RM No. L8A28

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RESEARCH MEMORANDUM

CURRENT STATUS OF LONGITUDINAL STABILITY

By

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

May 24, 1948

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SUMMARY

The problems of static and dynamic longitudinal stability both at high speeds and at low speeds are discussed and data are presented which indicate recent progress made in the solution of these problems.

It is shown that the incorporation of large amounts of sweepback on both the wing and the horizontal tail can significantly increase the Mach number at which critical trim changes and stability changes occur and can greatly reduce the trim changes and stability changes encountered at supercritical speeds. Data are also presented which demonstrate the possibility of obtaining satisfactory longitudinal stability in the landing configuration for wings with sweepback of the order of 45° utilizing various stall-control devices. Optimum arrangements for such devices, however, should be determined experimentally at the present time.

INTRODUCTION

The purpose of this paper is to focus attention on some recent investigations that have been concerned with longitudinal-stability problems both at high speeds and at low speeds and to summarize briefly the current state of affairs in regard to these problems.

SYMBOLS

W	weight
M	Mach number (V/a); pitching moment
V	velocity
a	speed of sound

[redacted]

AR aspect ratio (b^2/S)

b span

S wing area

C_L lift coefficient (L/qS)

q dynamic pressure $\left(\frac{1}{2}\rho V^2\right)$

q_t dynamic pressure at tail

ρ density

c chord

C_m pitching-moment coefficient (M/qcS)

ϵ downwash at tail

P period of short-period longitudinal oscillation, seconds

$T_{1/2}$ time for oscillation to damp to one-half amplitude, seconds

i_t stabilizer incidence

δ control-surface deflection

α angle of attack

HIGH-SPEED PROBLEMS

Static Stability and Control

Recent investigations.- A number of longitudinal-stability investigations of various airplane configurations have been conducted at high subsonic Mach numbers in the high-speed wind tunnels of the NACA and at transonic Mach numbers up to 1.2 utilizing the NACA wing-flow method and the associated wind-tunnel transonic-bump technique. A number of these investigations are reported in references 1 to 7, and some of the configurations investigated, together with the Mach number range covered, are summarized in figure 1.

For the tailless configuration (a), data were obtained in the Langley high-speed 7- by 10-foot tunnel for a sting-supported model and also for a semispan model up to a Mach number of 0.95. Wing-flow data were also obtained up to a Mach number of 1.2. The three sets of data are in general qualitative agreement, although the increase in the lift-curve slope with Mach number was somewhat more rapid for the sting-supported tunnel model than for the semispan tunnel model and semispan wing-flow model.

Configuration (b) was investigated as a semispan wing-flow model (reference 1) and was also tested on a transonic bump in the Langley high-speed 7- by 10-foot tunnel. This model is similar to the XS-1 model for which Langley 8-foot high-speed-tunnel data are available to a Mach number of 0.92 (references 2 and 3). The agreement between the data obtained by the wing-flow method and the transonic-bump method was satisfactory throughout most of the Mach number range.

Model (d) was similar to model (b) except for the swept tail. It also was tested as a wing-flow model (reference 4).

Model (c) was investigated on the transonic bump; model (e), as a semispan model in the Ames 16-foot tunnel (reference 5); and model (f), as a sting-supported model in the Langley 8-foot high-speed tunnel (references 6 and 7).

Despite the fact that most of the results available thus far are limited to relatively few configurations, it is interesting to observe in the data certain trends in regard to the manner in which stability and trim changes with Mach number are manifested.

Characteristic data.- Data representative of the variation of pitching-moment coefficient with lift coefficient for several Mach numbers for a straight-wing design are shown in figure 2. Although these data apply to the design indicated, similar trends in the data for other straight-wing designs have been observed. The data at $M = 0.600$ are typical of the behavior before force break, and some comments regarding the predicability of the characteristics in this range are probably pertinent at this point.

