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## WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

## VII - A MEDIUM AERODYNAMIC BALANCE OF TWO NOSE SHAPES USED WITH A 30-PERCENT-CHORD FLAP ON AN NACA 0015 AIRFOIL

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WASHINGTON

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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 with a balanced flap having a chord 30 percent of the airfoil chord and a flap-nose overhang 35 percent of the flap chord. The effect on the aerodynamic section characteristics of the shape of the flap-nose overhang and the gap at the flap nose was investigated. A few tests were made to determine the effectiveness of a 20-percent-flap-chord tab on the balanced control surface.

The test results, presented in the form of aerodynamic section coefficients, indicate that the lift effectiveness of the flap was practically identical with that of a similar flap previously tested on the NACA 0009 airfoil and with that of a plain unbalanced flap of the same chord on either airfoil. The slope of the curve of hinge-moment coefficient as a function of angle of attack was positive over a small range of angles of attack when the gap at the flap nose was unsealed. With a blunt-nose flap the variation of flap hinge-moment coefficient with flap deflection was about one-third, and with a medium-nose flap, about one-half that of a plain unbalanced flap of the same chord on the same airfoil. The flap-nose overhang was more effective as a balancing device when the gap at the flap nose was unsealed than when it was sealed.

## INTRODUCTION

The NACA has instituted an extensive two-dimensional-flow investigation of the aerodynamic section characteristics of control surfaces in an effort to provide experimental data for design purposes and to determine the types of flap arrangement best suited for use as a control surface. In the first phase of this investigation the pressure distribution of the NACA 0009 airfoil with many sizes of plain flap and tab was experimentally determined. 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 two-dimensional-flow investigation consisted of force-test measurements of the characteristics of an NACA 0009 airfoil with a 30-percent-airfoil-chord flap having various amounts of aerodynamic balance, various flap-nose shapes, and various sizes of gap at the flap nose. The results of these tests are reported in references 2, 3, 4, and 5. The effects of various circular, elliptical, and beveled trailing edges on the hinge moment of a flap of thickened profile on the NACA 0009 airfoil were investigated and the results are presented in reference 6.

A series of tests has been undertaken to provide data for the NACA 0015 airfoil with flap arrangements similar to those already tested on the NACA 0009 airfoil. The aerodynamic section characteristics of an NACA 0015 airfoil with a 30-percent-airfoil-chord (0.30c) plain flap with a 20-percent-flap-chord ($0.20c_f$) tab are given in reference 7. The present paper presents the aerodynamic section characteristics of an NACA 0015 airfoil having a 0.30c flap with a $0.35c_f$ aerodynamic balance of blunt and medium nose shapes and a $0.20c_f$ plain tab.

## APPARATUS AND MODEL

The tests were made in the NACA 4- by 6-foot vertical tunnel described in reference 8. 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 brass tab) to the NACA 0015 profile. (See table I.) It was equipped with a 0.30c flap and a 0.20$c_f$ plain tab. The flap had an aerodynamic balance that extended forward of the flap-hinge axis 35 percent of the flap chord. This balance had two nose shapes, blunt and medium (fig. 1 and table II), which were made in the form of interchangeable nose blocks and were fastened to the flap with wood screws. The gap at the nose of the flap was 0.5 of 1 percent of the airfoil chord and for the sealed-gap tests it was filled with light grease. The tab was made of brass, with a nose radius approximately one-half the airfoil thickness at the tab-hinge axis. The tab gap was 0.1 of 1 percent of the airfoil chord. When sealed-gap tests were made, this gap was filled with light grease.

The model, when mounted in the tunnel, completely spanned the test section. With this type of installation two-dimensional flow is approximated, and the section characteristics of the airfoil, the flap, and the tab can 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 electric drive. Flap and tab deflections were set inside the tunnel and were held by friction clamps on the torque rods that were used in measuring the hinge moments.

## 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 at deflections from 0° to 25° in 5° increments. The tab was set at deflections from 0° to 20° in 5° increments for both flap-nose shapes. The tab tests were made with the flap neutral and with both flap and tab gaps unsealed because in previous tests the balanced flap was found more effective with the gap unsealed. The blunt and medium nose shapes were tested throughout the flap-deflection range with 0.005c and the sealed gaps. The lift, the drag, and the pitching moments of the airfoil and the hinge moments of the flap and the tab were measured. For each flap and tab setting, force tests were made throughout the angle-of-attack range at 2° increments from negative stall to positive stall. When either stall position was approached, the increment was reduced to 1° angle of attack.

## RESULTS

### Symbols

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

$c_l$ airfoil section lift characteristics $(l/qc)$

$c_{d_o}$ 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

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| | |
|---|---|
| $h_t$ | 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

| | |
|---|---|
| $\alpha_o$ | angle of attack for airfoil of infinite aspect ratio |
| $\delta_f$ | flap deflection with respect to airfoil |
| $\delta_t$ | tab deflection with respect to flap |

Also the following parameters:

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

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

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

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

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

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

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

The subscripts outside the parenthesis indicate the factors held constant when measuring the parameter.

## Precision

The accuracy of the data is indicated by the deviation from zero of lift and moment coefficients at zero angle of attack. 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, therefore, are probably slightly higher than would be obtained in free air and, consequently, the values presented are considered to be 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

The aerodynamic section characteristics of the NACA 0015 airfoil with a balanced flap of blunt and medium nose shapes are presented in figures 2 and 3 as functions of airfoil section lift coefficients. Figures 2(a) and 3(a) present the characteristics with the gap at the flap nose sealed; figures 2(b) and 3(b) present the characteristics with the gap equal to 0.005c. Increments of drag coefficient caused by deflection of the flap are presented as a function of flap deflection at various angles of attack in figure 4 for the arrangements of flap tested. The characteristics of a $0.20c_f$ tab on the balanced flap with both blunt and medium flap-nose shapes are presented in figures 5 and 6.

