.005c and the tab gap was 0.001c. For the sealed-gap tests both the flap and tab gaps were filled with a light grease.

The model, when mounted in the tunnel, completely spanned the test section except for small clearances at each end. With this type of installation two-dimensional flow is approximated; and the section characteristics of the airfoil, the flap, and the tab may be determined. The model was attached to the balance frame by torque tubes that extended through the sides of the tunnel. The angle of attack was set from outside the tunnel by rotating the torque tubes with an electrical drive. Flap and tab deflections were set inside the tunnel and were held by friction clamps on the torque rods that were used to measure the hinge moments.

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TESTS

The tests were made at a dynamic pressure of 15 pounds per square foot, which corresponds to an air velocity of about 76 miles per hour at standard sea-level conditions. The effective Reynolds number of the tests was approximately 2,760,000. (Effective Reynolds number = test Reynolds number × turbulence factor. The turbulence factor for the 4- by 6-ft vertical tunnel is 1.93.)

The flap was set, in increments of 5°, at deflections from 0° to 30° for both sealed and unsealed gap tests. All the tab tests were made with both the gaps sealed and with the tab deflected in 5° increments. With the flap at 0° the tab was deflected from 0° to 25°; with the flap deflected 5°, the range of tab deflection was from 15° to -20°; at flap deflections of 15° and 25°, the tab deflection range was from 0° to 20°.

RESULTS

Symbols

The coefficients and the symbols used in this paper are defined as follows:

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_f}	flap section hinge-moment coefficient (h_f/qc_f^2)
c_{h_t}	tab section hinge-moment coefficient (h_t/qc_t^2)

where

l	airfoil section lift
d_o	airfoil section profile drag
m	airfoil section pitching moment about quarter-chord point of airfoil
h_f	flap section hinge moment
h_t	tab section hinge moment
c	chord of basic airfoil with flap and tab neutral
c_f	flap chord
c_t	tab chord
q	dynamic pressure

and

α_o	angle of attack for airfoil of infinite aspect ratio
δ_f	flap deflection with respect to airfoil
δ_t	tab deflection with respect to flap

$$c_{l_\alpha} = \left(\frac{\partial c_l}{\partial \alpha_o}\right)_{\delta_f,\ \delta_t}$$

$$c_{l_{\alpha(\mathrm{free})}} = \left(\frac{\partial c_l}{\partial \alpha_o}\right)_{c_{h_f} = 0}$$

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$$c_{h_{f_\alpha}} = \left(\frac{\partial c_{h_f}}{\partial \alpha_0}\right)_{\delta_f,\ \delta_t}$$

$$c_{h_{f_{\delta_f}}} = \left(\frac{\partial c_{h_f}}{\partial \delta_f}\right)_{\alpha_0,\ \delta_t}$$

$$c_{h_{f_{\delta_t}}} = \left(\frac{\partial c_{h_f}}{\partial \delta_t}\right)_{\alpha_0,\ \delta_f}$$

$$c_{h_{t_\alpha}} = \left(\frac{\partial c_{h_t}}{\partial \alpha_0}\right)_{\delta_f,\ \delta_t}$$

$$c_{h_{t_{\delta_t}}} = \left(\frac{\partial c_{h_t}}{\partial \delta_t}\right)_{\alpha_0,\ \delta_f}$$

The subscripts outside the parentheses represent the factors held constant during the measurement of the parameters.

Precision

The accuracy of the data is indicated by the deviation from zero of lift and moment coefficients at an angle of attack of 0°. The maximum error in effective angle of attack at zero lift appears to be about $\pm 0.2^\circ$. Flap deflections were set to within $\pm 0.2^\circ$. Tunnel corrections, experimentally determined in the 4- by 6-foot vertical tunnel, were applied only to lift. The hinge moments are probably slightly higher than would be obtained in free air and, consequently, the values presented are considered conservative. The increments of drag should be reasonably independent of tunnel effect, although the absolute value is subject to an unknown correction. Inaccuracies in the section data presented are thought to be negligible relative to inaccuracies that will be incurred in the application of the data to finite airfoils.

Presentation of Data

Aerodynamic section characteristics of the NACA 0015 airfoil with a 0.30c plain flap are presented as a function of lift coefficient in figure 2. Figure 2(a) presents the characteristics with the gap at the flap nose sealed; figure 2(b) presents the characteristics with the gap equal to 0.005c. Part of the data in figure 2 is replotted in figure 3 to show the effect of gap on the variation of c_{h_f} with c_l for three typical values of angle of attack. Increments of drag caused by deflection of the flap are given as a function of flap deflection in figure 4. The tab characteristics as a function of tab deflection at constant angle of attack for various flap deflections are shown in figure 5.

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AERODYNAMIC SECTION CHARACTERISTICS

Lift

Figure 2 indicates that the lift curves of the NACA 0015 airfoil for the various flap deflections are of the same general shape as the corresponding curves for the NACA 0009 airfoil (reference 2). At any given flap deflection, however, the angle of attack at which the airfoil stalls was about 5° greater for the thicker airfoil than for the thinner airfoil; consequently, the maximum lift coefficient of the thicker airfoil was greater by an increment Δc_l of about 0.4. This effect may be attributed to the greater nose radius of the thicker airfoil.

The slope of the lift curve c_{l_α} was 0.096 for the flap with a sealed gap and 0.089 for the flap with the 0.005c nose gap. The decrease in slope caused by unsealing the gap agrees qualitatively with the results for the NACA 0009 airfoil. With the gap both sealed and unsealed the slope for the thicker airfoil was, however, somewhat less than for the thinner airfoil.

The effectiveness of the flap in producing lift $\left(\frac{\partial \alpha_0}{\partial \delta_f}\right)_{c_l}$ was -0.58 for the flap with sealed gap and

-0.46 for the flap with the open gap. The lift effectiveness of the flap on the thicker airfoil was practically the same as that for the same chord flap on the NACA 0009 airfoil. The fact that the effectiveness was greater when the flap nose gap was sealed than when it was unsealed agrees with the test results for the NACA 0009 airfoil. The flap was effective in producing increments of lift at all deflections for all angles of attack at which tests were made. Because of separation phenomena, however, the effectiveness at large deflections was not so great as at small deflections.

The parameter $c_{l_{\alpha(\mathrm{free})}}$, listed in table II, is a measure of control-free stability. The decrease in the slope of the lift curve with a free-floating flap was nearly independent of the flap nose gaps tested.