The important changes in longitudinal stability for straight-wing designs at high Mach numbers are, of course, not indicated by formulas based on linear-perturbation theory. Such formulas, however, are useful in interpreting experimental trends at subcritical Mach numbers. In consideration of the Mach number effects on a wing and tail combination, the trends indicated by the theory may be divided into three categories: (1) direct changes in the position of the wing aerodynamic center, (2) changes in the downwash at the tail, and (3) disproportionate changes in the lift-curve slopes of the wing and tail resulting from the differences in aspect ratio. For a flat elliptic wing of aspect ratio 4, theory indicates a forward shift of the aerodynamic center of only about 1.4 percent at a Mach number of 0.8 (reference 8). However, forward shifts of the aerodynamic center of 5 percent or more have been obtained experimentally on straight wings at high Mach numbers, particularly for those employing sections having large trailing-edge angles. At the present time, therefore, it appears that the changes in wing aerodynamic-center position with Mach number must be determined experimentally even at subcritical speeds. A limited amount of German data has indicated that this effect is minimized for small trailing-edge angles.

The theories regarding the change in downwash characteristics at the tail and the change in the lift-curve slopes of the wing and tail with Mach number, however, appear to agree fairly well with experiment at subcritical Mach numbers (references 9 and 10). These two effects have indicated forward shifts in the neutral point of the order of 5 percent in some cases. At Mach numbers approaching that of force break and at supercritical Mach numbers, recourse must be made to experiment.

Marked changes in the variation of the basic wing-fuselage pitching moment with lift coefficient are apparent at a Mach number of 0.905 and 0.933, and the appearance of flat spots in the resultant pitching-moment curve in the lower lift range is somewhat characteristic for this type of design at supercritical speeds. In many instances local reversals in slope have been encountered, particularly for different stabilizer and elevator settings. The nonparallelism of the pitching-moment curves in this range for the different stabilizer settings is significant and evidences the nonlinear contribution of the tail to stability. Consequently, in evaluating the stability characteristics of a design possessing nonlinearities of this kind, it is essential, of course, to consider conditions at tail settings in the vicinity of trim at the particular lift coefficient in question and also the lift-coefficient range over which the nonlinearities extend.

Similar data for a sweptback tailless configuration are shown in figure 3. The data for $M = 0.70$ and 0.95 were obtained from Langley high-speed 7- by 10-foot tunnel tests of a semispan model. The data for $M = 1.00$ were obtained from wing-flow tests of a smaller model. The increased slope of the pitching-moment curves at the higher Mach numbers is again evident. At $M = 0.95$ the control effectiveness has been considerably reduced and appreciable trim changes occur, but the vicious changes in stability that are frequently manifested by straight-wing designs at supercritical speeds are absent.

The effect that sweepback can have on delaying the Mach number at which significant trim changes and stability changes are manifested is further illustrated in figure 4. The straight-wing design and the tailless design are the configurations for which typical data have been presented. (See figs. 2 and 3.) The model with a 45° swept wing and tail was an arbitrary configuration investigated on the transonic bump. In evaluating the control settings required for trim at the various Mach numbers, appropriate flight plans at altitude were assumed for each configuration. It is interesting to note the manner in which the initial trim changes have been postponed to higher Mach numbers for the swept configurations and, in particular, the extremely small trim changes associated with the 45° configuration. Above their respective critical speeds, both the straight-wing design and the tailless configuration manifested irregular trim changes. It is desirable to keep trim changes as small as possible, although the amount of trim change that can safely be tolerated depends to a considerable extent on the type of stability associated with $\left(\frac{\partial C_m}{\partial C_L}\right)_M$. For the straight-wing configuration two boundaries are presented for the parameter $\left(\frac{\partial C_m}{\partial C_L}\right)_M$ at supercritical speeds. The lower boundary is associated with the local flat spots in the pitching-moment data previously discussed. (See fig. 2.) These flat spots extended over a lift-coefficient range of less than 0.1 and are relatively unimportant for the particular flight plan employed for this example, inasmuch as the minimum lift coefficient attained is about 0.2. The response of the airplane to disturbances necessary to effect accelerations of the order of 2g or 3g is probably more nearly associated with some value between the two boundaries.

