FACTORS AFFECTING STATIC LONGITUDINAL STABILITY AND CONTROL

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INTRODUCTION

The purpose of this paper is to review the various factors that constitute static longitudinal stability and control and to indicate how these factors may be influenced by power effects and Mach number effects.

SYMBOLS

C_m	pitching-moment coefficient
C_L	lift coefficient
b	wing span
S	wing area
i_t	stabilizer incidence, degrees
ϵ'	increment of power-off downwash at horizontal tail (at given angle of attack) from zero-lift downwash, degrees
$\Delta\epsilon$	increment in downwash, at a given angle of attack, due to power, degrees
T_c	thrust coefficient $\left(\frac{\text{Thrust}}{\rho V^2 D^2}\right)$
ΔT_c	increment in thrust coefficient from power-off condition to a specified power condition
F	plan-form factor
M	Mach number

BASIC CONCEPTS

Static stability relates to the behavior of an airplane in a series of steady states of motion. It is of interest, therefore, to aline the practical conditions for stability as desired by pilots with the conditions for stability that result from a mathematical treatment of the subject. From the pilot's point of view an airplane possesses stick-position stability if the stick must be moved rearward to retrim the airplane at a speed lower than the initial trimmed speed or moved forward to retrim the airplane at a speed higher than the initial trimmed speed. If the rearward movement of the stick requires a pull force or if the forward movement of the stick requires a push force, the airplane also possesses stick-force stability.

The basic mathematical condition for static stability is that the constant term E of the quartic stability equation be positive:

$$\lambda^4 + B\lambda^3 + C\lambda^2 + D\lambda + E = 0 \tag{1}$$

The development of equation (1) for the stick-fixed condition may be found in references 1 and 2 and for the stick-free condition in reference 3.

Physically, a positive value of E indicates that one of the longitudinal modes of motion of the airplane will consist of a long-period oscillation, classically termed a phugoid oscillation. The question of the characteristics of this oscillation, and whether it is stable or unstable, is one of dynamic stability and therefore is not discussed herein. A discussion of its importance from the pilot's point of view may be found in reference 4. It will suffice to say that if E is positive, the phugoid oscillation will be present in some form but, more important, the previously mentioned relationships concerning stick-position and stick-force stability will be satisfied.

On the other hand, if E is negative, the long-period phugoid oscillation is replaced essentially by a slow divergence and the pilot will find it necessary to reverse his customary procedure for retrimming the airplane. This reversal of customary flight procedure, while not particularly desirable, is generally not catastrophic because the divergence that develops as a consequence of this type of instability depends on speed changes that take considerable time to develop.

The expression "static stability" has also been used to describe the weathercock tendencies of an airplane while flying at a constant speed. This type of stability is essentially angle-of-attack stability and is extremely important in that it prevents, for example, the airplane from developing excessive load factors when encountering a gust or other disturbances. Static stability is frequently referred to as "maneuvering stability," inasmuch as it also controls the inherent maneuverability of the airplane. The mathematical condition for this type of stability is that the coefficient C of equation (1) be positive. Physically, if C is positive, a short-period oscillation is present; if C is negative, the oscillation is replaced by a very rapid and dangerous divergence. It should be emphasized that from the point of view of safety it is the type of stability associated with C that is most important to the pilot.

In simplified treatments of stability where power effects and compressibility effects are ignored, little misunderstanding results from the different interpretations attached to the term "static stability" because the same factor, the slope of the curve of pitching-moment coefficient against lift coefficient, usually determines the sign of both E and C. When the effects of power and compressibility are taken into account, however, the terms E and C are no longer dependent on the same parameters and a more precise interpretation of their significance is essential.

The four concepts and definitions commonly employed in current discussions of longitudinal stability are summarized in table I. The type of stability associated with E is manifested as stick-position stability or as stick-force stability. The degree of stability is measured by the static margin, defined as $-\left(\frac{dC_m}{dC_L}\right)_{C_m=0}$. The parameter $-\left(\frac{dC_m}{dC_L}\right)_{C_m=0}$ can be evaluated from wind-tunnel tests with the controls either fixed or free if the tests are conducted to simulate the appropriate power condition and flight plan. The center-of-gravity position for which the static margin vanishes for either the stick-position or stick-force condition defines the neutral point.

