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AN INTERIM REPORT ON THE STABILITY AND CONTROL

OF TAILLESS AIRPLANES

By Stability Research Division

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ADVANCE CONFIDENTIAL REPORT

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SUMMARY

Problems relating to the stability and control of tailless airplanes are discussed in consideration of contemporary experience and practice. In the present state of the design of tailless airplanes, it appears that:

(1) Sweepback affords a method of supplying tail length for directional and longitudinal stability and control and allows the utilization of a high-lift flap but introduces undesirable tip stalling tendencies that must be overcome before the advantages of sweepback can be realized

(2) The damping in pitching appears to have little effect on the longitudinal behavior of the airplane provided the static margin is never permitted to become negative

(3) The directional stability must be as great as for conventional airplanes if the same requirements regarding satisfactory stability and control characteristics are to be adhered to

(4) The influence of the lateral resistance and the damping in yawing on the flying qualities is somewhat obscure; however it is believed that these parameters will be of secondary importance if adequate directional stability is supplied

(5) On account of the difficulties encountered in obtaining adequate stability and control with tailless airplanes, it appears that a thorough reevaluation of the relative performance to be expected from tailless and conventional designs should be made before proceeding farther with stability and control studies

INTRODUCTION

Much interest has been shown in tailless airplanes during the past few years. A number of tailless-airplane designs have appeared and prototypes of several of these designs have been flown extensively. It appears desirable at this time to amplify and expand an earlier work (reference 1) relating to the stability and control of tailless airplanes in the light of the recent flight experience acquired and the related studies that have accompanied the development of new designs.

It is the purpose of this paper to assemble and record some expressions of fact and opinion pertaining to numerous problems that have assumed significance in tailless-airplane design rather than to supply specific quantitative design data. The problems specifically discussed in this paper pertain to the requirements and attainment of longitudinal and lateral stability and control and to spinning, tumbling, and steadiness in flight as regards gunnery and bombing platform. A discussion is also included of some of the relative merits of tailless and conventional airplanes.

SYMBOLS

C_L lift coefficient

C_D drag coefficient

C_l rolling-moment coefficient

C_n yawing-moment coefficient

C_m pitching-moment coefficient

V airspeed

r yawing angular velocity

ρ density of air

m mass of airplane

q dynamic pressure $\left(\frac{1}{2}\rho V^2\right)$; also, pitching angular velocity

T_c	thrust coefficient $\left(\frac{\text{Thrust}}{\rho D^2 V^2}\right)$
C_h	hinge-moment coefficient
α	angle of attack
β	angle of sideslip
Λ	angle of sweep
λ	taper ratio; ratio of tip chord to root chord
S	wing area, except as designated otherwise by subscript
c	wing chord, except as designated otherwise by subscript
$\bar{c}$	mean aerodynamic chord
A	aspect ratio
x	distance of aerodynamic center from center of gravity
z	vertical displacement of thrust axis from center of gravity (positive when thrust axis is below center of gravity)
b	wing span, except as designated otherwise by subscript
D	propeller diameter
F_s	stick force
ϕ	trailing-edge angle (see fig. 11)
θ	landing-gear angle (see fig. 13)
δ	control-surface deflection

$$C_{h_\alpha} = \frac{\partial C_h}{\partial \alpha}$$

$$C_{h_\delta} = \frac{\partial C_h}{\partial \delta}$$

$$C_{n_{\delta_a}} = \frac{\partial C_n}{\partial \delta_a}$$

$$C_{l_{\delta_a}} = \frac{\partial C_l}{\partial \delta_a}$$

$$C_{n_r} = \frac{\partial C_n}{\partial \frac{rb}{2V}}$$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{qc}{2V}}$$

$$C_{l_r} = \frac{\partial C_l}{\partial \frac{rb}{2V}}$$

μ relative density $\left(\frac{m}{\rho Sb}\right)$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

Subscripts:

f flap; also, flipper

a aileron

e elevator

t tab

r rudder

$\bar{c}/4$ about quarter point of mean aerodynamic chord

LONGITUDINAL STABILITY AND CONTROL

It was noted in reference 1 that a straight wing with a slight reflex camber and dihedral has all the necessary aerodynamic characteristics for both longitudinal and lateral stability. A straight wing employing a trailing-edge flap as a trimming control, however, suffers an undesirable loss in maximum lift, particularly if the static margin is large. In order to improve this condition, the installation of leading-edge slats has been considered. This solution has found little favor, however, because of the accompanying increase in profile drag and the unusually high attitude required for landing with leading-edge slats. At the present time the most practicable method of overcoming the deficiency in maximum lift appears to be to incorporate sweepback (or sometimes sweepforward) into the wing. The majority of the contemporary problems in longitudinal stability of tailless airplanes arise from the adoption of this solution.

Effects of Sweep

Advantages of sweep.- Sweepback gives the wing an effective "tail length" and is therefore especially adaptable for tailless airplanes. This tail length is proportional to the product of one-half the span of the portion of the wing with sweep and the tangent of the sweep angle; consequently, (1) high-lift flaps can be located at the center of the wing where their lift increments produce only minor changes in the pitching moment about the center of gravity of the airplane, (2) flaps for longitudinal control can be located near the wing tips where only minor changes in lift are needed to produce the requisite pitching moments for trim, and (3) more leeway is permitted in locating the center of gravity inasmuch as the aerodynamic center of the wing can be controlled by the angle of sweepback.

If only high lift is considered, the results of an investigation relating to the use of various types of flap on swept-back wings have indicated that trailing-edge split flaps are particularly suitable for swept-back wings because of the relatively small pitching-moment increment accompanying the production of a given lift increment (reference 2). The ratio of the pitching-moment increment to the lift increment produced by a flap depends, of course, on the position of the centroid of the flap load relative to the aerodynamic center of the wing. The centroid of the flap load has been observed to move forward along the wing chord as the hinge-line position of the flap is shifted forward, with the consequence that the ratio of the flap pitching-moment increment to the flap lift increment is reduced. The extent of the forward movement of the centroid of the incremental flap load accompanying a forward shift of the flap hinge line that may be expected for full-span trailing-edge split flaps is given in figure 1. It was noted in reference 3 that the ratio of the flap pitching-moment increment to the flap lift increment could be considerably reduced by moving the flap hinge line forward with only slight losses in the magnitude of the flap lift associated with a given flap deflection. It appears, therefore, that shifting the hinge line of the flap affords a promising means of minimizing the pitching moments caused by high-lift flaps but more data on this effect are needed before specific recommendations can be made.

It is known that, for trailing-edge flaps, an increase in flap chord shifts the centroid of the incremental flap load forward and thus causes a reduction in the ratio of the flap pitching-moment increment to the flap lift increment. This effect can be observed in figure 1 by comparing the results for different flap chords. At the present time, the optimum combination of flap size and flap hinge-line position for specific designs must be determined by experiment.

The lift increments produced by flaps are governed also by the plan form of the basic wing design. The important factors are (1) the aspect ratio, (2) the taper ratio, and (3) the angle of sweep. Of particular interest for tailless airplanes is the so-called self-trimming flap, which is a flap arranged to produce zero pitching-moment increment about the aerodynamic center of the wing. The effect of aspect ratio on the lift-coefficient increment produced by a self-trimming trailing-edge split flap on a swept-back wing is shown in figure 2. The effect of taper ratio on the lift-coefficient increment produced by a flap is discussed in reference 4 and an indication of the effect to be expected can be obtained from figure 3. In general, a moderate taper ratio of the order of 2:1 is recommended. The effect of sweepback on the lift increment produced by a self-trimming trailing-edge split flap on a swept-back wing is shown in figure 4. The data in figures 2 to 4 were taken from an analytical investigation of self-trimming trailing-edge split flaps (reference 2).

Although trailing-edge split flaps have been found to be particularly beneficial on swept-back wings in producing high lift, it is cautioned that there are considerations other than high lift involved in the selection of a flap for a specific design. For example, consideration of the minimum drag of flaps for take-off, ground clearance, and the operation of a pusher propeller in the flap wake may lead to the adoption of some other flap even at some sacrifice in lift.

Increases in maximum lift can be expected with swept-forward wings, provided the high-lift flaps are placed on the outer portion of the wing span and the flap for longitudinal control is placed at the center of the wing.

Disadvantage of sweep.- A most disagreeable characteristic of a swept-back wing is the inherent tendency to stall prematurely at the tips, a phenomenon primarily associated with the lateral flow of the boundary layer. This characteristic is particularly undesirable because it occurs first over the rear portion of the wing where the control surfaces are located. The tip stall is manifested as a pronounced pitching and rolling instability accompanied by a tendency of the elevators or ailerons to float upward. An example of the effect produced by the tip stall on the pitching moment of a swept-back wing is given in figure 5(a). The rapid increase in positive pitching-moment coefficient accompanying the tip stall is characteristic.

Swept-forward wings tend to stall first at the central part of the wing. Center-section stalling causes pitching instability but the rolling instability associated with the tip stall of swept-back wings does not occur. This advantage of sweepforward, however, is partly offset by the difficulty created in obtaining adequate static balance on account of the forward shift in the aerodynamic center of the wing caused by sweepforward. With swept-forward wings, the fuselage or load-carrying element must be placed ahead of the wing in order that the center of gravity may be ahead of the aerodynamic center.

Remedies for tip stalling.- Before satisfactory flight behavior can be assured, provision must be made for delaying or eliminating the tip stall. Various schemes have been proposed for delaying or eliminating the tip stall and a number of such schemes are summarized as follows:

(1) Wing twist - It has been proposed to wash out the wing tips, that is, to lower the angle of attack of the section near the tip. Reference 5 shows that the amount

of washout required to benefit the tip stalling characteristics is sufficient to increase the drag of the wing seriously at low angles of attack. One method of avoiding the high drag is to have a portion of the wing tip rotatable in flight. The rotatable wing tips should be so proportioned with respect to the elevator that the airplane cannot be stalled until the tip angle has been sufficiently reduced to eliminate the tip stall.

(2) Change in airfoil section - The initial stalling of the wing sections on the outer span of the wing can be controlled somewhat by increasing the thickness or changing the camber of the airfoil sections used. The results of reference 5 indicate that this method can appreciably increase the angle of stall of a wing without flaps or sweepback, particularly if a change in camber is used in conjunction with wing twist. The analysis in reference 5 does not consider the effects of sweep or flaps. Changing the wing sections, however, generally has the disadvantage of increasing the drag of the wing at low angles of attack.

(3) Flat-plate separators - It has been suggested that the tip stall might be delayed by means of vertical flat plates or fins alined with the wing chord at about one-half the distance to the wing tip and extending around the trailing edge of the wing and forward almost to the leading edge. The function of the plate is to prevent cross flow of the boundary layer by "separating" the fields of flow along the wing span. Experiments on swept-back wings with flat-plate separators installed have indicated that some increase in the angle of stall can be obtained by this method alone but that generally a new stall is induced just inboard of the plate itself. Better results might be obtained if the flat-plate separators are used in conjunction with changes in wing plan form, particularly in the vicinity of the wing tip.

(4) Changes in plan form at tip - According to tests made in the Langley free-flight tunnel, a change in wing plan form at the tip alone has little effect on the tip stall (fig. 5), as evidenced by the instability manifested by the pitching-moment curves for all tip arrangements. It appears from associated tuft studies that flow separation always occurs at the junction between the tip and the inboard portion of the wing. In any event, the change in plan form should extend inboard of the original stalled regions.

(5) Leading-edge slats - The use of tip slats has been found to be the most effective method of delaying the tip stall. Leading-edge slats may increase the angle of stall as much as 10° if judiciously located. Tests of models in the Langley free-flight tunnel have indicated the necessity of extending the slat at least over the portion of the wing affected by the stall. It has been found that slat spans of the order of 30 to 50 percent of the wing span are necessary to abolish completely the effects of the tip stall. Typical stalled areas behind a swept-back wing with various slat arrangements are shown in figure 6.

If fixed slats are used, an undesirable increase in drag may result at low angles of attack. It may be possible, however, to build retractable slats that have only minor effects on the over-all drag of the wing at low angles of attack after more research and work on the development of retractable slats have been done.

(6) Taper-- Part of the stalling of swept-back wings can be attributed to high taper. The use of highly tapered swept-back wings should be avoided, therefore, inasmuch as data on tapered wings indicate that the beneficial effects of sweepback can be obtained with moderate taper ratios of the order of 2:1 (reference 5).

Longitudinal Stability

As with a conventional airplane, a tailless airplane is statically stable if the center of gravity is ahead of the aerodynamic center. The position of the aerodynamic center is appreciably affected by (1) the addition of a fuselage or a streamline nacelle, (2) sweepback, and (3) power. The extent of the forward shift of the aerodynamic center produced by a fuselage or nacelle has been discussed in reference 1. The basic procedures for calculating the aerodynamic center of wings of various plan forms are given in reference 4. Applications of lifting-surface theory to the determination of the span loading of swept-back wings can be found in references 6 and 7. The effects of power on longitudinal stability are discussed in the following paragraphs.

Effects of power.- The analysis of the effects of power on the longitudinal stability is somewhat simpler for tailless airplanes than for the conventional airplane on account of the absence of the horizontal tail. For convenience, the effects are divided into three parts:

(1) Effects associated with normal force and direct thrust of propellers

(2) Effects associated with slipstream velocity and downwash behind propellers

(3) Effects associated with dynamic action of jets

The effect of the propeller normal force is small for the conventional arrangements of propellers and is usually a fixed factor for a given design. Methods of estimating the effect are available in reference 8.

