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WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

IX - SOME ANALYTICAL CONSIDERATIONS AND EXPERIMENTAL TEST RESULTS FOR AN INTERNALLY BALANCED FLAP

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ADVANCE RESTRICTED REPORT

WIND-TUNNEL INVESTIGATION OF CONTROL-SURFACE CHARACTERISTICS

IX - SOME ANALYTICAL CONSIDERATIONS AND EXPERIMENTAL TEST RESULTS FOR AN INTERNALLY BALANCED FLAP

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SUMMARY

An analysis has been made to determine the probable aerodynamic section characteristics of a plain flap with various arrangements of an internal balance. Tests in two-dimensional flow have been made in the NACA 4- by 6-foot vertical tunnel of an NACA 0009 airfoil with an internally balanced flap in order to check the validity of the analytical calculation. The results of these tests, presented in this paper, indicate that the calculations are in agreement with experiment. The analysis has been extended on the basis of the lifting-line theory to include an approximate method for the design of an internal balance for a control surface of finite span.

The present investigation indicates that an internal balance is an aerodynamically desirable means of controlling the magnitude and the direction of the rate of change of flap hinge moment with angle of attack and with flap deflection. Because the internal balance is entirely concealed within the airfoil contour, the lift, the drag, and the pitching-moment characteristics of the control surface are in no way affected by the presence of the balancing surface. Analytical considerations indicate that a full-span balancing tab actuated by an internal balance should prove to be a feasible method of reducing control forces.

INTRODUCTION

The desirability of reducing the hinge moments of airplane control surfaces has long been apparent. The reduction of control-surface hinge moments should preferably be accomplished in such a manner as to improve and not to impair the flying qualities of the airplane. In an effort to solve this problem, the NACA is conducting an extensive investigation of the aerodynamic characteristics of control surfaces. The main objectives of this investigation are to arrive at a rational method for the design of airplane control surfaces, to determine the type of flap arrangements best suited for use as control surfaces, and to supply experimental data for design purposes.

Several years ago the NACA made measurements in two-dimensional flow of the pressure distribution on an NACA 0009 airfoil with plain flaps of various chords. The results of these tests are reported in references 1, 2, and 3. The pressure-distribution records of these tests have been analyzed to determine the possible characteristics of a flap with an internal balance. The internal balance is a mechanism by which the pressure difference between two points on the airfoil is used to act upon a flat plate or similar device entirely enclosed within the airfoil profile and thus to do work in deflecting the control surface. By the proper location of vents on the airfoil surface, it was found to be theoretically possible to vary independently the flap hinge-moment parameters to any desired magnitude and to provide the control surface with any desired initial hinge moment at 0° angle of attack and flap deflection.

The present paper presents a theoretical analysis of the characteristics of an internal balance and a method of calculating the physical characteristics of such a balancing device to give any desired section hinge-moment characteristics to a control surface. In order to check the analytical calculations, tests of an internally balanced flap have been made in two-dimensional flow and the results of these tests are discussed. The application of internal balance to tabs is briefly treated.

SYMBOLS

The symbols used in this paper are:

C_L airfoil lift coefficient (L/qS)

c_l airfoil section lift coefficient $(l/qc = dL/qcdb)$

C_h flap hinge-moment coefficient $(H/q\overline{c}_f S_f)$

c_h flap section hinge-moment coefficient

$$\left(h/qc_f^2 = \frac{dH}{qc_f^2 db}\right)$$

c_m airfoil section pitching-moment coefficient

$$\left(m/qc^2 = \frac{dM}{qc^2 db}\right)$$

P resultant pressure coefficient $\left(\frac{p_u - p_l}{q}\right)$

L airfoil lift

l airfoil section lift (dL)

H flap hinge moment

h flap section hinge moment (dH)

M airfoil pitching moment

m airfoil section pitching moment (dM)

S airfoil area

S_f flap area

c chord of airfoil section

c_f chord of flap measured at airfoil section from hinge axis to trailing edge of airfoil

$\overline{c}_f$ root-mean square chord of flap

c_b chord of balancing plate

q dynamic pressure of free air stream

p_u static pressure at point on upper surface of airfoil

p_l static pressure at corresponding point on lower surface of airfoil

α angle of attack

α_0 angle of attack for infinite aspect ratio

δ deflection of flap with respect to airfoil

b span of surface

x chordwise location of vent measured from airfoil nose

R nose radius of flap

k constant defining size of balancing plate

$c_{l_{a1}}$ span-load-distribution factor

$c_{l_{b1}}$ span-load-distribution factor

A aspect ratio

$$c_{h_\alpha} = \left(\frac{\partial c_h}{\partial \alpha}\right)_\delta = \left(\frac{\partial c_h}{\partial \alpha_2}\right)_\delta = c_{h_{\alpha_2}}$$

$$c_{h_\delta} = \left(\frac{\partial c_h}{\partial \delta}\right)_{\alpha_0} = \left(\frac{\partial c_h}{\partial \delta_2}\right)_{\alpha_0} = c_{h_{\delta_2}}$$

$$C_{L_\alpha} = \left(\frac{\partial C_L}{\partial \alpha}\right)_\delta = \left(\frac{\partial C_L}{\partial \alpha_3}\right)_\delta = C_{L_{\alpha_3}}$$

$$c_{l_\alpha} = \left(\frac{\partial c_l}{\partial \alpha_0}\right)_\delta = \left(\frac{\partial c_l}{\partial \alpha_2}\right)_\delta = c_{l_{\alpha_2}}$$

$$c_{l_{\alpha_3}} = c_{l_{a1}} \left(\frac{\partial C_L}{\partial \alpha_3}\right)_\delta = c_{l_{a1}} C_{L_{\alpha_3}}$$

$$C_{L_\delta} = \left(\frac{\partial C_L}{\partial \delta}\right)_\alpha = \left(\frac{\partial C_L}{\partial \delta_3}\right)_\alpha = C_{L_{\delta_3}}$$

$$c_{l_\delta} = \left(\frac{\partial c_l}{\partial \delta}\right)_{\alpha_0} = \left(\frac{\partial c_l}{\partial \delta_2}\right)_{\alpha_0} = c_{l_{\delta_2}}$$

$$c_{l_{\delta_3}} = c_{l_{b1}} \left(\frac{\partial C_L}{\partial \delta_3}\right) = c_{l_{b1}} C_{L_{\delta_3}}$$

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$$\left(c_{m_{c_l}}\right)_{\delta} = \left(\frac{\partial c_m}{\partial c_l}\right)_{\delta}$$

$$\left(c_{m_{c_l}}\right)_{\alpha} = \left(\frac{\partial c_m}{\partial c_l}\right)_{\alpha_o}$$

$$P_{\alpha_2} = \left(\frac{\partial P}{\partial \alpha_2}\right)_{\delta}$$

$$P_{\alpha_3} = \left(\frac{\partial P}{\partial \alpha_3}\right)_{\delta}$$

$$P_{\delta_2} = \left(\frac{\partial P}{\partial \delta_2}\right)_{\alpha_o}$$

$$P_{\delta_3} = \left(\frac{\partial P}{\partial \delta_3}\right)_{\alpha_o}$$

$$\left(P_{c_l}\right)_{\delta} = \left(\frac{\partial P}{\partial c_l}\right)_{\delta}$$

$$\left(P_{\delta}\right)_{c_l} = \left(\frac{\partial P}{\partial \delta}\right)_{c_l}$$

Subscripts:

0 initial force and moment at angle of attack of 0° and flap deflection of 0°

i induced angle

2 characteristics in two-dimensional flow

3 characteristics in three-dimensional flow

f flap characteristics

b balancing-surface characteristics

Subscripts outside parentheses around partial derivatives indicate the variables held constant when the derivatives are taken.

Prime indicates effective value for flap and balancing-surface combinations. The term "flap" refers to the movable part of the control surface behind the hinge axis (rudder, elevator, or aileron).