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## DISCUSSION OF AERODYNAMIC SECTION CHARACTERISTICS

### Lift

Figures 2 and 3 indicate that the lift curves of the NACA 0015 airfoil for the various flap deflections are of the same general shape as those for the NACA 0009 airfoil (reference 5). At any given flap deflection, however, the angle of attack at which the airfoil stalls is about $5^{\circ}$ greater for the thicker airfoil than for the thinner airfoil and, consequently, the maximum lift coefficient of the thicker airfoil is greater by about 0.4. This effect may be attributed to the greater nose radius on the thicker airfoil.

The slope of the lift curve $c_{l_{\alpha}}$ is listed in table III for each combination of flap-nose shape and gap. The value of $c_{l_{\alpha}}$ was practically independent of the flap-nose shapes tested and decreased appreciably when the gap at the flap nose was unsealed. This fact is in agreement with the results for the NACA 0009 airfoil (reference 5). Both with the gap sealed and unsealed, however, the slope for the thicker airfoil was somewhat less than that for the thinner airfoil.

The effectiveness of the flap in producing lift $\left(\frac{\partial\alpha_0}{\partial\delta_f}\right)_{c_l}$ is tabulated for small flap deflections in table III. A comparison with the data of reference 7 indicates that the sealed flap with a $0.35c_f$ overhang gave the same lift effectiveness as the plain flap. This result is in agreement with previous tests of balanced flaps on the NACA 0009 airfoil (references 2, 3, 4, and 5). A comparison of the present data with the data of these references indicates that the lift effectiveness of the flap on the thicker airfoil is practically identical with that for the same chord flap on the thinner airfoil regardless of the amount of flap overhang.

With a sealed gap the lift effectiveness $\left(\frac{\partial\alpha_0}{\partial\delta_f}\right)_{c_l}$ was independent of the nose shapes tested, but the reduction in lift effectiveness when a gap was introduced was greater with the medium nose shape than with the blunt nose shape. At large positive angles of attack and positive flap deflections, separation of flow caused the blunt-nose flap to lose all lift effectiveness when deflected beyond 15°; whereas, the medium-nose flap maintained some effectiveness to 25° flap deflection. For negative angles of attack and positive flap deflections, which is the normal operating range for a horizontal tail surface, however, the flap with either nose shape was effective in producing increments of lift to 25° deflection, the largest deflection tested. Because of separation phenomena, the effectiveness at large deflections was not so great as that at small deflections.

## Hinge Moment of Flap

The variation of flap hinge-moment coefficient with angle of attack at zero flap deflection was such that the curve had a large negative slope at large negative and large positive angles of attack and a very small slope at small angles of attack. Apparently, the nature of the pressure distribution over the flap on the NACA 0015 airfoil is different from that over the flap of conventional profile on the NACA 0009 airfoil (reference 2). It is probably similar to that for the flap of thickened profile on the NACA 0009 airfoil (reference 6). This similarity 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 the curves for the thicker airfoil are not so nearly linear over the entire angle-of-attack range as they are for the thinner airfoil. The probable nature of the air flow over a flap of thickened profile is discussed in reference 6.

Generally, the $0.35c_f$ balanced flap on the NACA 0015 airfoil, as on the NACA 0009 airfoil (reference 5), was much more effective in reducing the flap hinge moments when the flap was deflected in opposition to the angle of attack than when it was deflected in conjunction with it (figs. 2 and 3). The range wherein the balance was most effective, however, is the normal operating range for a control surface.

The hinge-moment parameters for all nose shapes and gaps tested are tabulated in table III. Because of

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nonlinearity of the curves, the parameters $c_{h_{f_\alpha}}$ and $c_{h_{f_{\delta_f}}}$ measured at 0° flap deflection and angle of attack, respectively, represent the curves over only a small range of angles. The relative values of the parameters for different nose shapes and gaps are indicative, however, of the relative merits of the balancing powers of each particular arrangement. For a complete picture of the merits of each flap-balance arrangement, the complete set of hinge-moment curves (figs. 2 and 3) must be taken into consideration and not too much reliance placed on the values of the slopes measured at one particular point. The effect of aspect ratio on the hinge-moment characteristics is discussed in reference 1.

In general, the slope $c_{h_{f_\alpha}}$ for the NACA 0015 airfoil with a 0.30c flap having a 0.35$c_f$ overhang was considerably smaller than that for the similar flap arrangement on the NACA 0009 airfoil (reference 5). The same result was found for the plain flap (reference 7). The slope was practically the same for the balanced flap on both airfoils, although a comparison of references 2 and 7 indicates that the value of $c_{h_{f_{\delta_f}}}$ for the plain unbalanced flap on the thicker airfoil was only half as great as that for the similar flap on the thinner airfoil.

Unsealing the gap at the nose of the flap increased the balance effectiveness for both the blunt and the medium flap-nose shapes. The slopes $c_{h_{f_\alpha}}$ became positive over a range of angles of attack of about ±5°. In this range, therefore, the flap will tend to float against the relative wind, which should cause the airplane static stability with controls free to exceed that with controls fixed. On the NACA 0009 airfoil a much larger flap overhang was required to obtain similar hinge-moment characteristics (references 3, 4, and 5).

Rudders with a large positive value of $c_{h_\alpha}$ and considerable frictional damping have been reported to cause undesirable flying qualities on a number of airplanes having small directional stability. These airplanes showed a tendency to oscillate in yaw but the undesirable characteristic has been cured by making $c_{h_\alpha}$ and $c_{h_{\delta_f}}$ more negative. Flight tests of one airplane at Langley Memorial Aeronautical Laboratory in which the rudder had a positive value of $c_{h_\alpha}$ and the airplane had a large amount of directional stability indicated that the behavior of the airplane was satisfactory. A theoretical analysis currently being made at the Laboratory shows that a positive value of $c_{h_\alpha}$ is desirable provided that other factors are properly controlled.

## Pitching Moment

The slopes of the curves of pitching-moment coefficient as a function of lift coefficient at constant flap deflection and also at constant angle of attack are tabulated in table III for the various arrangements of flap overhang.