As with conventional airplanes, the effect of the thrust on stability is directly proportional to the product of the thrust and the perpendicular distance from the center of gravity of the airplane to the thrust line. This effect is controlled, of course, by the vertical location of the propeller and the inclination of the thrust line. The farther above the center of gravity the thrust line passes, the greater is the stabilizing effect produced by a given thrust; and the farther below the center of gravity the thrust line passes, the greater is the instability produced by a given thrust. In any case, the farther from the center of gravity the thrust line passes, the greater are the changes in trim due to the thrust that accompany changes in power. This effect is illustrated in figure 7. The effects of power were small when the thrust-line axis passed close to the center of gravity of the airplane. When the thrust line was $0.048\bar{c}$ below the center of gravity, however, the stability decreased appreciably. At a lift coefficient of 0.8, the static margin decreased from 0.04 to 0.012 and the unbalanced pitching moment introduced by the thrust required about 10° of down elevator to trim the airplane.

The propeller slipstream is an important contributing item to the longitudinal stability characteristics of the airplane - particularly for tractor arrangements. The controlling factor is the location of the aerodynamic center of the portion of the wing immersed in the slipstream. If the aerodynamic center of this portion of the wing is behind the center of gravity of the airplane, the slipstream produces a stabilizing effect; if the aerodynamic center of this portion of the wing is ahead of the center of gravity of the airplane, the slipstream produces a destabilizing effect. Design parameters affecting the contribution of the propeller slipstream are (1) the location of the section aerodynamic centers, (2) the spanwise location of the propellers, and (3) the inclination of the propeller axis. The basic moment of the immersed wing sections also has an effect. Figure 8 indicates the magnitude of some of the power effects to be expected.

For the tractor-type tailless airplane shown in figure 8, the thrust line passes near the center of gravity so that the effect of the thrust is negligible. The aerodynamic centers of the wing sections immersed in the slipstream are ahead of the center of gravity, however, and the slipstream therefore produces a destablizing effect.

From consideration of changes in static margin and trim, it appears desirable on tailless airplanes of the pusher type to locate the thrust line close to the center of gravity of the airplane $\left(\frac{z}{c} < 0.01 \text{ is recommended}\right)$ and, if feasible, to locate the propeller so that the aerodynamic centers of the wing sections affected by the inflow to the propeller are either on or slightly behind the lateral axis through the center of gravity of the airplane.

For jet-propelled airplanes, the location and inclination of the jet axis exercises an effect on the stability characteristics of the airplane similar to the effect produced by the thrust of a propeller. At the present time, it appears that the location of the jet axis should be governed by the same factors which were considered in the discussion concerning the location of the thrust line of conventionally powered airplanes.

Damping in pitch.- As pointed out in reference 1, the low value of C_{m_q} associated with tailless airplanes is no serious disadvantage so far as the damping of the oscillations are concerned if the airplane has a positive static margin. It appears that damping is introduced by the particular coupling of the modes of motion as affected by the low value of C_{m_q} and by the reduced radius of gyration in pitch as shown in reference 1 and figure 9. The results of tests in the Langley free-flight tunnel (reference 6) indicated that changes in the rotational damping in pitch have little effect on the longitudinal steadiness for values of the static margin greater than 0.05.

It was pointed out in reference 1 that the reduced damping in pitch of a tailless airplane might result in an uncontrollable motion of the airplane if the static margin is allowed to become negative. This contention has been supported by subsequent tests in the Langley free-flight tunnel (reference 9). The tests indicated that a serious form of instability may develop when the static margin of a tailless airplane becomes negative. As a result of this danger of uncontrollable motions with negative static margins, it is recommended that the center of gravity of a tailless airplane never be permitted, under any conditions, to reach a position behind the aerodynamic center.

Tumbling.- A form of dynamic instability of tailless airplanes may be manifested as tumbling. Tumbling consists of a continuous pitching rotation about the lateral axis of the airplane. The maneuver is extremely violent and imposes severe accelerations on parts of the airplane. So far as is known, there are no authenticated instances of the occurrence of tumbling in flight. Models of tailless airplanes have been made to tumble in the Langley 20-foot free-spinning tunnel, however, by forcing the model to simulate a whip stall. At the present time, however, little is known about the mechanics of the tumbling motion. Tests conducted in the Langley 20-foot free-spinning tunnel have shown that the position of the center of gravity has a pronounced effect on the motion. It appears that provision of a large static margin prevents tumbling but that a stable tumbling condition may exist if the static margin is slight. Tests have shown also that once the tumbling motion has started the normal flying controls are relatively ineffective for recovery from this stable tumbling condition.

In view of the severity of the tumbling maneuvers, it is recommended that tumbling tests be required of models of all fighter tailless airplanes.

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Longitudinal Control

One of the difficult problems in the design of tailless airplanes is the provision of adequate longitudinal control. The type of longitudinal control usually employed consists of an elevator (or flap) placed at the trailing edge of the wing. With this type of control, the loss in lift caused by the flap deflection required to trim the airplane can be appreciable, particularly for a tailless airplane with a large static margin. The computed loss in lift that results from trimming the airplane at various values of static margin is shown in figure 10. It is evident from figure 10 that the loss in lift caused by the longitudinal control can be minimized by placing the control surfaces at the tips of highly swept-back wings of high aspect ratio. When the longitudinal control is placed near the wing tips, the elevator can be combined with the aileron in an arrangement to be discussed later in the section entitled "Aileron Control."

Design requirement.- It is to be expected that the elevator stick-force requirements for tailless airplanes should be the same as for conventional airplanes of the same class. The balance requirements for tailless airplanes, however, are more severe than for conventional airplanes. For the same static margin, the elevator of a tailless airplane usually must be deflected considerably more than that of a conventional airplane in order to produce the same changes in trim lift coefficient in flight. The elevator on tailless airplanes, being an integral part of the wing, must also operate at all angles of attack of the wing up to the stall. The elevator must therefore be balanced over a large range of angle of attack and deflection.

In order that push forces may be required to increase the airplane speed (from trim speed) and that pull forces may be required to reduce the airplane speed, the inherent upfloating tendencies of the elevator with increasing angle of attack must be reduced. The critical case for stick-force reversal (called elevator snatch) is that for neutral longitudinal stability (or zero static margin). If there is to be no stick-force reversal for this case, the variation of the elevator hinge moment with angle of attack must be zero or positive at all angles of attack throughout the flight range.

When this condition is fulfilled, the elevator either remains stationary or floats down as the angle of attack is increased. Further discussion of this point may be found in reference 10.

Types of control.- A plain flap is unsuitable for use as an elevator on a tailless airplane mainly because it floats upward as the angle of attack of the wing is increased. In figure 11, the upfloating tendency of the flap is manifested by the increasingly negative flap hinge moments that are developed as the angle of attack is increased. Various balancing schemes have been proposed for reducing or eliminating the upfloating tendency of plain flaps but no aerodynamic balances are yet known that completely satisfy the design requirements. Several balance arrangements, however, show promise of being satisfactory in two-dimensional tests but have received no experimental verification in three-dimensional tests. A few of the proposals are discussed in the following paragraphs:

(1) Bevels - Figure 11 presents the variation of elevator section hinge-moment coefficient with angle of attack at zero elevator deflection for straight-side and beveled elevators with and without internal balance vented at the hinge line. The curves indicate that the desired hinge-moment variation with angle of attack cannot be obtained with these arrangements of bevel and internal balance. Since the slopes for all elevators are nearly parallel at large angles of attack, it is not to be expected that favorable curves can be obtained either by further increasing the trailing-edge angle or by increasing the length of the internal balance vented at the hinge line.

Beveled elevators also affect the location of the wing aerodynamic center. The magnitude of the effect depends on the chord and span of the elevator. In general, the stick-fixed aerodynamic center of the wing moves forward with an increase in trailing-edge angle, and the stick-free aerodynamic center of the wing moves backward with an increase in trailing-edge angle.

(2) Special venting - It has been suggested that an internal balance be used which has a vent near the airfoil leading edge. Analysis of available data indicates that, at large angles of attack, however, this arrangement

would have the same unfavorable characteristics as the internal-balance arrangements vented at the hinge line.

An analysis of pressure-distribution data indicates than an internal balance vented near the trailing edge of the airfoil would give the desired hinge-moment variation with angle of attack. The fact that the pressure changes in this region of the airfoil are small, however, appears to demand an internal balance of such length as to be impracticable.

(3) Slots ahead of elevators - As the upfloating tendency inherent in all control surfaces at large angles of attack is caused by air-flow separation over the control surfaces, it has been proposed that slots be placed in the wing ahead of the elevator as one means of suppressing this effect. Very little research has been done on this particular scheme however and, at the present time, all that can be said is that it might be advantageous.

(4) Automatically controlled tabs - Several rather mechanically complex types of balance have been proposed to prevent elevator-force reversals. Because a tab is normally a powerful means of changing elevator hinge moments, it has been proposed to place a tab on the elevator and cause the tab to deflect upward in such a manner that the elevator floats down when the angle of attack is increased. The deflection of the tab would be controlled either by linking it to an internal balance, suitably vented, or by linking it to a free-floating spanwise portion of the elevator called a flipper. The flipper should be located along the span in a region where the stall is first manifested over the control surface. Two-dimensional characteristics of several such flipper-tab arrangements have been computed from section data, and the results are presented in figure 12. Some of the configurations result in hinge-moment slopes that are either zero or positive at all angles of attack. If similar characteristics could be obtained in three-dimensional flow, no stick-force reversal would occur for these combinations. The stick force could be controlled by adapting a spring either to the same tab or to an auxiliary tab.

(5) Spoilers - The possibility of using a spoiler as an elevator has been suggested as a means of avoiding

stick-force reversals. The loss in lift accompanying the production of a given pitching moment is greater with the spoiler control, however, than with the elevator control. Unpublished tests of rearwardly located spoilers on two different models confirm the fact that spoiler projections of less than 0.01c produce negligible changes in lift. Such a spoiler is undesirable for longitudinal control because a small stick movement produces no change in trim, whereas a larger movement of the stick may produce large changes in trim and normal acceleration. The characteristics of spoilers can be controlled somewhat by adjusting the spoiler span and by incorporating special venting to the spoiler.

Inasmuch as the spoiler may be located ahead of an aileron, an upward deflection of the spoiler would cause the aileron to have an upfloating tendency and at the same time cause the ailerons to be less nearly balanced.

Control for take-off.- Under take-off conditions, the longitudinal control, besides supplying a pitching moment large enough to trim the wing at the lift coefficient corresponding to the ground angle of the airplane, may be required to supply the "additional" pitching moment necessary to counteract (1) the pitching moment of the weight of the airplane about the point of contact with the ground, (2) the pitching moment created by the friction force on the wheels, and (3) pitching moments arising from interference caused by the proximity of the airplane to the ground (references 11 and 12). In order to make certain that the airplane has adequate longitudinal control to compensate for these additional pitching moments arising during the take-off, the Army requirements for an airplane equipped with a tricycle landing gear state that the longitudinal control shall be powerful enough to pull the nose wheel off the ground at 80 percent of the take-off speed during operation off terrain where the coefficient of friction is 1/10 (reference 13). An idea of the magnitude of the "additional" pitching moment that the longitudinal control must supply to compensate for the extraneous effects associated with take-off may be obtained from figure 13.

Because of the short moment arm associated with the elevator of a tailless airplane, it is extremely difficult to design an elevator that can alone supply the pitching moments necessary to meet the Army take-off requirements; for example, point A spotted on figure 13(c) was computed for a typical tailless airplane. For this case, a pitching-moment coefficient of -0.335 is needed to raise the nose wheel off the ground. The elevator effectiveness $C_{m_{\delta_e}}$ for this airplane is only -0.003 per degree, and thus the elevator cannot raise the nose wheel for take-off. In order to remedy this situation, it has been proposed to utilize the nose wheel as a jack to adjust the ground angle during the take-off run. If some scheme of this type is not provided, it appears likely that tailless airplanes may experience difficulty in raising the nose wheel off the ground at take-off if the landing-gear angle θ is large, particularly with large static margins.

Center-of-gravity range.- On the basis of the longitudinal stability and control problems which have been discussed, it appears that the permissible range of center-of-gravity position compatible with satisfactory flight behavior is more critical for tailless airplanes than for conventional airplanes. If the static margin becomes negative, there is danger of encountering longitudinal instability either as a divergence from straight flight or as tumbling. If the static margin is too great, the elevator control may not be powerful enough to raise the nose wheel off the ground at take-off. Furthermore, if the static margin is large, the elevator deflection required to trim the airplane in level flight may seriously impair the efficiency of the wing with a consequent loss in performance of the airplane. At the present time, a range of ultimate static margin from 0.02 to 0.08 appears to be reasonable for tailless airplanes.

LATERAL STABILITY AND CONTROL

Directional Stability

Since the publication of reference 1, several models of tailless airplanes have been tested in the Langley free-flight tunnel. It has been verified from these tests that the amount of directional stability possessed by tailless airplanes should be as great as required on conventional airplanes if the same requirements regarding satisfactory flying qualities are to be adhered to. The value of the directional-stability parameter C_{n_β}, recommended for conventional airplanes, is usually greater than 0.001 per degree. As evidenced from figure 14, however, models have been flown in the Langley free-flight tunnel and with a value of C_{n_β} of only one-third this amount although the best flying qualities of these models were obtained with values of C_{n_β} in excess of 0.001.