For the 35° swept design, this parameter is more precisely determinable and does not change appreciably up to a Mach number of 0.88, although it also increases rather rapidly at the higher supercritical Mach numbers.

For the 45° swept configuration, changes in the parameter have been delayed until a Mach number of about 0.95 has been reached and then $-\left(\frac{\partial C_m}{\partial C_L}\right)_M$ increases rather gradually. This comparison illustrates the need for employing a large degree of sweepback if trim and stability changes in the transonic region are to be minimized.

Two factors greatly affecting the value of $\left(\frac{\partial C_m}{\partial C_L}\right)_M$ are the wing-fuselage-aerodynamic-center position and the downwash at the tail. The manner in which these factors changed with Mach number for the straight-wing design and the 45° swept design are shown in figure 5.

The large variation in the local position of the wing-fuselage-aerodynamic-center position $\left(\text{denoted by } -\left(\frac{\partial C_m}{\partial C_L}\right)_M \text{ tail off}\right)$ for the straight-wing design is immediately apparent, and this variation is reflected in the behavior of the tail-on results, although the magnitude of the fluctuations has been decreased because of the increased tail effectiveness effected by the reduction in $\frac{d\epsilon}{dC_L}$ at the tail at the supercritical Mach numbers.

For the 45° swept configuration, the wing-fuselage-aerodynamic-center position varied only a small amount, and the increase in $\left(\frac{\partial C_m}{\partial C_L}\right)_M$ (tail on) at the higher Mach number was largely due to the increased tail effectiveness caused by the reduction in downwash slope at the tail.

Dynamic Stability

The parameter $\left(\frac{\partial C_m}{\partial C_L}\right)_M$ also influences to some extent the frequency of the short-period longitudinal oscillation. Some computations for a few characteristic designs were made in order to observe the manner in which this quantity affected the dynamic stability characteristics, and the results of the computations for a tailless design investigated are presented in figure 6. It is immediately apparent that altitude has a pronounced effect on the period of the oscillation and that the period becomes shorter as the speed is increased. The period varies in a somewhat hyperbolic manner with $\left(\frac{\partial C_m}{\partial C_L}\right)_M$ so that for the values $-\left(\frac{\partial C_m}{\partial C_L}\right)_M$ less than 0.05 the period will increase very rapidly, whereas for values of $-\left(\frac{\partial C_m}{\partial C_L}\right)_M$ greater than 0.15 the period will change only slightly. The importance of the frequency of the short-period oscillation will probably have to await flight experience, inasmuch as it will depend to some extent on the damping characteristics. It will be noted that while the damping, as evaluated by the number of seconds to damp to 1/2 amplitude, depends to a considerable extent on altitude and speed, it is independent of the parameter $\left(\frac{\partial C_m}{\partial C_L}\right)_M$. It is influenced significantly, however, by the damping in pitch; and for airplanes with a tail, the damping will be more rapid than that indicated here. For a particular design the characteristics of the short-period oscillation can be rapidly evaluated inasmuch as one needs only to determine the roots of the second-degree equation usually associated with this mode of the longitudinal motion.

LOW-SPEED PROBLEMS

One of the factors that has limited the amount of sweepback that can be beneficially employed on transonic designs has been the difficulty of providing satisfactory stability and control characteristics 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 7, which is taken from reference 11. Combinations of sweep and aspect ratio that fall above the line on 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 that stall has still been found to be consistent with that indicated in the figure.

While figure 7 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 in figure 7. 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 (references 12 to 15).

Stall-control devices.- At the present time stall-control devices have been successfully applied to wings with leading-edge sweep angles up to 42°. Some of the results of an investigation (references 12 and 13) covering the effect of stall-control devices on the pitching-moment characteristics of a 42° sweptback wing equipped with a split flap are shown in figure 8. This wing has an NACA 64_1-112 section and an aspect ratio of 4. This investigation was conducted in the Langley 19-foot pressure tunnel at a Reynolds number of about 6,840,000. The basic wing-fuselage combination exhibited an unstable pitching-moment variation at the stall. The addition of leading-edge flaps of the type indicated, covering about 60 percent of the span, resulted in a stable break of the pitching-moment curve at the stall, and this type of leading-edge device was the most satisfactory tested. Similar effects were also obtained with a leading-edge slat arrangement which covered 60 percent of the span except for a small region of instability just before $C_{L_{max}}$. This unstable region was removed by the addition of a fence located at the inboard end of the slot. This effect is somewhat typical of fence behavior. If located properly, fences, in general, have been found helpful in minimizing local unstable variations in the pitching-moment curve up to the maximum lift coefficient but do not appreciably affect the ultimate character of the pitching-moment variation at the stall.