ANALYSIS OF INTERNAL BALANCE IN TWO-DIMENSIONAL FLOW

An internal balance consists essentially of a flat plate enclosed in a sealed chamber within the airfoil (fig. 1). The plate is connected to the flap surface either directly as in figure 1(a) or by a linkage system as in figures 1(b) and 1(c). The free edges of the plate are sealed by a suitable means to the walls of the chamber in such a way that the static pressures at corresponding points on the upper and lower surfaces of the airfoil, admitted through vents, act on opposite sides of the plate. The resulting force on the flat plate causes a moment that tends to balance the aerodynamic hinge moment of the flap. The hinge-moment characteristics of the flap can be controlled by varying the location of the vents and the size of the balancing plate. The calculation of the section characteristics of a flap with an internal balance is described in the following analysis.

The distribution of pressure normal to the airfoil surface has been experimentally measured in two-dimensional flow for the NACA 0009 airfoil with plain flaps (references 1, 2, and 3). From a study of the pressure-distribution diagrams obtained in these investigations, it has been experimentally determined that the variation of pressure at any point on the airfoil surface is a linear function of both angle of attack and flap deflection. The range of linear variation, of course, is terminated by separation phenomena.

The rate of change of resultant pressure coefficient with angle of attack P_{α_2} and with flap deflection P_{δ_2} is plotted as a function of chordwise position in figure 2 for the NACA 0009 airfoil with a 0.30c, a 0.50c, and an 0.80c plain flap with sealed gap at the flap nose. Because of separation phenomena, the variation of P with α_2 has the slope P_{α_2} only within the limits $\alpha_2 = \pm 10^{\circ}$ and the variation of P with δ_2 has the slope P_{δ_2} only within $\delta_2 = \pm 10^{\circ}$.

The section hinge-moment coefficient of a flap equipped with an internal balance may be expressed as

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$$c_h = c_{h_o} + c_{h_\alpha}{}' \alpha + c_{h_\delta}{}' \delta \tag{1}$$

where

$$\left.\begin{aligned} c_{h_\alpha}{}' &= c_{h_\alpha} + kP_{\alpha_2} \\ \text{and} \qquad c_{h_\delta}{}' &= c_{h_\delta} + kP_{\delta_2} \end{aligned}\right\} \tag{2}$$

With the hinge-moment parameters c_{h_α} and c_{h_δ} of the flap to be balanced and the desired parameters $c_{h_\alpha}{}'$ and $c_{h_\delta}{}'$ for the balanced flap known, the required values of P_{α_2} and P_{δ_2} can be computed. The vent location that gives these rates of change of pressure can then be picked from the curves of figure 2. The physical dimensions of the balancing plate and the mechanical advantage of the linkage system that connects the plate to the flap are determined by the factor k which can be evaluated from equation (2):

$$\frac{P_{\alpha_2}}{P_{\delta_2}} = \frac{kP_{\alpha_2}}{kP_{\delta_2}} = \frac{c_{h_\alpha}{}' - c_{h_\alpha}}{c_{h_\delta}{}' - c_{h_\delta}} \tag{3}$$

In order to locate the proper vent, it is convenient to plot the ratio $P_{\alpha_2}/P_{\delta_2}$ as a function of chordwise position. The vent location that gives the ratio $P_{\alpha_2}/P_{\delta_2}$ calculated from equation (3) can be determined from this curve, which can be plotted from the data presented in figure 2.

The size of balancing plate required depends upon the type of motion the plate undergoes as the flap is deflected. If the plate is hinged along one edge, the size of plate required to do a given amount of work in balancing the flap will be twice as great as that required if the plate is allowed to move as a piston. In either case the size of plate required is determined by the factor k. After the vent locations have been determined, the values of P_{α_2} and P_{δ_2} are known and k can be evaluated from equation (2). Thus

$$k = \frac{c_{h_\alpha}' - c_{h_\alpha}}{P_{\alpha_2}} = \frac{kP_{\alpha_2}}{P_{\alpha_2}} \tag{4}$$

For a rectangular flat plate hinged at one edge, the moment about the hinge caused by a uniformly distributed pressure is

$$\frac{Pc_b{}^2 b_b}{2} q = kPc_f{}^2 b_f q$$

This quantity multiplied by the mechanical advantage $\partial\delta_f/\partial\delta_b$ of the connecting linkage is the balancing moment supplied to the flap. The size of the balancing plate in terms of the flap chord is, therefore,

$$\frac{c_b}{c_f} = \sqrt{2k \frac{b_f}{b_b} \frac{\partial\delta_f}{\partial\delta_b}} \tag{5}$$

If the vent on the upper surface is located at a different airfoil station from that of the vent on the lower surface, the internal balance will cause the flap to have an initial hinge-moment coefficient c_{h_o} at an angle of attack and a flap deflection of 0°. In this manner the internal balance can be designed to supply the flap with an initial floating tendency.

A series of calculations has been made to illustrate the possibilities of the internal balance as a means of regulating the hinge-moment parameters of a control surface. The resultant pressure characteristics for the NACA 0009 airfoil in two-dimensional flow as presented in figure 2 were used as the bases of the calculations, and the results for the 0.30c and the 0.50c flap are given in figure 3. The application of the analysis already derived is illustrated by the following example worked out for one particular point on the curves of figure 3: The hinge-moment parameters c_{h_α} and c_{h_δ} for the 0.30c plain flap

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on the NACA 0009 airfoil can be found by taking the moment about the 0.70c station of the areas under the curves of $P_{\alpha_2} = f_1(x/c)$ and $P_{\delta_2} = f_2(x/c)$ in figure 2. For the unbalanced flap, $c_{h_\alpha} = -0.0075$ and $c_{h_\delta} = -0.0130$. The vent locations and the length of the balancing plate required to make $c_{h_\alpha}' = 0$ and $c_{h_\delta}' = 0$ may be calculated from equation (3)

$$\frac{P_{\alpha_2}}{P_{\delta_2}} = \frac{0 - (-0.0075)}{0 - (-0.0130)} = 0.577$$

Figure 2 shows that $P_{\alpha_2}/P_{\delta_2}$ has the calculated value of 0.577 at $x/c = 0.66$. The vents should be located, therefore, at this station. The required length of the balance plate can be found from the factor k. From equation (4),

$$k = \frac{0 - (-0.0075)}{0.047} = 0.160$$

From equation (5), for $b_b = b_f$ and $\partial\delta_f/\partial\delta_b = 1$

$$\frac{c_b}{c_f} = \sqrt{2(0.160)\ (1)\ (1)} = 0.56$$

The section hinge-moment characteristics for 0.30c and 0.50c flaps on the NACA 0009 airfoil were computed, for various arrangements of internal balance (fig. 1(b)), to make $c_{h_\alpha}' = c_{h_\alpha}/2$, 0, and $-c_{h_\alpha}/2$. The length of the balancing plate required to give the specified values of c_{h_α}' and the resulting values of c_{h_δ}' are plotted as functions of vent location in figure 3. The mechanical advantage of the system is unity.

An inspection of figures 2 and 3 together indicates that small values of c_{h_δ}' may be obtained by locating the vents near the flap hinge axis because in this region the rate of change of resultant pressure with flap deflection is large. The size of balancing plate required for a given value of c_{h_δ}' will decrease, therefore, as the vent location approaches the hinge axis. Conversely, small values of c_{h_α}' without much reduction in c_{h_δ}' may be obtained by locating the vents near the airfoil nose because the size of balancing plate required for a given value of c_{h_α}' decreases as the vent location approaches the airfoil nose. Comparable amounts of balance are obtained for the 0.30c and the 0.50c flap by balancing plates of practically the same size relative to the size of the flap and by practically the same location of the vent with respect to the hinge axis. For either flap, therefore, a balancing plate approximately $0.50c_f$ long with vents located approximately $0.15c_f$ ahead of the hinge axis is required to reduce both c_{h_α}' and c_{h_δ}' to zero.

EXPERIMENTAL VERIFICATION

Apparatus, Model, and Tests

Tests of a model wing with an internally balanced flap have been made in the NACA 4- by 6-foot vertical tunnel in order to check the validity of the theoretical analysis. This tunnel, described in reference 4, has been modified for tests 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 can be made. The hinge moment of the flap was measured by an electrical strain gage built into the model.

