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PREDICTION OF WING CHARACTERISTICS

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INTRODUCTION

The problem of the prediction of wing characteristics is not necessarily restricted to the characteristics of the main lifting wing of an airplane. The characteristics of tail surfaces and of movable controls usually are also included since the factors that influence such characteristics are very similar to the factors that influence the characteristics of the main lifting wing. The general problem, therefore, is very broad and the number of aerodynamic quantities that need to be evaluated is considerable. Some of the important quantities are the lift, drag, and aerodynamic center, corresponding to various attitudes of the wing, the distribution of lift over the wing surface, the various forces and moments that affect the stability of the wing under dynamic flight conditions, the effectiveness of tail surfaces or of controls, and the aerodynamic forces that must be overcome in order to operate the controls. The present discussion is concerned with the various theoretical and empirical processes that have been found suitable for use in evaluating such quantities at flight speeds below the critical Mach number.

DISCUSSION

In order to evaluate the desired quantities, the theory of wing sections must be either supplemented or replaced by a theory of finite-span wings. In many instances, the desired quantities bear only a secondary relationship to the characteristics of wing sections. An example is the spanwise distribution of wing loading, which is influenced largely by the flow about the wing tips rather than by section characteristics. The chordwise distribution of loading also is affected by finite span; but in many instances, this effect is relatively unimportant. The assumption of a two-dimensional chordwise load distribution, therefore, is one reasonable simplification of the finite-wing theory.

A number of wing theories, based on various simplifying assumptions, have been developed. (See references 1 to 8.) The theories differ in accuracy and in the extent of their applicability. Before discussing specific details of the various theories, consideration will be given to some of the important factors that determine the usefulness of a wing theory. One important factor concerns the variety of wing plan forms to which the theory can be applied. Of equal importance, is the number of aerodynamic characteristics that may be treated by a given wing theory. A third factor concerns the suitability of a wing theory for consideration of appropriate wing section characteristics. This is important, since experiments have indicated that, through the action of the boundary layer, there may be large effects of the profile shape or of the surface condition. A fourth factor concerns the suitability of the theory for engineering applications or, more specifically, the time required for routine computations. With these items in mind, some of the physical concepts upon which the present-day theories are based might now be considered.

The practical wing theories make use of vortex lines for determining the load carried by the wing. (See fig. 1.) The theories differ in the manner in which the vorticity is assumed to be distributed over the wing surface and in the method employed for fixing the strength of the vorticity and, thereby, the magnitude of the lift. According to a very simple concept, which was proposed by Prandtl about 30 years ago and which is commonly called lifting-line theory (reference 1), the vorticity is assumed to be divided into bound and trailing elements, with the bound elements concentrated in a single line which should run approximately through the centers of pressure of the wing sections. The trailing vorticity leaves the wing in the form of a sheet and extends downstream to infinity. Downwash angles usually are calculated at a finite number of control points along the lifting line. The effective angle of attack of the wing is assumed to be the difference between the geometric angle of attack and the downwash angle. The strength of the vorticity, and hence the wing lift, is determined from section characteristics corresponding to the effective angle of attack. The lifting-line method, therefore, provides no indication of any possible distortion of the chordwise load distribution. Also, because the lifting line is necessarily straight, the method must be restricted to small angles of sweep.

Because of the recent emphasis on highly swept wings, consideration is being given to a more general (or lifting-surface) concept such as has been used by Falkner (reference 5) and Cohen (reference 6). According to this concept, the vorticity is assumed to be distributed both chordwise and spanwise over the wing surface. The strength of the vorticity is fixed by the condition that, at any point on the surface, the flow must be tangent to the surface. This method gives both the chordwise and the spanwise load distributions under potential-flow conditions. Wing section characteristics do not enter into the solution and, therefore, the effects of viscosity can be accounted for only in an indirect manner. For practical applications, the surface lift must be represented by a finite number of vortex lines and the boundary conditions must be satisfied at a finite number of control points. The simplest arrangement, which uses only one lifting vortex, is designated in figure 1 as the "simplified lifting-surface concept." This particular concept was suggested by Wieghardt (reference 3) and has been developed by Weissinger (reference 7) and Mutterperl (reference 8). The single lifting vortex is located along the wing quarter chord, and the boundary condition is satisfied along the wing three-quarter-chord line. Because the boundary condition is not satisfied at the lifting vortex, as in the case of lifting-line theory, the lifting vortex does not have to be a straight line; and the method, therefore, is applicable to swept wings. As in the case of lifting-line theory, however, this method does not account for any distortion of the two-dimensional chord loading.