The type of stability associated with the term C is interpreted and measured by the pilot in terms of the control movement or control force required to effect a given acceleration at a constant speed. The degree of stability is proportional to the so-called maneuver margin. The maneuver margin can be evaluated from wind-tunnel tests as the sum of the slope of the pitching-moment curve obtained at a constant Mach number and for a fixed power condition and a term representing the damping-in-pitch characteristics of the airplane. For heavily loaded airplanes flying at high altitudes K is negligible and the maneuver margin is given essentially as $-\left(\frac{\partial C_m}{\partial C_L}\right)_M$ which can easily be obtained from wind-tunnel tests. The maneuver point coincides with the center-of-gravity position corresponding to zero maneuver margin.

If the manner in which the pitching-moment coefficient varies with the lift coefficient is known, all the essential stability parameters can be evaluated.

STABILITY AT SUBCRITICAL SPEEDS

The stability of a conventional-type airplane is determined by the relative contributions of the wing-fuselage combination and the horizontal tail. At subcritical speeds the contribution of the basic wing-fuselage combination can be estimated fairly reliably, and numerous papers and charts are available for simplifying such calculations. (See references 5 to 10.) The contribution of the horizontal tail in the absence of slipstream or jet effects can also be estimated fairly reliably for both the flaps-retracted and flaps-deflected conditions (reference 11) with the aid of downwash charts such as those prepared by Silverstein and Katzoff (reference 12). Reliable methods are also available for estimating the hinge-moment characteristics of the elevator; thus, rational estimates of the stick-free stability characteristics can be made. (See reference 13.) The addition of a propeller or a jet may, however, cause important changes in the contributions supplied by the various components, and a knowledge of the manner in which these effects are manifested is extremely helpful in design.

POWER EFFECTS

Propeller effects.- Successful methods have been developed for estimating the effects of the slipstream on the wing-fuselage characteristics (references 14 to 18), but attempts to predict the complex changes in flow at the tail plane have been less successful.

During the war years a large amount of experimental data pertaining to propeller effects were obtained particularly for single-engine airplanes. Typical investigations are reported in references 19 to 28. These data have been analyzed and a method has been developed for estimating the effects of power on the contribution of the tail to stability. The essence of the method is presented in figures 1 and 2, which were taken from an unpublished analysis.

The data of figure 1 constitute a correlation of the change in downwash angle resulting from an increment in thrust coefficient above the windmilling condition. A correlation study of 26 specific model configurations has indicated that the most powerful factors influencing the incremental downwash angle are the initial downwash angle ϵ' and a factor F dependent on the wing plan form. It has been observed that taper ratio is of particular importance, and the manner in which the plan-form correlation factor F varies with wing taper ratio is also shown in figure 1. The dashed lines parallel to the design curve represent the order of accuracy which might be expected in applying this chart to a new design.

A correlation chart for estimating the power-on tail effectiveness is shown in figure 2. The dependency of the tail-effectiveness ratio on the relative position of the slipstream and tail position should be noted. The lines parallel to the design curve again indicate the order of accuracy of the correlation. These correlation charts at present are applicable only to single-engine tractor monoplanes with flaps retracted, but it is hoped eventually to obtain similar correlation charts for the flap-down condition.

From correlation charts such as those shown in figures 1 and 2 it is possible to construct curves of the variation of pitching-moment coefficient with lift coefficient for any power condition, and from these curves all of the essential stability parameters can be evaluated. References 29 and 30 contain graphical methods for determining the location of the neutral point.

The scarcity of systematic data on multiengine installations has thus far prevented the development of similar correlations for these configurations.

Jet effects.- The influence of jets on the longitudinal stability is, in general, not as pronounced as propellers. (See reference 31.) Direct jet effects are easily computable and charts are available for estimating the inflow field about a jet; thus, the calculation of downwash changes in the vicinity of the horizontal tail is possible (reference 32).