The 2-foot-chord by 4-foot-span model (fig. 4) was made of laminated mahogany to the NACA 0009 profile (table I). It was equipped with an internally balanced flap having a chord 30 percent of the airfoil chord. The internal balance consisted of a full-span flat plate $0.41c_f$ in length and fastened rigidly to the flap. The plate was attached to the flap in such a way that when the flap was neutral the plate was deflected down 13.5°. With this installation the flap could be deflected 24° positively. The edges of the plate were sealed to the walls of the balancing chamber by a rubber sheet. At the 0.56c station a series of holes 1/8 inch in diameter (0.0052c) spaced spanwise 5/16 inch ($2\frac{1}{2}$ diam.) on centers were drilled through the upper and lower surfaces of the airfoil to serve as vents. For a part of the tests, the gap between the airfoil and the nose of the flap was sealed with a light grease.

For other tests, the vent location was moved back near the hingo axis, to $x/c = 0.69$, by removing the grease that filled the gap and by sealing the original vents with scotch tape.

Because the model completely spanned the tunnel, two-dimensional flow was approximated. The tests were made at a dynamic pressure of 15 pounds per square foot corresponding at standard sea-level conditions to an air velocity of about 76 miles per hour and a test Reynolds number of 1,430,000. Lift, drag, pitching moment, and flap hinge moment were measured for each flap deflection throughout the angle-of-attack range from positive to negative stall of the airfoil in 2° increments of angle of attack. Tests were made at flap deflections of 0°, 1°, 2°, 5°, 10°, 15°, 20°, and 24° with the forward location of the vent. The outer 25 percent of the vents at each end of the span were then sealed and tests were made at flap deflections of 0° and 10°. With the vent located near the hinge axis, tests were made at flap deflections of 0°, 5°, 10°, 15°, 20°, and 23.5°.

Procision

The maximum error in the angle of attack or in flap setting appears to be about $\pm 0.2^{\circ}$. An experimentally determined tunnel correction has been applied only to lift. The hinge moments, therefore, are probably slightly higher than would be obtained in free air. Because of an unknown tunnel correction, values of drag coefficient should not be considered absolute; the relative values, however, are generally independent of tunnel effect.

Computed Characteristics of Flap Tested

The balancing plate was rigidly fastened to the flap in such a way that the flap nose formed the rear wall of the balancing chamber (fig. 4). The predicted characteristics of figure 3, therefore, do not strictly apply for this particular type of installation. Because the pressure in both sides of the balancing chamber acts uniformly on all walls of the chamber and because one wall of the chamber was the flap itself, the balancing moment must be calculated to include the moment of the force on the flap nose. The forward edge of the balancing plate was sealed to the forward wall of the chamber by a rubber sheet. For a properly designed seal, therefore, half the force on this seal may be considered as being transmitted to the flap as a balancing moment. For the type of installation tested, with the dimensions shown in figure 4, the balancing moment is

$$Pc_b(R + c_b/2)b_bq = kPc_f^2 b_f q$$

Therefore, because $b_b = b_f$

$$k = \frac{c_b(R + c_b/2)}{c_f^2} = \frac{2.945(0.680 + 2.945/2)}{(7.200)^2} = 0.122$$

With the forward location of the vent, at $x/c = 0.56$, from figure 2

$$P_{\alpha_2} = 0.062$$
$$P_{\delta_2} = 0.060$$

The hinge-moment parameters of the plain unbalanced flap are, from reference 5,

$$c_{h_\alpha} = -0.0070$$
$$c_{h_\delta} = -0.0120$$

These values are slightly less than those measured in the pressure-distribution investigation (reference 1) but, because the chord of the model of reference 5 was smaller (2 ft instead of 3 ft) possible tunnel effects are smaller than for reference 1 and therefore these values are considered more accurate.

From equation (2), the computed characteristics of the internally balanced flap tested are

$$c_{h_\alpha}' = (-0.0070) + (0.122)(0.062)$$
$$= 0.0006$$

$$c_{h_\delta}' = (-0.0120) + (0.122)(0.060)$$
$$= -0.0047$$

Similarly, with the vent located slightly forward of the hinge axis, at $x/c = 0.69$,

$$P_{\alpha_2} = 0.041$$

$$P_{\delta_2} = 0.120$$

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For this vent location, therefore,

$$c_{h_\alpha}' = (-0.0070) + (0.122)\ (0.041)$$
$$= -0.0020$$
$$c_{h_\delta}' = (-0.0120) + (0.122)\ (0.120)$$
$$= 0.0026$$

Experimental Results

The experimentally determined aerodynamic section characteristics of an internally balanced flap on the NACA 0009 airfoil are presented as functions of airfoil section lift coefficient in figure 5 for two vent locations. The values of certain aerodynamic parameters measured from the data presented by the curves of figure 5 are listed in table II. The effect on the aerodynamic section characteristics of sealing the outer 25 percent of the forward vent holes at each end of the span is shown for flap deflections of 0° and 10° by the dashed curves in figure 5(a).

The lift, the drag, and the pitching-moment characteristics of the internally balanced flap were the same as those for the plain, unbalanced flap of the same chord on the same airfoil (reference 5). This result is to be expected because the air flow over the airfoil is not disturbed in any way by the presence of the balancing device.

The computed hinge-moment characteristics are in remarkably good agreement with the experimentally determined characteristics. A comparison of the measured and the computed hinge-moment parameters is made in table II. With the forward vent location, at $x/c = 0.56$, the slope c_{h_α}' was nearly the same for all flap deflections tested; whereas with the conventional inset-hinge type of aerodynamic balance c_{h_α} generally increases negatively as the flap is deflected. The hinge-moment characteristics were not affected appreciably by sealing the outer 25 percent of the vents at each end of the span. Because, at 0° and 10° flap deflection, the curves $c_h = f(c_l)_\delta$ did not change slope when the outer vents were sealed the slight change in c_{h_δ}' can probably be attributed to experimental error.

The flap was overbalanced at deflections less than 10° when the vent was located near the hinge axis, at $x/c = 0.69$, (fig. 5(b)). The flap with this arrangement of internal balance will require the use of a leading, that is, unbalancing, tab in order to give satisfactory characteristics. The magnitude of overbalancing moment was not so great as that predicted from analytical considerations.

It should be noted that the experimental tests reported in this paper were made for steady-state attitudes of the model and no attempt was made to investigate possible lag effects or damping caused by the rate of change of the angle of attack or the flap deflection. The determination of the optimum size of vent for minimum lag and for proper damping are subjects for future investigations.

THEORETICAL APPLICATION OF INTERNAL BALANCE

TO CONTROL SURFACES OF FINITE SPAN

The spanwise as well as the chordwise distribution of resultant normal pressure over the surface of the wing must be known in order to calculate the vent locations and the size of balancing plate required to balance a control surface of finite span. Unfortunately, because the lifting-line theory assumes the induced downwash to be constant along the chord, the chordwise distribution of resultant pressure at a section of a wing in three-dimensional flow cannot be accurately computed by the application of theoretical aspect-ratio corrections based on the lifting-line theory to the chordwise distribution of resultant pressure for a wing in two-dimensional flow. Until the lifting-surface theory provides an adequate method for the computation of chordwise distribution of resultant pressure at any section of a wing of finite aspect ratio or until empirical correction factors are experimentally determined for the existing lifting-line theory, the pressure distribution and hence the hinge-moment characteristics of control surfaces of finite span cannot be accurately estimated from two-dimensional-flow data. A research program to correlate two- and three-dimensional-flow aerodynamic characteristics both theoretically and experimentally is being conducted by the NACA.

Section data, corrected according to the lifting-line theory, can serve as a first approximation for the calculation of the hinge-moment characteristics of a finite-span control surface with an internal balance. An internal balance for a finite control surface may be designed from the pressure-distribution diagrams for two-dimensional flow corrected in the manner to be indicated in the discussion which follows. If experimental tests of such a balanced surface fail to give quite the desired hinge-moment characteristics, the direction and the order of magnitude of modifications to the internal-balance design can be estimated from the available pressure-distribution diagrams even though they are not exact.

