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Airplane Aerodynamics

Fourth Edition

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CHAPTER 12

Theory and Design of Control Surfaces

12 : 1. Control-Surface Terminology—Symbols

In general, a control surface may be considered as a movable or hinged flap which forms a portion (usually the aft portion) of a fixed aerodynamic surface (wing, horizontal tail, vertical tail) and which is employed to vary the lift coefficient of that surface. Several sketches are shown in Fig. 12 : 1 to supplement the following list of definitions with physical pictures.

α = angle of attack of fixed surface, deg

b = surface span, ft

c = chord of any surface, fixed or movable, ft

$\bar{c}$ = effective flap chord (root mean-square value), ft

$$C_h = \text{hinge-moment coefficient} = \frac{H}{qb\bar{c}^2} = (\Delta C_h)_\alpha + (\Delta C_h)_\delta$$

$\dfrac{\partial C_h}{\partial \alpha}$ or C_{h_α} = rate of change of flap hinge-moment coefficient with change in fixed-surface angle of attack, flap deflection held constant

$\dfrac{\partial C_h}{\partial \delta}$ or C_{h_δ} = rate of change of flap hinge-moment coefficient with change in angle of surface deflection, angle of attack of fixed surface constant

$(\Delta C_h)_\alpha$ = part of C_h due to angle of attack; equal numerically to $\alpha \dfrac{\partial C_h}{\partial \alpha}$

$(\Delta C_h)_\delta =$ part of C_h due to angle of deflection; equal numerically to $\delta \dfrac{\partial C_h}{\partial \delta}$

$\delta =$ angle of deflection of any movable surface with respect to surface to which it is attached

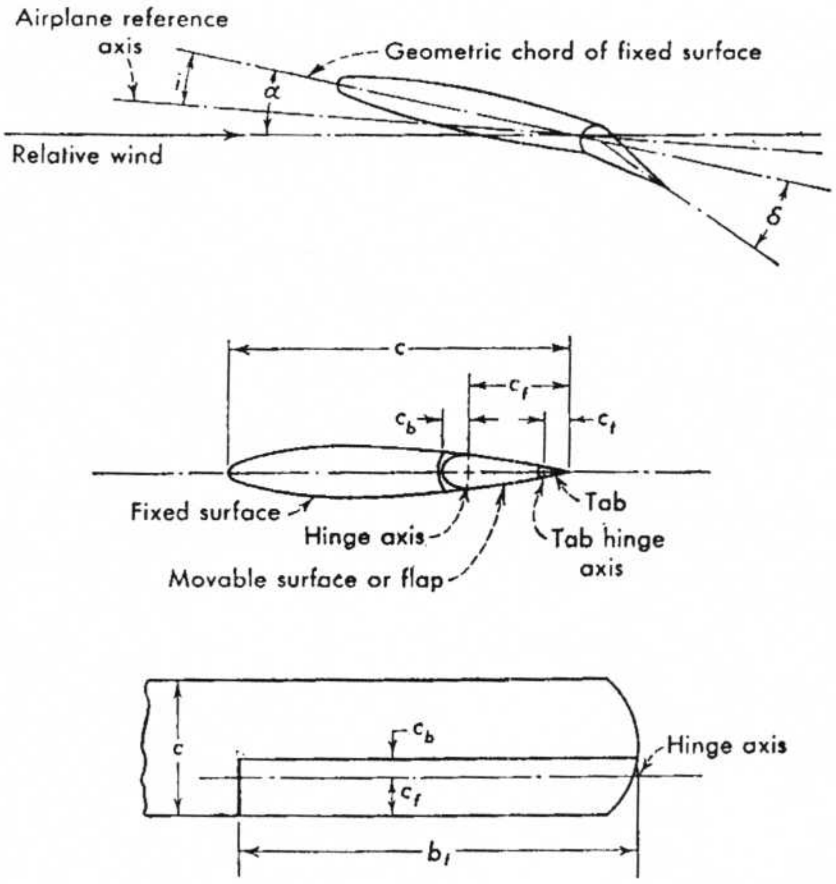

Fig. 12 : 1. Control-surface geometry.

$\dfrac{dC_L}{d\alpha} =$ rate of change of fixed-surface lift coefficient with variation in angle of attack, flap deflection constant (or slope of curve of surface C_L versus α)

$\dfrac{dC_L}{d\delta} =$ rate of change of fixed-surface lift coefficient with variation in flap deflection, angle of attack constant (or flap effectiveness parameter)

$H =$ flap hinge moment, lb-ft

$k =$ control-system mechanical advantage, ft^{-1}

$S =$ surface area, ft^2

$\tau =$ alternative flap effectiveness parameter, $\dfrac{\dfrac{dC_L}{d\delta_f}}{\dfrac{dC_L}{d\alpha}} = \dfrac{d\alpha}{d\delta_f}$

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Subscripts used with the foregoing symbols are

a = aileron;	f = any flap;
b = leading-edge balance;	r = rudder;
e = elevator;	t = tab, tail.

12 : 2. General Considerations—Types of Controls

A control may be considered as a device or means by which the airplane is caused to roll, pitch, or yaw to the flight attitude desired by the pilot, human or mechanical. In practice, the pilot moves the control, and the airplane, responding to the effect of the control movement, reflects the will of the pilot. A control must be adequate, that is, it must be effective in causing the airplane to perform all required flight maneuvers in a safe fashion, and the forces involved in moving the controls should be logical in direction and within the physical capabilities of the pilot.

In general, a control functions by causing a change in the pressure distribution on the surface of which it is a part, which results in a change in the lift coefficient of the surface. This change in lift coefficient causes a change in the moment balance of the airplane and results in angular movement about one or more of the airplane's axes. The *longitudinal control,* which controls the airplane's attitude in pitch, is called the *elevator.* The *lateral control,* which controls the airplane's attitude in roll, is called an *aileron.* The *directional control,* which controls the airplane in yaw, is called the *rudder.*

In this chapter we shall consider only the basic characteristics of the several types of surfaces, namely:

(a) *Control effectiveness,* which is the effectiveness of control deflection in changing the lift or force characteristics of the surface of which it is a part.

(b) *Control hinge moments,* which govern the forces required to move the controls.

(c) *Type of control-surface balances* used to vary hinge moments.

(d) *Special types of controls.*

In considering the ability of the controls to maneuver an airplane and the control forces required, it is necessary to consider the stability characteristics of the airplane together with the control-surface characteristics. This tie-in will be made in the following chapters on longitudinal and lateral stability.

12 : 3. Control Effectiveness

The concept of control surface or flap effectiveness can be illustrated by a practical approach. In Chapter 5, the effect of a flap at the trailing

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edge of an airfoil in increasing the section lift coefficient while the airfoil remained at the same angle of attack was demonstrated. It was shown that the general effect of a flap was to change the camber of the basic airfoil.

We shall take as the starting point a section often used for horizontal or vertical tail surfaces, the NACA 0009, with a plain flap whose chord

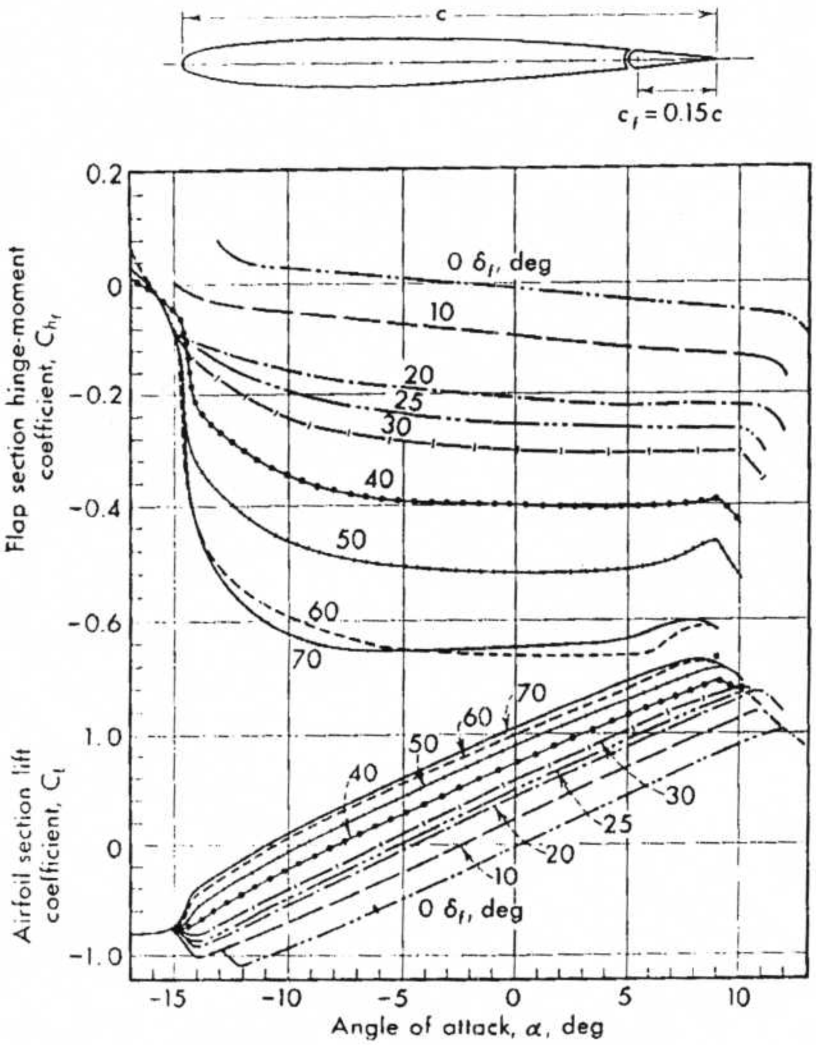

FIG. 12 : 2. NACA 0009 airfoil, with 0.15c plain flap and 0.005c gap. (*National Advisory Committee for Aeronautics.*)

aft of the hinge line is 0.15 of the airfoil chord, or $c_f/c = 0.15$. By plain flap, we mean no effective area of the flap is forward of the hinge line; just enough radius is allowed to permit rotation of the flap. A nominal open gap of 0.005c is left to allow free movement of the surface. This airfoil-flap combination, with pertinent dimensions expressed in terms of the chord c, is shown in Fig. 12 : 2. A series of curves consisting of the section lift coefficient c_l versus angle of attack α for varying flap deflections δ_f are also given in Fig. 12 : 2.