Hinge Moment of Flap

The nature of the distribution of pressure over the flap on the NACA 0015 airfoil is, apparently, different from that over the flap on the NACA 0009 airfoil. This condition is indicated by the fact that the slope $c_{h_{f_\alpha}}$ is much smaller for the thicker airfoil than for the thinner airfoil and that the curves for the thicker airfoil (fig. 2) are not so nearly linear over the entire angle-of-attack range as they are for the thinner airfoil (reference 2). The air flow over the trailing-edge portion of the thicker airfoil is probably similar to that discussed in reference 3 for flaps of thickened profile and beveled trailing edges. The aerodynamic characteristics of the plain flap on the NACA 0015 airfoil are remarkably similar to those reported in reference 3 for the NACA 0009 airfoil with a flap of thickened profile and a long beveled trailing edge.

The hinge-moment parameters for both gaps are given in table II. Because of the nonlinearity of the hinge-moment curves, the parameters $c_{h_{f_\alpha}}$ and $c_{h_{f_{\delta_f}}}$ measured at 0° flap deflection and 0° angle of attack, respectively, represent the curves over only a small range of angles. The values of the parameters for different gaps are indicative, however, of the relative merits of each particular arrangement. For a complete picture of the merits of each flap-gap arrangement, the entire set of hinge-moment curves (fig. 2) must be taken into consideration and too much reliance should not be placed on the values of the slopes measured at one particular point.

In general, the slope $c_{h_{f_\alpha}}$ for the NACA 0015 airfoil with a 30-percent-chord plain flap was about one-third as great as that for a similar flap arrangement on the NACA 0009 airfoil (reference 2). The slope $c_{h_{f_{\delta_f}}}$ for the thicker airfoil was about one-half as great as that for the thinner airfoil. The effect of aspect ratio on the various slopes is discussed in reference 1.

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Figure 3 indicates that for small flap deflections at angles of attack of -8° and 0° the airfoil with a 0.005c gap had a smaller hinge-moment coefficient at constant lift than the airfoil with the sealed gap. At all other attitudes of the airfoil and flap the hinge-moment coefficient for the unsealed flap was greater. Corresponding curves for the NACA 0009 airfoil (reference 2) show qualitatively the same results.

Pitching Moment

The slopes of the curves of the pitching-moment coefficient as a function of lift coefficient at constant flap deflection and at constant angle of attack are shown in table II. The aerodynamic center was at the 0.23c point for both sealed and unsealed gap conditions when the circulation was varied by changing the angle of attack of the airfoil. This fact agrees with the test results obtained in reference 5. When the circulation was varied by changing the effective camber of the airfoil, that is, by deflecting the flap, the aerodynamic center was at the 0.41c station with the gap unsealed and at the 0.42c station when the gap was sealed. The position of the aerodynamic center for deflection of the flap is a function of aspect ratio (reference 1) and moves toward the trailing edge as the aspect ratio is decreased.

Drag

Because of the unknown tunnel correction, the values of drag coefficients cannot be considered absolute; the relative values, however, should be independent of tunnel effect. Increments of drag coefficient, plotted as a function of flap deflection in figure 4, were determined by deducting the drag coefficient of the airfoil with the flap and tab neutral from the drag coefficient with the flap deflected, with all other factors constant. At positive flap deflections and positive angles of attack, the increment of drag coefficient was larger for the flap with unsealed gap than for the flap with the sealed gap.

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In these tests, the minimum profile-drag coefficient, uncorrected for tunnel effects, was found to be 0.0130 for the NACA 0015 airfoil with the flap sealed at the hinge. Unsealing the gap increased the value of this coefficient by 0.0004, an increment that is of the same magnitude as the corresponding increment for an NACA 0009 airfoil (reference 2).

Tab Characteristics

The increments of lift and flap hinge-moment coefficients caused by tab deflection (fig. 5) were obtained by deducting the coefficient with tab neutral from that with the tab deflected, with all other factors constant. The tab was effective in producing increments of flap hinge moment at all tab deflections tested and, in general, was more effective when the angle of attack and the tab deflections were of the same sign. The slope $c_{h_{\delta_t}}$ was roughly -0.001, a value that is of the same order of magnitude as the value of the slope for a similar tab on the NACA 0009 airfoil (reference 2).

The lift effectiveness of the tab $\left(\frac{\partial \alpha_0}{\partial \delta_t}\right)_{c_l}$ was slightly greater than that for a similar tab on the NACA 0009 airfoil (reference 2). With the flap deflected, however, the increments of lift caused by tab deflection were of about the same magnitude for both airfoils.

The curve of the variation of tab hinge-moment coefficient with tab deflection was fairly linear, with a slope $c_{h_{t_{\delta_t}}}$ of approximately -0.005. With angle of attack, however, the slope of the tab hinge-moment-coefficient curves $c_{h_{t_\alpha}}$ was positive over a small range of angles of attack. This fact can probably be attributed to the relatively thick trailing-edge profile on the NACA 0015 airfoil and agrees qualitatively with the results presented in reference 3 for a flap of thickened profile. The effect of profile thickness of the flap, apparently, becomes greater as the flap chord is decreased.

CONCLUSIONS

The results of the tests of the NACA 0015 airfoil with a plain flap having a chord 30 percent of the airfoil chord compared with the results of previous tests of a similar flap in the NACA 0009 airfoil indicate the following conclusions:

1. The slope of the lift curve for the NACA 0015 airfoil was slightly less than that for the NACA 0009 airfoil and decreased when the gap at the flap nose was unsealed.

2. The lift effectiveness of the plain flap on the NACA 0015 airfoil was practically the same as that of the similar flap on the NACA 0009 airfoil. Unsealing the gap at the flap nose appreciably decreased the flap lift effectiveness.

3. The hinge-moment curves for the NACA 0015 airfoil were not so nearly linear with angle of attack and flap deflection as those for the NACA 0009 airfoil. The slope of the curve of flap hinge-moment coefficient as a function of angle of attack was about one-third and the slope of the curve of flap hinge-moment coefficient as a function of flap deflection was about one-half of the corresponding values for the similar plain flap on the NACA 0009 airfoil.

4. In general, the results indicate that, on both the NACA 0015 and the NACA 0009 airfoils, the plain flap gave a greater lift effectiveness with smaller hinge moments with the flap gap sealed than with it unsealed. The effect was smaller, however, for the thicker than for the thinner airfoil.