The inherent aerodynamic characteristics of the wing alone have sometimes been tried as the source for directional stability. The amount of stability contributed by the wing depends on the wing plan form and the lift coefficient. The effect of the wing plan form does not appear large but more data are needed on this subject. The directional stability of the wing alone increases somewhat with lift coefficient. The directional stability at low angles of attack for the wing alone has generally been found to be inadequate although adequate stability may sometimes exist at high angles of attack.

A pusher propeller usually contributes a small degree of directional stability because of the stabilizing normal propeller force. If, in addition, the pusher propeller is mounted behind a vertical tail surface, an additional increment in directional stability is realized from the vertical tail surface because of the effects produced by the inflow of air into the propeller.

The destabilizing effect of a fuselage or streamline nacelle on the directional stability has been discussed in reference 1. The destabilizing effect of the fuselage and nacelle of tailless airplanes is usually at least as great as the stabilizing effects contributed by the wing alone. It is therefore necessary on tailless airplanes to provide some method of supplying directional stability.

The provision of adequate directional stability for tailless airplanes is more difficult than for conventional airplanes because of the short longitudinal moment arm. A variety of fin arrangements and end plates of the type discussed in reference 1 has been tested on models of tailless airplanes in the Langley free-flight tunnel in an effort to improve the directional stability of specific models. A résumé of some of the more pertinent considerations that have evolved from these tests is given in the subsequent discussions.

(1) Fins - It has been found that, for a tailless airplane having a straight wing, adequate directional stability can be provided by vertical tail surfaces located at the center section of the wing near the trailing edge (or on the fuselage if one is available). The size and number of vertical tails necessary for a specific design of course depends primarily on the degree of directional stability required. When multiple tails are used, it appears to be preferable to use as few tails of as high aspect ratio as possible because (a) fins of high aspect ratio are more effective than fins of low aspect ratio, (b) the interference effects between adjacent vertical fins are minimized, and (c) much of the fin is outside the relatively thick boundary layer on the upper rear surface of the wing.

If the tailless airplane has a swept-back wing, the usual practice is to place the vertical tail surfaces at the tips rather than at the center section in order to take advantage of the longer moment arm available. When vertical fins are placed at the wing tip extremities, however, the moment arm associated with the drag of the tip fin is so large (one-half the span) that the drag characteristics as well as the lift characteristics of the tip fins exert an influence on the directional stability. The relative contribution of the lift and drag of the tip fins to the directional stability of the airplane of course depends on their inherent aerodynamic characteristics. Some attention must accordingly be devoted to setting the initial angle of the tip fins.

If directional stability is to be obtained with tip fins of low aspect ratio (less than about 2), the tip fin must be set with some initial toe-in because of the large induced drag associated with lifting surfaces of low aspect ratio. When the airplane is yawed, the stabilizing moments generated by tip fins are produced by the large induced drag of the forward wing tip. If, on the other hand, directional stability is to be obtained with tip fins of moderate or high aspect ratio, the tip fins must be set with some initial toe-out. With toed-out tip fins, the stabilizing moments are generated by the outwardly directed lift as explained in reference 1. The stalling characteristics of the tip fins, moreover, are an important design consideration. When an airplane with toed-out tip fins is yawed to an angle sufficient to stall the rear tip fin, a large destabilizing moment is generated by the increased drag of the rear tip fin. On the other hand, when an airplane with toed-in tip fins is yawed to an angle sufficient to stall the forward tip fin, a large stabilizing moment is produced. The manner in which the stalling of toed-in and toed-out tip fins affects the directional stability of the airplane is illustrated in figure 15.

It has been suggested that the effectiveness of drag tip fins can be augmented by employing an airfoil section possessing aerodynamic characteristics similar to those shown in figure 16 for the NACA 4306 airfoil. In practice, the tip fins are set at the correct angle of toe-in for zero lift in straight flight. When the airplane sideslips, the angle of attack of the leading tip fin is made more negative and thus causes a large increase in the profile-drag coefficient due to flow separation; whereas, at the same time, the angle of attack of the trailing tip fin is increased positively and thus causes only a relatively small increase in its profile-drag coefficient. Drag fins of this type have not been tested in flight. A lateral oscillation may possibly develop as a result of drag hysteresis, although such an effect has not been observed in tests of small-scale models.

The most effective tip fins tested in the Langley free-flight tunnel have been based on the profile-drag principle. Tip fins based on induced-drag principles have been somewhat less effective. The tip fins based on lift principles have been the least effective tested because of the short moment arm associated with the lift tip fins. The moment arm, however, is controlled by the angle of sweep so that, for wings with a large amount of sweepback, it may be feasible to design an effective lift tip fin. Central fins have generally been satisfactory, particularly if mounted on the end of a fuselage.

(2) Turned-down wing tips - The amount of inherent directional stability possessed by a wing may be increased by turning down the wing tips; thus, in effect, the wing tips are made to function somewhat as lower-surface tip fins and the increased directional

stability is manifested through the outward lift developed on the wing tips. The incorporation of positive dihedral angle on the wing, however, results in a decrease in directional stability because the lift of the wing itself is directed inward rather than outward (fig. 17). The destabilizing influence of a positive dihedral angle must be taken into account in computing the directional stability required of the wing tips. An examination of figure 17 indicates that the effects of the dihedral can practically nullify the effects of the turned-down wing tips. Turned-down wing tips are believed to be less satisfactory for securing directional stability than fins of the types previously discussed.

(3) Automatic control - It has been suggested that a tailless airplane of very low directional stability with fixed controls could be flown satisfactorily if an automatic pilot were geared to the directional control in such a manner that when the airplane sideslipped the amount of directional control supplied would be sufficient to increase the effective value of C_{n_β}. Reference 1 includes the suggestion that the directional control could be linked with the aileron control in order to minimize the effects of adverse aileron yaw. It is believed that satisfactory flight behavior could be obtained with such automatic-stabilizing schemes although, at the present time, no flight investigations of such applications have been reported.

Directional Control

The requirements of rudder control for tailless airplanes are essentially the same as for conventional airplanes. Rudder control is necessary to counteract the adverse yaw occurring during rolling maneuvers and to provide sufficient directional control to trim the airplane directionally at operation under asymmetric power conditions. At the present time, the solution to the problem of creating adequate directional control rests primarily in reducing the yawing moment that such a control must overcome; thus, it is of particular advantage on tailless airplanes to locate the propellers as close as possible to the center line and to provide ailerons that create favorable yawing moments when deflected.

The provision of adequate directional control on a tailless airplane with rudders based on lift principles is difficult because of the small moment arm available for control. Computations have indicated that rudders based on lift principles alone generally are not able to counteract the yawing moments generated by severe asymmetric thrust conditions even if mounted at the tip of a swept-back wing. Lift rudders must also develop an appreciable side force because of the short moment arm. In order to compensate for this side force, the tailless airplane must be sideslipped or banked an appreciable amount because of its low lateral resistance. Some of the flight difficulties that may arise as a result of these circumstances are discussed in reference 14. Some use has been made, therefore, of directional control that is dependent upon drag characteristics because of the large moment arm which can be obtained by locating the drag directional control at the wing tip.

It appears possible to design a rudder based on drag principles utilizing a double split flap (brake flap) that could trim the yawing moments caused by asymmetric thrust conditions (fig. 18). It is cautioned, however, that split-flap rudders may generate undesirable rolling moments along with the yawing moments produced. This type of rudder may also affect the performance of the airplane if the drag increments necessary for control are very large. At the present time, specific designs of rudders of this type should be developed experimentally.

The use of propellers mounted in the wing tips has been proposed as a method for supplying directional stability and control. Such a system could, of course, be used easily with an automatic pilot. It is believed, however, that structural considerations may make such an arrangement impracticable at the present time.

Dihedral

The requirements of dihedral for stability are essentially the same for a tailless airplane as for a conventional airplane. Computations of the type presented in references 15 and 16 and investigations conducted in the Langley free-flight tunnel (fig. 14 and reference 17) have indicated that, in the interest of lateral control and steadiness in gusty air, it is desirable to keep the effective dihedral angle small. The results of these investigations have indicated that, for satisfactory lateral stability, the effective dihedral angle should not exceed a value corresponding to $C_{l_\beta} = 0.001$ per degree. This value of C_{l_β} corresponds to a geometric dihedral angle of about 5° on a plain wing with no sweepback. It is noted that for a wing with no sweepback C_{l_β} is practically independent of lift coefficient.

Effect of sweepback.- Systematic investigations to determine the effect of sweepback and taper on C_{l_β} are being conducted. The limited data available at the present time indicate that the effective dihedral of a swept-back wing increases with angle of attack; it is thus advisable to use a geometric dihedral angle of about 0° in order that, at the higher lift coefficients, the effective dihedral does not exceed 3° or 4°. The increase in C_{l_β} with angle of attack for a swept-back wing is not so detrimental as might first be supposed, however, because of the accompanying increase in weathercock stability. An empirical formula for estimating the effect of sweep on C_{l_β} is discussed in reference 18.

Effect of sweepforward.- The effective dihedral of a swept-forward wing decreases as the angle of attack is increased. Some idea of the magnitude of the effect to be expected is given in reference 18. There is an indication also that the weathercock stability of a swept-forward wing may decrease with increase in angle of attack. This effect would make the attainment of lateral stability over a large range of angle of attack difficult. More information on swept-forward wings is needed, however, in order to evaluate these effects.

Aileron Control

The aileron control of a tailless airplane presents no problems greatly different from those for conventional airplanes. An effort should be made, however, to avoid adverse aileron yawing moments, particularly if the directional stability is low, in order to minimize the sideslip developed during rolling maneuvers. Adverse aileron yawing moments can be minimized by uprigging both ailerons or by utilizing rotatable wing tips of the type previously described. In order to overcome the effects of adverse aileron yaw, it may be of advantage to employ a spring connection between the aileron and rudder control in a manner described in the section entitled "Tactical maneuvers." It is desirable also that no pitching moments be produced by the deflection of the ailerons because the ailerons have nearly the same moment arm as the elevators. It is necessary therefore to use ailerons with an equal up and down deflection.

Spoiler control.- The use of spoilers for ailerons on tailless airplanes has been advocated from time to time. If only upgoing spoiler projections are used, the pitching moments developed are prohibitive. A spoiler arrangement employing equal up and down projections would improve this condition but the data available are insufficient for evaluating conclusively the merits of such a system.

Elevon control.- For some tailless airplanes utilizing a swept-back wing, ailerons placed near the wing tips have been made to act also as elevators because the most effective position for both controls is near the wing tips and because larger-span lift flaps can be employed if the two controls are combined. Such an arrangement, called elevons, combines the design requirements of both aileron and elevator in one control and introduces additional problems.

The total effective deflection range for an elevon must be the sum of the ranges required for the aileron and elevator. The fact that the neutral position of the elevon may be at some upward deflection when it is functioning as an aileron can be utilized to a certain extent in reducing the aileron stick forces. With a large static margin, however, the full aileron deflection used with the large upward elevator deflection required at low speed may produce large pitching moments and small rolling moments because the upgoing elevon may stall. In order to improve this condition in some designs, the use of an auxiliary longitudinal trimming device called a pitch flap has been proposed. The pitch flap is located outboard of the aileron. With such a device, the lateral control could be obtained at low speeds by supplying most of the trim with the pitch flaps and thereby minimizing the upward deflection of the elevons. The elevons then would be deflected as ailerons over a greater linear range of the curve of rolling moment against deflection.

The conditions regulating the balance of an elevon for a typical large tailless airplane are indicated in figure 19. The ranges of values of C_{h_δ} and C_{h_α} that satisfy the stipulated elevator and aileron requirements independently were evaluated by the methods given in references 10 and 19. The crosshatched region includes all values of C_{h_δ} and C_{h_α} that satisfy simultaneously the stipulated elevator and aileron requirements. The elevon must be balanced over a much larger deflection range than either the elevator or aileron alone and, because of the increased deflection range required, greater physical limitations are imposed concerning the length of the internal balance that can be used. The considerations that have already been discussed in regard to controlling the upfloating tendency of the elevator with angle of attack also apply to the elevons.

Trimming-tab operation of elevons differs from that for ailerons alone in that the tab must trim the hinge moment of each elevon to zero when it is desired to trim the airplane in roll in order to prevent the development of elevator stick forces. For ailerons alone, it is essential only that the tab cause one aileron hinge moment to balance that of the other aileron.

Section data from unpublished tests of an internally balanced, beveled, 0.18c elevon with $0.25c_e$ tab indicate that for angles of attack up to the stall a full-elevon-span tab deflected $\pm 20^\circ$ could trim to zero the hinge moment of an elevon deflected $\pm 25^\circ$. The same data, however, indicate that little if any additional rolling moment can be produced by deflecting the elevon upward beyond 25° at large angles of attack.