COMPRESSIBILITY EFFECTS

Up to the speed at which the critical Mach number of the wing is exceeded, the effects of compressibility on the stability characteristics of an airplane are relatively small, and rational estimates of these effects can be made utilizing formulas based on linear perturbation theory. The more significant changes in stability occur when the critical speed of the wing is exceeded and shock waves are found which result in large pressure changes over the wing. As a consequence, the lift and the lift-curve slope decrease rapidly, and for cambered sections the angle of attack for zero lift shifts in a positive direction. These changes are generally more pronounced for wings having greater camber.

The aerodynamic center of the wing may shift either in a forward or rearward direction depending upon the thickness and shape of the airfoil section and the wing plan form. The wing-aerodynamic-center shift associated with a particular airplane will also be affected by the fuselage or nacelles.

An example of the manner in which compressibility effects were manifested on a World War II fighter is shown in figure 3. (See reference 33.) The characteristics exhibited at $M = 0.5$ are typical of the behavior below the force break. As the critical speed of the wing was exceeded the aerodynamic center of the wing-fuselage combination moved forward as evidenced by the increased slope of the tail-off pitching-moment curve at $M = 0.76$. Despite the forward movement of the wing aerodynamic center, however, the slope $\left(\partial C_m/\partial C_L\right)_M$ for the tail-on configuration was actually increased. A noticeable change in trim is also evident. Thus, while the maneuver margin is considerably increased the static margin, as a consequence of the trim change, becomes unstable. The cause of this behavior usually is that the airplane will experience a nose-down tendency that is so great that either the elevator is not powerful enough to pull the nose of the airplane up or the control forces become too great for the pilot to handle. This behavior is referred to as the "tucking under" tendency.

If an airplane has an adjustable stabilizer, severe trim changes of this type can be compensated for without much difficulty. If the airplane has a fixed stabilizer, however, another solution to this problem is required. The solution adopted for the airplane having the characteristics shown in figure 3 involved the use of dive-recovery flaps. The essential characteristic of a dive-recovery flap is illustrated in figure 4 (reference 34). The dive flap is located on the under surface of the wing and, when deflected, causes an increase in the local downwash at the tail and a change in the angle of zero lift. The effect is the same as though the stabilizer had been moved nose downward, and a powerful positive pitching moment is created. The optimum flap deflection for a particular configuration, however, must be determined experimentally.

Severe compressibility effects may be delayed to higher Mach numbers by utilizing thinner wing sections and by employing plan forms having low aspect ratios or plan forms incorporating sweepback. (See references 35 and 36.) The incorporation of sweepback is particularly beneficial and can significantly increase the Mach number at which serious longitudinal-stability problems are encountered and might be expected also to reduce the trim changes and stability changes encountered at supercritical speeds.

LOW-SPEED PROBLEMS OF SWEPTBACK WINGS

One of the factors that limits the amount of sweepback that can be employed, however, is the difficulty of providing satisfactory stability and control in the landing condition.

Basic-wing characteristics.- At lift coefficients prior to that at which separated flow ensues on the wing, the position of the aerodynamic center of the wing can be estimated fairly reliably. The shift in the aerodynamic-center position that occurs at high lift coefficients is less amenable to theoretical computations, and numerous experimental investigations have been concerned with this effect. From the data examined thus far it appears that aspect ratio and sweep angle are still the two most important factors that influence the type of pitching-moment variation to be expected at the stall. The familiar manner in which sweep angle and aspect ratio affect the character of the pitching-moment variation at the stall is illustrated in figure 5, which is taken from reference 37. Combinations of sweep and aspect ratio that fall above the line in the figure have been found to yield the characteristically unstable pitching-moment variation indicated. Other factors such as airfoil section, wing taper, Reynolds number, and surface roughness have been found to influence the lift coefficient at which instability is first manifested, but the ultimate variation at the stall has still been found to be consistent with that indicated in figure 5.

While figure 5 reflects the behavior of plain wings, it has been found that the addition of trailing-edge flaps has resulted in an unstable pitching-moment variation even for wings falling in the stable region. A considerable number of investigations have, therefore, been concerned with the development of devices designed to alleviate the tip stalling that is responsible for this behavior.