All of the subsonic wing theories are based on the assumption of incompressible potential flow. The so-called first-order effects of compressibility can be accounted for, however, by resorting to a generalization of the Prandtl-Glauert rule (references 9 to 11), as indicated in figure 2. This rule implies that characteristics of a wing in compressible flow can be obtained by analyzing an equivalent wing in incompressible flow. The equivalent wing is obtained by increasing all longitudinal dimensions of the actual wing by the factor $1/\sqrt{1 - M^2}$. This results in a decrease in the aspect ratio A and an increase in the sweep angle Λ, as indicated by the equations given in figure 2. The compressible-flow pressures P_{comp} are obtained by multiplying the incompressible-flow pressures $P_{e_{inc}}$ for the equivalent wing by the factor $1/\sqrt{1 - M^2}$. This procedure, of course, does not account for changes in boundary-layer effects which may accompany changes in Mach number.

The general utility of the three wing-theory concepts is summarized in table I. The comparison is made on the basis of the Multhopp, Falkner, and Weissinger adaptations, which are considered to be the most suitable for practical use. With regard to applicability to wing geometry, the lifting-line method is subject to the most severe restrictions inasmuch as it is limited to high aspect ratio and low sweep angle. The lifting-surface theory has general applicability, and the simplified lifting-surface theory of Weissinger is applicable to all wings having straight leading and trailing edges. The lifting-line theory is readily applicable to a wide variety of wing characteristics (references 12 to 21); whereas, the lifting-surface and simplified lifting-surface theories, being considerably more cumbersome, have so far been applied to only a limited number of characteristics. Wing section characteristics can be easily accounted for only by the lifting-line concept. The lifting-line theory is most desirable from the standpoint of the time required for solutions. For example, in calculating a spanwise load distribution, the lifting-surface method takes about 60 times as long as the lifting-line method which uses four control points, and the simplified lifting-surface method takes about eight times as long as the lifting-line method for the same number of control points. Doubling the number of control points approximately quadruples the time required for solutions.

The importance of one of the factors considered in table I, that is, the suitability of a theory for consideration of wing section characteristics, is illustrated in figure 3. Chordwise load distributions resulting from angle of attack and from flap deflection, $(\Delta P)_\alpha$ and $(\Delta P)_\delta$, are shown. The particular distributions shown were obtained from two-dimensional thin-airfoil theory (references 16 and 22) and from tests of a two-dimensional NACA 0009 airfoil with a thickened trailing-edge portion (reference 23). As has been mentioned previously, some distortion of the two-dimensional chordwise load distributions would be expected to result from finite-span effects. The comparison of the experimental and theoretical load curves for the two-dimensional airfoil nevertheless provides a qualitative indication of differences that exist for finite-span wings.

The areas of the chordwise load curves represent the lift due to angle of attack and the lift due to flap deflection. The rates of change of these quantities with angle of attack and with flap deflection are commonly represented by the symbols C_{L_α} and C_{L_δ}, respectively. Integration for moment, about the flap hinge point, of the parts of the loads carried by the flap yields the hinge moment due to angle of attack and the hinge moment due to flap deflection. The rates of change of these latter quantities with angle of attack and with flap deflection are conventionally represented by the symbols C_{h_α} and C_{h_δ}, respectively. The greatest differences between the experimental and theoretical distributions are in the trailing-edge region where the boundary layer is relatively thick. Because of the convex contour in the vicinity of the trailing edge of the selected airfoil, the differences between theory and experiment are greater than would normally be obtained. The indicated differences do, however, provide a qualitative representation of usual conditions. Comparison of the total areas of the load curves indicates that the theoretical value of the lift due to angle of attack C_{L_α} would be subject to only a small error and that the lift due to flap deflection C_{L_δ} would be subject to a somewhat larger error. The theoretical values of the hinge moment due to angle of attack C_{h_α} and of the hinge moment due to flap deflection C_{h_δ} would be considerably different from the experimental values because of the large differences in the loads near the trailing edge. If a theory is to be applied to determination of the effectiveness and hinge moments of finite-span controls, it is important, therefore, that some means be provided for accounting for the effects of viscosity on the wing section characteristics.

The effects of viscosity also influence the variation of characteristics with Mach number, as is illustrated in figure 4. Comparisons are shown for the actual and theoretical variations with Mach number of the lift-curve slope C_{L_α} and of the rate of change of aileron hinge-moment coefficient with deflection C_{h_δ} for the wing of a fighter-type airplane (reference 24). The calculated curves are based on applications of the generalized Prandtl-Glauert rule which assumes no viscosity (reference 9). The calculated results for the lift-curve slope C_{L_α} are in good agreement with experiment almost up to the Mach number for which the force break occurs. Good agreement was not obtained, however, for the hinge-moment parameter C_{h_δ} even at moderate Mach numbers. The poor agreement probably is caused by variations, with Mach number, of the characteristics of the boundary layer, which were shown in figure 3 to have an important effect on hinge moments. As yet, there is no satisfactory method of accounting for such boundary-layer effects.