Dynamic Stability

Damping in yawing.- For tailless airplanes, the rotational damping is invariably low on account of the reduction of the tail length. A comparison of the measured damping-moment coefficient due to yawing at a lift coefficient of 0.60 for various tailless airplanes and a conventional airplane is given in figure 20. The values were obtained by the free-oscillation method described in reference 20. The portion of C_{n_r} contributed by the wings can be estimated from the data in reference 21. It was pointed out in reference 1, however, that within the usual limits of dihedral and directional stability the damping of the lateral oscillations is generally greater than would be indicated from only the damping due to yawing velocity. Subsequent experience in flying tailless models in the Langley free-flight tunnel has substantiated this statement, and it appears that the small values of the damping parameter C_{n_r} associated with tailless airplanes will not be excessively detrimental to the flying qualities provided the directional stability of the airplane is adequate. The damping of the lateral oscillations is likely to be critical in the high-speed conditions because both C_{n_r} and the coupling between the yawing and rolling motion tend to diminish at the low angles of attack.

On account of the low values of C_{n_r} associated with tailless airplanes, some apprehension has existed concerning the large angles of sideslip that may be developed when the airplane is subjected to a disturbance of the type produced by asymmetric loss of thrust. There appear to be no data pertaining to the direct effect of C_{n_r} on a sideslipping motion of this type. The experience acquired in flying tailless-airplane models in the Langley free-flight tunnel has indicated that the effect of C_{n_r} is probably secondary to other parameters. The results presented in reference 15 indicate that the maximum amplitude of the sideslip oscillation is influenced markedly by the rolling moment due to the sideslip C_{l_β} and particularly by the yawing moment due to the sideslip C_{n_β}. Increasing either the directional stability or the dihedral reduces the magnitude of the sideslip generated by a yawing moment but the greatest reduction in sideslip appears to result from increasing the directional stability.

Spinning.- Tests conducted in the Langley 20-foot free-spinning tunnel have indicated that the steady-spin characteristics of tailless airplanes are essentially the same as for conventional airplanes. The control manipulations required for recovery from a steady spin, however, have been found to depend on the type and location of the control surface employed.

[redacted]

For tailless airplanes that have a vertical tail mounted at the rear of a fuselage, the application of rudder control would probably affect the spin in a manner similar to that for a conventional airplane because the vertical tail is not blanketed by the wing. If the vertical tail is located on the rear upper surface of the wing, however, the rudder control is likely to be ineffective because of the blanketing effect of the wing.

For tailless airplanes that have vertical tails at the wing tips, the application of rudder control would probably be effective for spin recovery, particularly if the rudder extends below the wing. For tailless-airplane designs without a fuselage, spin recovery has been found to be expedited by application of rolling moments against the spin. The ailerons therefore should be moved against the spin for best recovery. The moments produced by trailing-edge drag rudders in the stalled range of angle of attack may be considerably different from those in the unstalled range. Some types of drag rudder have been found to produce appreciable pro-spin rolling moments when applied against the spin and therefore are not effective for recovery. It is recommended, therefore, that the aerodynamic characteristics in yaw for different rudder deflections of tailless-airplane designs that have drag rudders be obtained at angles of attack beyond the stall if the possibility of a spin appears likely. The results of these tests would facilitate the evaluation of the relative merits of alternative rudder designs. For a complete investigation of the recovery characteristics, spin tests of the model are usually required.

Tactical maneuvers.- The suitability of tailless airplanes for performing tactical maneuvers of the nature required for formation flying, bombing, and aerial combat has been the subject of frequent discussion. From considerations previously discussed, it appears that adequate directional stability is a necessary requirement for steadiness and ease of control. The fact that the lateral resistance associated with tailless airplanes is low may preclude the possibility of making flat turns with the rudder alone. At the present time, however, little information is available concerning the influence of side area on the lateral flying qualities of tailless airplanes. More research is needed on this subject, particularly in regard to the effects produced by the different directional-control devices mentioned in this paper.

The argument has been advanced that a pilot flying a fighter tailless airplane will experience difficulty in keeping his gunsight alined with the target. It is believed however that, if the tailless airplane possesses the same directional stability and dihedral characteristics as are demanded for conventional airplanes, the controlled motions during the normal accelerated maneuvers should not differ appreciably from those of the conventional airplane.

In view of the likelihood that the successful tailless-airplane design may yet have lower directional stability than conventional airplanes, the effect of adverse aileron yaw on the pilot's aim may be more pronounced and in such cases a spring connection between the aileron and a trimming tab on the rudder may be necessary in order to satisfy the following criterion:

$$\frac{C_{n_\beta}}{C_{l_\beta}} > \frac{C_{n_{\delta_a}}}{C_{l_{\delta_a}}} < \frac{C_{n_r}}{C_{l_r}}$$

Such an arrangement should improve the steadiness of flight.

GENERAL CONSIDERATIONS OF TAILLESS AND CONVENTIONAL AIRPLANES

In recent years opinion has been divided as regards the relative adaptability of tailless and conventional airplanes for both fighter and bomber airplanes as evidenced by the variety of designs that have appeared. Some observations concerning the relative merits of tailless and conventional designs are offered here from consideration of the stability and control problems that have been discussed.

Small airplanes.- On account of the thin wing sections required for high speed, the volume enclosed by the wings of a small airplane is not large enough to carry all the load; consequently, it is necessary on small airplanes of either the tailless or conventional type to incorporate a fuselage or some other load-carrying element. It appears also that a vertical tail is necessary for directional stability. The difference between a small tailless airplane and a small conventional airplane, therefore, is essentially due to the suppression of a horizontal tail as a means of obtaining longitudinal stability and control. If the conventional airplane were permitted a reduction in maximum lift comparable with that tolerated on tailless airplanes, the tail size could be reduced considerably. With the small horizontal tail then allowable, the conventional airplane might have a performance comparable with that usually claimed for tailless airplanes without the restrictions attached to the longitudinal control.

Large airplanes.- For large airplanes, having spans of 150 to 500 feet, the volume of the wing alone may be sufficient to enclose bulk or weight of an appreciable magnitude even with the thin wing sections required for high speed. There is little reason to suspect that conventional airplanes of equal span will have any less wing space available for cargo purposes than tailless airplanes. It appears, therefore, that the suppression of the fuselage as a load-carrying element is primarily a matter of airplane size rather than of type.

In spite of the suppression of the fuselage, however, a vertical tail may be necessary on any large airplane, particularly on bombers, if optimum directional stability and control are to be obtained. Some method must also be provided for obtaining longitudinal control. Whether the longitudinal control is obtained by elevons or by a horizontal tail located on a tail boom would seem to have a secondary influence on the ultimate performance to be expected. On the basis of the present knowledge of the stability and control characteristics of tailless airplanes, it appears desirable to make a comprehensive study of the comparative performance to be expected from tailless and conventional airplanes before proceeding farther with stability and control studies.

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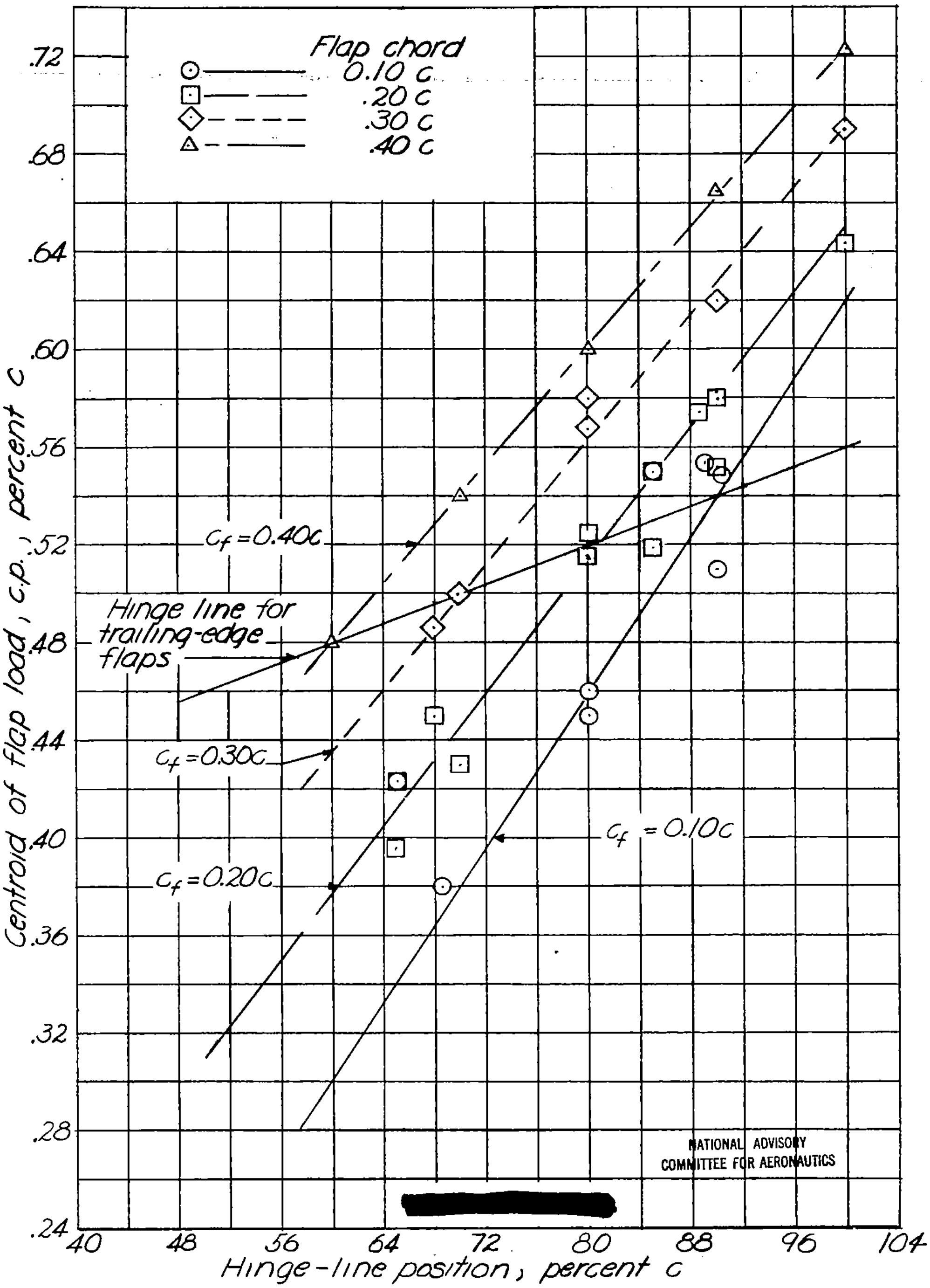

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Figure 1.- Variation of centroid of incremental flap load with flap hinge-line position for full-span trailing-edge split flaps.

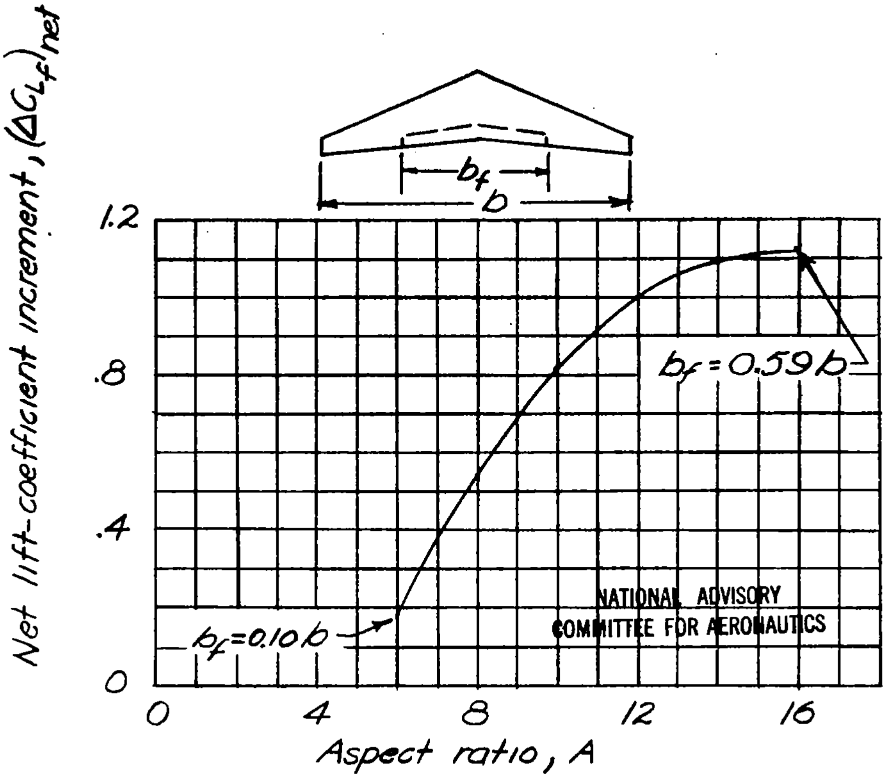

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Figure 2.- Effect of aspect ratio on the increment in lift coefficient produced by trailing-edge split flap having zero pitching-moment increment about the aerodynamic center of the wing. $1/\lambda = 4:1$; $\Lambda = 20°$; $c_f = 0.30c$; $\delta_f = 60°$.