Stall control devices.- Methods that have been tried in attempts to alleviate the tip stalling of sweptback wings have included wing twist, changes in wing plan form at the tip, flat-plate separators - which attempt to control the lateral flow of the boundary layer - and leading-edge flaps and slats. Combinations of these methods have also been tried on specific configurations. Perhaps the most successful stall control device thus far investigated has been the leading-edge slat. Figure 6 illustrates the behavior of this device on a moderately swept wing. (See reference 38.) It will be noticed that in this example the slat had to be extended over approximately 50 percent of the wing semispan before the desired stable pitching moment at the stall was attained. Inasmuch as the leading-edge slat modifies the span loading along the wing it might be expected that the optimum extent of flap for a particular configuration would depend on the wing plan form and the location of the wing on the fuselage.

Effect of tail location.– The attainment of satisfactory pitching-moment characteristics for the wing-fuselage combination does not guarantee that the configuration with a horizontal tail added will also be satisfactory. The optimum location of the tail must usually be found experimentally. Figure 7 which is taken from reference 39 illustrates a case where the basic wing-fuselage pitching-moment behavior was satisfactory but the resultant pitching-moment behavior with the tail in position was unsatisfactory. It is generally easier, however, to find a tail location that will result in satisfactory stability for the complete configuration if the basic wing-fuselage combination also possesses a stable pitching-moment variation at the stall.

CONCLUDING REMARKS

It must constantly be borne in mind that even if ample rigid-model wind-tunnel data are available on which to base predictions of stability, the effects of aeroelastic distortion may result in the airplane having completely different characteristics from those estimated. Some of the effects of elevator-fabric distortion are indicated, for example, in reference 40. At the same time the basic concepts of stability discussed still apply and if wind-tunnel data on an aeroelastically similar model were available reliable stability estimates could be made. There is, however, a great deal of research necessary before satisfactory methods of predicting aeroelastic effects can be developed.

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TABLE I

TYPE	CRITERION
STICK-POSITION STABILITY	STATIC MARGIN = $-\left(\frac{dC_m}{dC_L}\right)_{C_m=0}$ WITH ELEV. FIXED
STICK-FORCE STABILITY	STATIC MARGIN = $-\left(\frac{dC_m}{dC_L}\right)_{C_m=0}$ WITH ELEV. FREE
STICK-POSITION MANEUVERING STABILITY	MANEUVER MARGIN = $-\left(\frac{\partial C_m}{\partial C_L}\right)_M + K$ WITH ELEV. FIXED
STICK-FORCE MANEUVERING STABILITY	MANEUVER MARGIN = $-\left(\frac{\partial C_m}{\partial C_L}\right)_M + K$ WITH ELEV. FREE