Effect of fuselage.- The percent span of leading-edge flap or slat required to effect satisfactory pitching-moment behavior at the stall depends somewhat on the size of the fuselage to which the wing is attached and, to a lesser extent, on the position of the wing on the fuselage. The effect is illustrated in figure 9 (reference 13). The configuration represented by 0.575 leading-edge slots is the same wing configuration discussed in figure 8 and the fuselage is seen to have little effect on the character of pitching-moment variation at the stall. When the leading-edge flap span was increased to $0.725\frac{b}{2}$, however, the wing-fuselage combination was unstable at the stall; whereas the wing alone still exhibited favorable characteristics. Similar results were obtained for a high- and low-wing arrangement. It appears from tuft studies of these configurations that the flow over the fuselage delays the stalling of the center section to such an extent that initial separation again began over the flapped portion of the wing.

Effect of tail location.- The addition of a tail adds further complications but, in general, it has been found that stable behavior of the resultant pitching moment at the stall is most likely to be achieved when the basic wing-fuselage pitching moment exhibits a stable variation. The location of the tail, however, is an important consideration and the effect of adding a tail to the wing-fuselage configuration with $0.575\frac{b}{2}$ leading-edge flaps and $0.50\frac{b}{2}$ trailing-edge flaps is shown in figure 10.

A study of these data indicates that the most satisfactory pitching-moment behavior at the stall was actually achieved with the low tail position by virtue of the decreased rate of change of downwash associated with this tail location. This low position was close to the edge of the wing wake, however, and may be objectionable from other considerations. The more desirable midtail location possessed a local region of instability just before $C_{L_{max}}$ which was removed by the addition of a fence.

CONCLUSIONS

In recapitulation, the following generalizations can be made:

1. The incorporation of large amounts of sweepback on both the wing and the horizontal tail has been found to increase the Mach number at which trim changes and stability changes are first manifested and to reduce greatly the trim changes and stability changes encountered at supercritical speeds.

2. Longitudinal stability in the landing condition has been attained for configurations with sweep angles of the order of 45° utilizing various stall-control devices, but at the present time optimum arrangements for these devices must be determined experimentally.