It can be seen that the slope of the family of curves of C_L versus α

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Ref. HANDLING Q.

is merely the slope of the normal C_L versus α curve for the particular airfoil. Deflection of the flap does not sensibly change this slope, but merely changes the angle of attack for zero lift and the angle of attack for any numerical value of $C_{L_{max}}$. We conclude that for a given surface the lift slope $dC_L/d\alpha$ is not affected by flap deflection but depends upon the effective aspect ratio of the entire surface, as discussed in Chapter 5.

Going back to Fig. 12 : 2 and selecting any constant angle of attack α, we find that a change in δ_f produces a change in C_L. A flap deflection

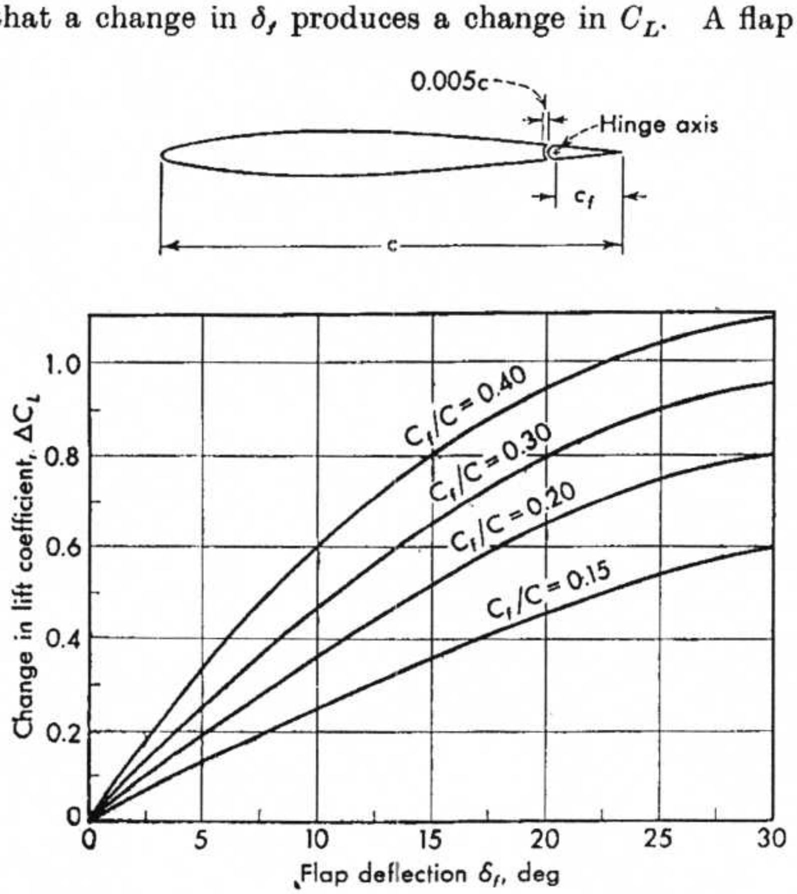

Fig. 12 : 3. Change in lift coefficient (with constant angle of attack) versus flap deflection for several values of flap-airfoil chord ratios. NACA 0009 airfoil with plain, unsealed flap and 0.005c gap.

that produces a positive change in C_L of a surface is given a positive sign. In the case of a horizontal surface, down flap would be positive. If we take $\alpha = 0°$, we find that changing δ_f from $0°$ to $+10°$ gives a change in lift coefficient ΔC_L of $+0.23$. Increasing δ_f to $+20°$ gives a total ΔC_L of $+0.45$. It is to be noted that for the linear portions of the curves of C_L versus α the values of ΔC_L for given values of δ_f remain constant for any value of α. We can therefore cross-plot and derive curves of ΔC_L versus δ_f. This is done in Fig. 12 : 3. The lower curve marked $c_f/c = 0.15$ is for the airfoil-flap combination used as the example in the foregoing discussion. If the same type of data as given in Fig. 12 : 2 is prepared for the same airfoil, but using flap-chord ratios of

c_f/c of 0.20, 0.30, and 0.40, we can cross-plot ΔC_L versus δ_f and obtain the other three curves given in Fig. 12 : 3, marked $c_f/c = 0.20$, $c_f/c = 0.30$, and $c_f/c = 0.40$. Inspection shows that these curves retain approximate linearity for values of δ_f up to about 15°. We then express the effect of flap deflection for this linear range as the slope of the ΔC_L versus δ_f curve, or differentially, as $dC_L/d\delta_f$. It is noted that owing to the choice-of-sign convention, a $+\delta_f$ produces a $+\Delta C_L$, and a $-\delta_f$ produces a $-\Delta C_L$. *The sign of $dC_L/d\delta_f$ is therefore always positive.* The derivative $dC_L/d\delta$

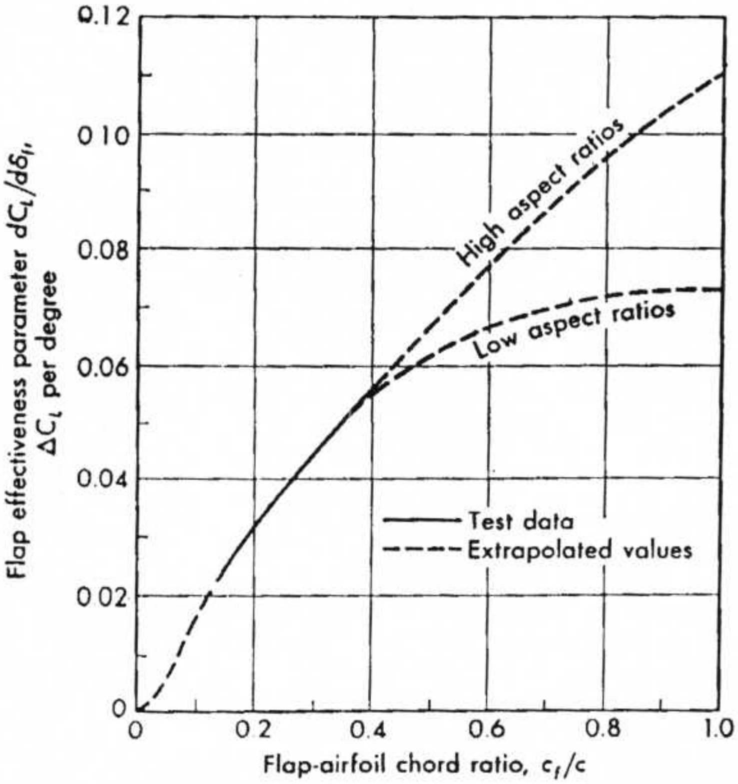

FIG. 12 : 4. Flap effectiveness parameter versus flap-airfoil chord ratio for NACA 0009 airfoil with plain unsealed flap and 0.005c gap. For $c_f/c = 1$, $dC_L/d\delta_f$ is equal to $dC_L/d\alpha$ for the aspect ratio of the surface under consideration.

is called the *flap or control effectiveness parameter* and expresses the ability of a movable flap to change the lift coefficient of the surface of which it is a part.

In some of the literature, a term τ is used as an alternative method of presenting flap effectiveness, giving

$$\tau = \frac{\dfrac{dC_L}{d\delta_f}}{\dfrac{dC_L}{d\alpha}} = \frac{d\alpha}{d\delta_f}. \qquad (12:1)$$

Fig. 12 : 3 gives data for four values of c_f/c. This family of curves can be extended to other values of c_f/c from test data of flaps on airfoils.

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Assuming reasonable linearity up to $\delta_f = \pm 15°$, we can then plot the flap effectiveness parameter $dC_L/d\delta_f$ as a function of the c_f/c ratio. This is done in Fig. 12 : 4. The solid portion of the curve covers the range of c_f/c from 0.15 to 0.30. The dotted portions are extrapolated values. It may be seen that when $c_f/c = 1.0$, we have the case of the all-movable control surface, and the control or flap effectiveness parameter $dC_L/d\delta_f$ is equal to the value of the surface lift slope $dC_L/d\alpha$. NACA data (Ref. 1) indicate that flap effectiveness as presented in the foregoing discussion is practically independent of surface planform. It is also indicated that the section data of $dC_L/d\delta_f$ may be used with reasonable accuracy for finite span surfaces. Only the shape of the basic lift curve $dC_L/d\alpha$ must be corrected for aspect ratio. An example is given as follows.