The fact that the lifting-line theory is inadequate at small aspect ratios, such as may be employed for tail surfaces or for high-speed wings, is illustrated in figure 5. This figure shows theoretical variations with aspect ratio of the lift-curve slope C_{L_α} and of the hinge-moment parameters C_{h_α} and C_{h_δ}. Results given by lifting-line-theory equations are compared with results indicated by a lifting-surface-theory method. (See references 25 to 28.) In the latter method, lifting-surface theory was used only to obtain corrections that could be applied to the usual lifting-line-theory equations. By this procedure, equations in terms of arbitrary section parameters could be retained. The curves shown were calculated from the measured section characteristics of an NACA 0009 airfoil equipped with a 30-percent-chord plain sealed flap. The results indicate that the difference between the two theories increases as the aspect ratio decreases; and, in the case of the hinge-moment parameters, the differences may be very large. The two test points in figure 5 represent results obtained from tests of two specific configurations. The results tend to be in better agreement with the lifting-surface theory than with the lifting-line theory; and, in general, tests of other models have given similar results. The errors of the lifting-line theory are of such a magnitude as to be intolerable for most design purposes.

As had been mentioned previously, the lifting-line theory cannot be applied to wings with large sweep angles. The simplified lifting-surface theory of Weissinger (reference 7) has been found to be very useful for the calculation of certain swept-wing characteristics, as, for example, the spanwise load distribution. Calculations of the load distributions have been carried out for a wide variety of wing plan forms (reference 29); and, in general, good agreement has been obtained with experiment, at least for low lift coefficients. (See reference 30.) Comparisons of measured and theoretical load distributions for an unswept wing, a sweptback wing, and a sweptforward wing are shown in figure 6. The agreement is fairly typical of what has been obtained for all but the most extreme plan forms. Comparison of the load curves for the unswept and sweptback plan forms shows the usual reduction in load near the wing root and increase in load near the wing tip as the wing is swept back. An increase in load near the root and a decrease in load near the wing tip is obtained as the wing is swept forward. These effects of sweep on the load distribution cause a tendency for the tip sections of sweptback wings to stall before the root sections; whereas, for sweptforward wings, the root sections generally stall before the tip sections.

The peculiar stalling characteristics of swept wings limit the lift-coefficient range over which any theory, if based on potential-flow concepts, can be expected to give reliable results. This fact is illustrated in figure 7. Comparisons of theoretical and experimental values of the aerodynamic-center location are given for an unswept wing and a wing with 45° sweepback (reference 31). Both wings had an aspect ratio of 4.1. For the unswept wing the aerodynamic center showed little movement to a lift coefficient at least as high as 1.0, and the experimental results were in good agreement with the value given by the Weissinger theory. For the wing with 45° sweepback, however, the aerodynamic center showed a large rearward movement, starting at a lift coefficient of about 0.6. Although the theoretical value was in good agreement with experiment at low lift coefficients, the agreement was very poor in the high lift-coefficient range where the wing probably was partially stalled. This limitation of the theory is illustrated only for the case of the aerodynamic center, but similar limitations have been observed for almost all of the aerodynamic characteristics. At the present time, it is possible only to make qualitative estimates of the characteristics at high lift. Wind-tunnel tests must be relied upon in order to obtain quantitative answers.

Rigorous theories have not yet been applied to all of the characteristics which are of interest. For certain purposes, however, reasonably reliable indications of the effects of a given geometric variable can be obtained from very simple considerations. The effects of sweep on finite-span wings, for example, are sometimes assumed to be the same as the effects of sweep on infinite-span wings. (See reference 32.) This approach neglects any consideration of the induced angle of attack or of the effects of sweep on the span loading. An example of the reliability of such an approach for one particular characteristic is shown in figure 8. This figure gives a comparison of experimental and calculated values of the aileron rolling-monent effectiveness C_{l_δ}. Infinite-span considerations indicate that the aileron rolling-moment effectiveness should decrease as the square of the cosine of the sweep angle. By applying this correction factor to the effectiveness parameter measured for the unswept wing, the dashed curve is obtained. Test results (reference 33) obtained with two sweptback wings were in reasonably good agreement with the calculated curve. Since unswept wings have been investigated rather thoroughly, both by theory and experiment, rough estimates of the aileron rolling-moment effectiveness for almost any swept-wing plan form can be obtained by this simple procedure. Several other wing characteristics have been handled in a similar manner. A somewhat different approach, in which consideration is given to the induced angle of attack, as well as to the infinite-span effect but with the effects on the load distribution still neglected, has been applied to the estimation of the stability derivatives of swept wings (reference 34).