In order to arrive at a first approximation to the variation of resultant pressure coefficient with angle of attack and flap deflection for a wing of finite aspect ratio, the span-load distribution should be computed. From the tables presented in references 6 and 7, for wings of various aspect ratios and taper ratios, the section lift coefficient c_l at any spanwise station can be computed in terms of the characteristics of the complete wing. Thus, at any section of a wing,

$$c_l = c_{l_{a1}} C_{L_{\alpha_3}} \alpha_3 + c_{l_{b1}} C_{L_{\delta_3}} \delta_3$$

Therefore

$$c_{l_{\alpha_3}} = c_{l_{a1}} C_{L_{\alpha_3}}$$

and

$$c_{l_{\delta_3}} = c_{l_{b1}} C_{L_{\delta_3}}$$

The terms $c_{l_{a1}}$ and $c_{l_{b1}}$ are span-load distribution factors and can be evaluated from references 6 and 7.

If, in accordance with the lifting-line theory, the induced angle of attack at any section of a wing is assumed constant across the airfoil chord, the aspect-ratio correction to the variation of the resultant pressure distribution with angle of attack is the distribution of pressure caused by the induced angle of attack at the section in question. This correction is illustrated in figure 6. Thus

$$P_{\alpha_3} = P_{\alpha_2} + P_{\alpha_i}$$

Because

$$c_{l_{\alpha_3}} = c_{l_{a1}} \; C_{L_{\alpha_3}} = \int_0^c P_{\alpha_3}\,(x)dx$$

it can be shown that the curve $P_{\alpha_2} = f_1(x/c)$ should be corrected in proportion to the slope of the lift curve to obtain the curve $P_{\alpha_3} = f_3(x/c)$. Thus

$$P_{\alpha_3} = P_{\alpha_2}\frac{c_{l_{\alpha_3}}}{c_{l_{\alpha_2}}}$$

$$= \frac{P_{\alpha_2}}{c_{l_{\alpha_2}}} c_{l_{a1}} \; C_{L_{\alpha_3}}$$

$$= \left(P_{c_l}\right)_\delta \; c_{l_{a1}} \; C_{L_{\alpha_3}}$$

This form of aspect-ratio correction is similar to that discussed in reference 8 for the hinge-moment parameter C_{h_α}.

The variation of resultant pressure distribution with flap deflection should be corrected for aspect ratio by the distribution of pressure caused by the effective induced angle of attack at the section under consideration when the lift is changed by flap deflections. Thus, as illustrated by the curves of figure 6,

$$P_{\delta_3} = P_{\delta_2} + P_{\delta_i}$$

$$= P_{\delta_2} + P_{\alpha_i}\frac{c_{l_{\delta_3}}}{c_{l_{\alpha_3}}}$$

$$= P_{\delta_2} + (P_{\alpha_3} - P_{\alpha_2})\frac{c_{l_{\delta_3}}}{c_{l_{\alpha_3}}}$$

$$= \left(P_\delta\right)_{c_l} + P_{\alpha_3} \frac{c_{l_{\delta_3}}}{c_{l_{\alpha_3}}}$$

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$$= \left(P_\delta\right)_{c_l} + \left(P_{c_l}\right)_\delta c_{l_{b1}} C_{L_{\delta_3}}$$

The final expression for P_{δ_3} is similar to the aspect-ratio correction for the hinge-moment parameter C_{h_δ} (reference 8). The resultant pressure distribution caused by flap deflection can be divided, therefore, into two parts as in figure 7. One part $\left(P_\delta\right)_{c_l} = f_5(x/c)$ is due to camber and, according to the lifting-line theory, is independent of aspect ratio. The other part $\left(P_{c_l}\right)_\delta c_{l_{b1}} C_{L_{\delta_3}} = f_6(x/c)$ is dependent on lift and must be corrected for aspect ratio in the manner indicated; $\left(P_{c_l}\right)_\delta$ is theoretically independent of aspect ratio.

The curves $P_{\alpha_3} = f_3(x/c)$ and $P_{\delta_3} = f_4(x/c)$ for a finite wing can be computed from the curves $P_{\alpha_2} = f_1(x/c)$ and $P_{\delta_2} = f_2(x/c)$ for the airfoil in two-dimensional flow. Such computations, of course, are subject to all the limitations of the lifting-line theory. At best, therefore, the pressure distribution calculated by this method can offer only a first approximation to the actual chordwise distribution of resultant pressure at a section of a finite wing. For small aspect ratios, the effect of induced streamline curvature probably causes considerable discrepancy between the actual and the computed distribution because the parameters $\left(P_{c_l}\right)_\delta$ and $\left(P_\delta\right)_{c_l}$ cease to be independent of aspect ratio.

Once the curves $P_{\alpha_3} = f_3(x/c)$ and $P_{\delta_3} = f_4(x/c)$ have been determined at several spanwise locations, the calculation of the characteristics of the internal balance should be made in the same manner as has been discussed for a model in two-dimensional flow. Thus it should be possible to calculate the size of the balancing plate and the vent location that give any desired hinge-moment parameters to a control surface of finite span.

As a part of the NACA wind-tunnel investigation of control surfaces, experimental tests are scheduled to check the proposed method of making design calculations for an internally balanced control surface of finite span. The experimental tests of an internally balanced flap in two-dimensional flow have shown good agreement with the calculations for a control surface of infinite aspect ratio. The tests in two-dimensional flow can serve, therefore, to indicate the direction in which the vent location should be moved on a control surface of finite span if the calculated location should fail to give the desired hinge-moment characteristics. The vent location should be moved toward the leading edge of the airfoil to decrease c_{h_α}' and should be moved toward the flap hinge axis to decrease c_{h_δ}'. The magnitude of the balancing moment may be varied by altering the size of the balancing plate. This procedure does not change the ratio of the balancing moment proportional to the angle of attack and the balancing moment proportional to the control-surface deflection.

PROPOSED APPLICATION TO BALANCING TABS

One possible use of internal balance that is worth noting is its application to balancing tabs. A full-span balancing tab is a powerful device for reducing the hinge moments of a control surface provided that the tab can be deflected as a function of angle of attack as well as of flap deflection. It is therefore proposed to provide a control surface with a full-span balancing tab actuated by an internal balance to govern the rate of tab deflection with angle of attack and with flap deflection. If the flap is provided with a moderate nose overhang, the amount of work the tab must do to balance the flap is reduced and a tab of small chord that operates well within the linear range may be used. The internal balance, because it has only to augment the tab hinge moments, can be made small and compact and most probably in the form of a piston and cylinder. The principal objection to an internal balance, size, can therefore be largely overcome.

Calculations indicate that with the type of installation described, the tab would float freely in such a manner

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that the hinge moments would be reduced, the pilot's control being attached directly to the flap. If the internally balanced tab is arranged to float in such a way that $C_{h_{f_{\alpha}}}$ is positive, $C_{h_{f_{\delta_f}}}$ is negative, and the pilot's control effects a trim setting to the balancing tab, the system becomes the equivalent of a servocontrol system that has a tendency to float against the relative wind.

The application of an internal balance to tabs became apparent in the study of the characteristics of the internal balance and it is mentioned in this paper only as a possible application of the device. The detailed characteristics of such a system are beyond the scope of this paper and remain a subject for further investigation.

CONCLUSIONS

The theoretical analysis presented in this paper and the experimental results of tests in two-dimensional flow of an internally balanced flap on an NACA 0009 airfoil indicate the following conclusions:

1. An internal balance is a feasible and an aerodynamically desirable means of controlling the magnitude and the direction of the rate of change of flap hinge moment with angle of attack and with flap deflection.

2. Section hinge-moment parameters calculated for an internally balanced flap from experimentally determined pressure-distribution diagrams are in satisfactory agreement with parameters measured experimentally on a model in two-dimensional flow.