ILLUSTRATIVE EXAMPLE. The horizontal tail on an airplane employs an NACA 0009 airfoil and has a full-span elevator whose chord is 27% of the total chord. Find:

(a) The elevator effectiveness parameter $dC_L/d\delta_e$.

SOLUTION. This value may be found directly from Fig. 12 : 4, which for $c_e/c = 0.27$ gives

$$\frac{dC_L}{d\delta_e} = 0.0405.$$

(b) The tail-lift coefficient when $\alpha_t = +3°$ and $\delta_e = -6°$ (for infinite span).

SOLUTION.

$$C_{L_t} = C_{L_{\delta f=0}} + \delta_e \frac{dC_L}{d\delta_e}.$$

When $\alpha_t = +3°$ and $\delta_f = 0°$, Fig. 12 : 2 gives

$$C_L = +0.27,$$

$$C_{L_t} = 0.27 + (-6)(+0.0405) = +0.027.$$

Several factors may tend to alter the value of $dC_L/d\delta_f$. Sealing the gap between the flap and fixed surface tends to raise the value because this prevents leakage flow between upper and lower surfaces. Extending the portion forward of the hinge line for aerodynamic balance tends to increase the control effectiveness, provided the balance portion is exposed to the wind stream. The use of tabs (as discussed in a later section) can either increase or decrease the control effectiveness. A leading tab (one that moves in the same direction as the flap) increases the effectiveness, and a lagging tab (one that moves in opposite direction from the flap) decreases the flap effectiveness. It can be seen that a tab is a flap on a flap, and its effect is either additive to or subtractive from the flap to which it is attached.

The best source of data on control-surface effectiveness is test data that may be found in the various NACA reports on the subject. A number of these reports are listed in the bibliography for this chapter.

The data for the NACA 0009 airfoil with a plain flap are given for the purpose of illustrating the principles involved and not for use as exact engineering design data.

12 : 4. Hinge Moments

If we examine an airfoil with a hinged flap, it is evident that the pressure distribution on the flap can cause a moment to be set up about

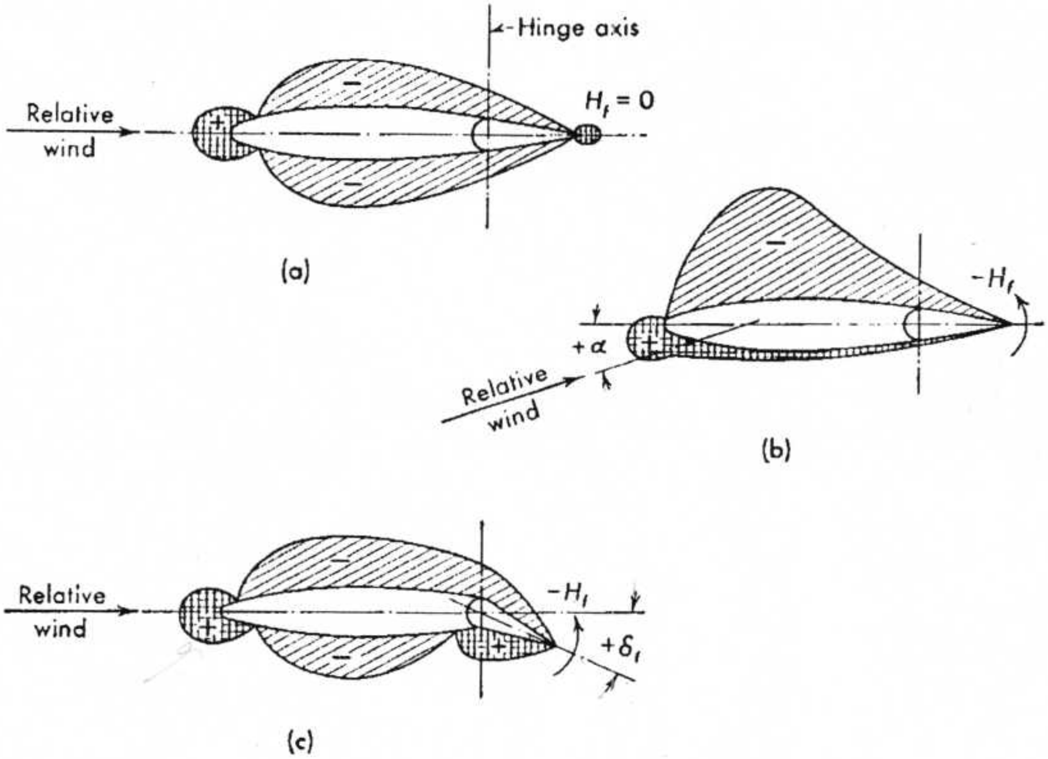

FIG. 12 : 5. Pressure distributions about a typical symmetrical airfoil which produce aerodynamic hinge moments. (a) $\alpha = 0°, \delta_f = 0°$, basic pressure distribution; (b) $\alpha = +15°$, $\delta_f = 0°$, change in pressure distribution due to change in α; (c) $\alpha = 0°$, $\delta_f = +15°$, change in pressure distribution due to change in δ_f.

the flap hinge. Such a moment will either cause the flap to rotate about its hinge or will require an equal and opposite restraining moment to be applied to the flap in order to hold it at a given deflection.

This moment is called the *hinge moment* of the flap. Fig. 12 : 5 is designed to illustrate this point. A symmetrical airfoil at $\alpha = 0 (C_L = 0)$ has been chosen as a starting point. A plain flap of any chord has been added. In part (a) of the figure, it can be seen that a symmetrical pressure distribution exists over both upper and lower surfaces of the airfoil, including the flap. Consequently, there is no resultant moment about the hinge axis. In part (b), the angle of attack of the airfoil has been changed to $+15°$, and the flap deflection has been held at $0°$. It can be seen from the resultant pressure distribution, particularly aft of the hinge axis, that positive pressures exist on the lower surface, and negative pressures exist on the upper surface. The resultant is a force upward aft of the hinge axis that tends to rotate the flap up. This hinge moment that results from change in angle of attack of the basic airfoil is termed *the hinge moment due to angle of attack*. In part (c), the angle of attack is again 0° as in part (a), but the flap has been deflected down to +15°. It can be seen that a rather distinct change has taken place in the pressure distribution, particularly, the formation of a positive pressure area on the lower surface of the flap. It can be seen again that the resultant force on the flap is up and aft of the hinge axis, producing a moment tending to rotate the flap up. This hinge moment that results from flap deflection is termed *the hinge moment due to deflection*.

Hinge moments are designated by the symbol H_f and have the units of pounds-feet. Mathematically, the hinge moment is expressed in an equation analogous to the wing pitching-moment equation, as follows:

$$H_f = q b_f \bar{c}_f^{\,2} C_{h_f}, \tag{12:2}$$

where C_{h_f} is the nondimensional hinge-moment coefficient. The group of terms $b_f \bar{c}_f^{\,2}$ can be broken down into

$$(b_f \cdot \bar{c}_f)\bar{c}_f,$$

where $(b_f \cdot \bar{c}_f)$ is equivalent to the flap area S_f. If the hinge moment of a given surface is known, the hinge-moment coefficient can be determined by

$$C_{h_f} = \frac{H_f}{q b_f \bar{c}_f^{\,2}}. \tag{12:3}$$

Experimentally, hinge moments are measured on a surface for varying angle of attack and for varying flap deflections. Hinge-moment coefficients are determined from Eq. 12 : 3, and the data are plotted as curves of C_{h_f} versus α, one curve being drawn for each value of flap deflection δ_f. A series of these curves are given in Fig. 12 : 2 for the NACA 0009 airfoil with a 0.15c plain flap as discussed in Sec. 12 : 3. Using these data, it is possible to enter the curves directly with given values of α and δ_f and read the value of the flap hinge-moment coefficient C_{h_f}. This value may then be applied directly with known values of dynamic pressure (q) and flap size (b and $\bar{c}$) to Eq. 12 : 2, and the hinge moment may be computed.

This direct procedure, using test curves to select points, does not lend itself readily to analytical procedures such as will be presented in the following chapters on stability and control. Therefore, an additional method of treating hinge-moment data will be presented. Examination of the hinge-moment coefficient curves in Fig. 12 : 2 indicates two facts. First, the curves of C_h versus α for flap deflections of up to 30° are essentially straight lines over a range of angles of attack of about $\pm 12°$ from α for zero lift. The part of the total hinge-moment coefficient due to angle of attack can then be expressed as the slope of the C_{h_f} versus α curves multiplied by the angle of attack; that is,

$$(\Delta C_{h_f})_\alpha = \alpha \frac{\partial C_{h_f}}{\partial \alpha}, \tag{12:4}$$

where $(\Delta C_{h_f})_\alpha$ = the part of C_{h_f} due to angle of attack;

$\frac{\partial C_{h_f}}{\partial \alpha}$ = the slope of the C_{h_f} versus α curves.

Second, at any given angle of attack in the linear range discussed above, it may be noticed that the curves of C_{h_f} versus α for various values of δ_f up to 30° have a uniform spacing. Cross-plotting these data as curves of C_{h_f} versus δ_f for constant values of α will again give a family of essentially straight lines. The part of the total hinge-moment coefficient due to flap deflection may be expressed as the slope of C_{h_f} versus δ_f curves multiplied by the flap deflection, or

$$(\Delta C_{h_f})_\delta = \delta_f \frac{\partial C_{h_f}}{\partial \delta_f}, \tag{12:5}$$

where $(\Delta C_{h_f})_\delta$ = the part of C_{h_f} due to flap deflection;

$\frac{\partial C_{h_f}}{\partial \delta_f}$ = the slope of the C_{h_f} versus δ_f curves.