The results indicate that the aerodynamic center of the airfoil was at the 0.23c station for the gap-sealed condition and approximately at the 0.22c point with the unsealed gap, when the circulation was varied by changing the angle of attack of the airfoil. These positions are the same for both overhang nose shapes. The position for the sealed-gap condition agrees with that reported in reference 7. When the circulation was varied by changes in the effective camber of the airfoil, caused by deflecting the flap, the aerodynamic center was at the 0.43c station with the unsealed gap and at the 0.41c station with the sealed gap. This position was practically the same as that for the plain flap reported in reference 7. The position of the aerodynamic center for deflection of the flap is a function of aspect ratio (reference 1) and will move toward the trailing edge as the aspect ratio is decreased.

## Drag

Because of a relatively large unknown tunnel correction, the drag coefficients cannot be considered absolute; the relative values, however, should be independent of tunnel effect. The increments of drag coefficient were determined by deducting the drag coefficient of the airfoil with flap and tab neutral from the drag coefficient with flap deflected, all other factors being constant.

The minimum profile drag of the airfoil with a blunt-nose balanced flap was the same as that for the airfoil with a plain flap (reference 7). The minimum profile drag of the airfoil was greater by 0.0011 with the medium-nose overhang than with the blunt-nose overhang. Figure 4 indicates that the increments of profile-drag coefficient caused by flap deflection were of nearly the same magnitude for both the blunt and the medium nose-flap shapes. With the gap unsealed the increments of drag were generally greater than with the gap sealed.

## Tab Characteristics

The increments of lift and flap hinge-moment coefficients caused by tab deflection, presented in figures 5 and 6, were obtained by deducting the coefficient with tab neutral from the coefficient with tab deflected, all other factors being constant.

In general, the tab characteristics are very similar to those for a tab on the plain flap (reference 7) although with the balanced flap the increments of flap hinge-moment coefficient caused by tab deflection were slightly smaller at most angles of attack. The tab characteristics are presented only for the flap-neutral condition; the increments caused by tab deflection have been shown by previous tests (reference 7) to be nearly independent of flap deflection.

## CONCLUSIONS

The results of the tests of the NACA 0015 airfoil with a balanced flap having a chord 30 percent of the airfoil chord and a flap-nose overhang 35 percent of the flap chord indicate the following conclusions when compared with the results of previous tests of a similar flap on the NACA 0009 airfoil:

1. The slope of the lift curve for the NACA 0015 airfoil was found to be independent of the flap-nose shapes tested and decreased appreciably when the gap at the flap nose was unsealed. With the gap both sealed and unsealed the lift-curve slopes for the NACA 0015 airfoil were somewhat less than those for the NACA 0009 airfoil.

2. The lift effectiveness of the flap with an overhang having a chord 35 percent of the flap chord on the NACA 0015 airfoil was practically identical with that of the similar flap on the NACA 0009 airfoil and with that of the plain flap on either airfoil.

3. The lift effectiveness of the flap with a sealed gap was independent of the nose shapes tested. The reduction in lift effectiveness when a gap was introduced was greater with the medium nose shape than with the blunt nose shape.

4. When deflected in conjunction with the angle of attack, the blunt-nose flap lost all lift effectiveness when deflected greater than $15^{\circ}$, but the medium-nose flap was somewhat effective to $25^{\circ}$. When deflected in opposition to the angle of attack, the flap with either nose shape was effective to $25^{\circ}$.

5. The rate of change of flap section hinge-moment coefficient with angle of attack was much smaller for the flap having an overhang 35 percent of the flap chord on the NACA 0015 airfoil than for the similar flap on the NACA 0009 airfoil. The curves for the thicker airfoil were not so nearly linear as those for the thinner airfoil. Because of this nonlinearity, these values apply for only a small range of angles of attack.

6. The rate of change of flap section hinge-moment coefficient with flap deflection was practically the same for the balanced flap on both the NACA 0009 and the NACA 0015 airfoils.

7. Unsealing the gap at the nose of the flap increased the balance effectiveness for flaps with both the blunt and the medium nose shapes. The rate of change of flap section hinge-moment coefficient with angle of attack became positive over a small range of angles of attack.

8. The curves of pitching-moment coefficient indicate that the aerodynamic center of the airfoil was located at the 0.23-chord station for the gap-sealed condition and approximately at the 0.23-chord point with the unsealed gap.

9. The minimum profile drag of the airfoil with a blunt-nose balanced flap was the same as that for the plain flap, but with the medium-nose balance the minimum profile-drag coefficient was increased by 0.0011.

10. The increments of flap hinge-moment coefficient caused by tab deflection on the balanced flap were slightly smaller at most angles of attack than those caused by a tab on the plain flap.

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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

TABLE II.- STATIONS AND ORDINATES FOR MEDIUM-NOSE

$0.35c_f$ OVERHANG

| Station (percent c) | Ordinate (percent c) |
|---|---|
| 0 | 0 |
| .15 | .90 |
| .90 | 2.12 |
| 1.90 | 2.92 |
| 2.90 | 3.45 |
| 3.90 | 3.80 |
| 4.90 | 4.07 |
| 6.90 | 4.40 |
| 8.90 | 4.50 |
| 10.90 | 4.45 |
| 13.00 | 4.27 |
| 14.67 | 4.06 |
| Fair to NACA 0015 profile to trailing edge | |
| Nose radius = 1.75 percent c | |

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# TABLE III.- PARAMETER VALUES FOR 0.30c FLAP WITH 0.35$c_f$ OVERHANG ON NACA 0015 AIRFOIL

| Parameters | Blunt nose shape | | Medium nose shape | |
|---|---|---|---|---|
| | Gap sealed | Gap 0.005c | Gap sealed | Gap 0.005c |
| $\left(\frac{\partial c_l}{\partial \alpha_0}\right)_{\delta_f, \delta_t}$ | 0.093 | 0.079 | 0.094 | 0.080 |
| $\left(\frac{\partial \alpha_0}{\partial \delta_f}\right)_{c_l, \delta_t}$ | -.58 | -.53 | -.58 | -.45 |
| $\left(\frac{\partial c_{h_f}}{\partial \alpha_0}\right)_{\delta_f, \delta_t}$ | -.0019 | .0013 | -.0015 | .0006 |
| $\left(\frac{\partial c_{h_f}}{\partial \delta_f}\right)_{\alpha_0, \delta_t}$ | -.0039 | -.0022 | -.0053 | -.0033 |
| $\left(\frac{\partial c_m}{\partial c_l}\right)_{\delta_f, \delta_t}$ | .020 | .035 | .020 | .030 |
| $\left(\frac{\partial c_m}{\partial c_l}\right)_{\alpha_0, \delta_t}$ | -.160 | -.168 | -.155 | -.170 |