3. Experiment indicates that because the internal balance is entirely concealed within the airfoil contour, the lift, the drag, and the pitching-moment characteristics of the control surface are in no way affected by the presence of the balancing surface.

4. Section data, corrected for aspect ratio according to the lifting-line theory, can serve as a first approximation for the calculation of the distribution of resultant pressure and hence the hinge-moment characteristics for a finite-span control surface with an internal balance.

5. Analysis indicates that a full-span balancing tab actuated by an internal balance should prove to be a feasible method of reducing control forces.

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TABLE I. - ORDINATES FOR NACA 0009 AIRFOIL

[Stations and ordinates in percent of airfoil chord]

Station	Upper surface	Lower surface
0	0	0
1.25	1.42	-1.42
2.5	1.96	-1.96
5	2.67	-2.62
7.5	3.15	-3.15
10	3.51	-3.51
15	4.01	-4.01
20	4.30	-4.30
25	4.46	-4.46
30	4.50	-4.50
40	4.35	-4.35
50	3.97	-3.97
60	3.42	-3.42
70	2.75	-2.75
80	1.97	-1.97
90	1.09	-1.09
95	0.60	-0.60
100	(.10)	(-.10)
100	0	0
L. E. Radius: 0.89		

TABLE II

COMPUTED AND EXPERIMENTAL PARAMETERS FOR 0.30c INTERNALLY BALANCED FLAP ON NACA 0009 AIRFOIL

Parameter	Vent location				
	x/c = 0.56			x/c = 0.69	
	All vents open	Outer 25 percent vents sealed	Computed	Continuous open vent	Computed
$\left(c_{l_\alpha}\right)_\delta$	0.098	0.098	------	0.099	------
$\left(\alpha_\delta\right)_{c_l}$	-.58	-.58	------	-.58	------
$\left(c_{m_{c_l}}\right)_\delta$	.010	.010	------	.010	------
$\left(c_{m_{c_l}}\right)_\alpha$	-.158	-.158	------	-.158	------
$\left(c_{h_\alpha}'\right)_\delta$	-.0005	-.0005	0.0006	-.0023	-0.0020
$\left(c_{h_\delta}'\right)_\alpha$	-.0050	-.0047	-.0047	[a].0006	.0026

[a]Non-linear.

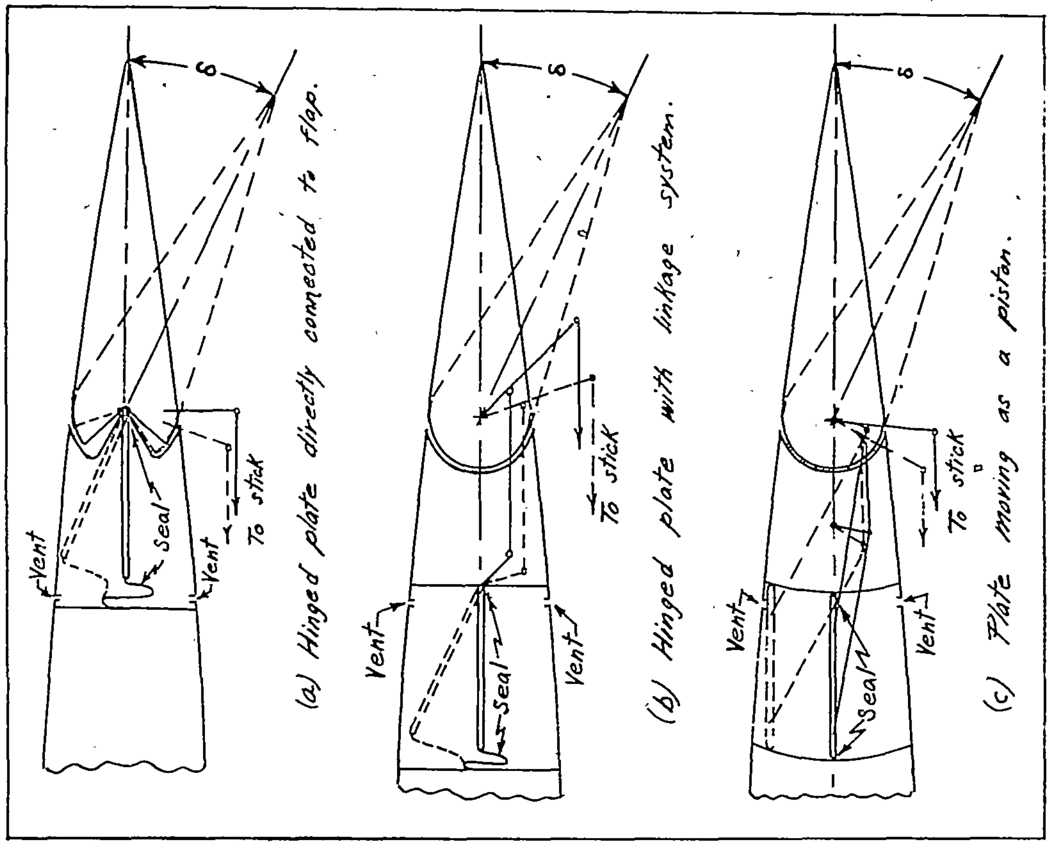


Figure 1.-Various arrangements of internal balance.

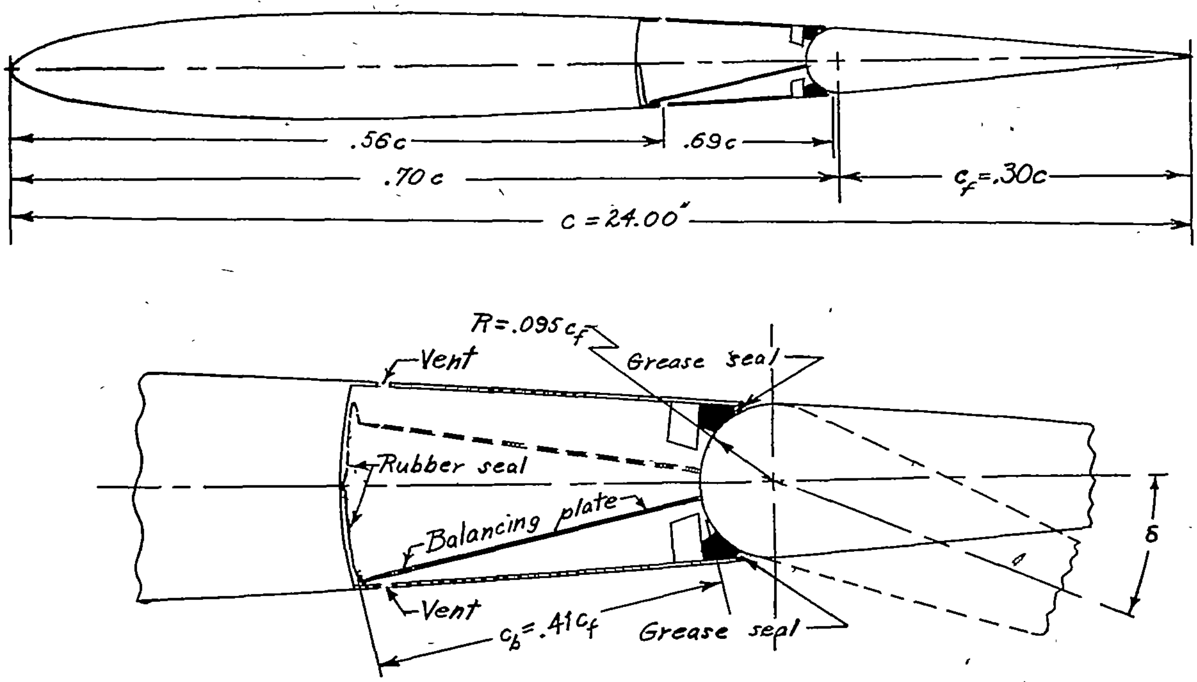


Figure 4.- Arrangement of internally balanced flap on NACA 0009 airfoil as tested experimentally.