5. The flap with a sealed gap gave a smaller minimum profile-drag coefficient than the flap with unsealed gap.

6. The tab was effective in producing increments of flap hinge moment at all deflections at which tests were made and was slightly more effective when the angle of attack and the tab deflection were of the same sign.

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3. Jones, Robert T., and Ames, Milton B., Jr.: Wind-Tunnel Investigation of Control-Surface Characteristics. V - The Use of a Beveled Trailing Edge to Reduce the Hinge Moment of a Control Surface. NACA A.R.R., March 1942.

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Ames, Milton B., Jr., and Eastman, Donald R., Jr.: Wind-Tunnel Investigation of Control-Surface Characteristics. IV - A Medium Aerodynamic Balance of Various Nose Shapes Used with a 30-Percent-Chord Flap on an NACA 0009 Airfoil. NACA A.R.R., Sept. 1941.

TABLE I.- ORDINATES FOR NACA 0015 AIRFOIL
[Stations and ordinates in percent of airfoil chord]

Station	Upper surface	Lower surface
0	0	0
1.25	2.37	-2.37
2.5	3.27	-3.27
5	4.44	-4.44
7.5	5.25	-5.25
10	5.85	-5.85
15	6.68	-6.68
20	7.17	-7.17
25	7.43	-7.43
30	7.50	-7.50
40	7.25	-7.25
50	6.62	-6.62
60	5.70	-5.70
70	4.58	-4.58
80	3.28	-3.28
90	1.81	-1.81
95	1.01	-1.01
100	(.16)	(-.16)
100	0	0

L. E. radius: 2.48

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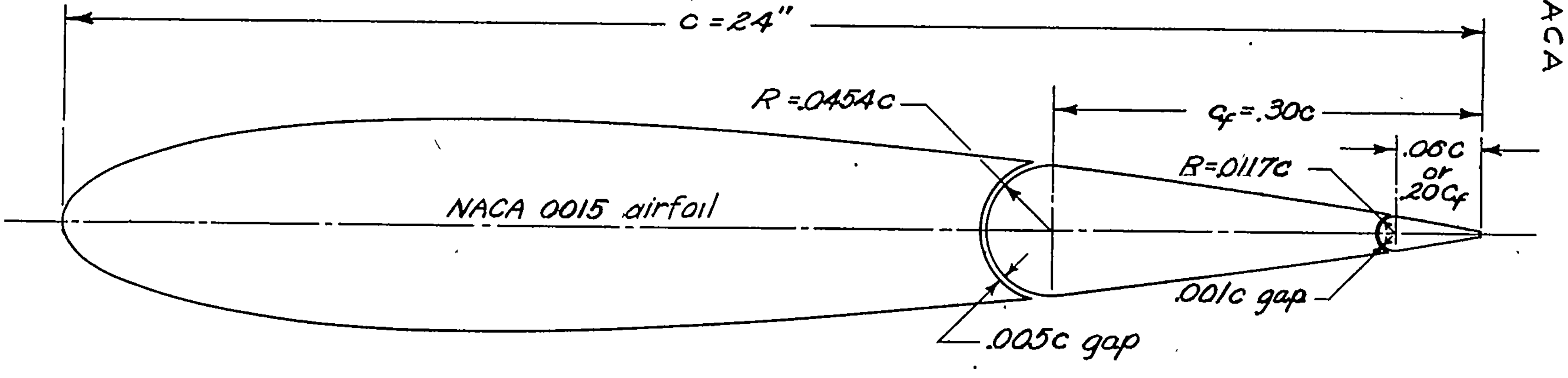
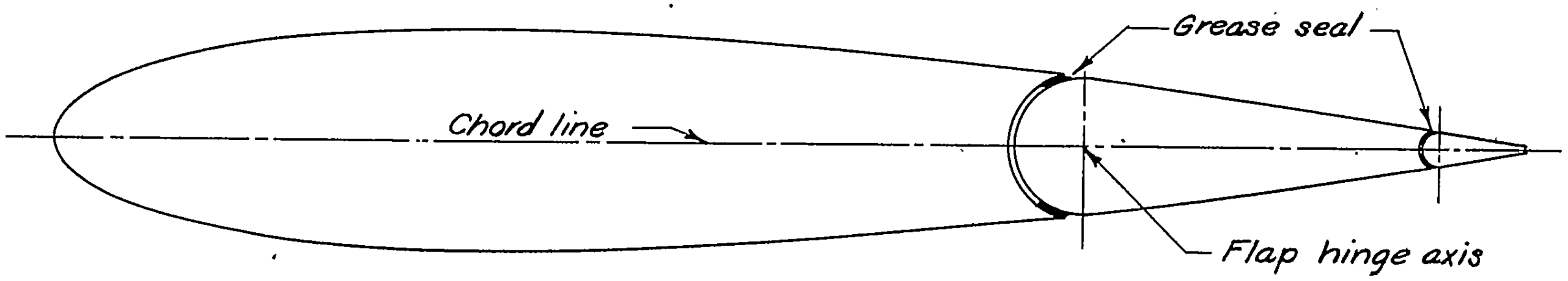
TABLE II.- PARAMETER VALUES FOR 0.30c PLAIN FLAP ON A NACA 0015 AIRFOIL

Parameter	0.005c gap	Sealed gap
$\left(\frac{\partial\alpha_0}{\partial\delta_f}\right)_{c_l,\ \delta_t}$	-0.460	-0.580
$\left(\frac{\partial c_l}{\partial\alpha_0}\right)_{\delta_f,\ \delta_t}$	.089	.096
$\left(\frac{\partial c_l}{\partial\alpha_0}\right)_{free}$	.075	.080
$\left(\frac{\partial c_m}{\partial c_l}\right)_{\delta_f,\ \delta_t}$	.020	.020
$\left(\frac{\partial c_m}{\partial c_l}\right)_{\alpha_0,\ \delta_t}$	-.170	-.155
$\left(\frac{\partial c_{h_f}}{\partial\alpha_0}\right)_{\delta_f,\ \delta_t}$	-.0022	-.0023
$\left(\frac{\partial c_{h_f}}{\partial\delta_f}\right)_{\alpha_0,\ \delta_t}$	-.0063	-.0080
$\left(\frac{\partial c_{h_f}}{\partial\delta_t}\right)_{\alpha_0,\ \delta_t}$	-------	-.001
$\left(\frac{\partial c_{h_t}}{\partial\delta_t}\right)_{\alpha_0,\ \delta_f}$	-------	-.005
$\left(\frac{\partial\alpha_0}{\partial\delta_t}\right)_{c_l,\ \delta_f}$	-------	-.21