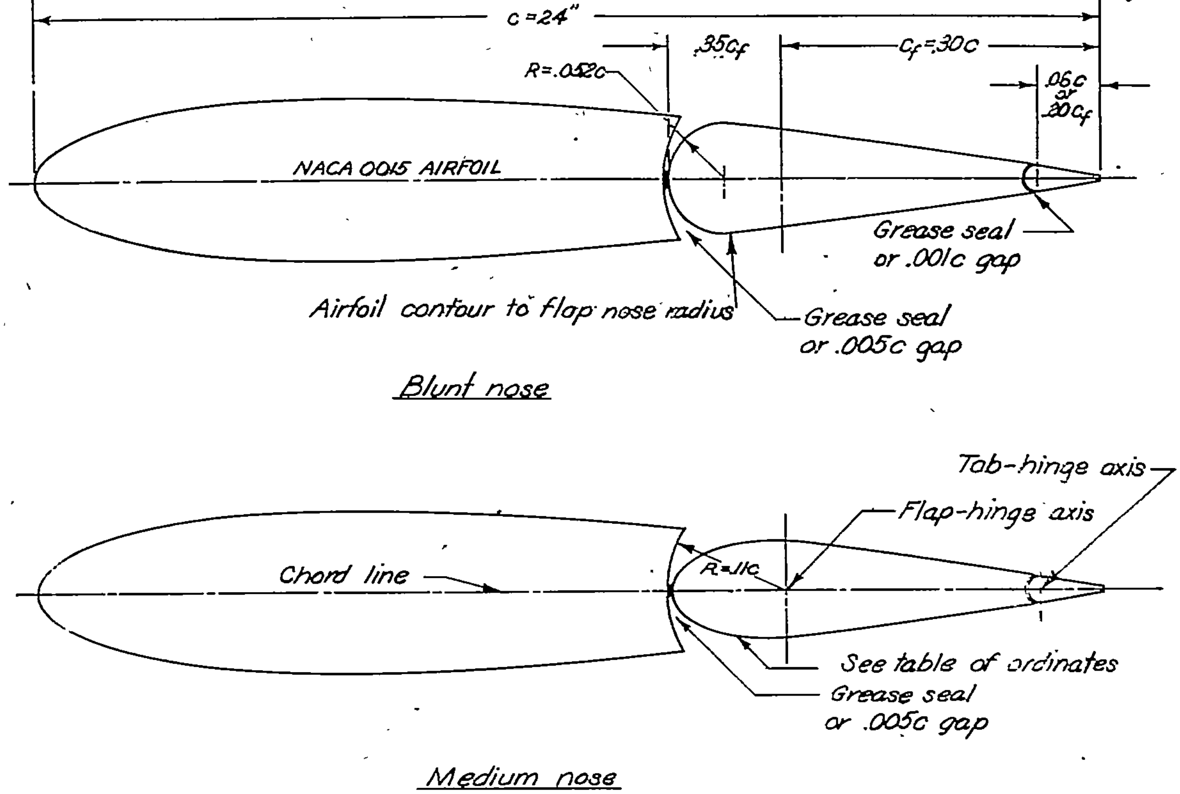



Figure 1.- Nose shapes for a 0.30c flap with 0.35$c_f$ overhang on an NACA 0015 airfoil.