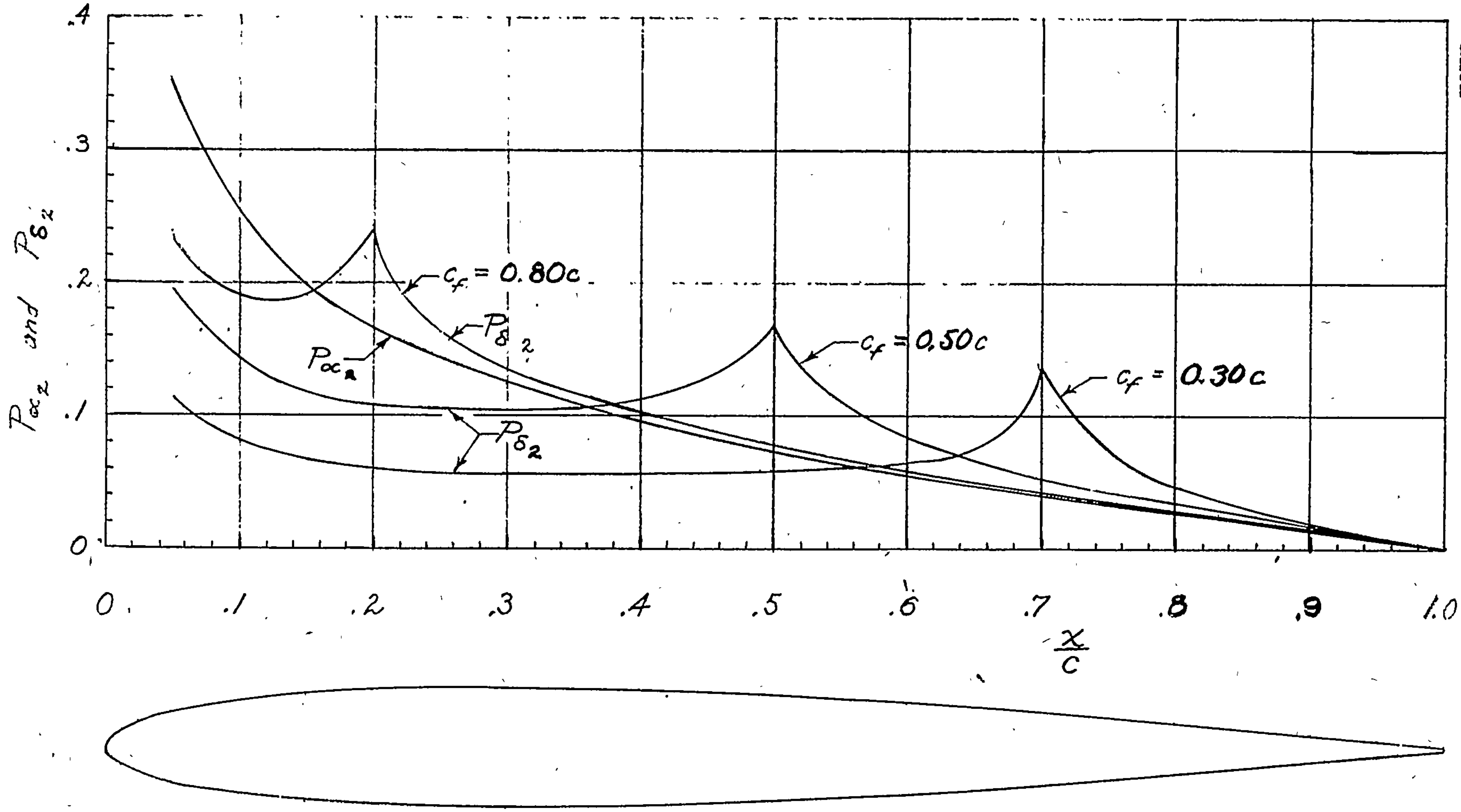
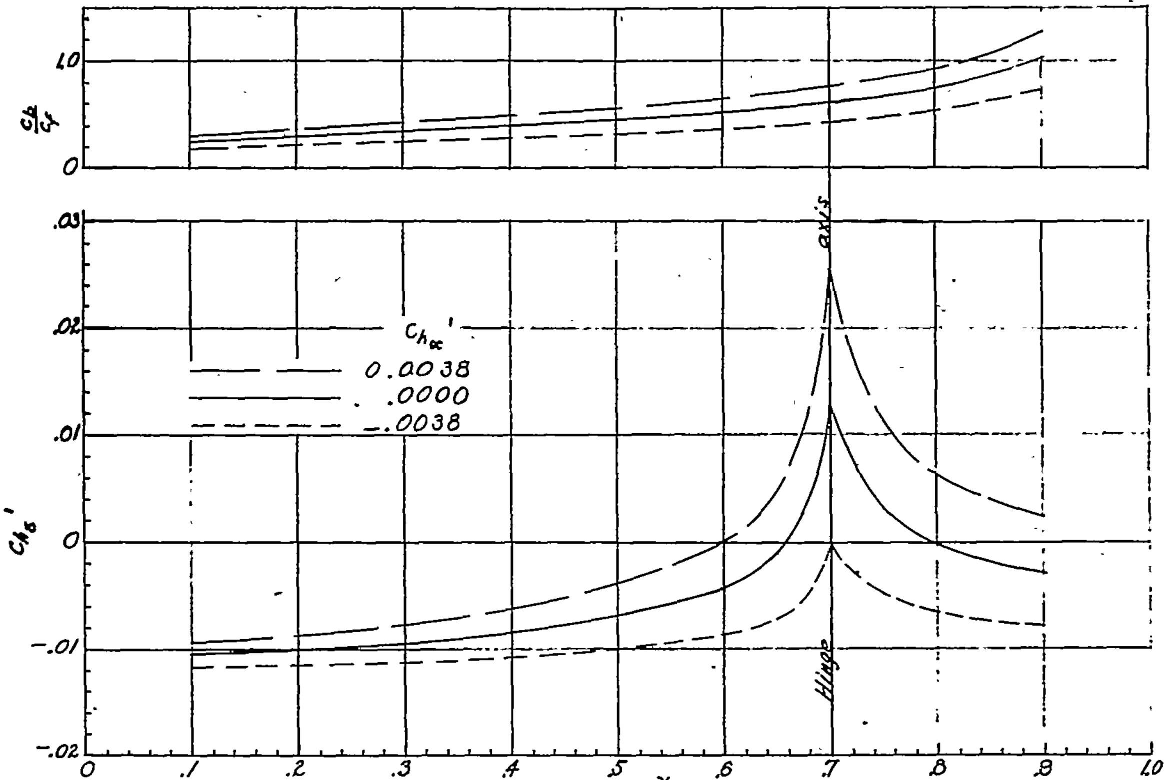
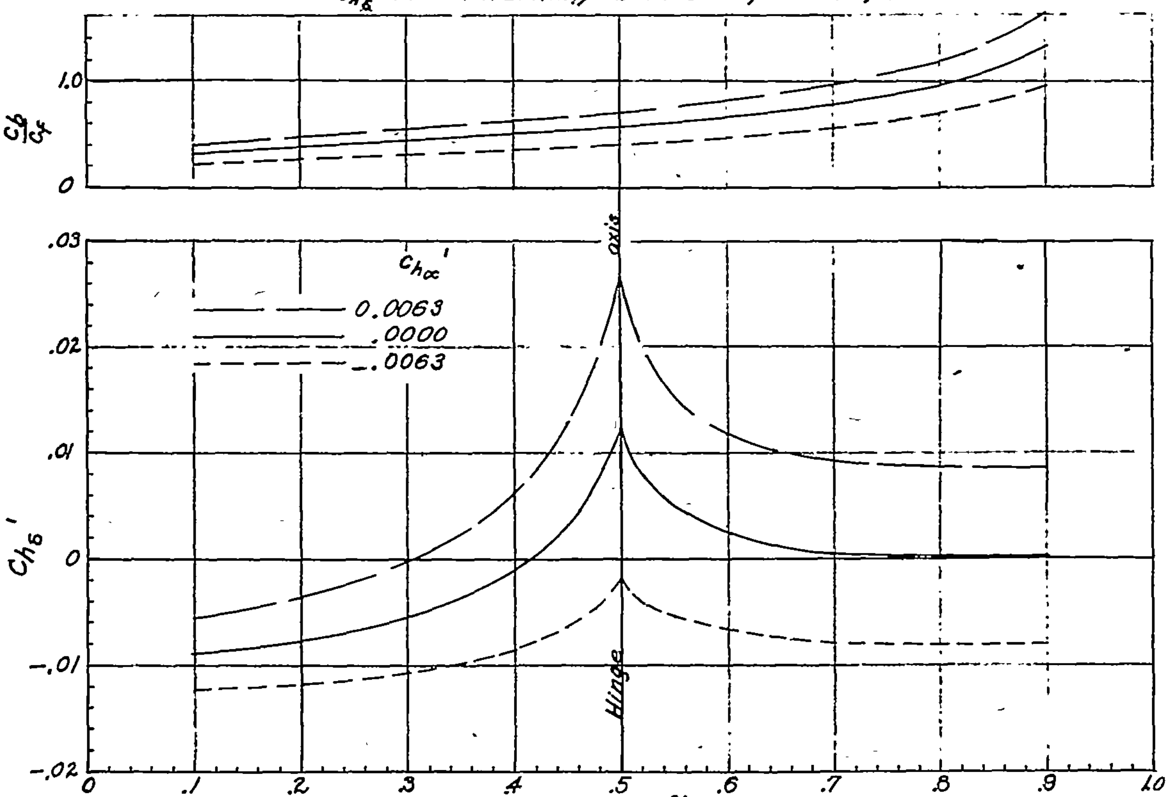