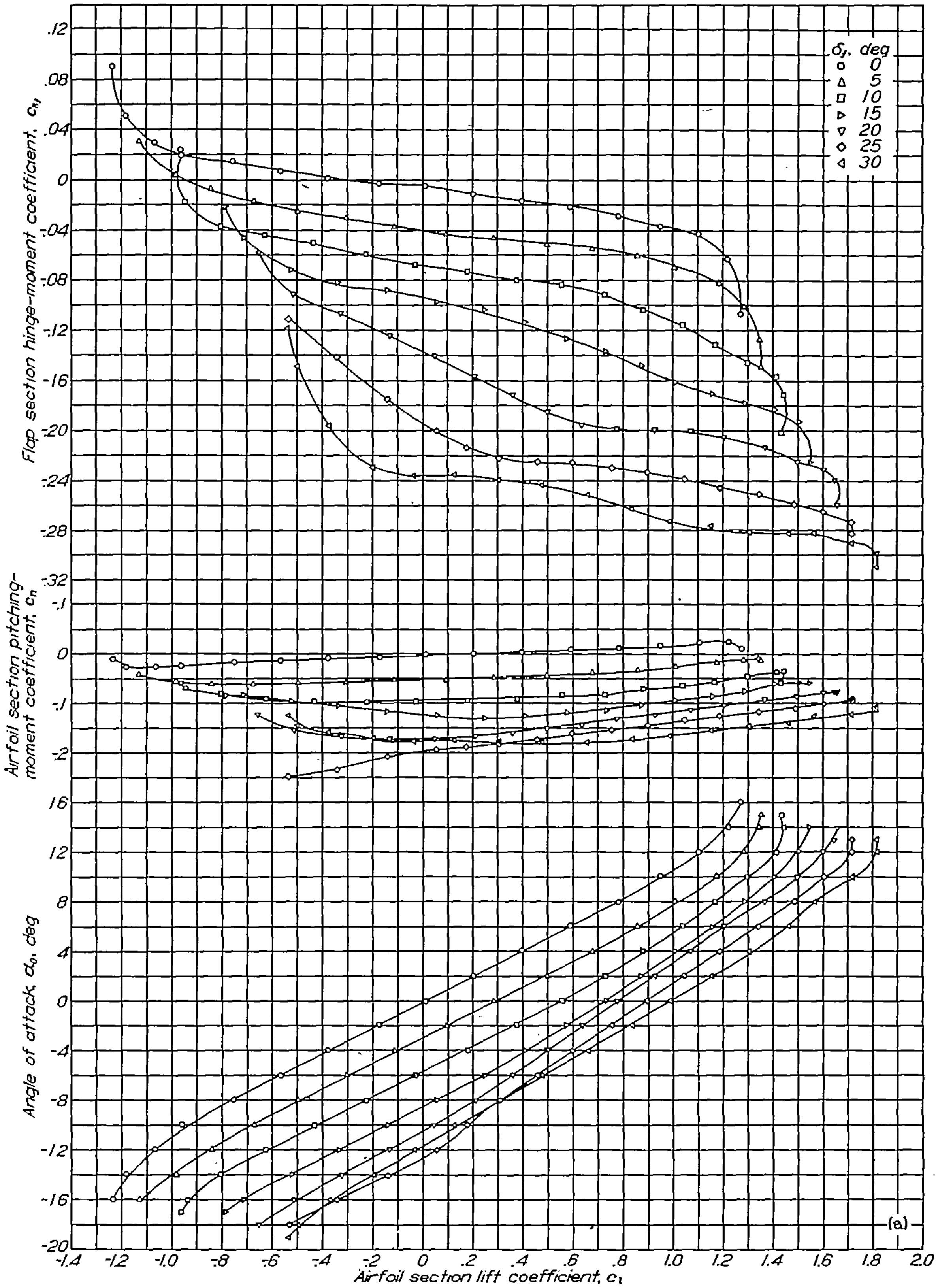


Plain flap with 0.005c gap

Figure 1.- Two-foot chord NACA 0015 airfoil with 0.30c plain flap and 0.20 c_f tab



Plain flap with sealed gap



(a) Sealed gap

Figure 2(a,b).- Section aerodynamic characteristics of an NACA 0015 airfoil with a 0.30c plain flap.