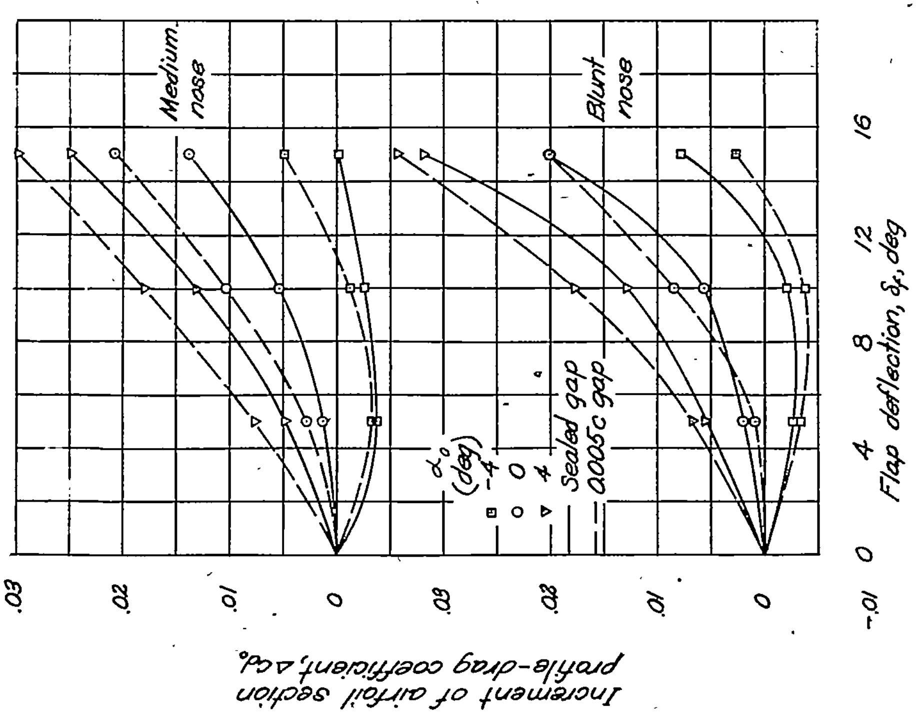
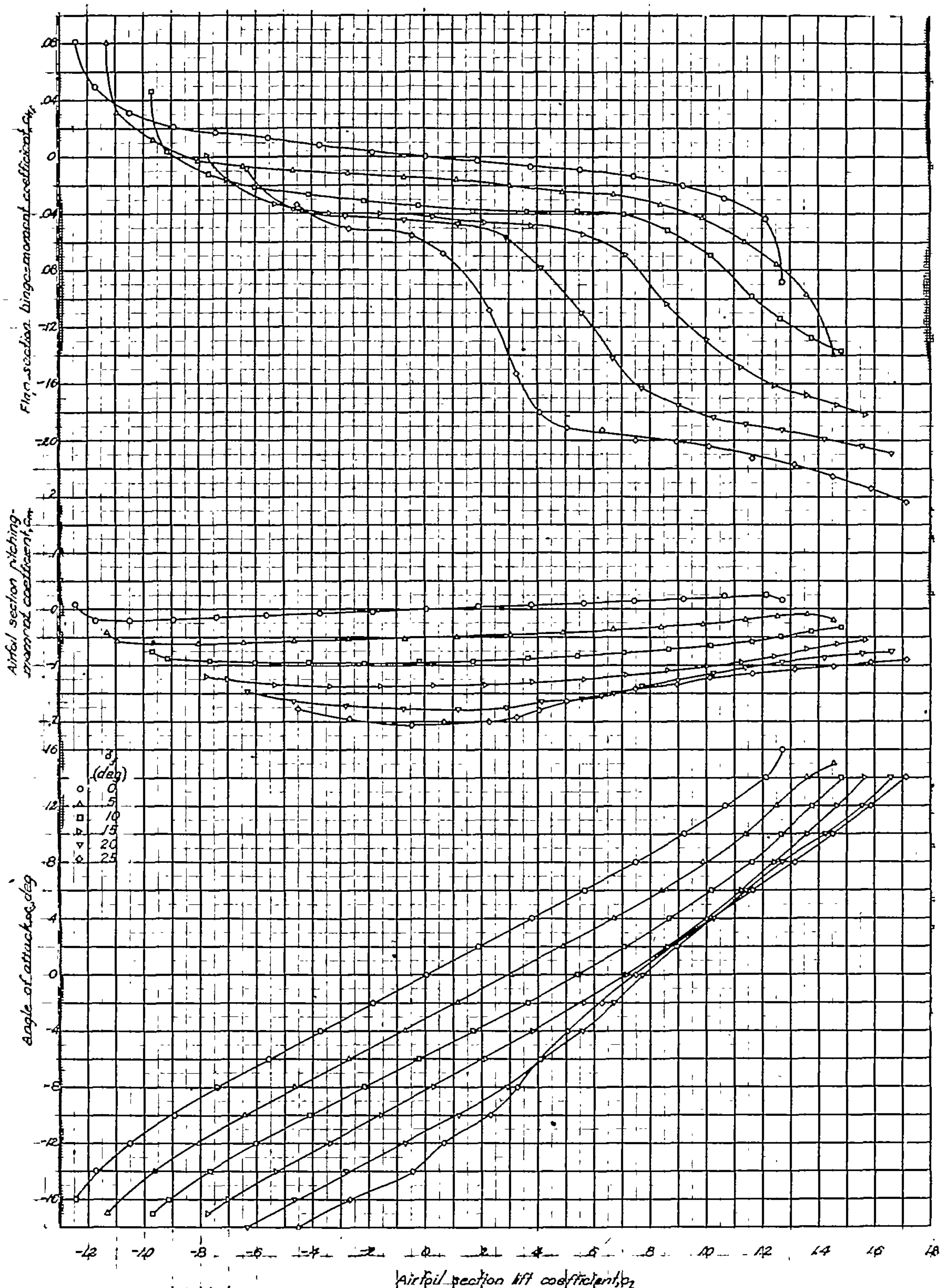



Figure 4.- Increment of airfoil section profile-drag coefficient caused by deflection of a 0.30c flap with 0.35$c_f$ overhang with blunt and medium nose and with sealed and 0.005c gap.




(a) Sealed gap.

Figure 2.- Aerodynamic section characteristics of an NACA 0015 airfoil with a 0.30c flap having a 0.50 $c_f$ overhang with blunt nose.