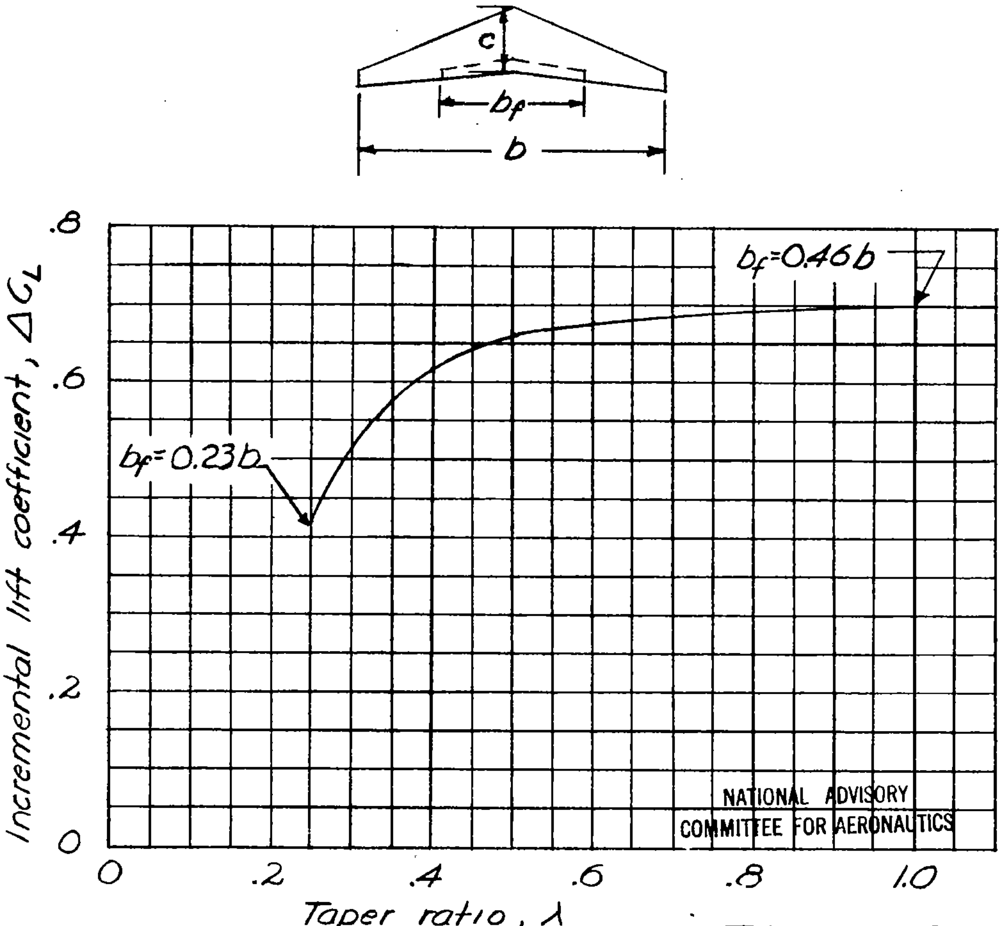

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Figure 3.- Effect of taper ratio on the increment in lift coefficient produced by trailing-edge split flap having zero pitching-moment increment about the aerodynamic center of the wing. $\Lambda = 20°$; $A = 7.3$; $c_f = 0.30c$; $\delta_f = 60°$.

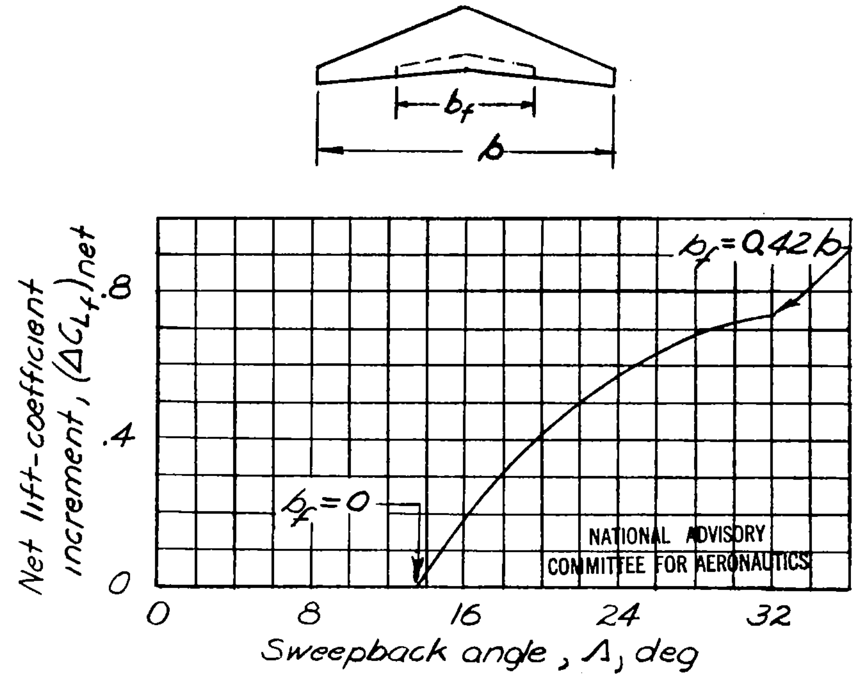

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Figure 4.- Effect of sweepback on the increment in lift coefficient produced by trailing-edge split flap having zero pitching-moment increment about the aerodynamic center of the wing. $1/\lambda = 4:1$; $A = 7.3$; $c_f = 0.30c$; $\delta_f = 60°$.

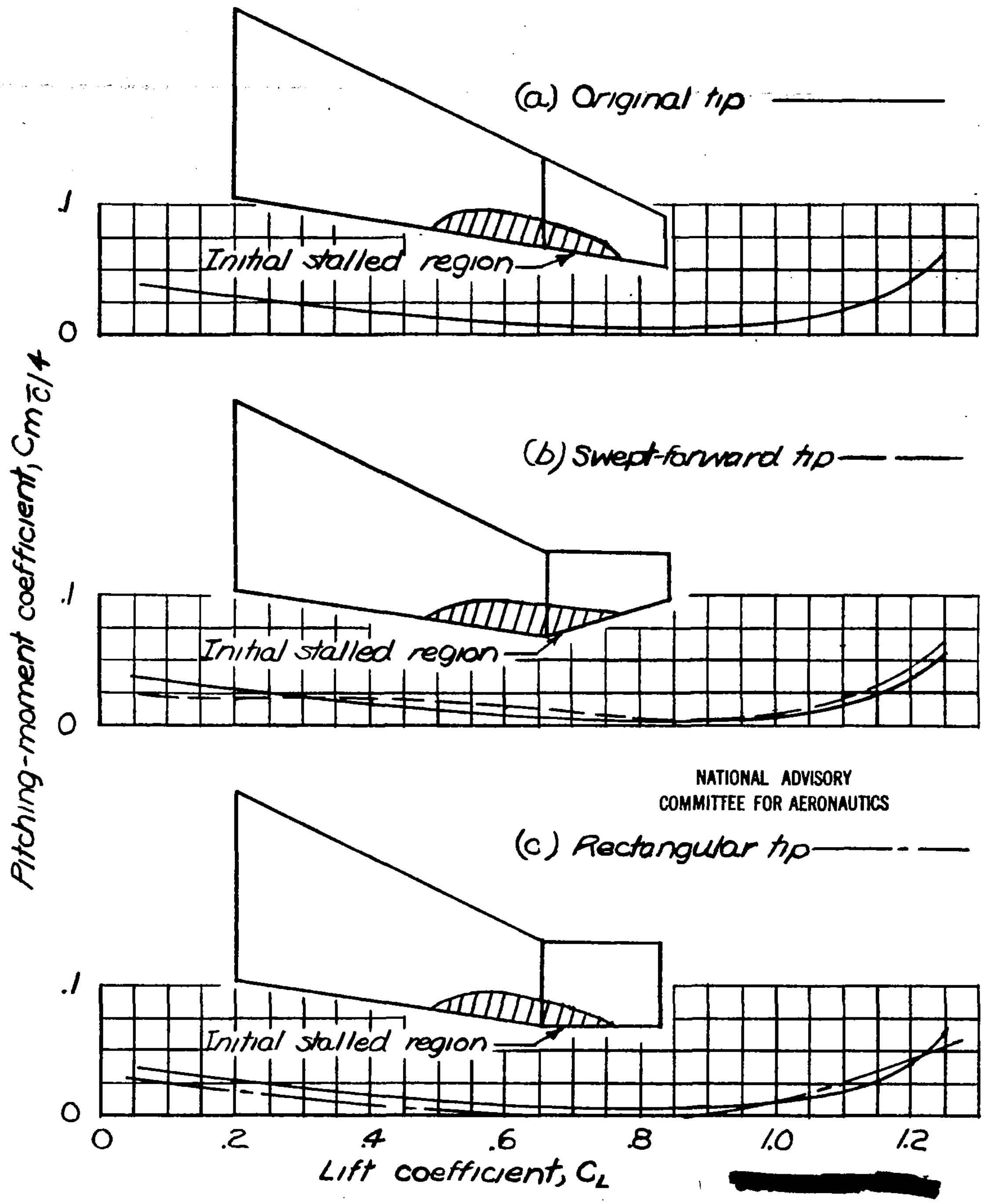

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Figure 5.- Effect of change in tip shape on the pitching-moment characteristics of a swept-back wing.

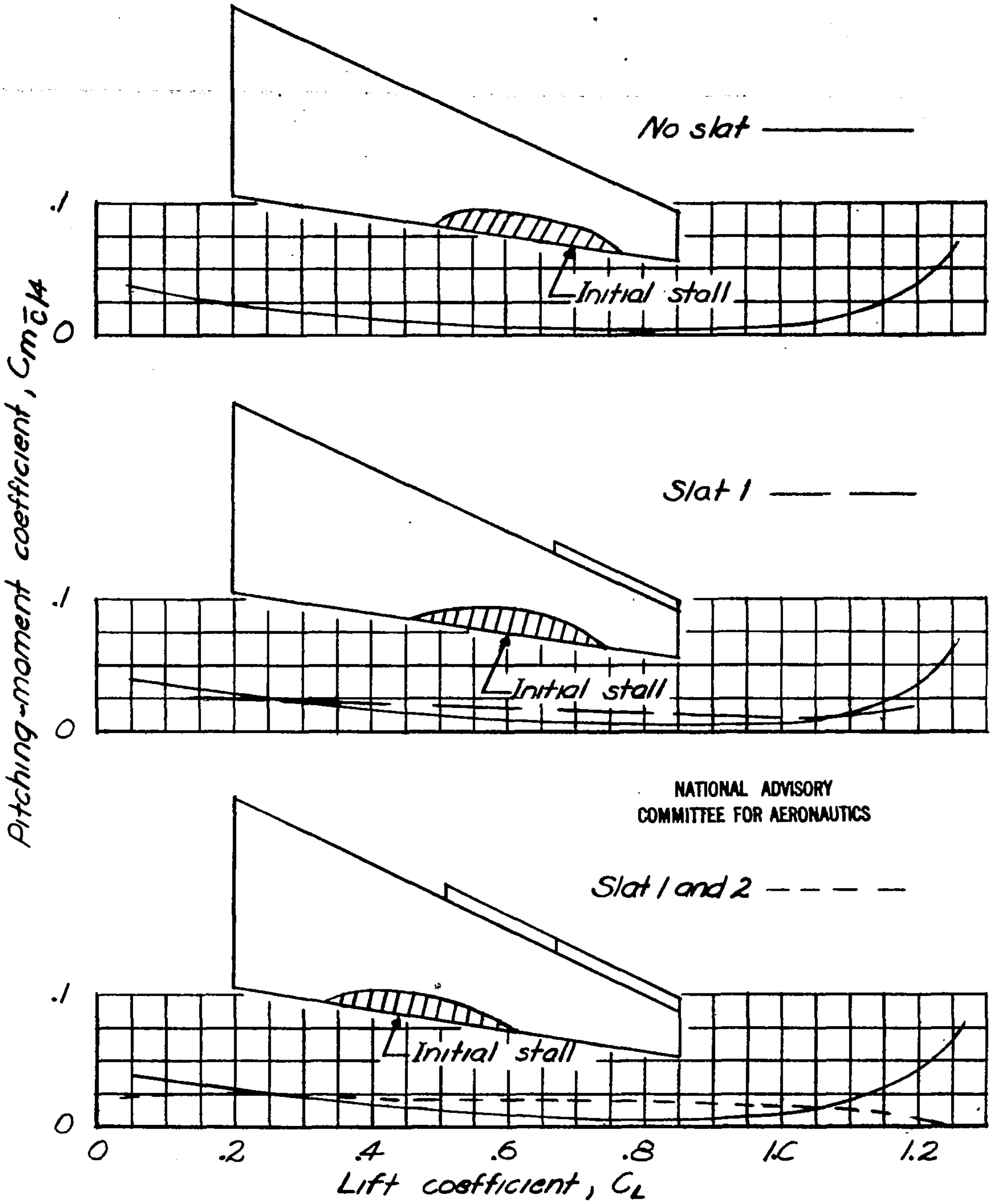

Figure 6.– Effect of slat on the pitching-moment characteristics of a swept-back wing.