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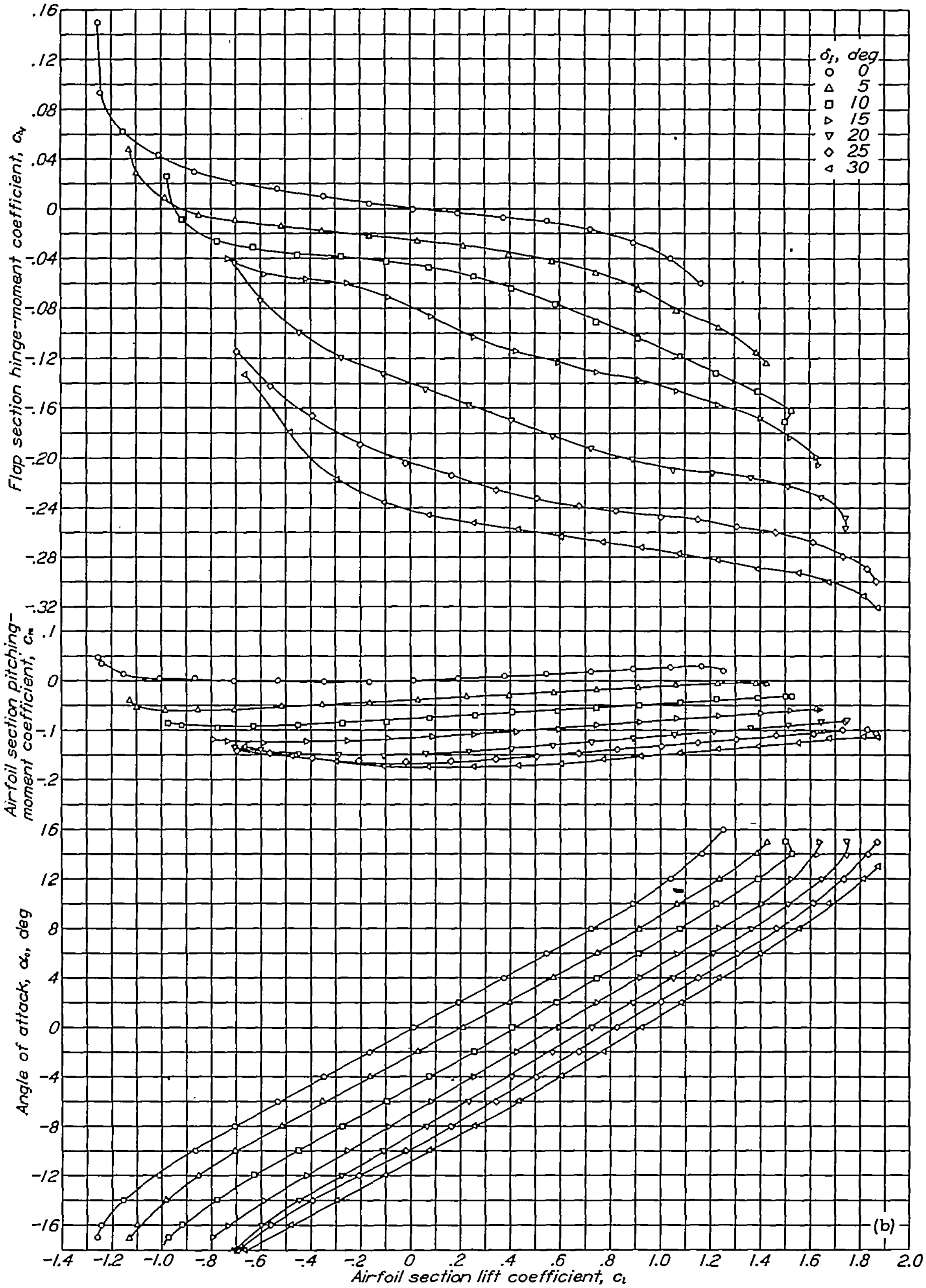

(b) Gap, 0.005c
Figure 2.- (Concluded)

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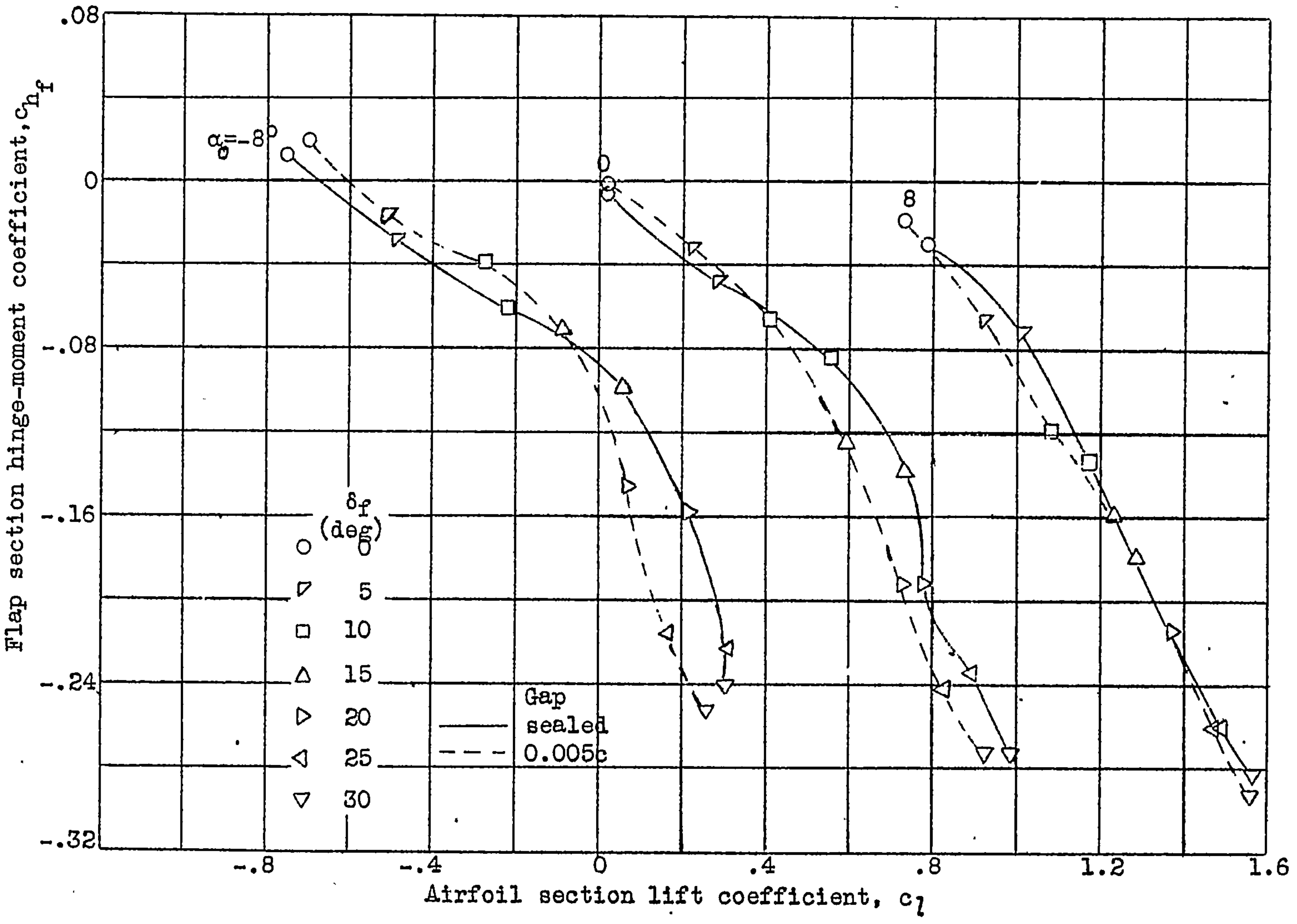

Figure 3.- Variation of flap section hinge-moment coefficient with airfoil section lift coefficient at several angles of attack and flap deflections. NACA 0015 airfoil, δ_t = 0°, plain flap.