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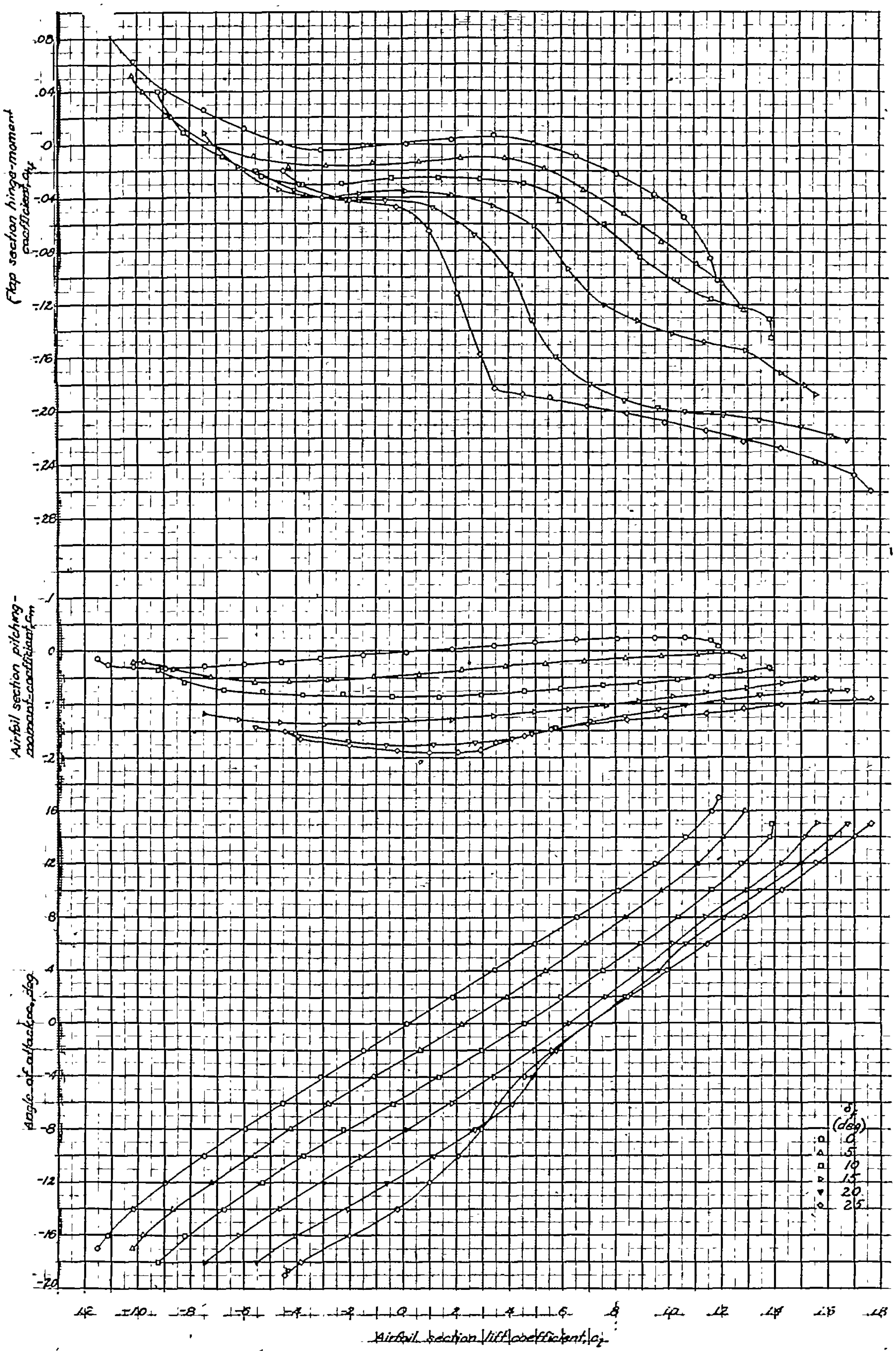
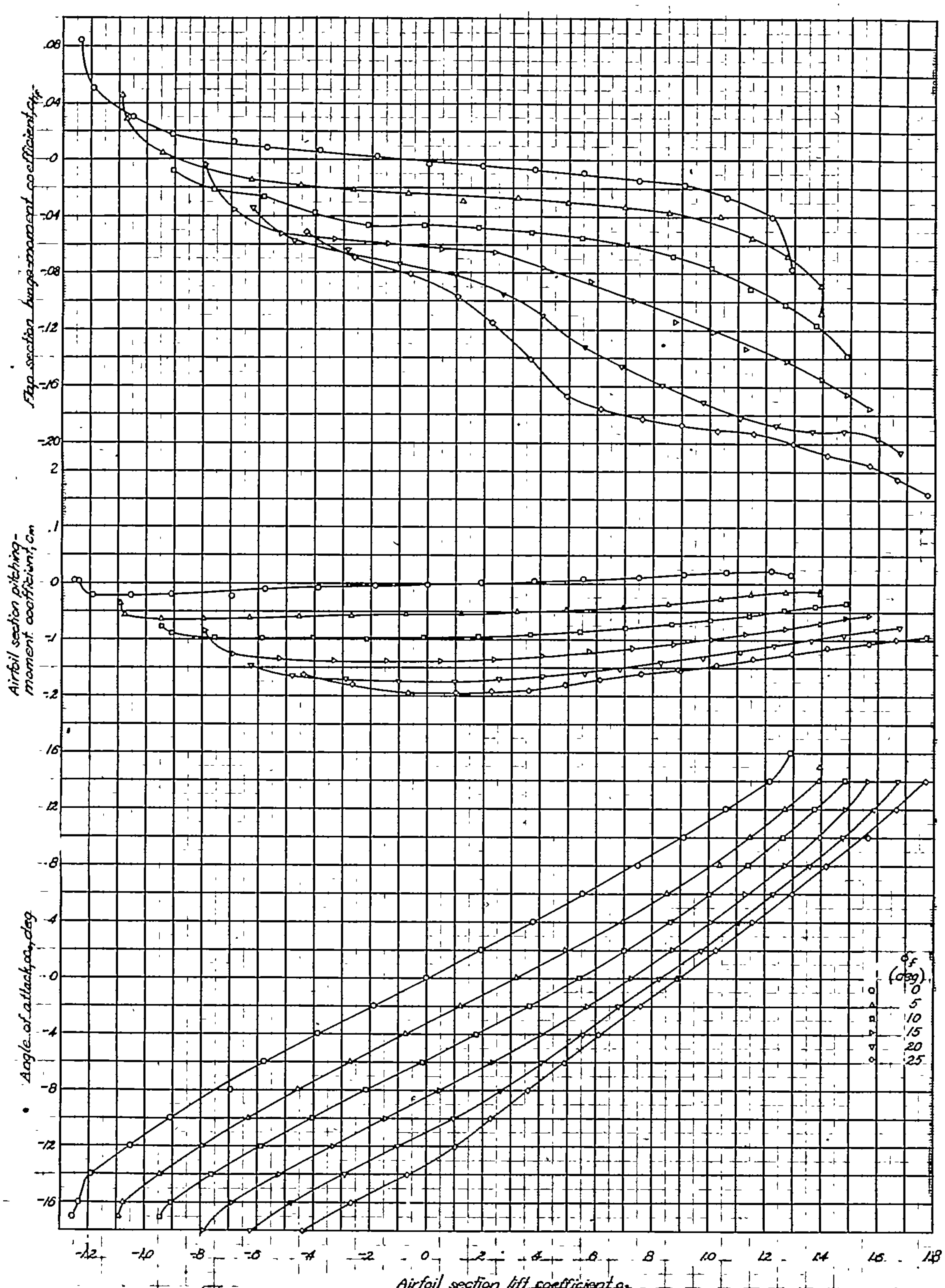
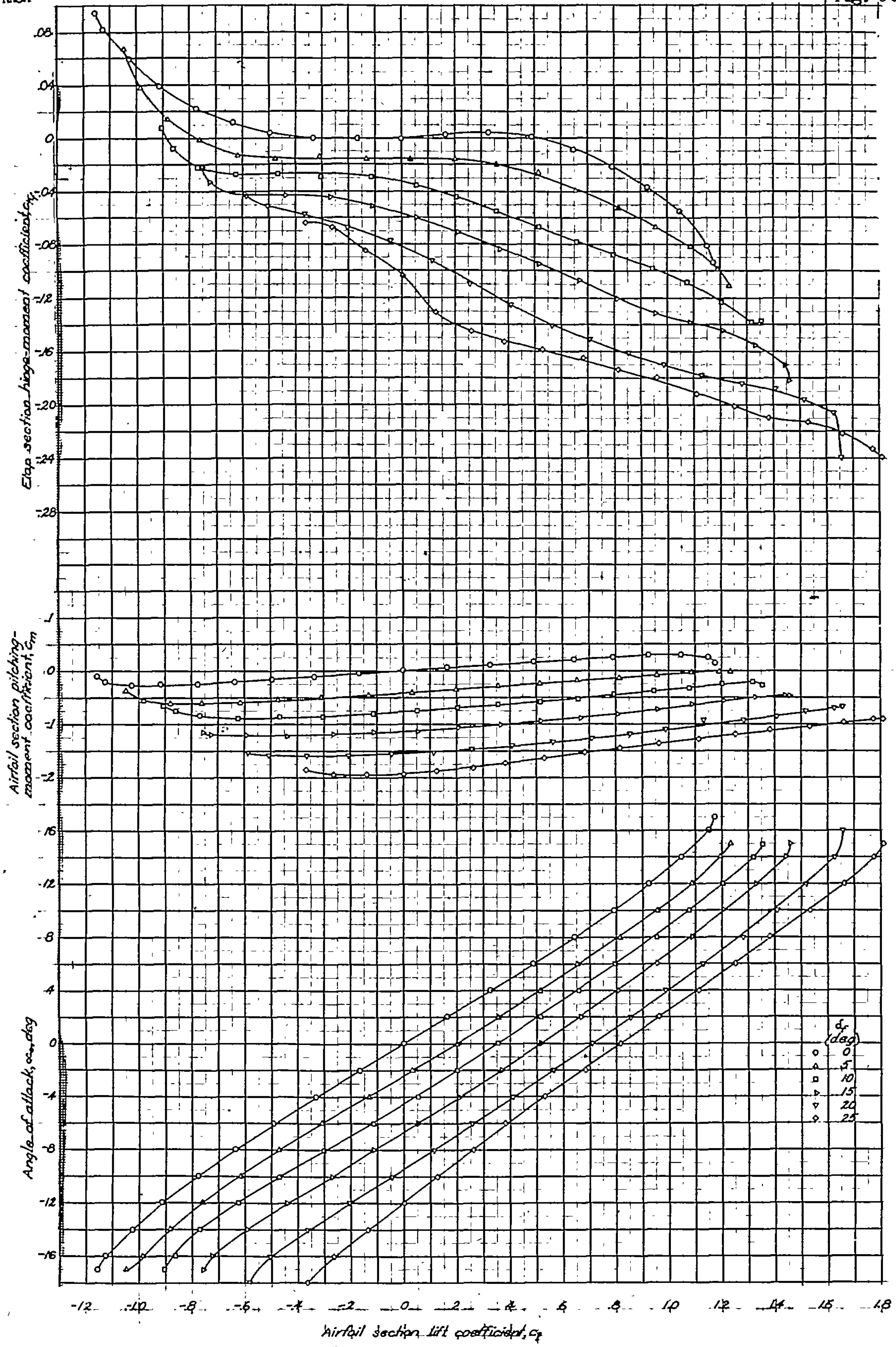