The total hinge-moment coefficient is

$$C_{h_f} = (\Delta C_{h_f})_\alpha + (\Delta C_{h_f})_\delta, \tag{12:6}$$

and substituting from Eqs. 12 : 4 and 12 : 5, we get

$$C_{h_f} = \alpha \frac{\partial C_{h_f}}{\partial \alpha} + \delta_f \frac{\partial C_{h_f}}{\partial \delta_f}. \tag{12:7}$$

In some cases C_{h_f} is not zero when α and δ_f are zero (as in the case where a trim tab is deflected) and a term C_{h_0} is then added to the left side of Eq. 12 : 7 to account for this.

Equation 12 : 7 may be used for any type of surface that has linear variation of hinge-moment coefficient with angle-of-attack or flap deflection. It will be demonstrated later that some surface configurations may have nonlinear characteristics. These are not only difficult to handle mathematically but also produce undesirable flying characteristics. In general, surfaces with linear characteristics should be selected.

The sign convention for hinge moments is logical. A moment that tends to rotate the flap so as to increase δ_f in a positive sense (downward) is given a positive sign and a moment that tends to rotate the flap so as to increment in α causes a negative increment in C_{h_f}, the sign of $\partial C_{h_f}/\partial\alpha$ is positive. The converse would make the sign of $\partial C_{h_f}/\partial\alpha$ negative.

Referring to Fig. 12 : 5 (b), it is seen that the hinge moment that results from a positive change in angle of attack is negative and tends to rotate the flap so as to reduce the angle that it makes with the relative wind, thus representing a negative $\partial C_{h_f}/\partial\alpha$. The parameter $\partial C_{h_f}/\partial\alpha$ is often referred to as the *floating tendency*. The plain flap of Fig. 12 : 5 has, then, a negative floating tendency. In a similar manner, if a positive increment in δ_f causes a positive increment in C_{h_f} or a negative increment in δ_f causes a negative increment in C_{h_f}, the sign of $\partial C_{h_f}/\partial\delta_f$ is positive. The converse makes the sign of $\partial C_{h_f}/\partial\delta_f$ negative. Referring again to the plain flap of Fig. 12 : 5, it is seen that $\partial C_{h_f}/\partial\delta_f$ is negative. Inspection of

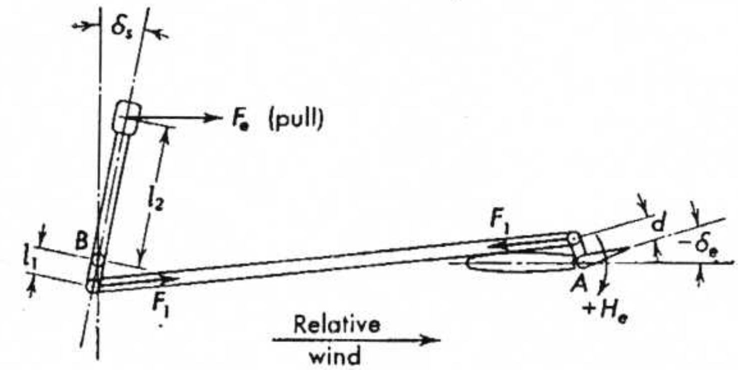

Fig. 12 : 6. Elevator control system.

the hinge-moment-coefficient curves of Fig. 12 : 2 shows again that the plain flap possesses a negative $\partial C_{h_f}/\partial\alpha$ and a negative $\partial C_{h_f}/\partial\delta_f$.

The consequences of control-surface hinge moments are important. The surfaces are connected to the airplane controls. In general, every time the attitude of the airplane changes or the deflection of a surface is changed to maneuver the airplane, the pilot must exert a force on the control. Fig. 12 : 6 shows a schematic elevator control system connected in the conventional manner, so that rearward movement of the stick causes an upward or negative δ_f.

Assuming a plain flap with a $-\,\partial C_{h_f}/\partial\delta_f$ and using Eq. 12 : 7, we get

$$(-\,\delta_e)\left(-\,\frac{\partial C_{h_e}}{\partial\delta_e}\right) = +\,C_{h_e}.$$

Therefore, if C_{h_e} is positive, when it is used in Eq. 12 : 2 H_e is also positive (that is, tends to move the elevator to a more positive value of δ_e). Conversely, if the elevator is moved down, δ_e is positive, and applying it as before in Eq. 12 : 7, we get

$$(+\,\delta_e)\left(-\,\frac{\partial C_{h_e}}{\partial\delta_e}\right) = -\,C_{h_e}.$$

As before, if C_h is negative, when it is used in Eq. 12 : 2 we find that the hinge moment H_e is also negative. If we establish the mechanical characteristics of the linkage system which connects to the control system, it can be shown that the force required on the control stick F_e is equal to some constant k times the hinge moment H_e. This constant k is the mechanical advantage of the system. For the case in Fig. 12 : 6, k is derived below, where

A = the elevator hinge axis;
B = the control-stick pivot axis;
d = length of the elevator horn, ft;
l_1 = length of control stick below pivot axis, ft;
l_2 = length of control stick between center of hand grip and pivot axis, ft;
k = mechanical advantage of control system.

Summing moments about A, we get

$$H_e = F_1 \cdot d,$$

whence

$$F_1 = \frac{H_e}{d}.$$

Summing moments about B, we get

$$F_e \cdot l_2 = F_1 \cdot l_1,$$

or

$$F^1 = \frac{F_e \cdot l_2}{l_1}.$$

Equating the two expressions for the common force F_1 and solving for F_e, we obtain

$$\frac{F_e \cdot l_2}{l_1} = \frac{H_e}{d}$$

$$F_e = \left(\frac{l_1}{l_2 \cdot d}\right) H_e,$$

or

$$F_e = kH_e, \qquad (12:8)$$

where

$$k = \left(\frac{l_1}{l_2 \cdot d}\right);$$

or, alternatively,

$$F_e = kqb_e\bar{c}_e^2 C_{h_e}. \qquad (12:8A)$$

The details of the derivation presented above are for the simple push-pull rod type of elevator control system shown in Fig. 12 : 6. Employment of cables and pulleys, intermediate bell cranks, worm gears, eccentrics, and the like will change the details of calculating k, which in the final analysis is a relatively simple mechanics problem. Once the details of any control system have been selected and the value of k has been determined, Eq. 12 : 8 applies in the computation of the control forces from the known hinge moment H. The control force is given the sign of the hinge moment. For the elevator system shown, a pull force to the rear is positive. *Care must be taken in all control-force computations to establish correct sign notations and to see that they are preserved throughout all computations.*

The principles of hinge moments discussed so far apply not only to the determination of control-surface characteristics but also to the solution of such problems as the loads involved in the lowering of landing flaps, extension of dive brakes, and the like. Airfoil data for airfoils with various kinds of flaps generally include hinge-moment data.

Examination of the basic hinge-moment Eq. 12 : 2 shows several interesting facts. The equation is repeated below:

$$H_f = qb_f\bar{c}_f^2C_{h_f}.$$

Eq. 12 : 7, which is repeated below, gives C_{h_f} in terms of the basic hinge-moment parameters:

$$C_{h_f} = \left(\frac{\partial C_{h_f}}{\partial \alpha}\alpha + \frac{\partial C_{h_f}}{\partial \delta_f}\delta_f\right). \qquad (12:7\text{A})$$

Substituting for C_{h_f} in Eq. 12 : 2, we get

$$H_f = qb_f\bar{c}_f^2\left(\frac{\partial C_{h_f}}{\partial \alpha}\alpha + \frac{\partial C_{h_f}}{\partial \delta_f}\delta_f\right). \qquad (12:9)$$

The effect of air speed is given by the term q. It shows that if all other factors are held constant, the hinge moment (hence the control force) varies directly as the *square* of the equivalent air speed (or directly as the density ρ times the true air speed squared, V_T^2). If the speed is doubled, the control force will be four times as great. The effect of size is given by the product $b_f\bar{c}_f^2$. If all other factors are held constant, the hinge moment varies as the *cube* of the scale. Doubling the size of an airplane will increase the control forces eightfold. The hinge-moment parameters enter the picture linearly. The combination of large size and high indicated speeds can produce enormous control forces that conceivably may be beyond the capabilities of a pilot to handle unless the hinge-moment coefficients are reduced to low values. **For a given fixed area of control surface, it can be seen that if the chord is kept small, the forces will be lowered.** These effects should be kept in mind in the discussion to follow. It will be shown later, in the chapters on stability and control, that this basic hinge-moment equation can be tied to the stability characteristics of the airplane, giving a rather complete picture of the control forces involved in flying an airplane.