There are certain problems that can be handled most satisfactorily by purely empirical procedures. An example is the determination of the control-surface balance configuration required in order to obtain specified values of the hinge-moment parameters. Theoretical procedures have so far been indequate for analyzing the characteristics of the various balancing devices; consequently, the effects of the many details of control-surface balances have been studied experimentally (references 35 to 38). Some of the important results of this work are summarized in figure 9.

The form of figure 9 has been found convenient for a number of different analyses of hinge-moment characteristics. It is a plot of the parameter C_{h_α} against the parameter C_{h_δ}, and the dashed line represents combinations of these parameters that would result in zero control force for a typical aileron. Lines of constant values of the control force for a given flight speed and a given altitude could be represented by lines drawn parallel to the zero-force line. Increasing heaviness, or underbalance, is obtained in moving to the left of the zero-force line, and increasing overbalance results from moving to the right of the zero-force line. A point, determined by the characteristics of a plain aileron (without balance), is represented on the chart by the small circle. The manner in which the hinge-moment parameters are altered through the addition of various aerodynamic balances is indicated by the lines radiating from the point for the plain aileron. The distance moved along a given line depends, of course, on the size or geometry of the balancing device. Empirical procedures are available for estimating the extent to which the geometry of the various balances must be altered in order to produce prescribed changes in the hinge-moment parameters (reference 37). The chart shows that the different devices vary considerably in the manner in which they affect the hinge-moment parameters. The balancing tab, for example, may have a large effect on C_{h_δ}, but a negligible effect on C_{h_α}. The addition of a beveled-trailing-edge balance, on the other hand, affects C_{h_α} and C_{h_δ} almost equally. Intermediate variations are obtained with a sealed internal balance and with balances of the plain overhang type. By proper choice of the balance or by combinations of various balances, it is possible to obtain almost any desired values of the hinge-moment parameters.

CONCLUDING REMARKS

In the foregoing discussion, a brief description has been given of the physical principles of the wing theories that are presently available to the aerodynamicist, and an indication has been given of some of the procedures that are being used to obtain solutions to specific problems. The procedures in use do not always utilize sound fundamental principles. The reason for this is not lack of a sound theory, but rather that the present theories are, in many instances, too cumbersome for practical applications. None of the present theories is satisfactory with regard to all of the points mentioned at the beginning of this paper. A theory that would combine applicability to arbitrary geometry with the many advantages of the present lifting-line theory would be extremely useful. The effects of compressibility, particularly for thick finite-span wings, and the effects of the boundary layer cannot yet be adequately accounted for. There is no reliable method of anticipating the conditions under which the flow first begins to break down on swept wings or of estimating the characteristics after the breakdown occurs. Many of the problems are complicated by the fact that wing flexibility enters as an important additional factor for some of the wing plan forms that are of current interest. The extent to which wing flexibility may have to be considered has not yet been well-established.

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TABLE I.- COMPARISON OF WING THEORIES

CONCEPT	LIFTING LINE	LIFTING SURFACE	SIMPLIFIED LIFTING SURFACE
METHOD	MULTHOPP	FALKNER	WEISSINGER
APPLICABILITY TO WING GEOMETRY	HIGH ASPECT RATIO, LOW SWEEP	GENERAL	STRAIGHT L.E. AND T.E.
APPLICABILITY TO WING CHARACTERISTICS	WIDE	LIMITED	LIMITED
WING-SECTION CHARACTERISTICS	EASILY HANDLED	NOT EASILY HANDLED	NOT EASILY HANDLED
*RELATIVE TIME REQUIRED	4 POINTS: 1 8 POINTS: 4	60	4 POINTS: 8 8 POINTS: 30