Figure 2.- Rate of change of resultant pressure coefficient with angle of attack and with flap deflection as a function of chordwise position. NACA 0009 airfoil with 0.30c, 0.50c, and 0.80c plain flaps with sealed gaps. Two-dimensional flow.



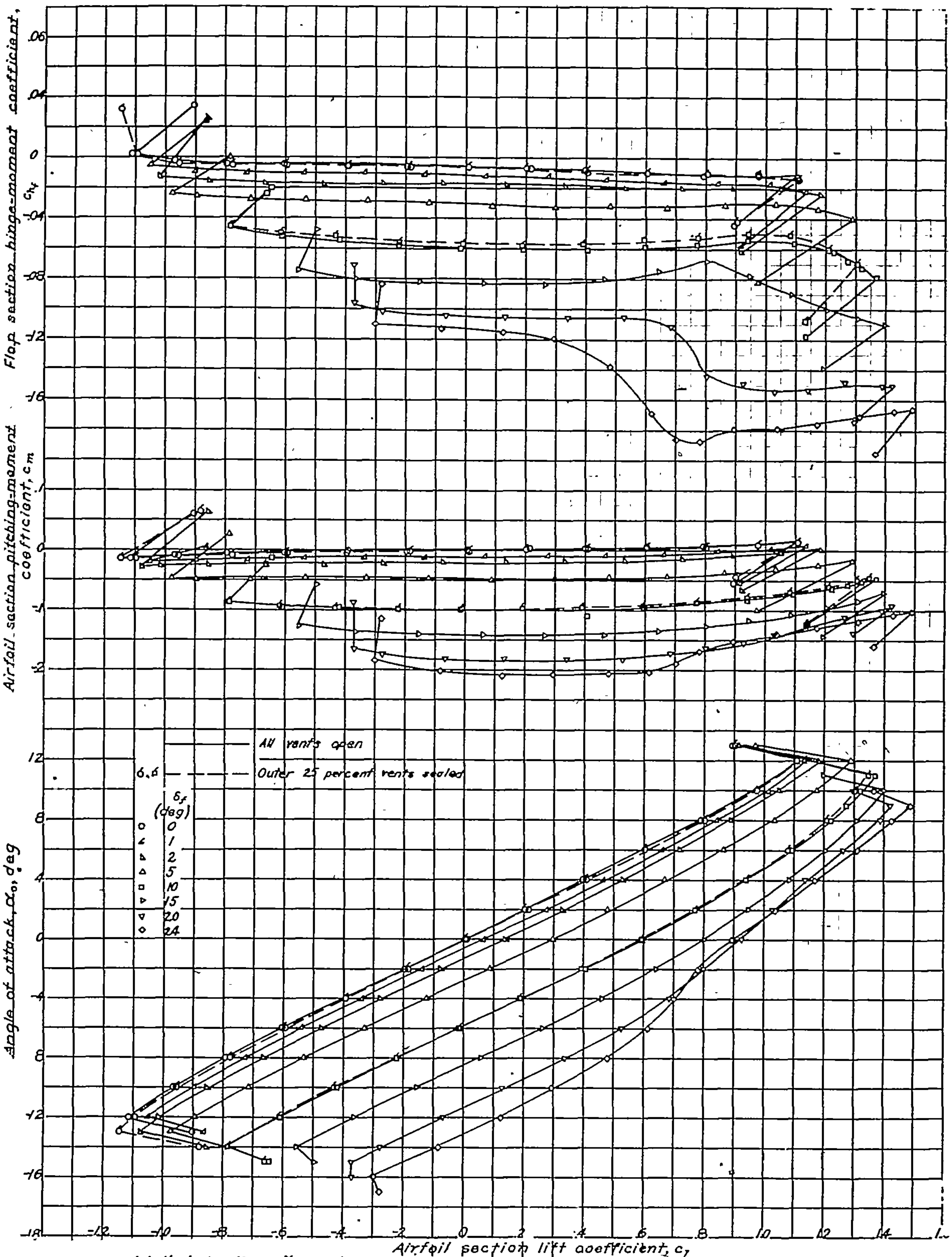
(a) 0.30 c flap. Vent location, $\frac{x}{c}$

Figure 3.- Effect of vent location and balance length on c_{h_α}' and c_{h_δ}' for internally balanced plain flaps on NACA 0009 airfoil.



(b) 0.50 c flap. Vent location, $\frac{x}{c}$

Figure 3.- Concluded.



(a) Vent location, $\frac{x}{c} = 0.56$.

Figure 5.- Aerodynamic section characteristics of NACA 0009 airfoil with a 0.30c internally balanced flap.