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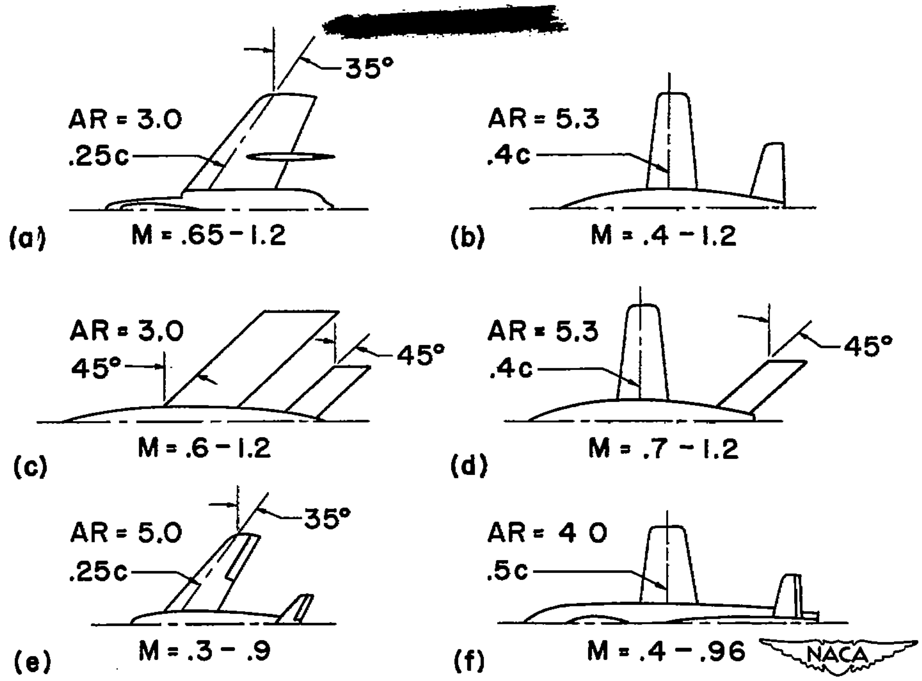
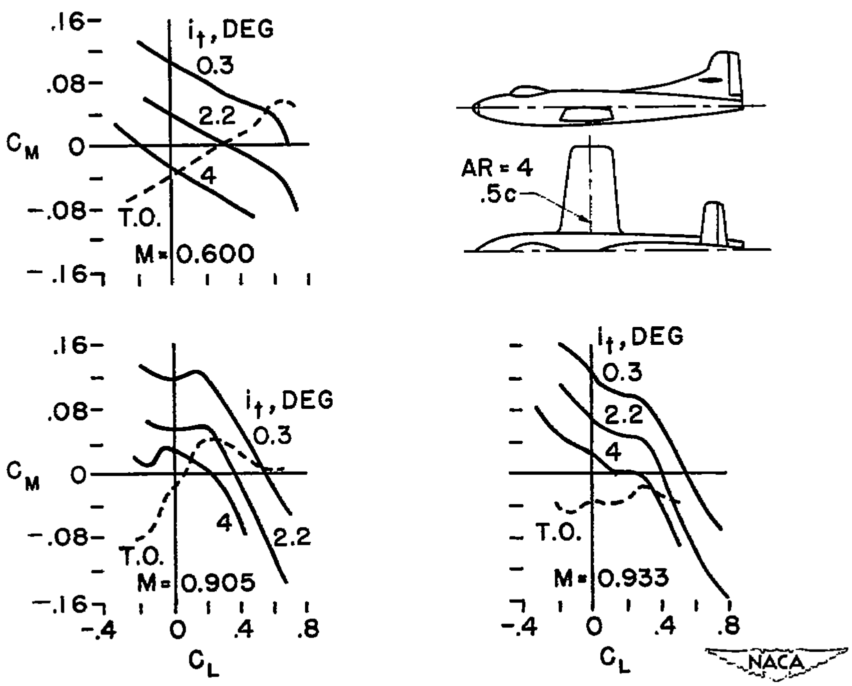


COMPLETE MODEL INVESTIGATIONS

Figure 1.



PITCHING CHARACTERISTICS OF A STRAIGHT-WING DESIGN

Figure 2.