Fig. 3

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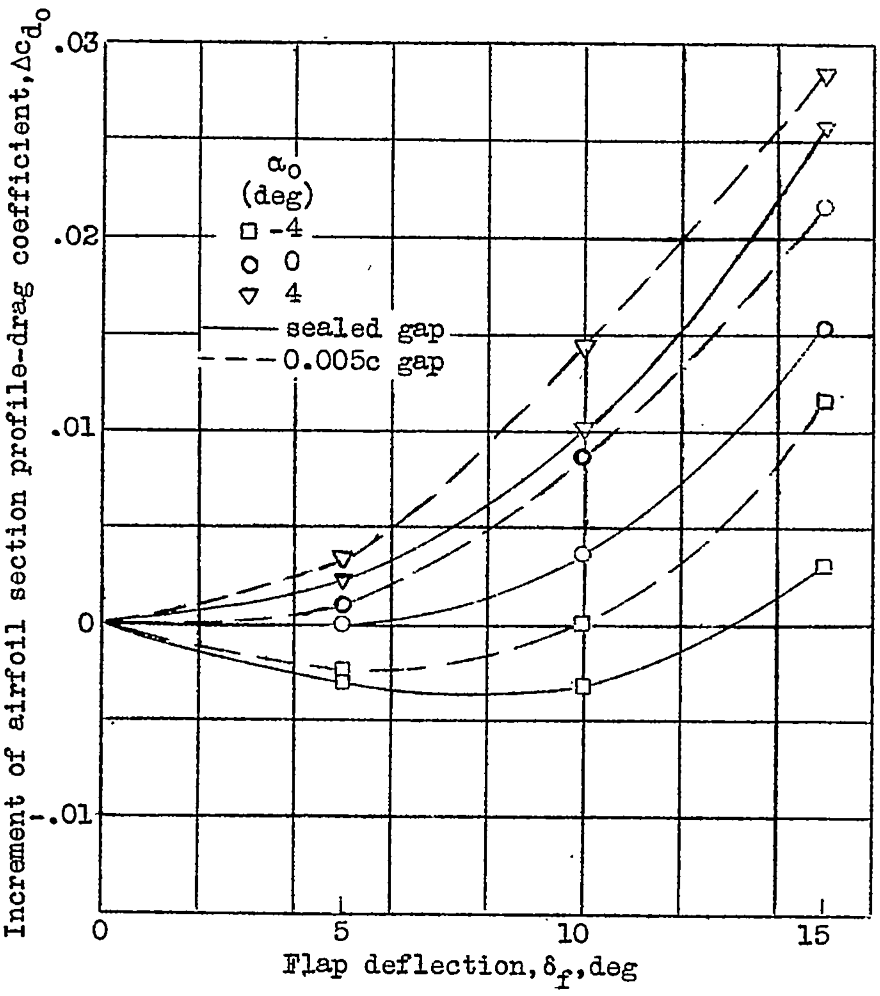


Figure 4.- Increment of airfoil section profile-drag coefficient caused by deflection of a 0.30c plain flap with sealed and with 0.005c gaps.

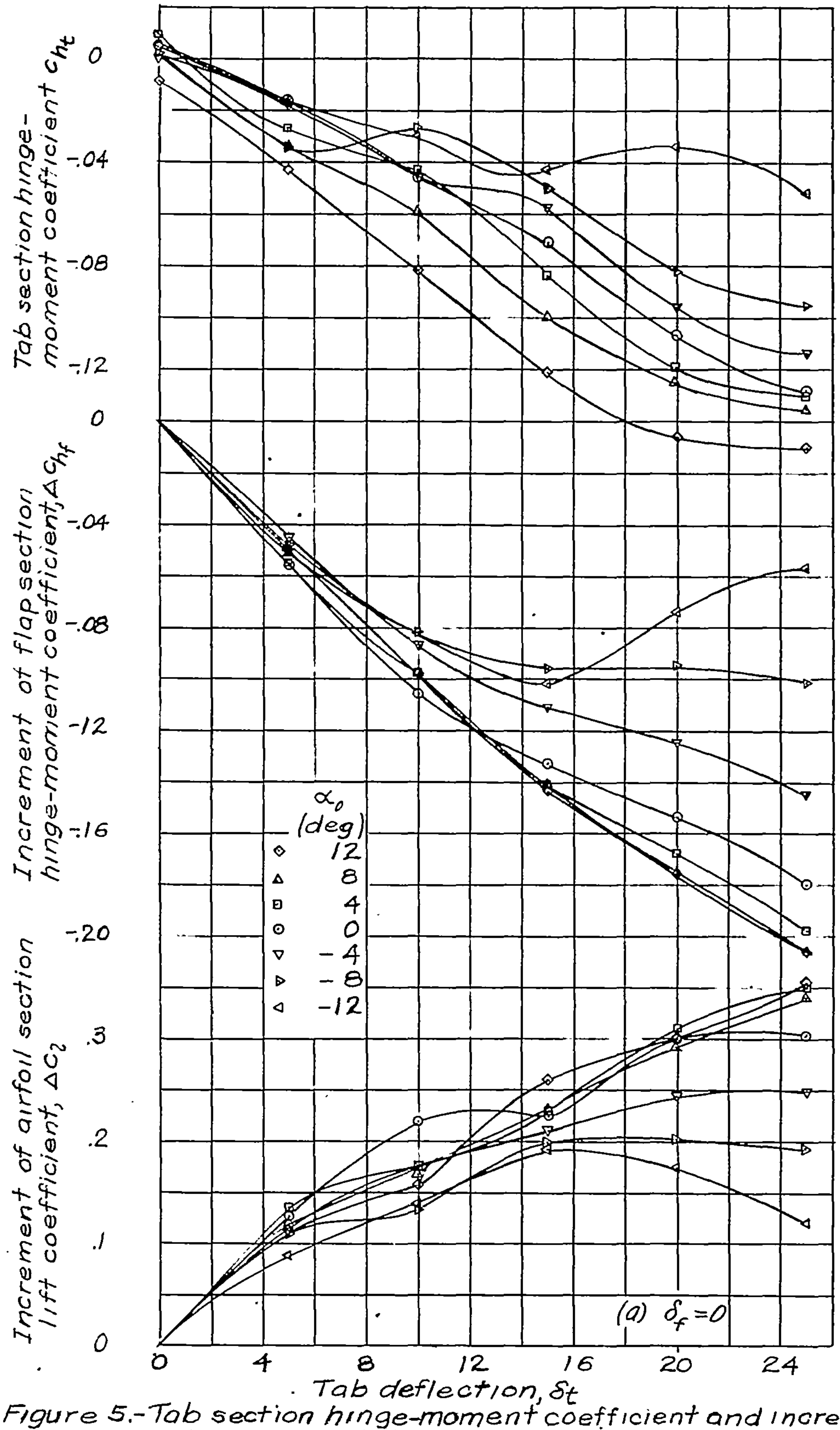


Figure 5.-Tab section hinge-moment coefficient and increments of airfoil section lift coefficient and flap section hinge-moment coefficient caused by deflection of a 0.20c_f plain tab. Plain 0.30c. flap with sealed gap.