The hinge-moment parameters of a plain flap on an NACA 0009 airfoil may be conveniently summarized by the type of curves given in Fig. 12 : 7. The values of $\partial C_h/\partial\alpha$ and $\partial C_h/\partial\delta$ are plotted as functions of the ratio of flap chord to the airfoil chord. Use of these parameters for the plain flap in the hinge-moment equation to determine control forces will show that for low equivalent air speeds and very small airplanes (that is, small surfaces), a plain flap is satisfactory. As indicated air speeds

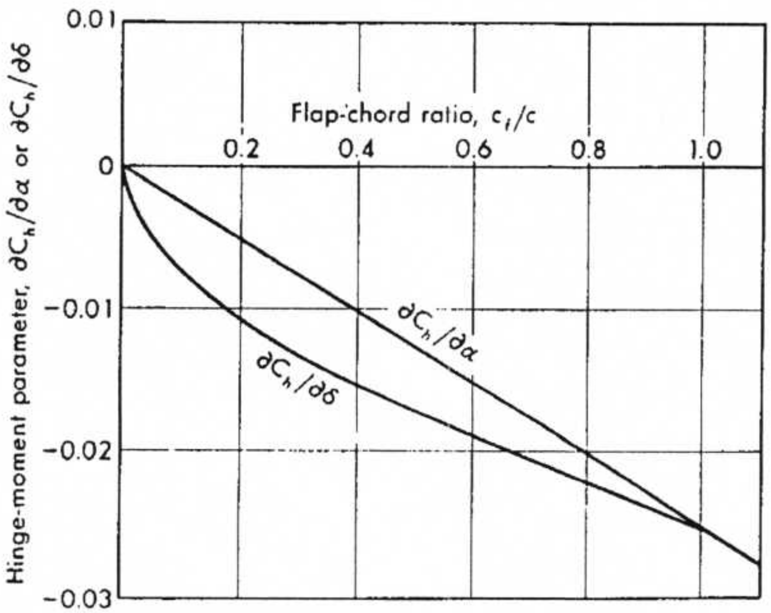

FIG. 12 : 7. Hinge-moment parameter, $\partial C_h/\partial\alpha$ or $\partial C_h/\partial\delta$, versus flap-chord ratio c_f/c.

increase and as the size of the airplane increases, the forces resulting from plain flaps are too great for a pilot to handle. An illustrative example is given below.

ILLUSTRATIVE EXAMPLE. Two geometrically similar airplanes use a tail incorporating an NACA 0009 airfoil with plain flap elevators having $c_f/c = 0.30$. When airplane (1) is at $V_e = 150$ knots and airplane (2) is at $V_e = 300$ knots, both have a stabilizer angle of attack of $+1°$ and an elevator deflection of $+3°$. For both airplanes the elevator control-system mechanical advantage is $k = 0.35$. Airplane (1) has an elevator span of 8.0 ft and an elevator chord of 1.0 ft. Airplane (2) has an elevator span of 16.0 ft and an elevator chord of 2.0 ft. Find the elevator control force for each airplane.

SOLUTION. Airplane (1). From the curves of Fig. 12 : 7, when $c_f/c = 0.30$,

$$\frac{\partial C_h}{\partial\alpha} = -0.0075 \qquad \text{and} \qquad \frac{\partial C_h}{\partial\delta} = -0.0132.$$

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Using Eq. 12 : 7 to find C_{h_e}, we get

$$C_{h_e} = \left(\frac{\partial C_{h_e}}{\partial \alpha}\alpha + \frac{\partial C_{h_e}}{\partial \delta_e}\delta_e\right)$$

$$= [(-0.0075) \times (+1.0) + (-0.0132) \times (+3.0)]$$

$$= -0.0471.$$

Solving for F_e (using Eq. 12 : 8A), we get

$$F_e = kqb_e\bar{c}_e{}^2C_{h_e}$$

$$= 0.35 \times \left[\frac{0.002378}{2}(1.69 \times 150)^2\right] \times 8 \times 1^2 \times (-0.0471)$$

$$= -10.1 \text{ lb or } 10.1 \text{ lb push force.}$$

Solution. Airplane (2). Since the geometry of this airplane is similar to that of airplane (1), C_{h_e} is the same. Therefore, again using Eq. 12 : 8a, we get

$$F_e = 0.35 \times \left[\frac{0.002378}{2}(1.69 \times 300)^2\right] \times 16 \times 2^2 \times (-0.0471)$$

$$= -323 \text{ lb or } 323 \text{ lb push force.}$$

The 10.1 lb push force for airplane (1) is satisfactory, but it is self-evident that the 323 lb for airplane (2) is beyond the physical capabilities of any human. This tremendous change is brought about by doubling both the physical size and the operating air speed.

For the smaller, lower-speed aircraft, plain-flap control surfaces will be satisfactory for elevator and rudder. However, even for ailerons on small, high-speed airplanes and for all surfaces on the larger, faster airplanes some means must be provided to reduce the control forces to a reasonable magnitude. The value of the mechanical advantage k offers some opportunity to make reductions, but there are very practical limits because of restrictions on the total angular (or linear) movement of the control stick and the required deflection of the control surface. Size and speed are determined by the basic characteristics of the airplane. The one remaining factor that may be manipulated is the hinge-moment coefficient. There are two methods of altering the value of the hinge-moment coefficient. One is by the use of aerodynamic balance and the other by the use of tabs on the surface trailing edge. In a true sense, the tab is an aerodynamic balance, but usage generally assigns the term aerodynamic balance only to a fixed contour device. The following sections will treat aerodynamic balance and tabs separately.

12 : 5. Aerodynamic Balance

It has been demonstrated that hinge moments of flaps or control surfaces are due to the distribution of surface pressures about the hinge axis. It can therefore be reasoned that any change in pressure distribution about the hinge axis will also produce changes in the value of the hinge moment.

OVERHANG BALANCE

Since most of the area of the plain flap is aft of the hinge axis, adding area forward of the hinge axis gives an opportunity to vary the pressure-

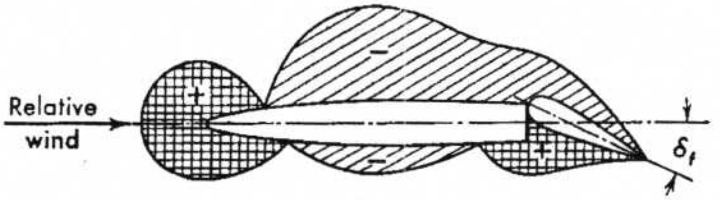

FIG. 12 : 8. Approximate pressure distribution on an NACA 0009 airfoil with a 0.20c flap with a leading-edge extension or overhang of $0.5c_f$.

distribution moments. This can be seen in Fig. 12 : 8, which shows an NACA 0009 airfoil with a 0.20c flap to which a rounded leading-edge extension of $0.5c_f$ has been added. The leading edge emerging into the

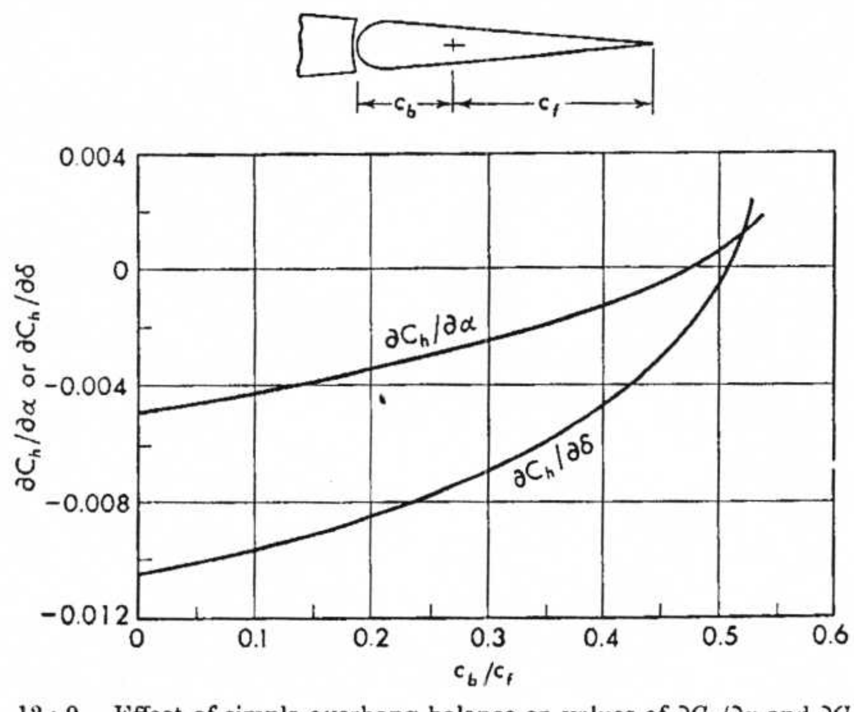

FIG. 12 : 9. Effect of simple overhang balance on values of $\partial C_h/\partial \alpha$ and $\partial C_h/\partial \delta$.

air stream on the upper surface produces a rather large secondary negative pressure peak. It can be seen by inspection that the pressures on the leading-edge extension produce moments about the hinge line that are opposite to the moments produced by the pressure distribution on the portion of the flap aft of the hinge line. Thus, the overhang changes the value of $\partial C_h/\partial \delta$ in a positive direction. Similarly, it can be shown that if the angle of attack is changed, the increase in pressure difference between the upper and lower surfaces of the overhang produces a moment that opposes the moment due to the flap area aft of the hinge line. Thus, the overhang also tends to change the value of $\partial C_h/\partial \alpha$ in a positive direction. The general effect of overhang balances is shown in Fig. 12 : 9 for the NACA 0009 airfoil with $c_f/c = 0.20$ and a plain overhang of varying

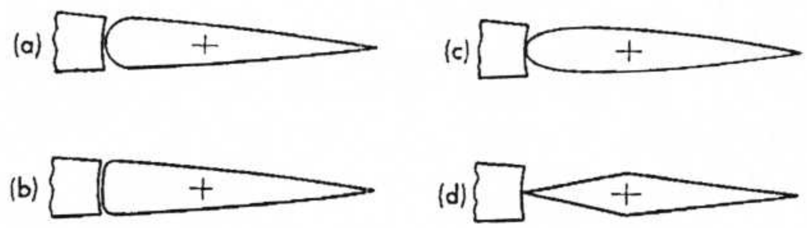

FIG. 12 : 10. Common types of overhang or leading-edge balance. (a) Simple rounded overhang; (b) blunt-nosed overhang; (c) elliptical overhang; (d) Handley-Page or sharp-edged overhang.

chord c_b. The figure shows $\partial C_h/\partial \alpha$ and $\partial C_h/\partial \delta$ plotted against the balance-flap chord ratio c_b/c_f.