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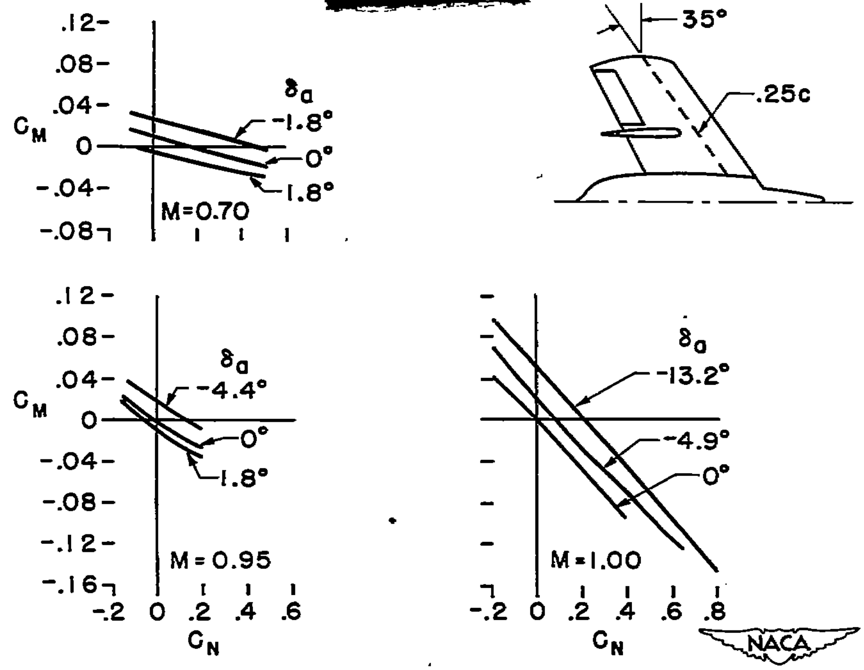
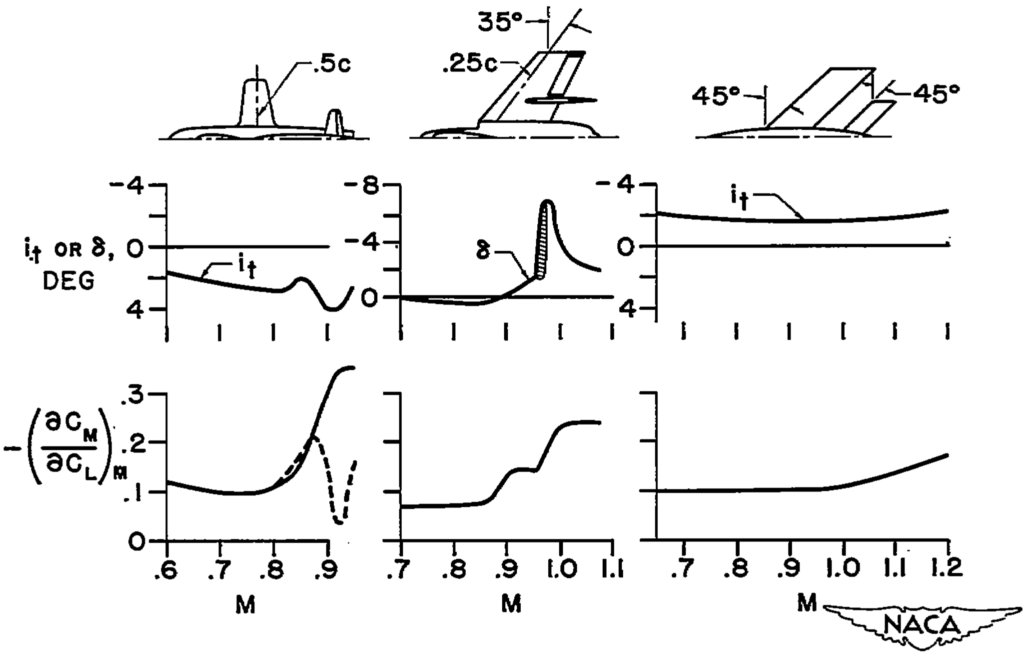
[redacted]



PITCHING CHARACTERISTICS OF A TAILLESS DESIGN

Figure 3.



LONGITUDINAL STABILITY OF THREE TRANSONIC DESIGNS

Figure 4.