*FOR SPAN LOAD CALCULATIONS

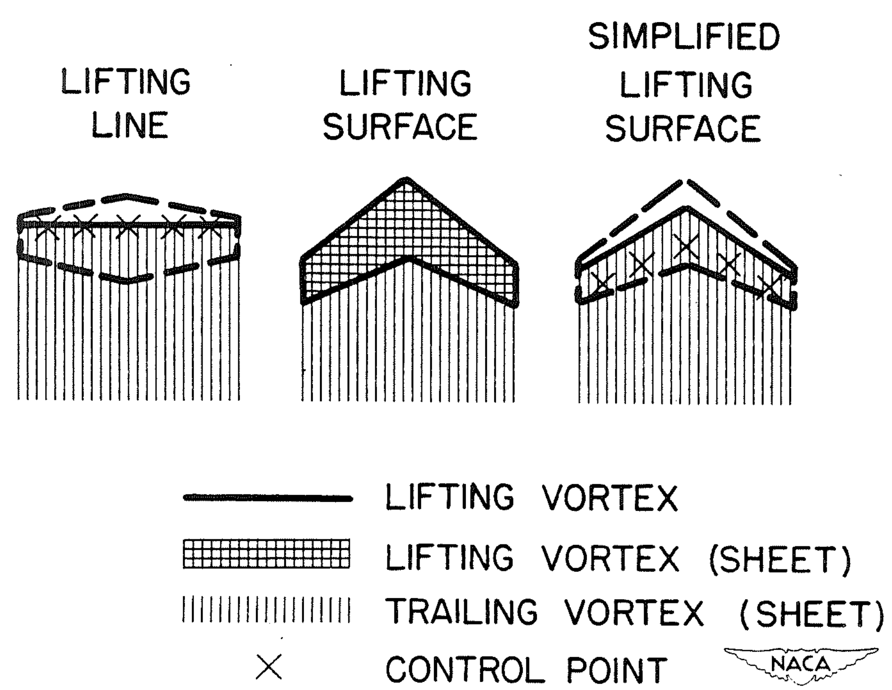
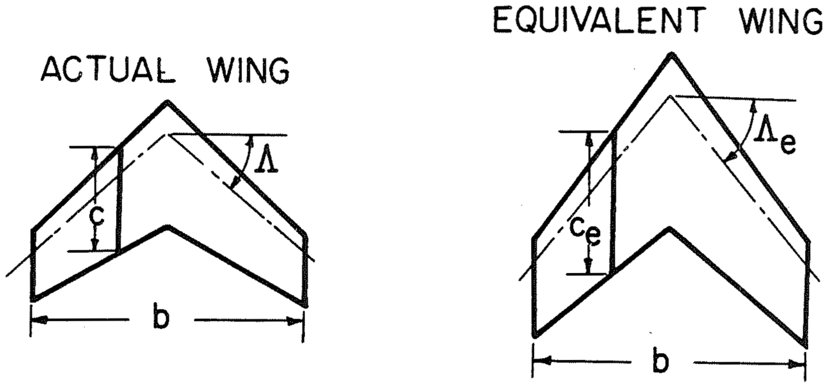


Figure 1.- Basic wing-theory concepts.



$$A_e = \sqrt{1-M^2}\; A$$

$$\tan \Lambda_e = \frac{1}{\sqrt{1-M^2}}\; \tan \Lambda$$

$$P_{COMP} = \frac{1}{\sqrt{1-M^2}}\; P_{e_{INC}}$$

Figure 2.- Actual and equivalent wings in compressible flow.

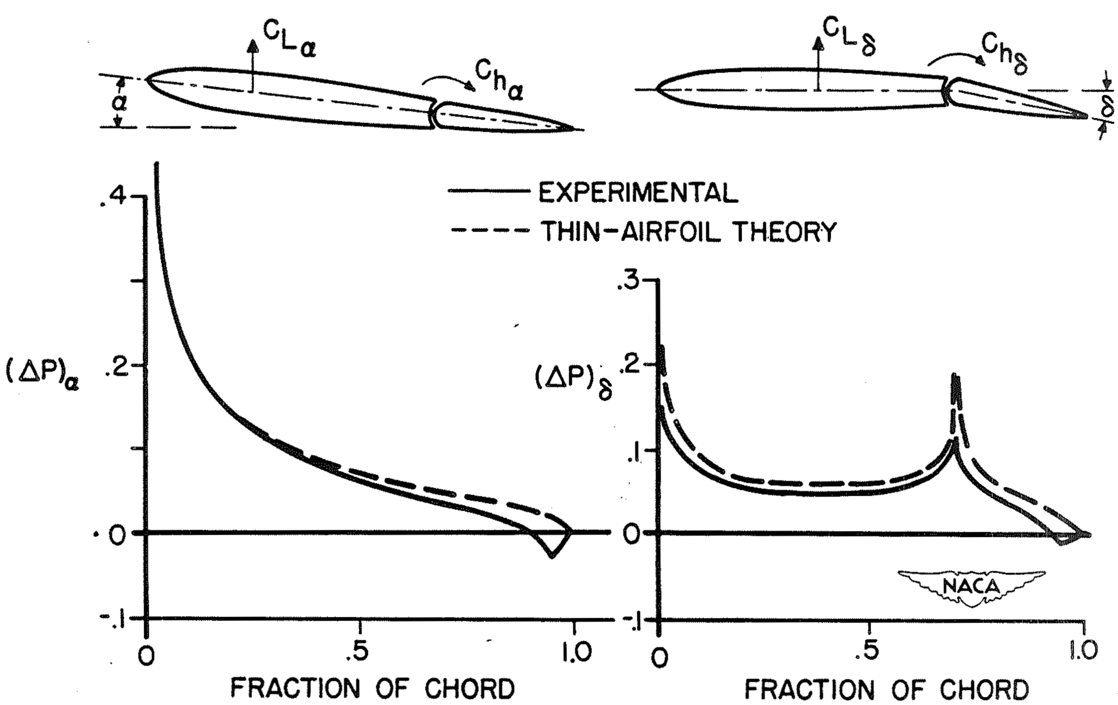


Figure 3.- Chordwise pressures for two-dimensional airfoil.