The curves of Fig. 12 : 9 are presented solely to illustrate the trends and are not sufficiently accurate for design purposes; however, they may be used for problem work. NACA Wartime Report L-663 is a good source of hinge-moment data for overhang balances. Some representative shapes of leading-edge balances included in this report are given in Fig. 12 : 10.

HORN BALANCE (PADDLE BALANCE)

Another means of employing leading-edge balance is to concentrate the balance area at one portion of the span of the flap. This type of

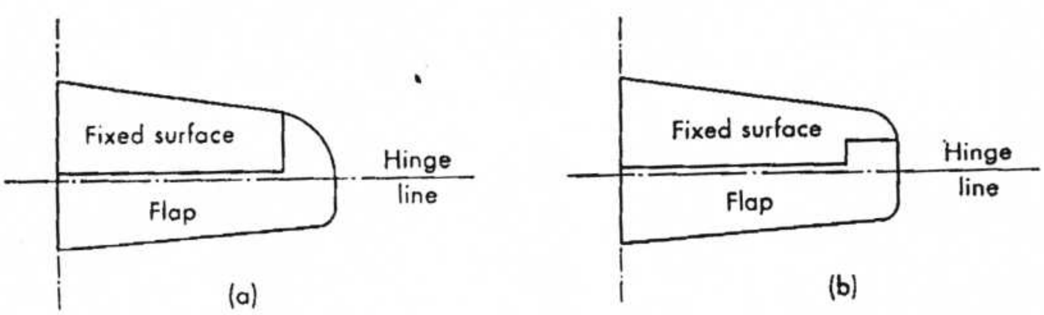

FIG. 12 : 11. Types of horn balance. (a) Unshielded horn; (b) shielded horn.

balance is called the horn balance. If the horn extends all the way to the leading edge of the fixed surface, it is called an unshielded horn, whereas one that has some fixed surface ahead of it is called a shielded horn. Planform sketches illustrating the two types are given in Fig. 12 : 11.

The action of a horn balance is similar to that of the overhang balance except that the horn has a much more pronounced effect on the value of $\partial C_h/\partial\alpha$. The unshielded horn is more effective than the shielded horn. The effectiveness of the horn balance is determined by the ratio of the moment of the horn area forward of the hinge line to the moment of the flap area aft of the hinge line. The moment is defined as the area of flap or horn multiplied by the distance of the respective area centroid from the hinge line. The effects of varying horn area on a 0.20c plain

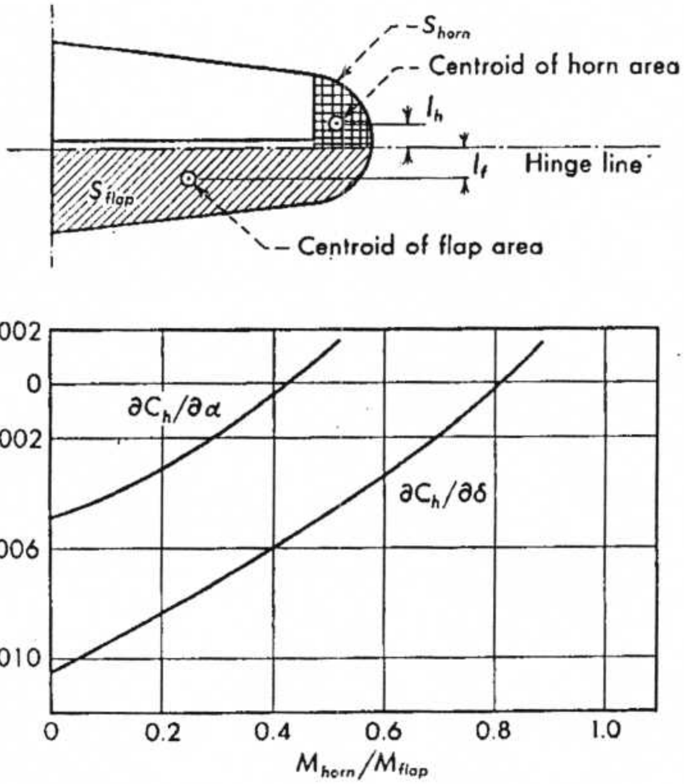

FIG. 12 : 12. Effects of horn balance on values of $\partial C_h/\partial\alpha$ and $\partial C_h/\partial\delta$. $M_{horn} = S_{horn} \times l_h$; $M_{flap} = S_{flap} \times l_f$.

flap on an NACA 0009 airfoil are shown in Fig. 12 : 12 as curves of $\partial C_h/\partial\alpha$ and $\partial C_h/\partial\delta$ plotted against ratio of horn-area moment to flap-area moment.

INTERNAL BALANCE

A newer type of balance is the internal balance, which is completely contained within the contour of the surface and is vented to upper and lower surface pressures at one chordwise point. This balance may or may not be sealed by a flexible curtain of some sort. The seal increases the effectiveness of the balance and is generally incorporated. The effect of the sealed internal balances is similar to that produced by the overhang except that $\partial C_h/\partial\alpha$ is less affected. Representative characteristics of the sealed internal balance incorporated on a 0.20c flap on an NACA

0009 airfoil are given in Fig. 12 : 13. Accurate hinge-moment data for this type of balance can be found in several NACA Reports which are listed in the bibliography for this chapter.

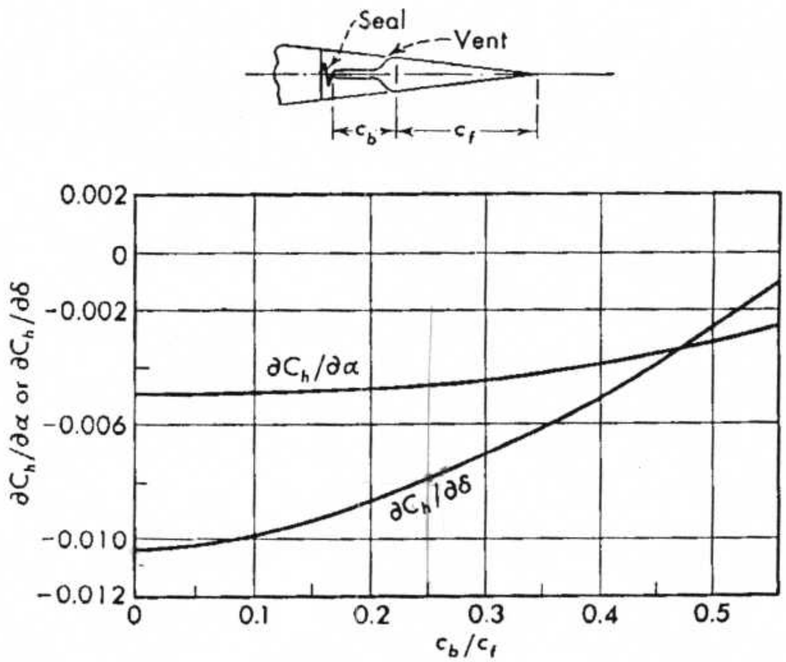

FIG. 12 : 13. Effects of a sealed internal balance on values of $\partial C_h/\partial \alpha$ and $\partial C_h/\partial \delta$.

TRAILING-EDGE MODIFICATIONS

Modifications to the trailing edges of control surfaces may also produce changes in pressure distributions that affect the hinge-moment characteristics. The usual method is to change the contour of the flap so as to provide a wedge-shaped trailing edge. Increasing the wedge angle increases the effectiveness. A beveled trailing edge on a flap with an unsealed gap may produce exaggerated effects at small angles of deflection which will result in overbalance for the small deflection range. If used, the bevel-edged flap should also have the gap sealed. Typical characteristics of this type of balance on a 0.20c plain sealed flap on an NACA 0009 airfoil are shown in Fig. 12: 14.