(b) 0.20c flap.
Figure 2.- Concluded.




(a) Sealed gap.

Figure 3.— Aerodynamic section characteristics of an NACA 0015 airfoil with a 0.30c flap having a 0.35$c_f$ overhang with medium nose.




(b) 0.005c gap.
Figure 3.- Concluded.

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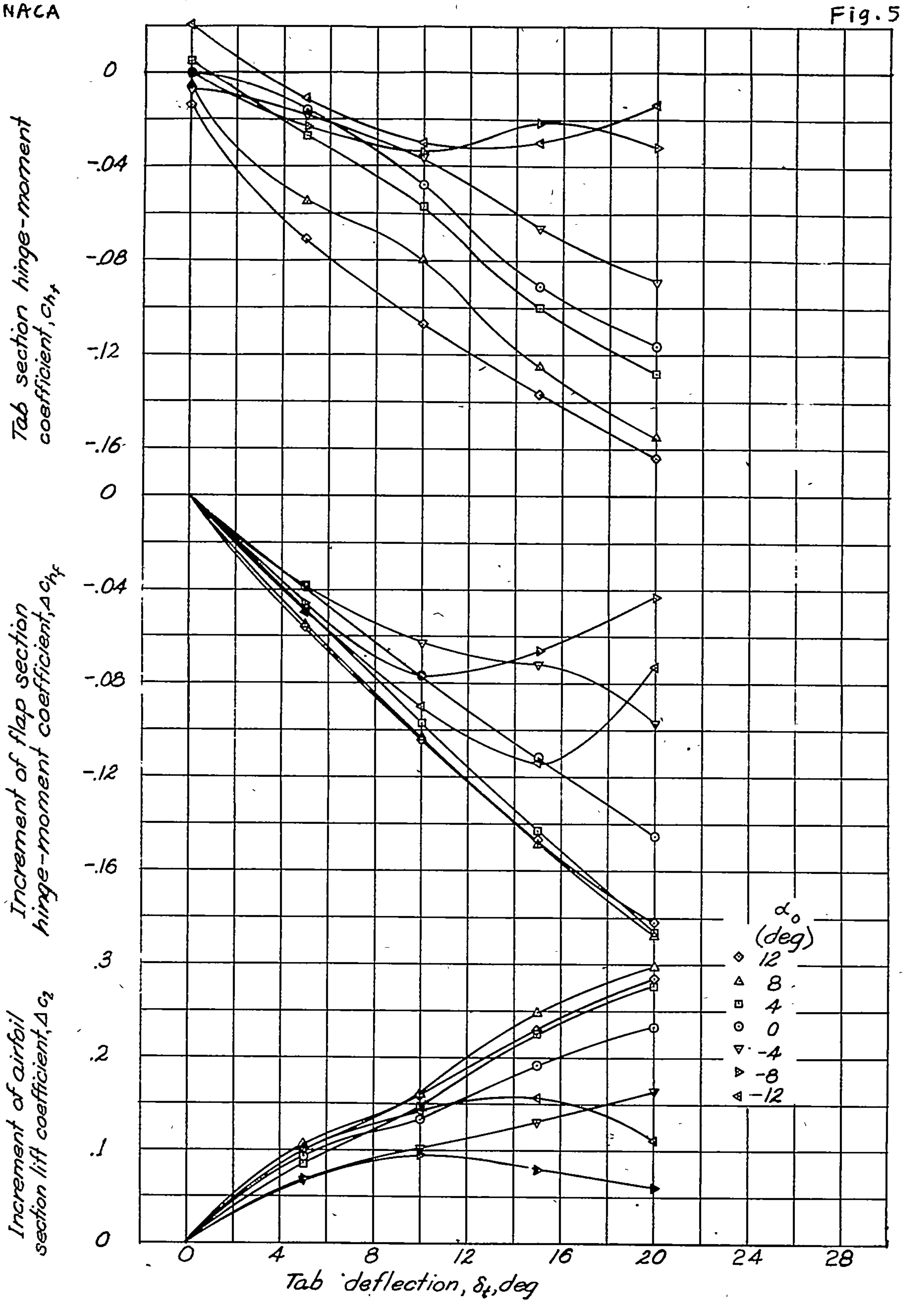