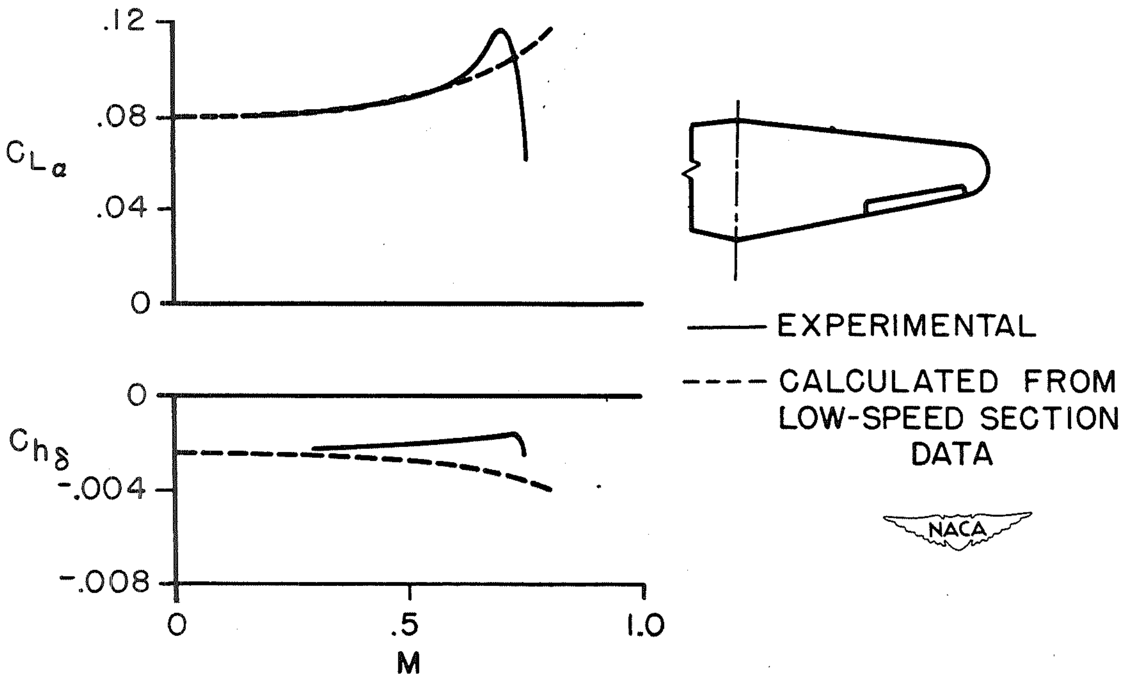


Figure 4.- Effect of Mach number on lift and hinge moments.