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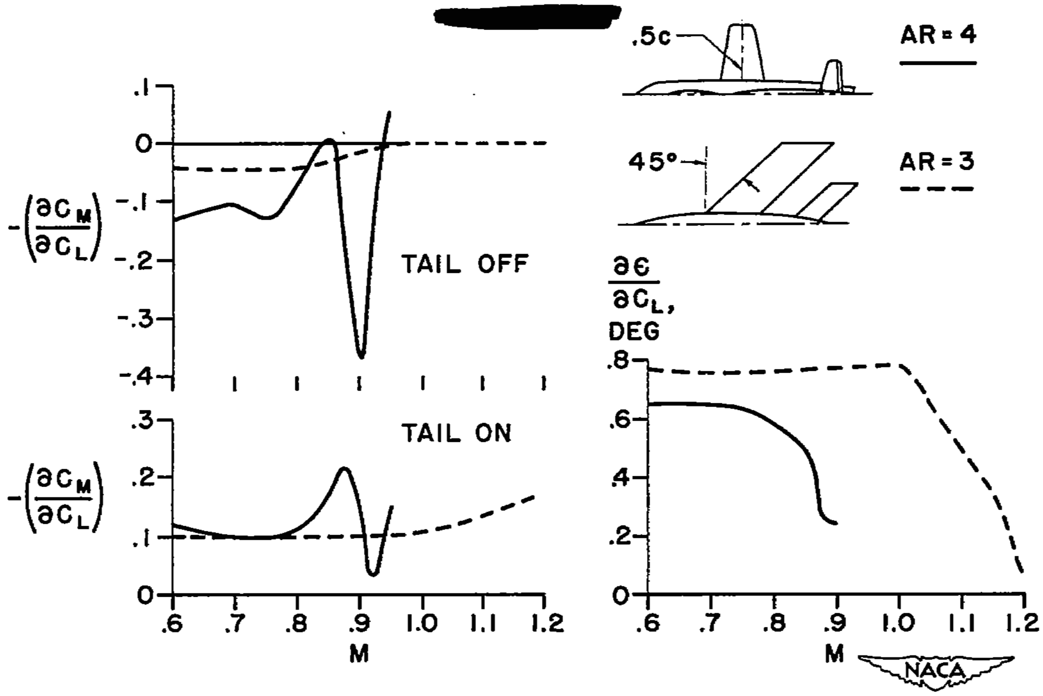
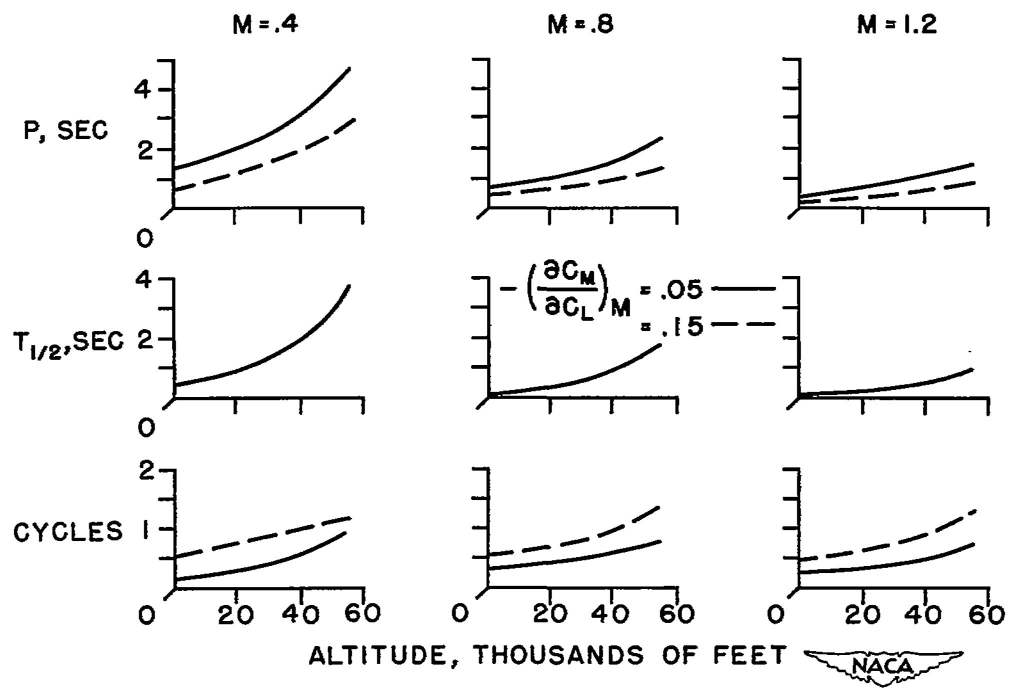
[redacted]



EFFECT OF SWEEP ON STABILITY COMPONENTS

Figure 5.



DYNAMIC STABILITY OF A TAILLESS DESIGN W/S = 28.0

Figure 6.