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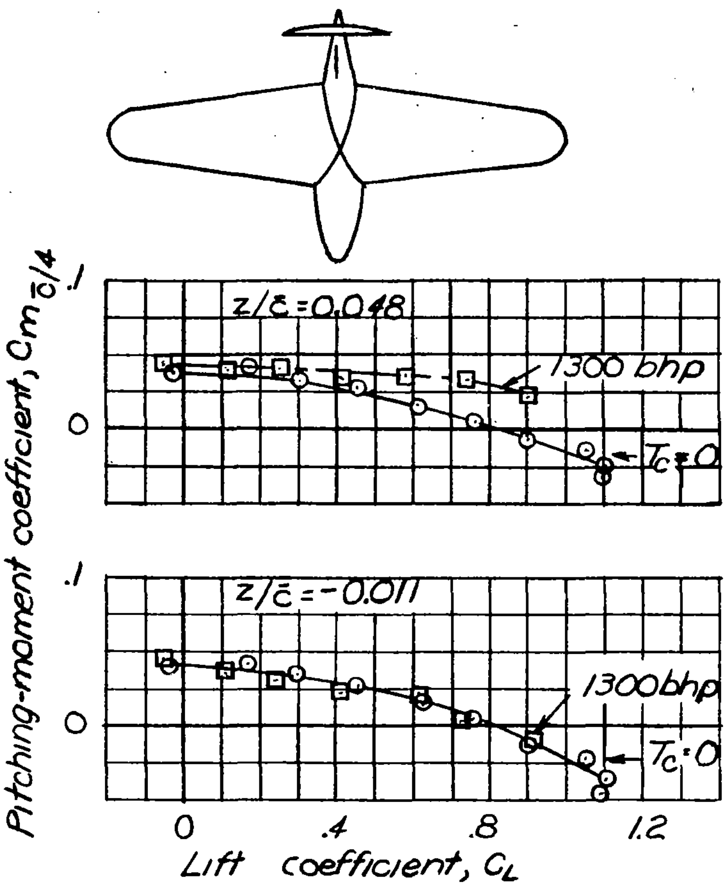

Figure 7.- Effect of power on the longitudinal stability of a pusher-type tailless airplane.

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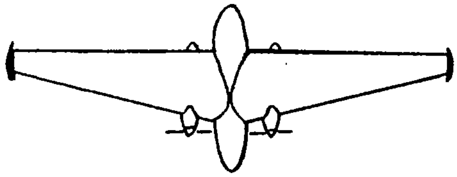

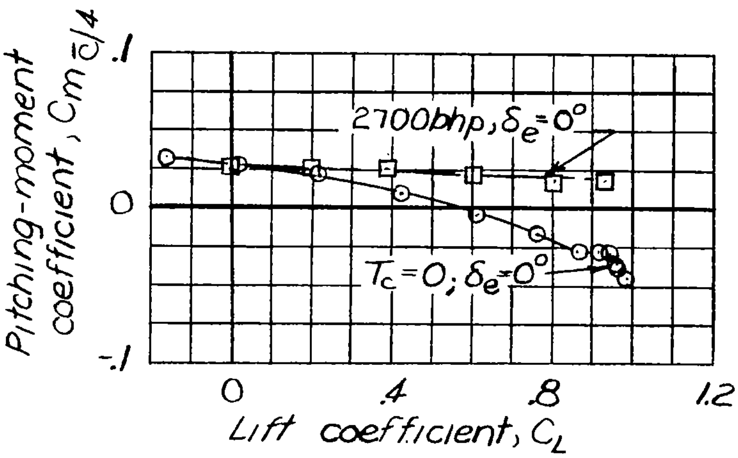

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Figure 8.- Effect of power on the longitudinal stability of a tractor-type tailless airplane. $z/\bar{c} = 0$.

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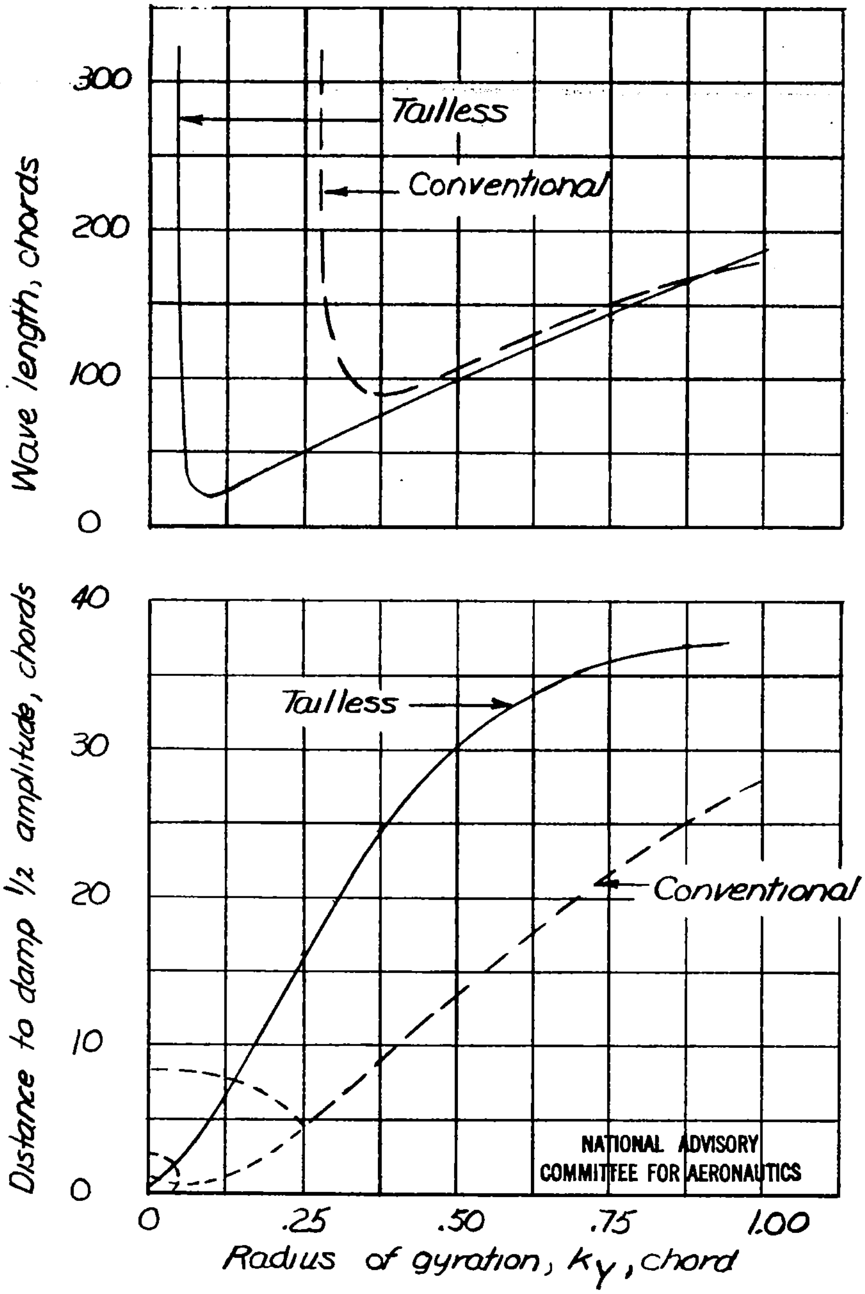

Figure 9. Effect of radius of gyration in pitch on the short-period longitudinal oscillation of a tailless and a conventional airplane. Static margin = 0.075; μ = 12.

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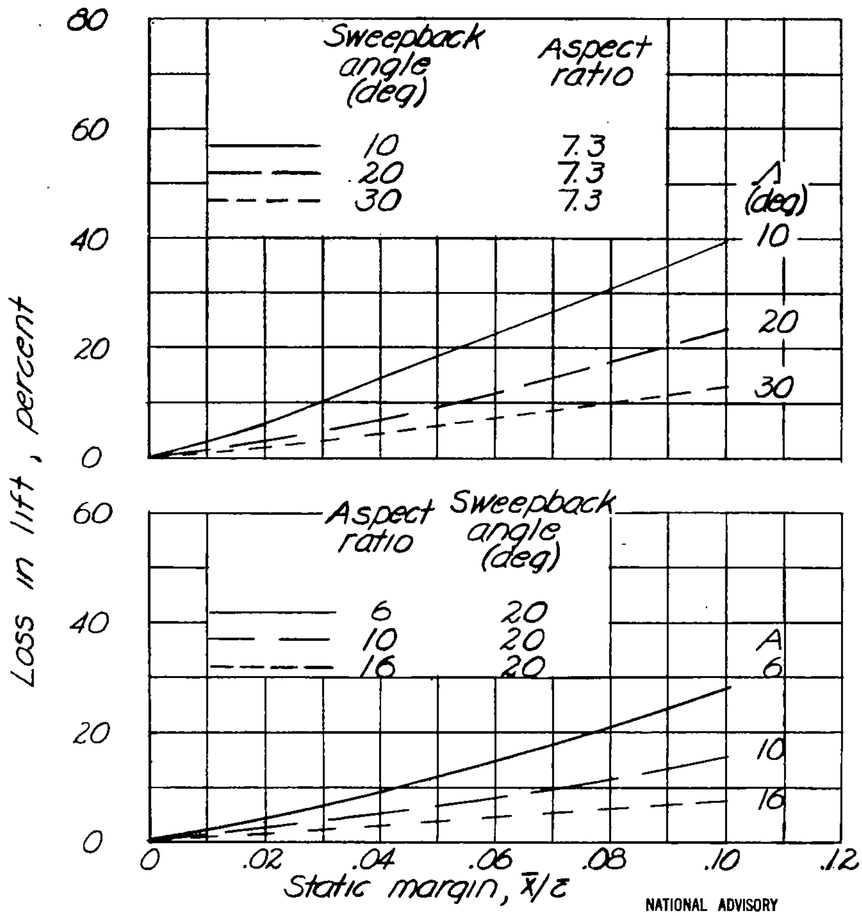

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Figure 10.- Percent loss in lift caused by longitudinal control. $c_e = 0.30c$; $\delta_e = 21°$; $l/\lambda = 4:1$. Control consists of extending elevator span inboard from tip until the resulting pitching moment about the center of gravity is zero.

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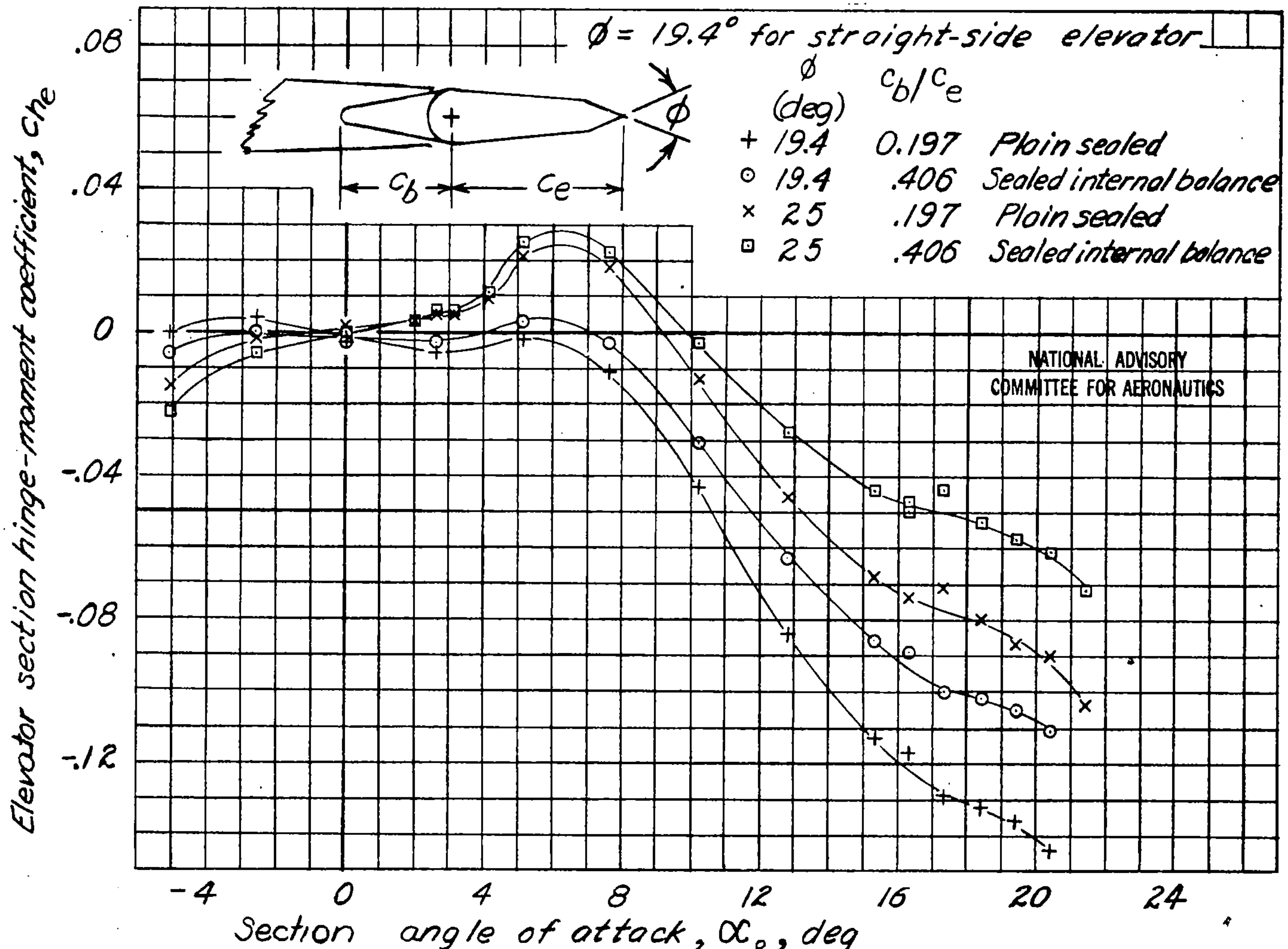