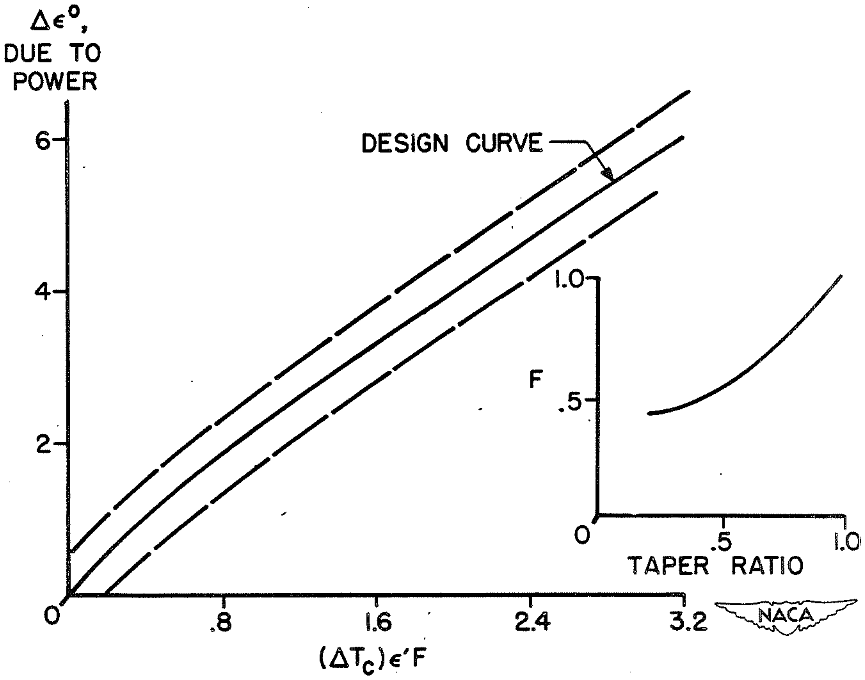

Figure 1.- Downwash correlation for single-engine tractor airplanes.

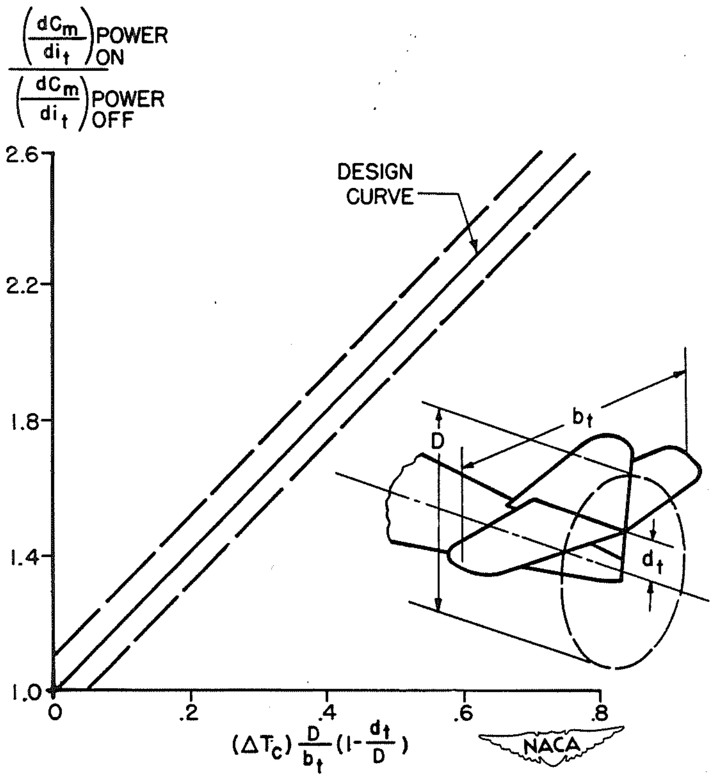

Figure 2.- Tail-effectiveness correlation for single-engine tractor airplanes.