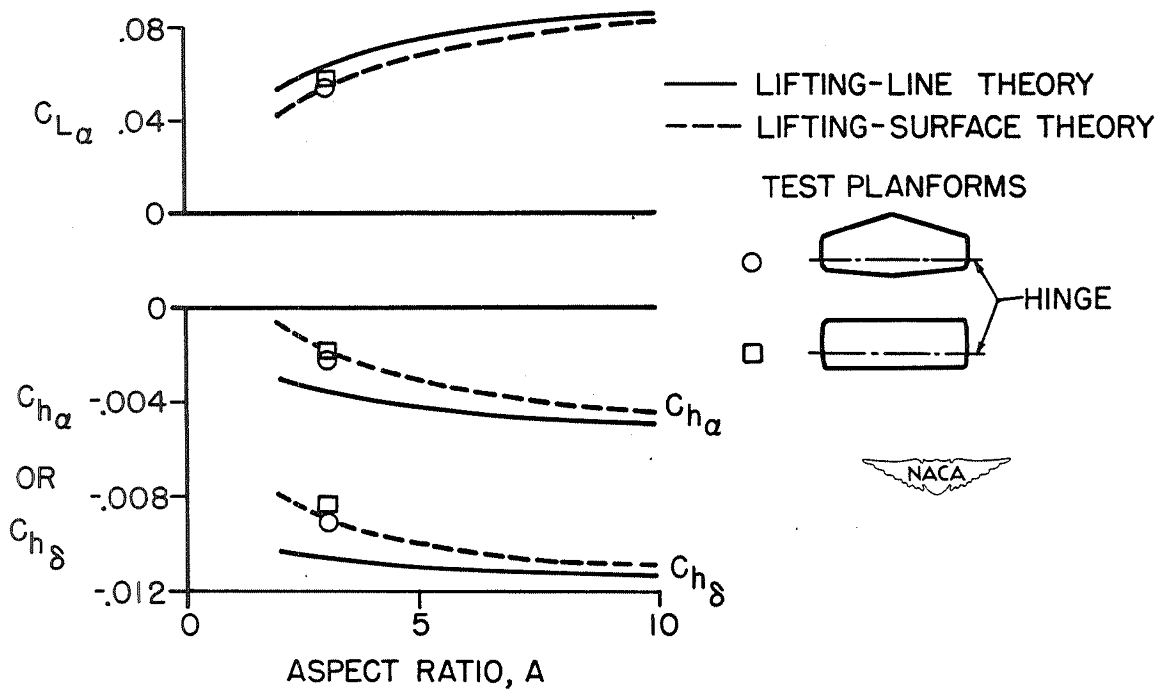


Figure 5.- Lift and hinge-moment parameters for 0.3 chord flaps.
NACA 0009 section.

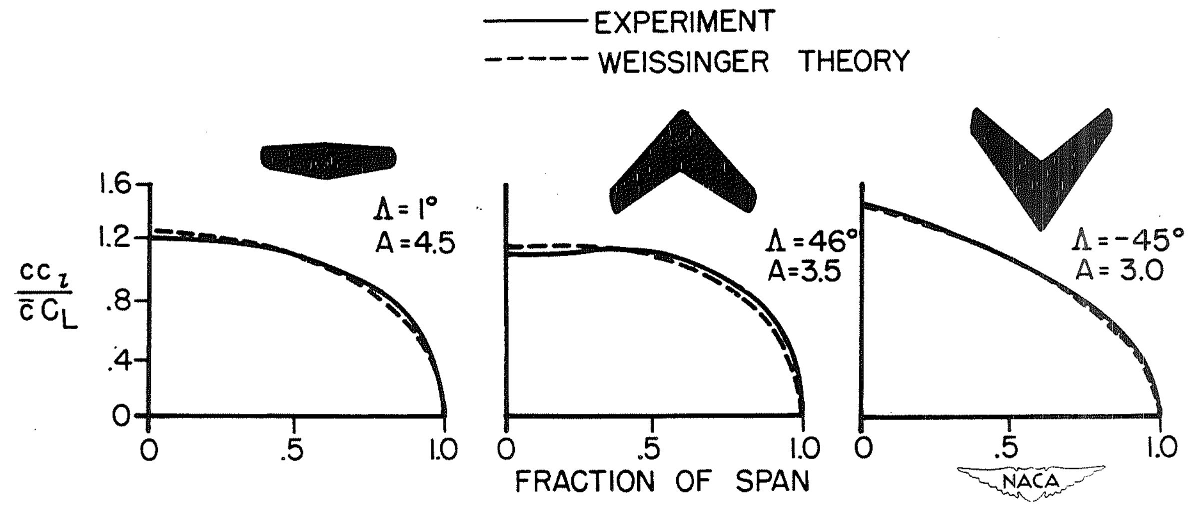


Figure 6.- Experimental and theoretical spanwise load distributions.

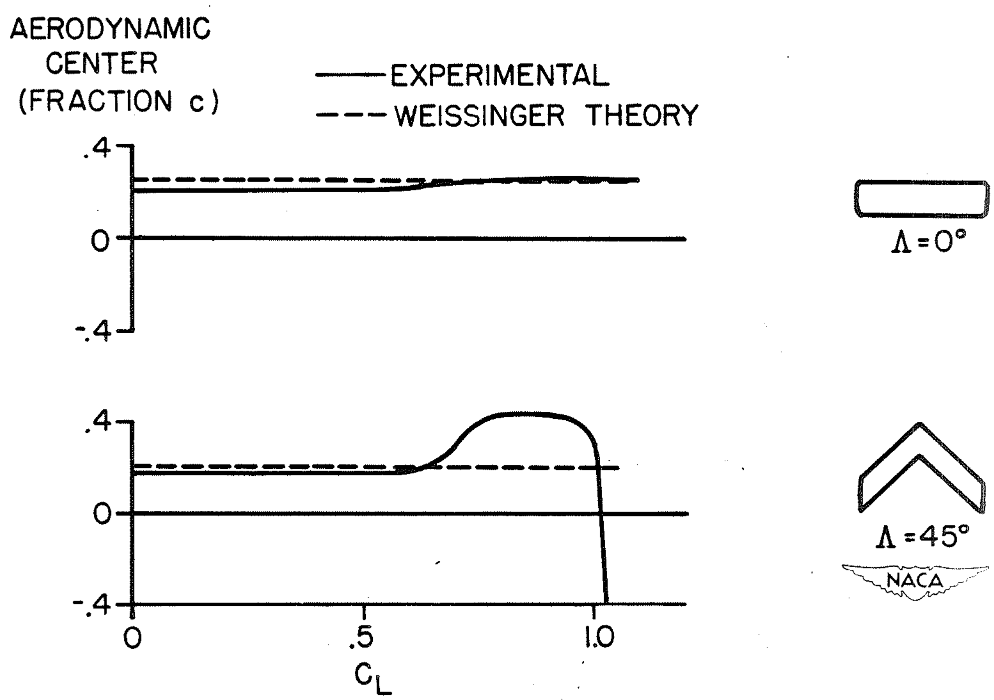


Figure 7.- Effect of sweep on aerodynamic center.