Figure 11. — Variation of section hinge-moment coefficient with angle of attack for 0.18c elevators on a modified NACA 65, 3-018 airfoil. $\delta_e = 0°$; q = 59.4 pounds per square foot. [redacted]

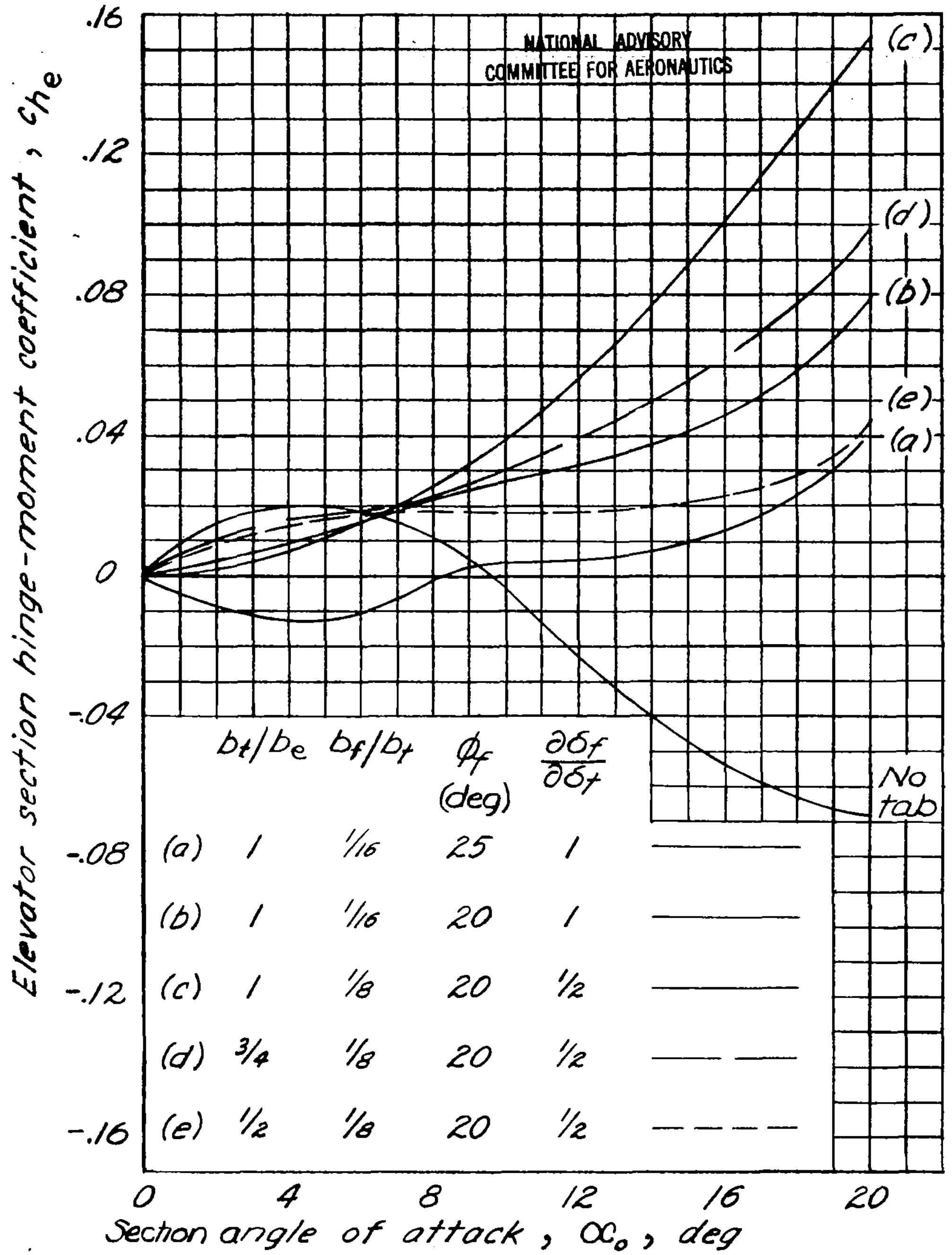

Figure 12.- Variation of c_{h_e} with α_0 at $\delta_e = 0°$ for various flipper-tab arrangements on a beveled elevator. Section data. [redacted]

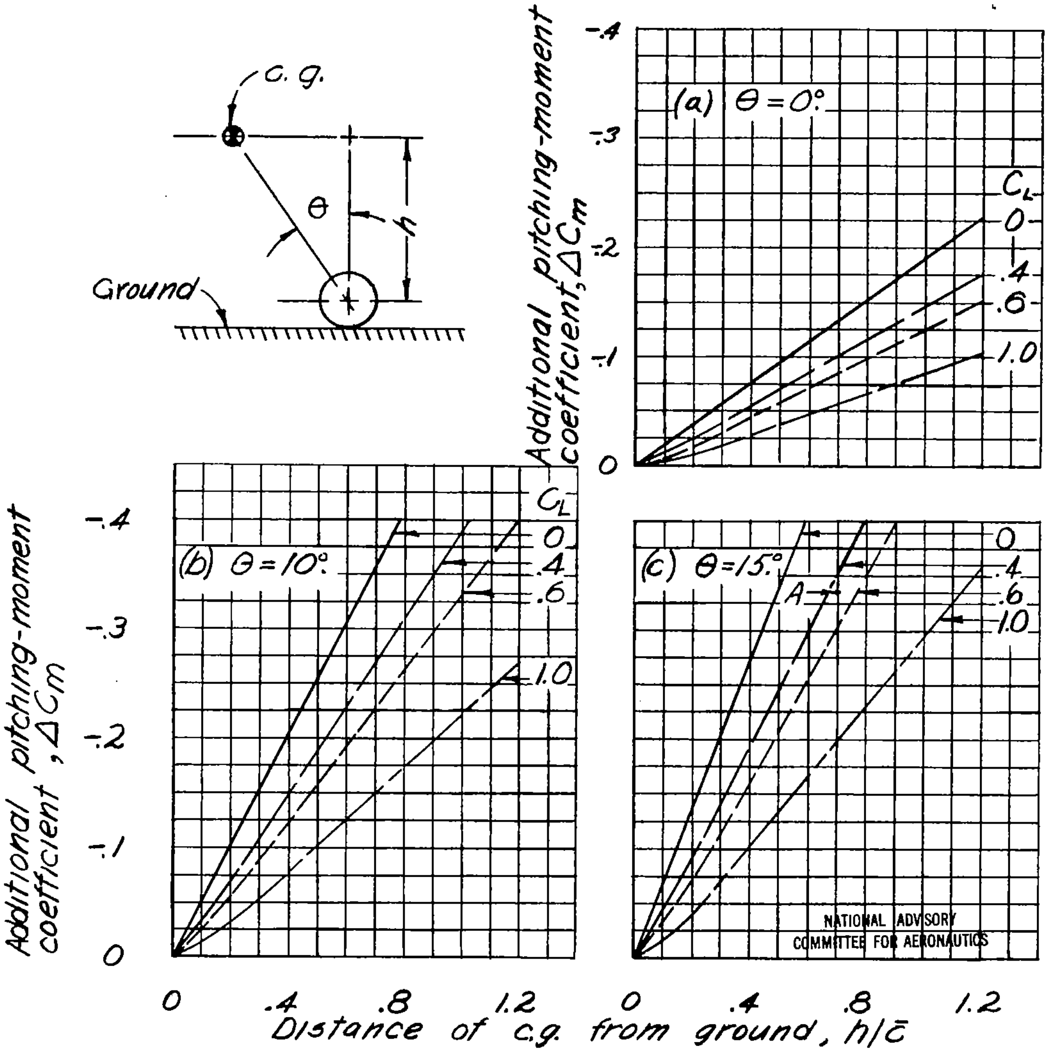

Figure 13.- Additional pitching-moment coefficient required to pull the nose wheel of a tailless airplane off the ground at 80 percent of the take-off speed. Assumed take-off $C_L = 1.16$.

[redacted]

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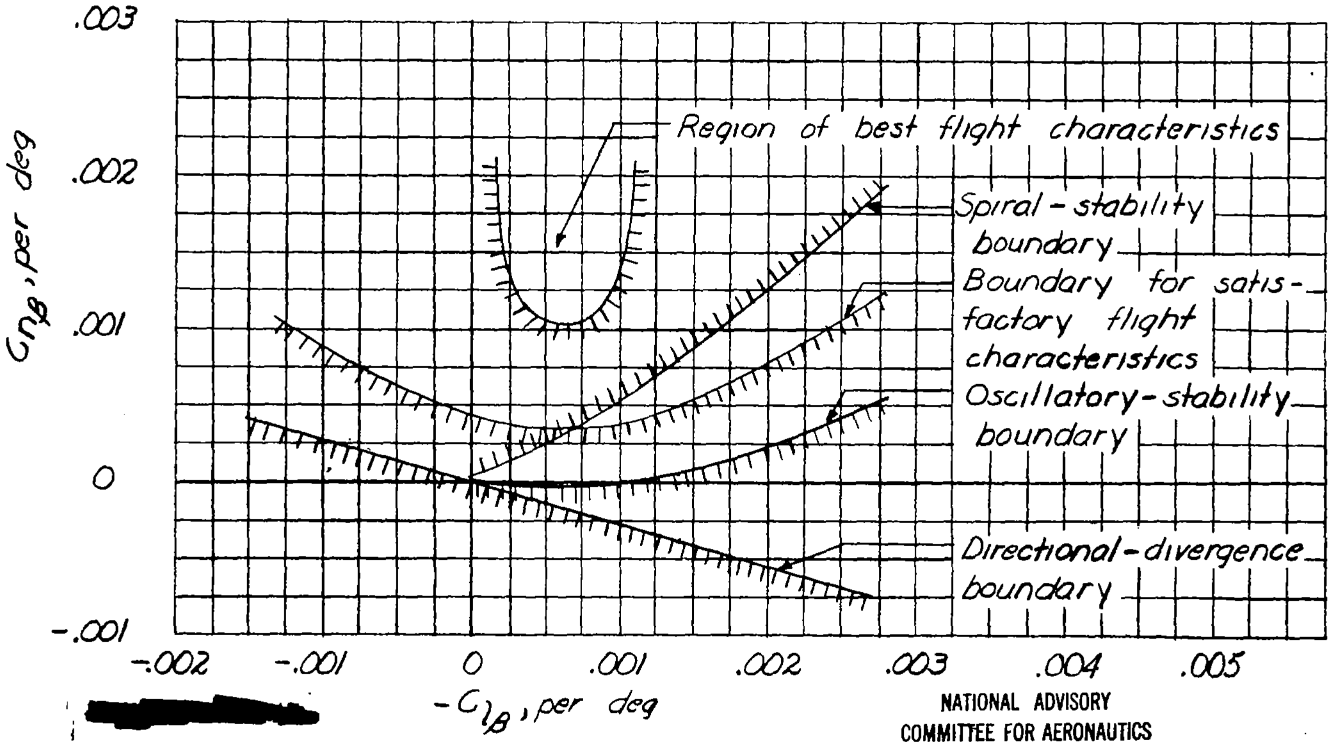

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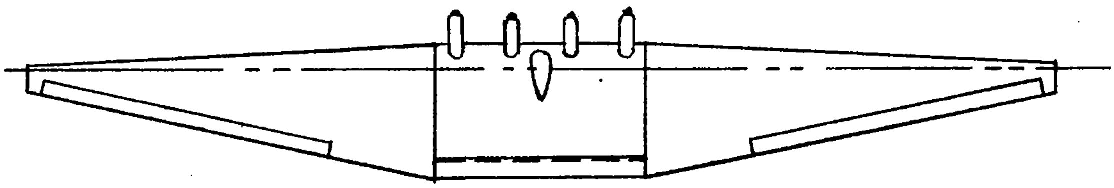
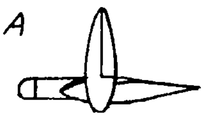
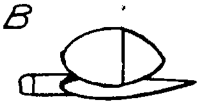
Figure 14.- Effect of directional stability C_{n_β} and dihedral effect C_{l_β} on flight characteristics as determined by tests of a model in Langley free-flight tunnel. $C_L = 1.0$.