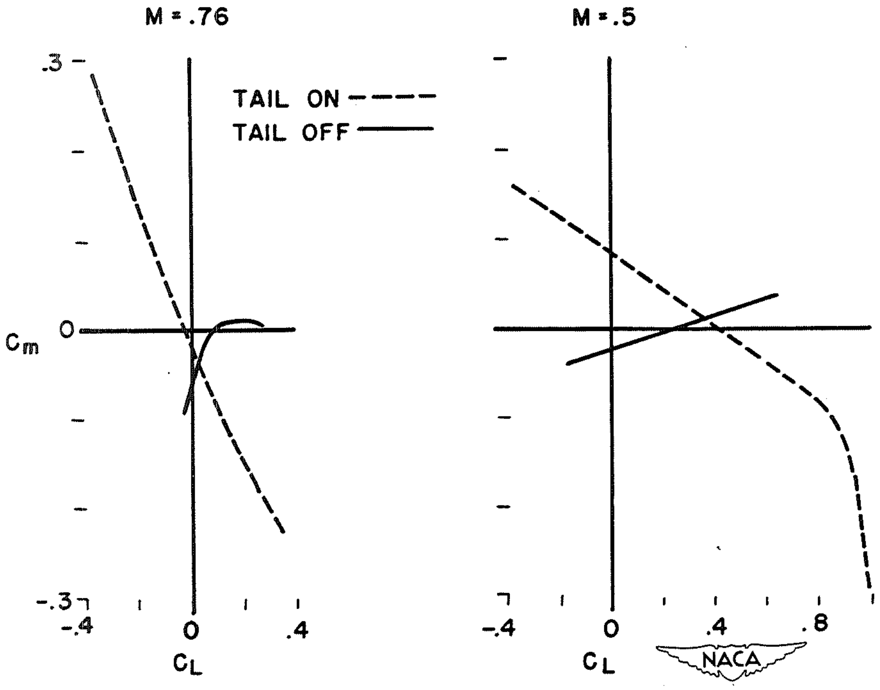

Figure 3.- Typical effect of compressibility on airplane pitching-moment characteristics.

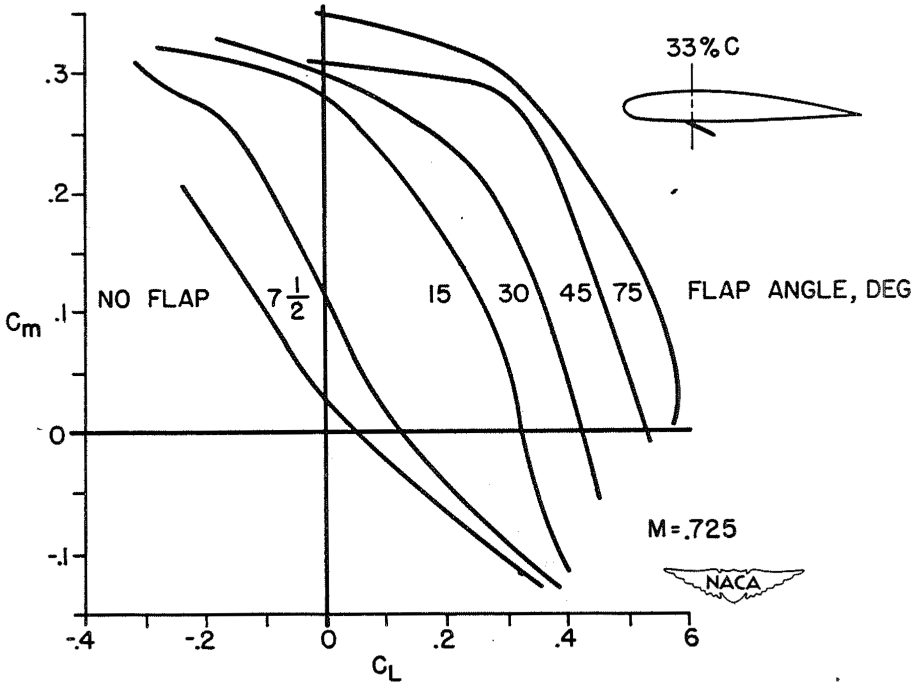

Figure 4.- Effect of dive-recovery flap on airplane pitching-moment characteristics.

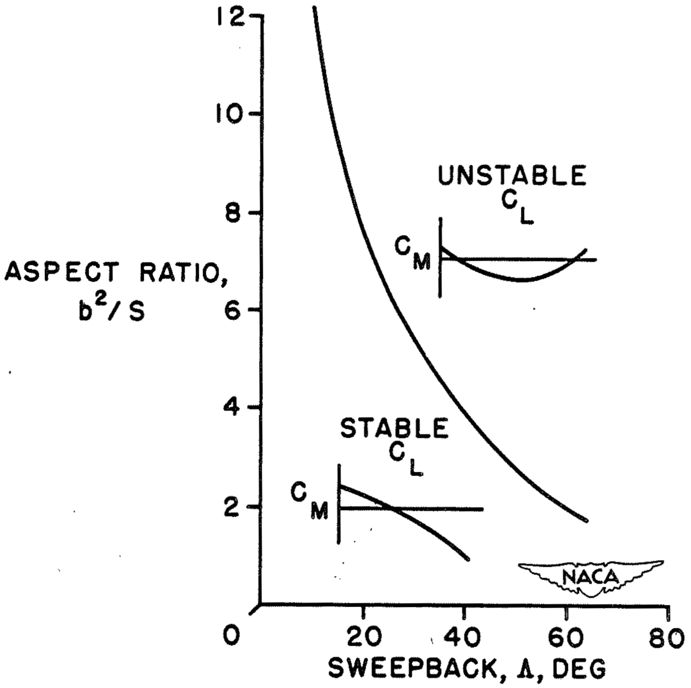

Figure 5.- Pitching-moment behavior of sweptback wings.