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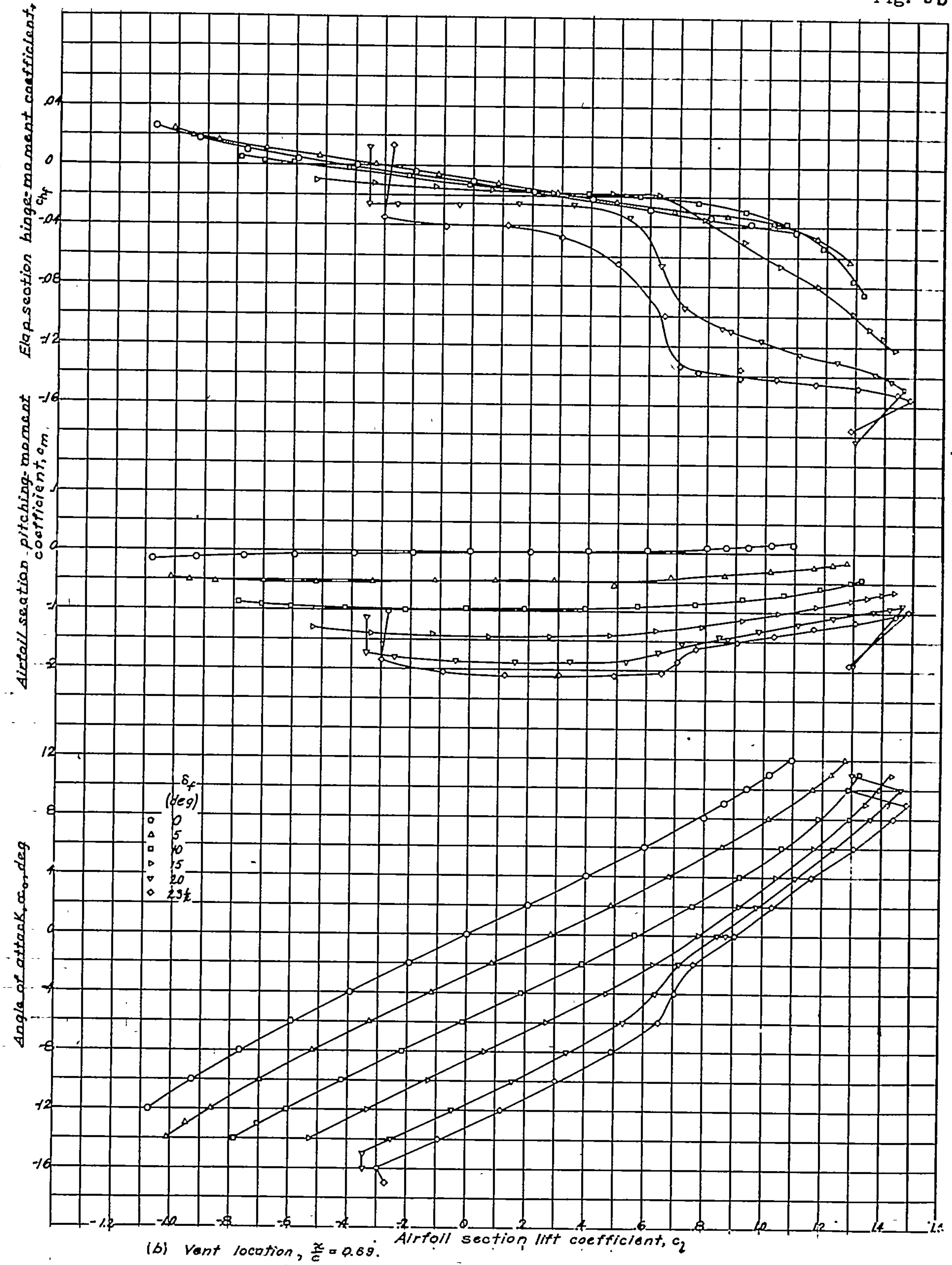

(b) Vent location, $\frac{x}{c} = 0.69$.

Figure 5.- Concluded.

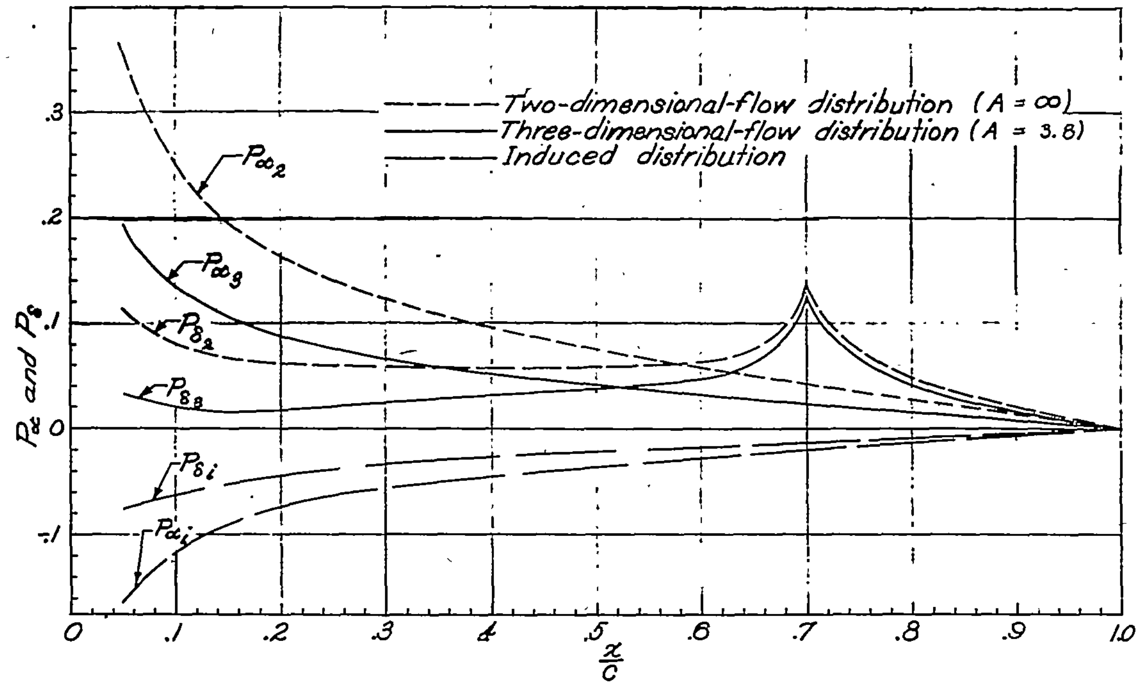

Figure 6.- Rate of change of resultant pressure coefficient with angle of attack and with flap deflection as a function of chordwise position for two-and three-dimensional flow. NACA 0009 airfoil with a 0.30c plain flap with sealed gap.

$$P_{\alpha_3} = P_{\alpha_2} + P_{\alpha_i} \qquad P_{\delta_3} = P_{\delta_2} + P_{\delta_i} = P_{\delta_2} + P_{\alpha_i}\frac{c_{l_{\delta_3}}}{c_{l_{\alpha_3}}}$$

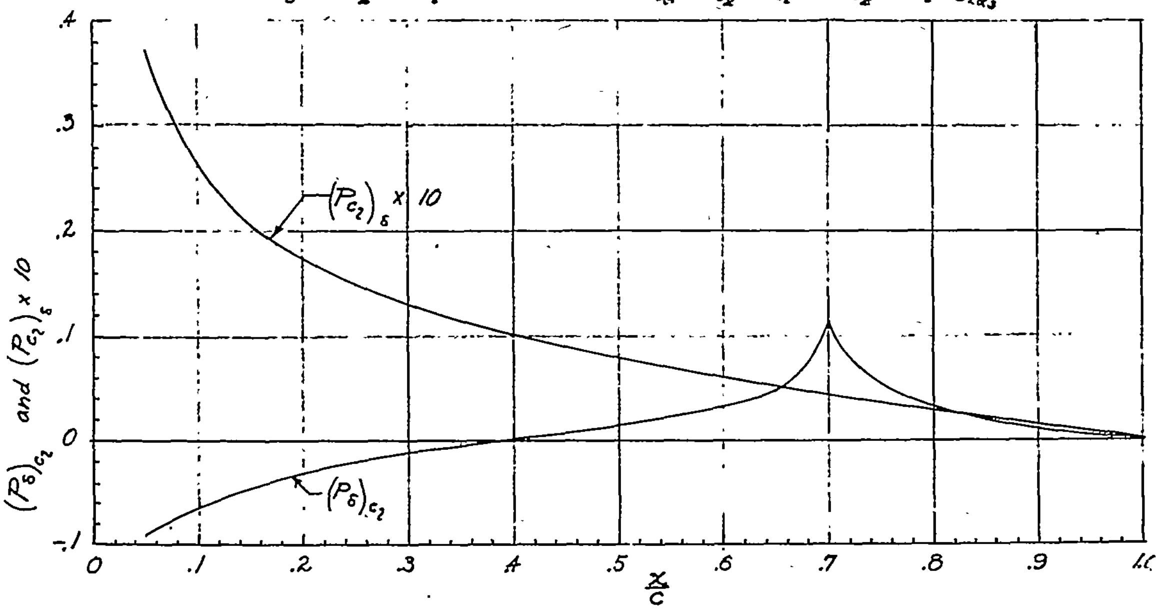

Figure 7.- Chordwise distribution of resultant pressure parameters which according to lifting line theory are independent of aspect ratio. Data experimentally determined in two-dimensional flow for a 0.30c plain flap with sealed gap on NACA 0009 airfoil.

$$P_{\alpha_3} = (P_{c_l})_\delta \, c_{l_{a1}} \, C_{L_{\alpha_3}} \qquad P_{\delta_3} = (P_\delta)_{c_l} + (P_{c_l})_\delta \, c_{l_{b1}} \, C_{L_{\delta_3}}$$