Vertical tails tested on a tailless-airplane model



Plan view of tailless-airplane model

Tail	A  Two wing-tip tails toed-out 5°	B  Two wing-tip tails toed-in 5°
Area (percent S)	5	10
Aspect ratio	4	0.5
C_{n_β}	0.00010	0.00012

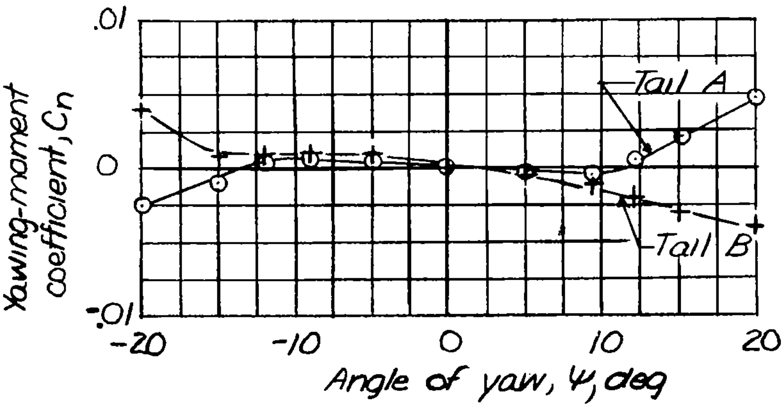


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Figure 15.- Directional stability characteristics of a tailless airplane equipped with toed-in and toed-out tip fins. [redacted]

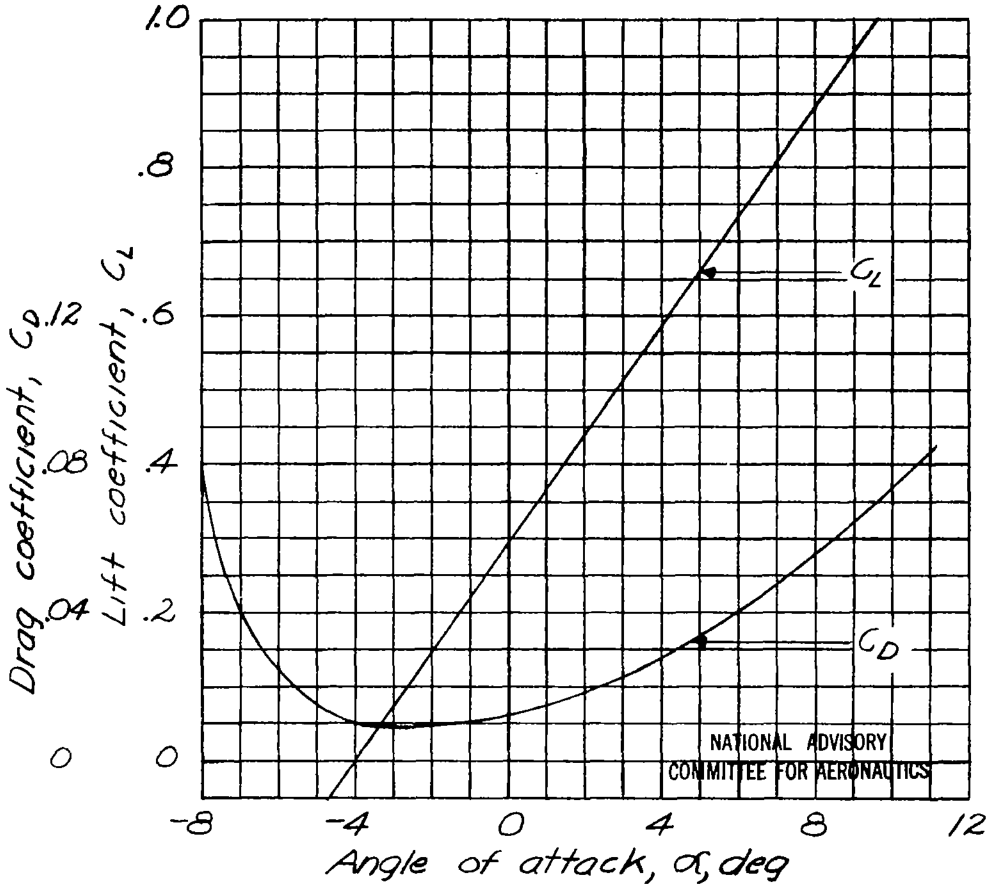
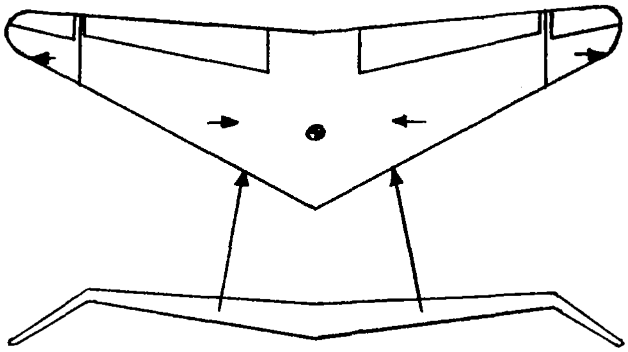
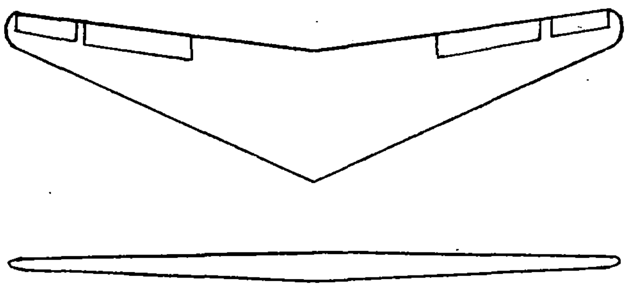


Figure 16.- Aerodynamic characteristics of NACA 4306 airfoil section.

[redacted]



(a) Swept-back wing with 8° dihedral of center section and -30° dihedral of wing tips. $C_L = 0.25$; $C_{n_\beta} = 0.00033$ ($C_{n_\beta} = 0.00024$ for wing without turned-down tips).



(b) Swept-back wing with 0° dihedral. $C_{n_\beta} = 0.00027$ ($C_L = 0.3$) to 0.00055 ($C_L = 1.0$).

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Figure 17.– Comparison of directional stability of two tapered swept-back wings.

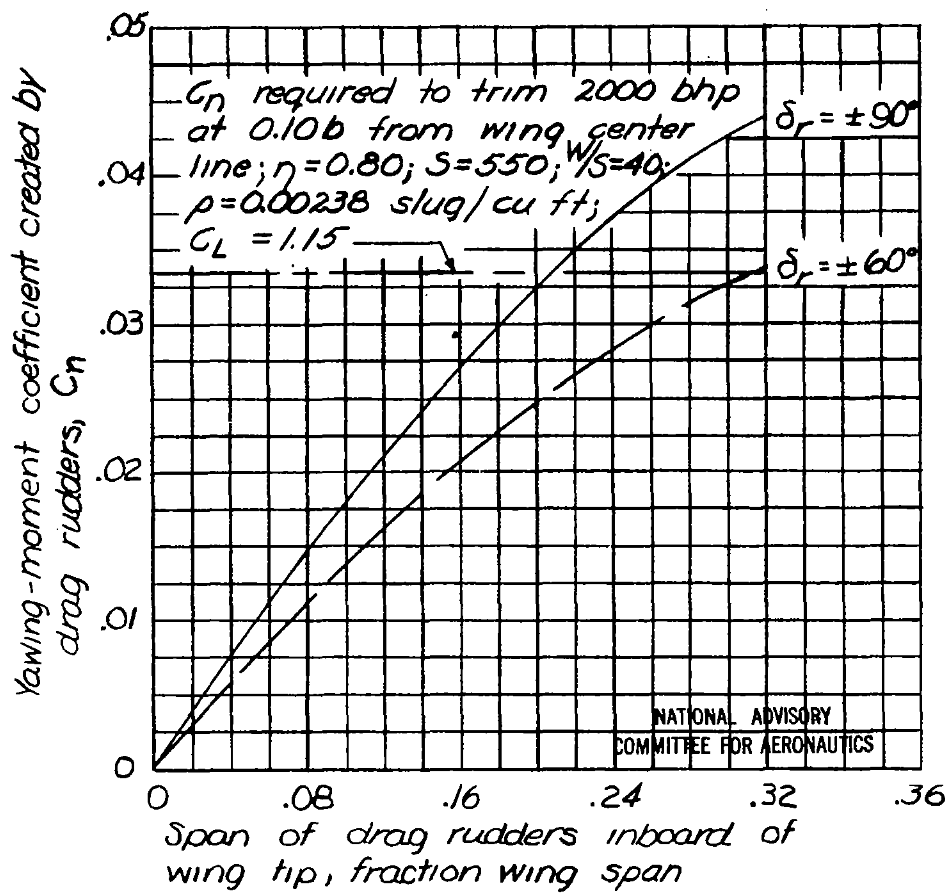


Figure 18.- Yawing moments created by double split perforated drag rudders mounted at wing tips. $c_f = 0.20c$; η, propulsive efficiency; W/S, wing loading, pounds per square foot.

[redacted]

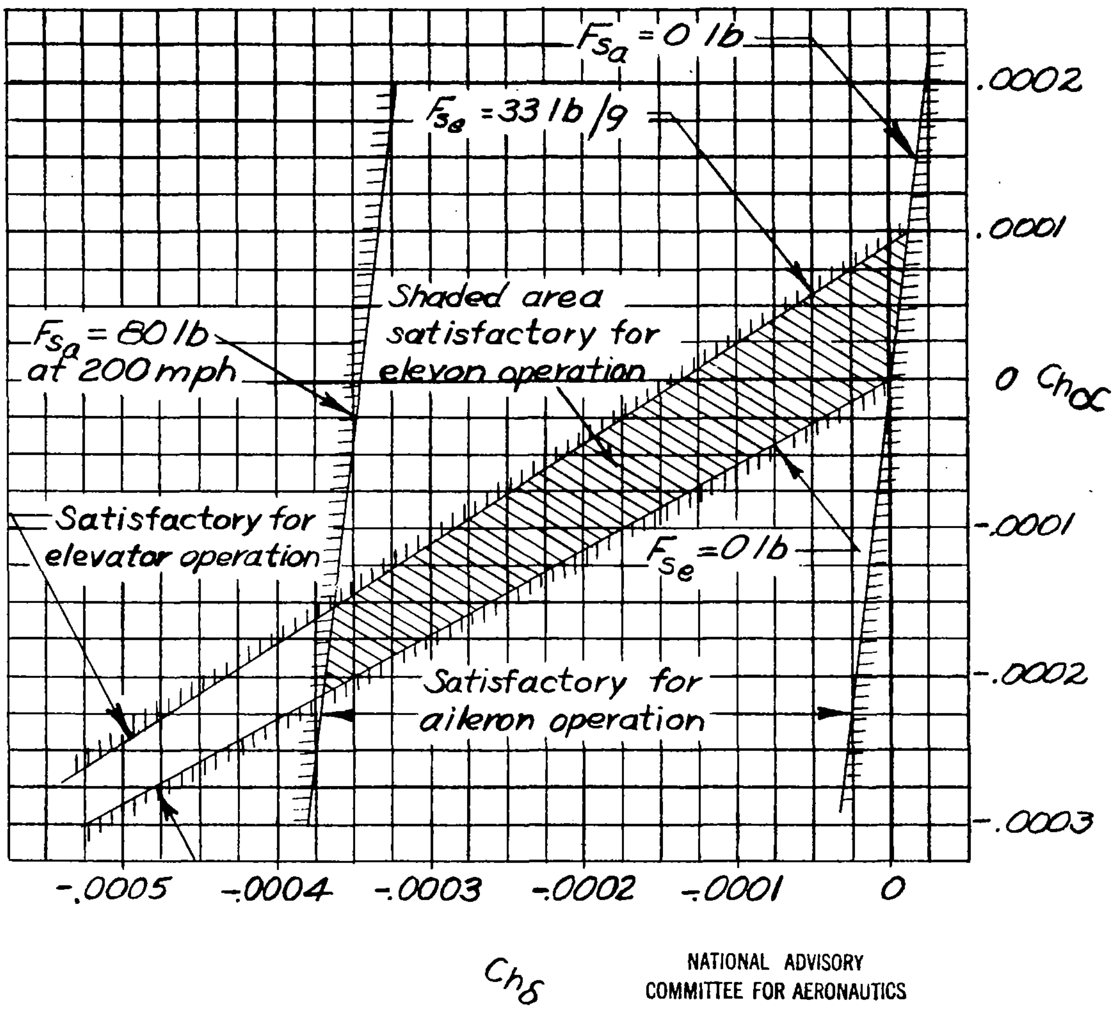


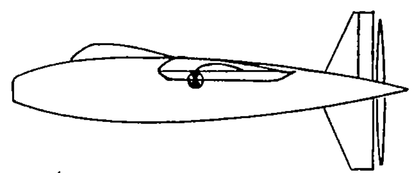
Figure 19. - Values of C_{h_α} and C_{h_δ} required of elevons for a large tailless airplane. $\bar{x}/\bar{c}$ = 0.03.

[redacted]

	C_{n_β}	C_{n_r}
Power off	0.00070	-0.105
Power on	——	-.290

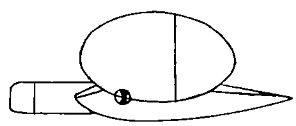
Typical conventional airplane

C_{n_β}	C_{n_r}
0.00072	-0.044



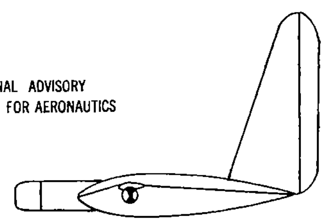
Straight-wing tailless fighter airplane

Tail toe-in angle, deg	C_{n_β}	C_{n_r}
5	0.00031	-0.014
10	.00033	-.018
15	.00045	-.025



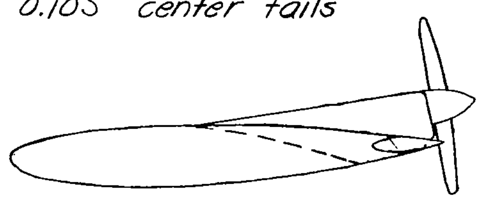
Tailless all-wing airplane with 0.10S tip tails

C_{n_β}	C_{n_r}
0.00063	- 0.017



Tailless all-wing airplane with 0.10S center tails

C_{n_β}	C_{n_r}
0.00038	-0.017



Tailless all-wing airplane with sweepback (no tails)

[redacted]

Figure 20.- Values of damping-in-yaw derivative C_{n_r} for a conventional airplane and various tailless airplanes. $C_L = 0.60$.