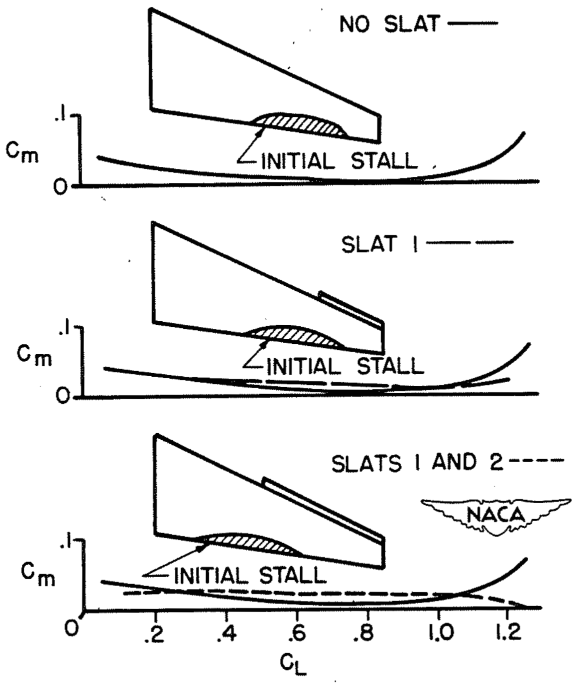

Figure 6.- Effect of leading-edge slats on pitching-moment characteristics.

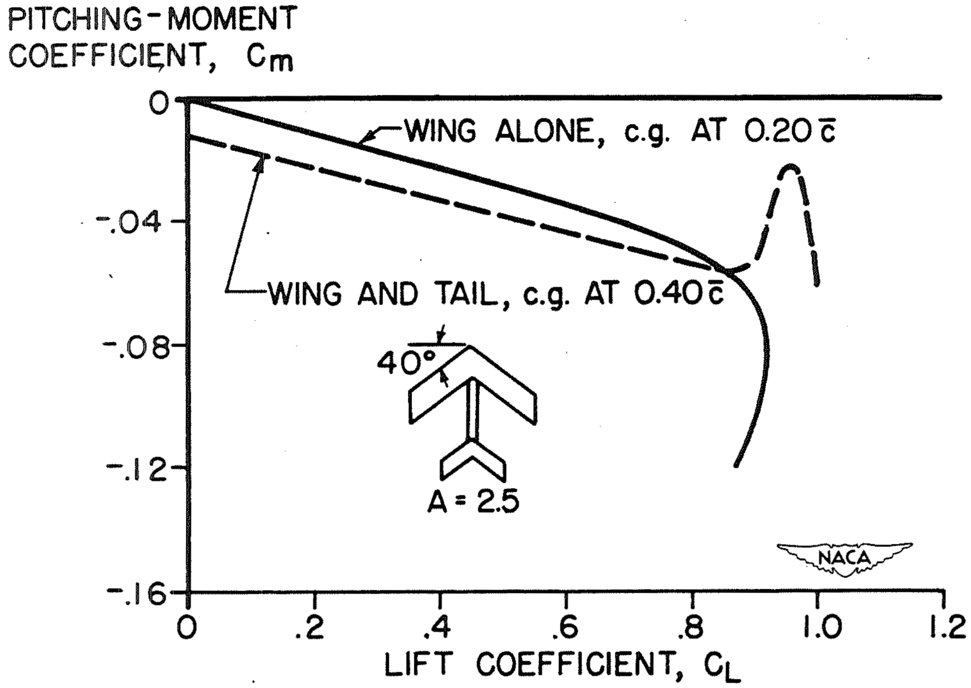

Figure 7.- Effect of tail on pitching-moment characteristics at stall.