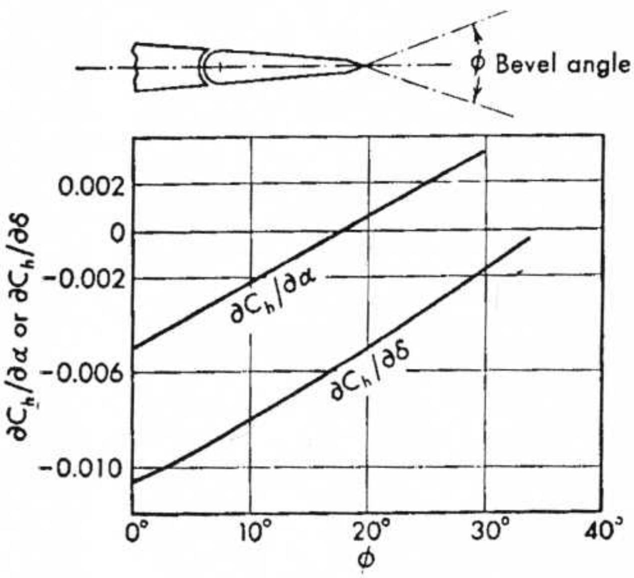

FIG. 12 : 14. Effects of trailing-edge bevel on values of $\partial C_h/\partial \alpha$ and $\partial C_h/\partial \delta$.

FRISE BALANCE

A type of balance often used for ailerons is the Frise balance. The leading edge of the aileron is so shaped that the down-deflected aileron has a negative value of $\partial C_h/\partial\delta$ and the up-deflected aileron on the other side has a positive value of $\partial C_h/\partial\delta$. The ailerons are interconnected so that the stick forces represent the net hinge moment of the two ailerons; that is, the negative moment or underbalance of the down-deflected surface is partially compensated for by the positive moment or overbalance of the up-deflected aileron. The geometry of this balance and a

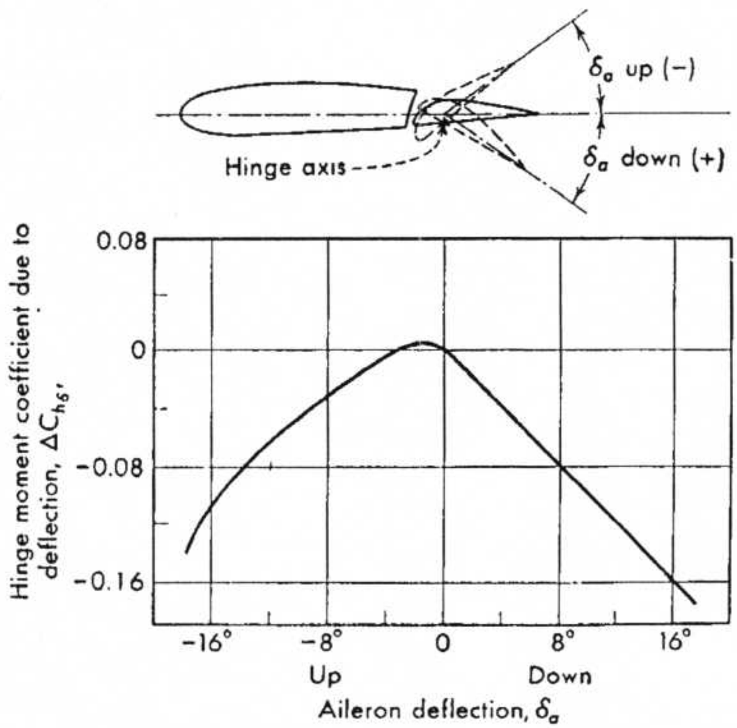

FIG. 12 : 15. Hinge-moment characteristics of a single Frise aileron.

typical curve of hinge-moment coefficient versus surface deflection is shown in Fig. 12 : 15.

The effects of $\partial C_h/\partial\alpha$ are of second-order importance for ailerons, as will be discussed in the chapter on lateral stability and control. The curve of Fig. 12 : 15 shows that very careful synchronization of the up-deflected and down-deflected ailerons is required to achieve the degree of balance desired. Stretch in the control-system linkages under load, particularly at high angles of attack, or distortion and flexing of the wings under load may destroy the normal static relation of the two ailerons. This usually results in a sudden abnormal overbalance of the ailerons as they are deflected. This phenomenon is called *snatch* and is dangerous. Frise balances are not recommended for large or high-performance airplanes, but have their particular utility for the small and moderate-sized airplanes of

PECULIARITIES OF AERODYNAMIC BALANCES

The various forms of aerodynamic balances have been discussed and their effects on hinge moments have been illustrated. It is also necessary to understand some of their limitations in practical use.

With the possible exception of a horn balance, any open or exposed overhang balance is not suited for flight above the critical Mach number of the airfoil on which it is used. The internal balance may be used for supercritical speeds, but it rapidly loses effectiveness once the critical Mach number is exceeded. Therefore, a balance of the type discussed, if made large enough for supercritical speeds, may tend to overbalance at subcritical speeds. Some cases are known where a satisfactory subcritical speed balance will exhibit an oscillating or variable overbalance in the transonic speed range (that is, the mixed-flow speed range).

As higher operating air speeds and larger-sized airplanes are employed, the hinge-moment coefficients must be reduced in size by balancing to give reasonable control forces. This reduction may easily require values of $\partial C_h/\partial\delta$ that are below the value of 0.0002. It has been shown by experiment and flight tests that even with metal-covered surfaces made to the closest production tolerances (supposedly identical surfaces), it is possible to have variations in $\partial C_h/\partial\delta$ and $\partial C_h/\partial\alpha$ of $\pm$ 0.005. It is apparent, then, that for certain kinds of airplanes other means than aerodynamic balance must be employed to keep control forces within reason and to permit different airplanes of the same design to exhibit uniform control-force characteristics.

A control surface which has a skin that is subject to deflection under load or that is subject to torsional deflection along its span will exhibit unusual and generally undesirable hinge-moment characteristics due to distortions. Great care should be exercised in the structural design to minimize these effects.

It has been found through long experience with movable control surfaces (other than flaps used for high-lift devices) that any convexity of a control surface aft of the hinge line tends to produce an undesirable and dangerous short-period oscillation of the surface. Straight-sided or concave surfaces aft of the hinge line are generally satisfactory. Therefore, in some airfoils that normally have convex contours, modifications must be made to provide flat-sided contours for the movable surface portions aft of the hinge line.

12 : 6. Tabs

A tab is a small, partial-span, short-chord flap on the trailing edge of a control surface. The purpose of the tab is to alter the pressure distribution on the control surface in the region of the trailing edge. The tab, producing its effect a large distance from the hinge line, is very effective in changing the hinge-moment characteristics. This action is illustrated in Fig. 12 : 16.

The tab is a very useful means of reducing or controlling the value of $\partial C_h/\partial\delta$ but does not affect the value of $\partial C_h/\partial\alpha$. It is not subject to the

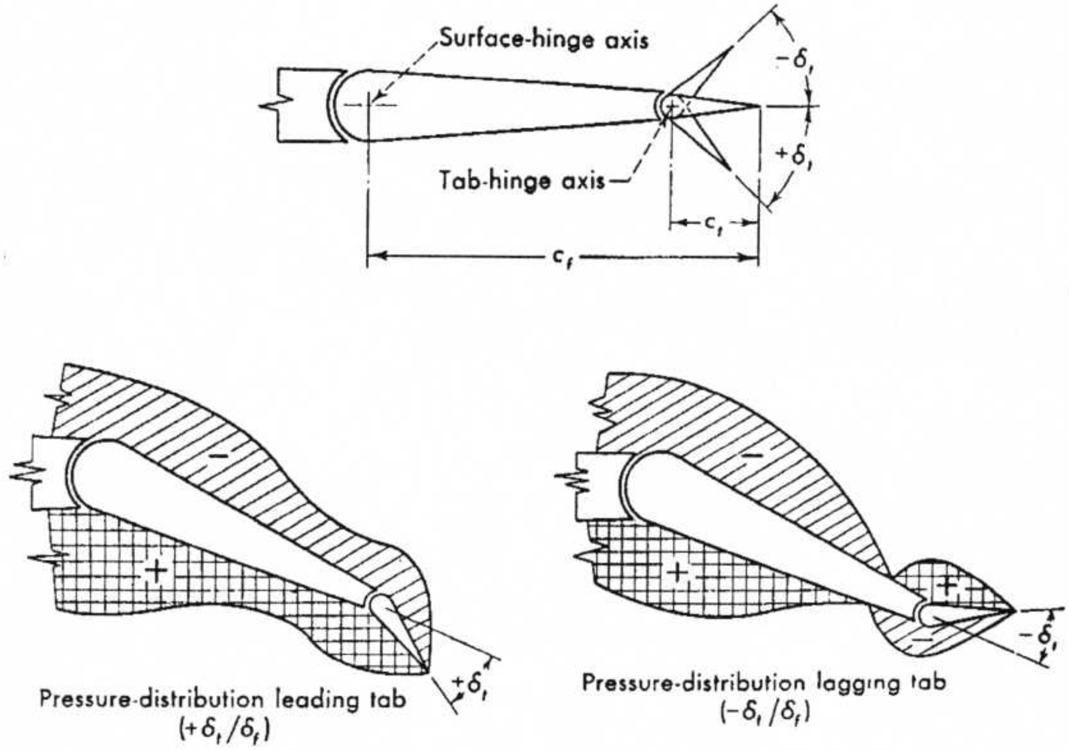

FIG. 12 : 16. Tab nomenclature and pressure distributions due to tab deflections.

size or contour restrictions found on the leading-edge types of aerodynamic balance. Several schemes of employment of the tab render it extremely versatile. The following discussions will demonstrate the basic schemes and illustrate the mechanisms used to actuate the tabs. The tab deflection angle δ_t is measured between the reference chord of the movable surface and the chord of the tab.