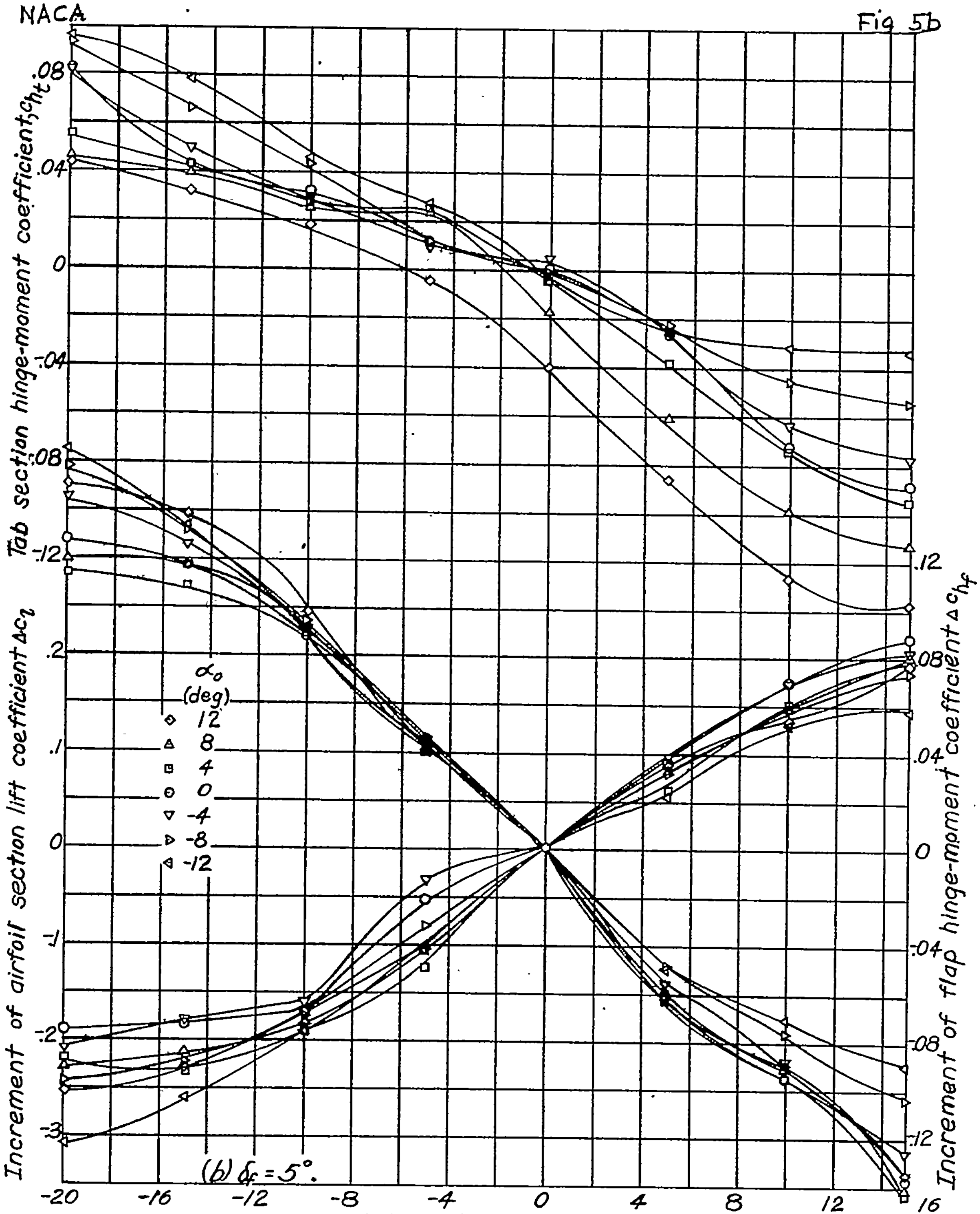
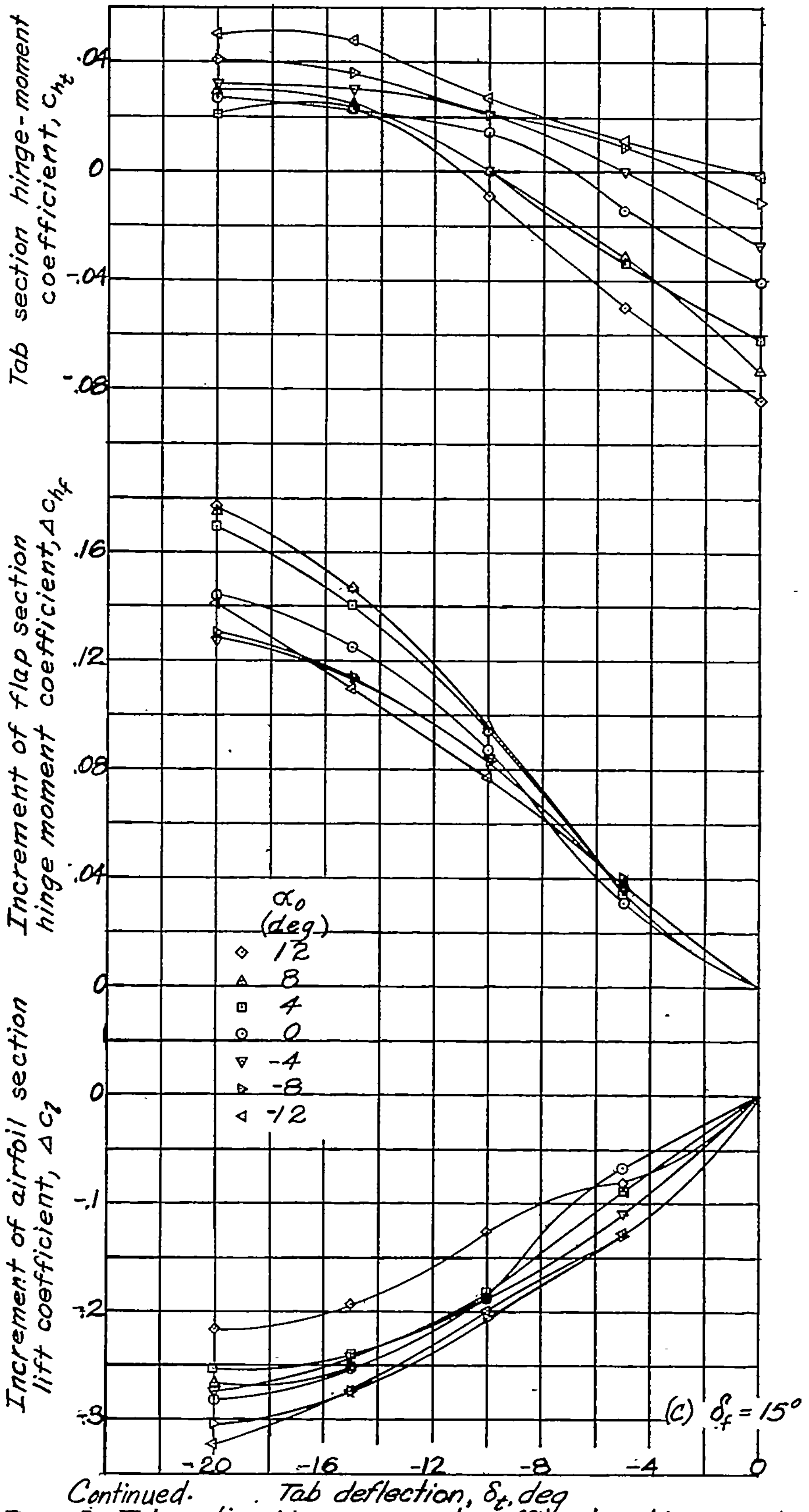