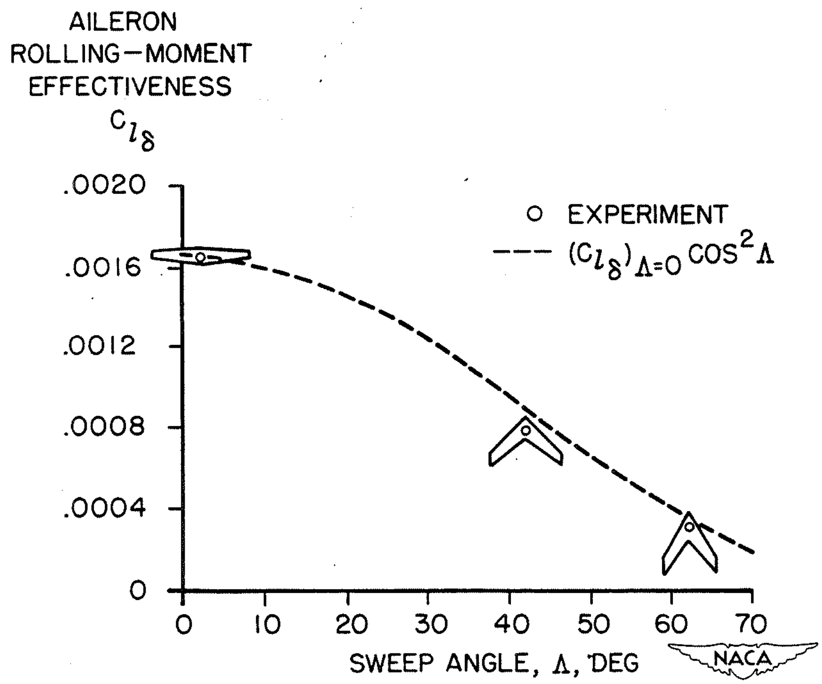


Figure 8.- Effect of sweep on aileron effectiveness.

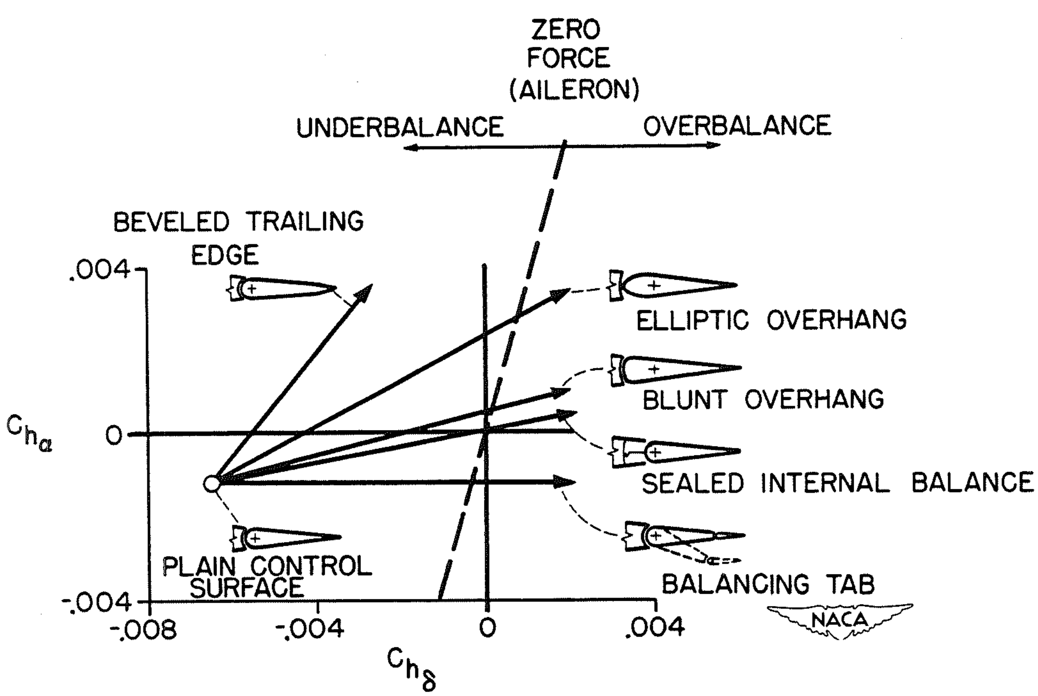


Figure 9.- Effects of control-surface balance on hinge moments.