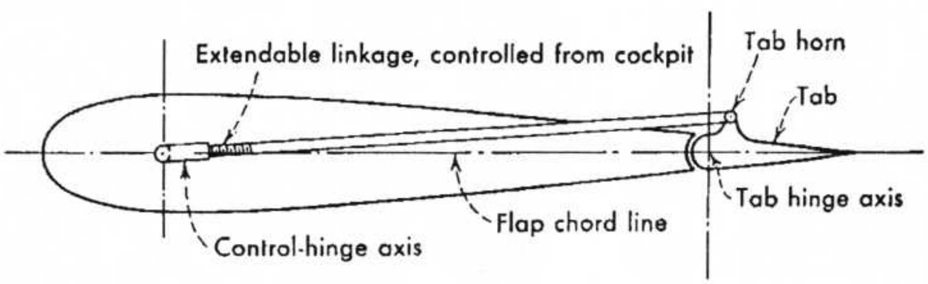

FIG. 12 : 17. Schematic arrangement of trim-tab mechanism.

TRIM TAB

A trim tab is a tab employed to reduce the hinge moment of a surface to zero for any given flight condition resulting in the trimmed or zero control-force condition. This type of tab may be set at the desired angle on the ground or, preferably, is adjustable from the cockpit at the will of the pilot. The tab once set maintains a given deflection until reset. A trim tab to be adequate should be effective in reducing the control forces to zero over the entire speed range for the various conditions under which the airplane will fly. Fig. 12 : 17 shows the usual trim-tab linkage.

LINK BALANCE TAB

The link balance tab is a tab geared to the control surface in such a way that it moves at a given ratio to the control-surface movement.

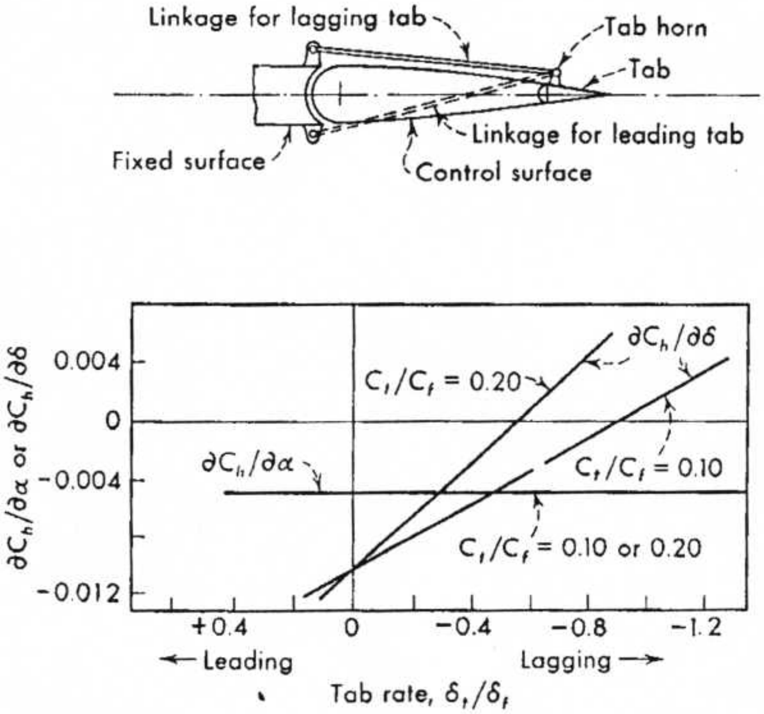

FIG. 12 : 18. Schematic arrangement of link-balance tab and effect on hinge-moment characteristics of full-span balancing tabs.

This ratio is usually expressed as δ_t/δ_f. The general effect is to change the value of $\partial C_h/\partial\delta$ without changing the value of $\partial C_h/\partial\alpha$. If the tab moves in the opposite direction to the surface, it is called a lagging tab and serves as a booster to reduce the hinge moments. If the tab moves in the same direction as the surface, it is called a leading tab and acts as an antiboost to increase the hinge moments. Fig. 12 : 18 shows a typical linkage for a link balance tab used as a booster and the effect on the hinge-moment characteristics of the 0.20c flap on the NACA 0009 airfoil, which has been used as an example throughout the previous discussions.

By incorporating a variable-length linkage in the system, the tab can be made to serve the functions of both a trim tab and a balance tab.

SERVO TABS

By connecting the tabs directly to the cockpit controls, the tab can be made to supply all the hinge moment required to move the control surface. The only control forces required are those necessitated by the hinge-moment characteristics of the tab itself. This system has been used on some very large aircraft. Fig. 12 : 19 shows a schematic linkage

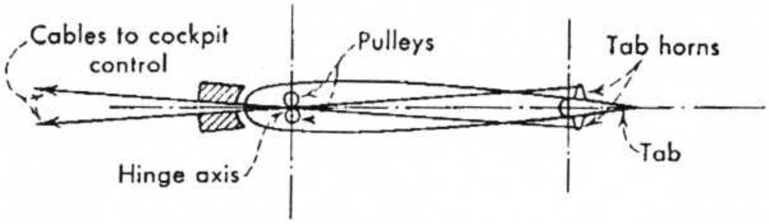

Fig. 12 : 19. Schematic arrangement of typical servo-tab mechanism.

for a servo tab. Note that the control cables have no direct connection to the control surface.

SPRING TABS

By incorporating a spring between the main control horn and the control surface itself, a tab may be connected that will operate to supply a fixed percentage of the required control force by acting as a boost tab. In effect, it is a variable-demand assist type of mechanism. Fig. 12 : 20 shows a schematic sketch of a spring-tab linkage. The actual appearance

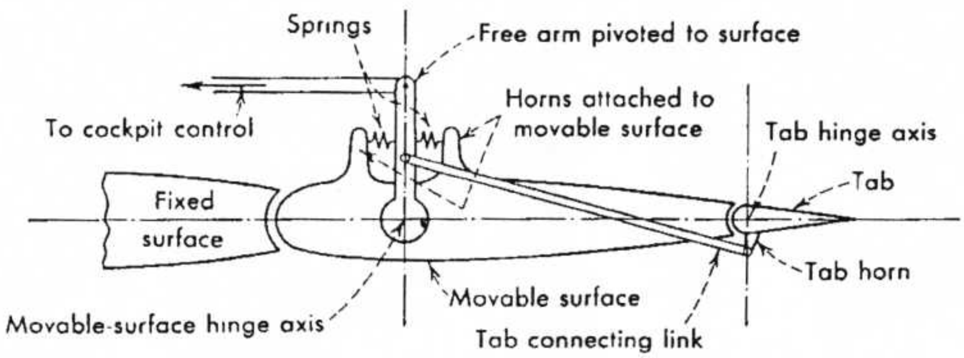

Fig. 12 : 20. Schematic arrangement of typical spring-tab mechanism.

of the spring mechanism may vary at the desire of the designer and according to the space limitations where it is to be applied.

Several NACA reports on the applications of spring tabs are listed in this chapter's bibliography. The amount of servo action depends upon the rate of the spring employed. It can be seen that an infinitely weak spring (no spring at all) causes the tab to behave as a servo tab, and that an infinitely stiff spring produces no boost action at all. By incorporating a variable-length linkage, the spring tab can also be made to serve the additional function of a trim tab. By preloading the springs, the boost action of the tab can be delayed until some predetermined control force is reached. The spring tab has been widely used in modern airplanes with good success. On very large surfaces, the spring tab (or servo tab) may produce a spongy feel in the controls to which the pilot may object.

EMPLOYMENT OF TABS

All tabs must be installed with tight linkages with *no backlash*. Loose tabs can cause destructive flutter of the surfaces to which they are attached. This applies with double emphasis to spring tabs.

It was pointed out that the functions of *trim and balance* or *trim and spring* can be combined in a single tab. Never more than two functions should be combined in a single tab (or tab system), and under no circumstances should the functions of *balance and spring* be combined in a single tab.

Tabs are useful, and the designer who properly employs them can do much to alleviate some of the difficult hinge-moment (control-force) problems that arise.

It is pointed out that tabs acting as a flap on a flap can alter the control-surface effectiveness parameter $dC_L/d\delta_f$ of the control surface to which they are attached. A leading tab will increase $dC_L/d\delta_f$ while a lagging tab will decrease $dC_L/d\delta_f$. A large span tab used as a boost, servo, or spring tab may seriously compromise the ability of a control surface to perform its function adequately. The NACA reports, which furnish most of the design information and numerical data for tabs, contain data on the effects of tab deflection on $dC_L/d\delta_f$.

12 : 7. Power-Boosted and Power-Operated Systems

In the preceding discussion on control-surface balance, it has been emphasized that as the speed and size of airplanes increase, some means of reducing the control forces to reasonable values is required. It has been shown that for a system in which the pilot's control is linked directly to the surface, the principal means of reducing control forces is to keep the value of the hinge-moment coefficient small. It was further shown that the use of aerodynamic balances that depend upon the *contour* of the control surface is limited, owing to the impossibility of getting consistent results when the required value of C_h falls below certain minimum values. The use of tabs (balance, spring, or servo), which are really servo mechanisms, minimizes the contour problem and *extends* the possibility of getting satisfactory results from a directly connected system. It was further pointed out that for very large surfaces, spring or servo tabs give an undesirable spongy feel to the control. In going through the transonic speed zone, erratic results from any kind of aerodynamic hinge-moment reducing device may be expected while mixed subsonic and supersonic flow exists on the control surface.