Figure 5.-Tab section hinge-moment coefficient and increments of airfoil section lift coefficient and flap section hinge moment coefficient caused by deflection of a 0.20 c_f plain tab. Plain 0.30c flap with sealed gap. (Continued)



Continued.

Figure 5.– Tab section hinge-moment coefficient and increments of airfoil section lift coefficient and flap section hinge-moment coefficient caused by deflection of a 0.20 c_f plain tab. Plain 0.30c flap with sealed gap.

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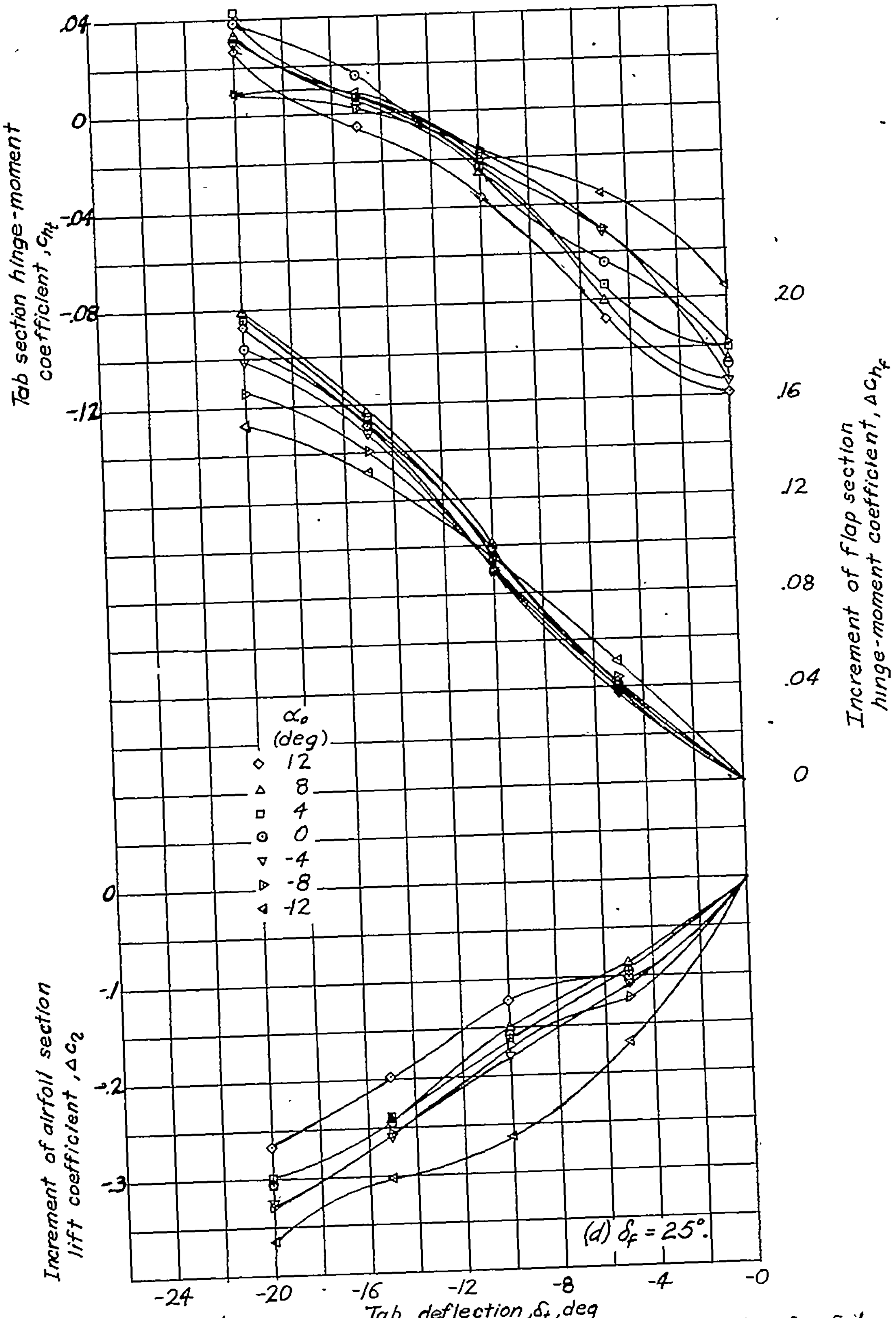

Figure 5.- Continued. Tab section hinge-moment coefficient and increments of airfoil section lift coefficient and flap section hinge-moment coefficient caused by deflection of a 0.20 c_f plain tab. Plain 0.30c flap with sealed gap