Figure 5 - Tab section hinge-moment coefficient and increments of airfoil section lift coefficient and flap section hinge-moment coefficient caused by deflection of a 0.20$c_f$ plain tab. Blunt nose 0.35$c_f$ overhang with 0.005c gap. $\delta_f$=0°.

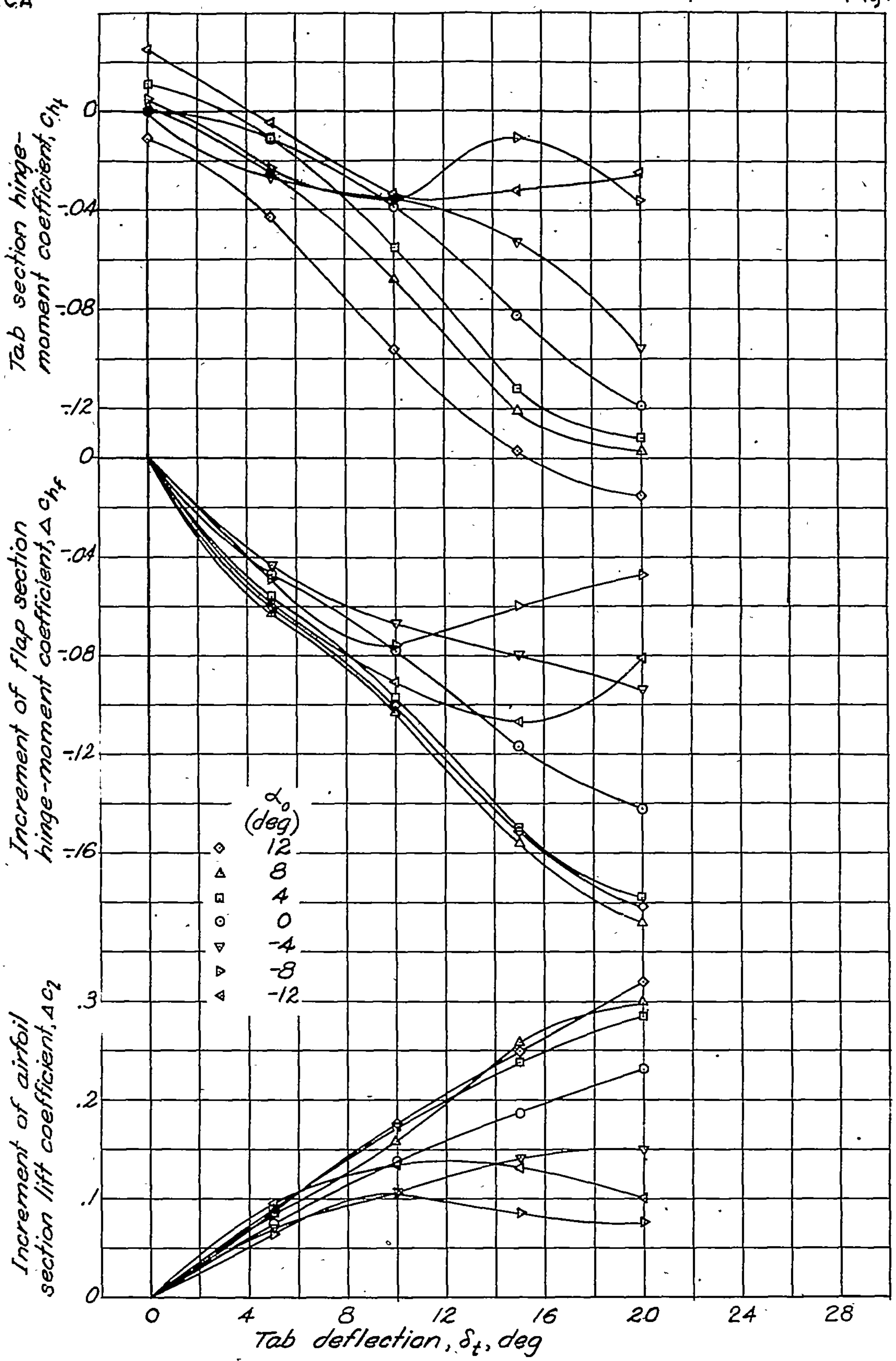


Figure 6 – Tab section hinge-moment coefficient and increments of airfoil section lift coefficient and flap section hinge-moment coefficient caused by deflection of a 0.20 $c_f$ plain tab. Medium nose 0.35$c_f$ overhang with 0.005 c gap. $\delta_f = 0°$