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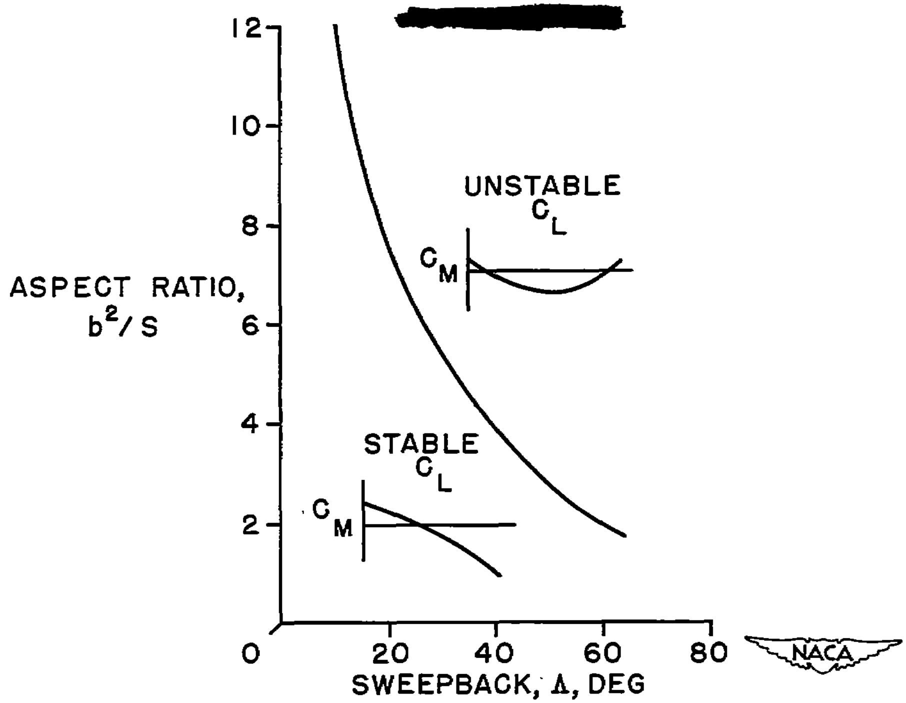
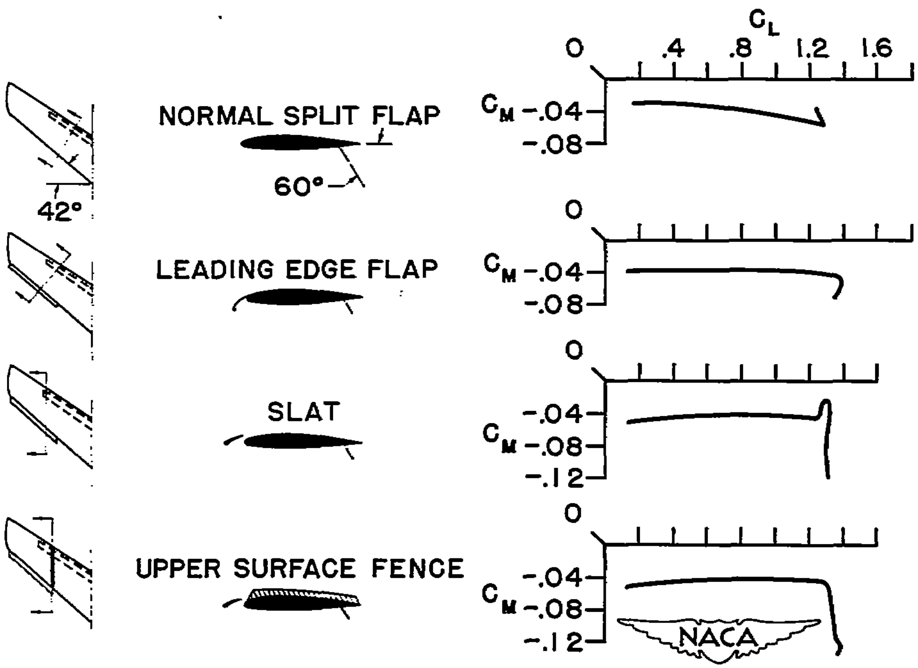
[redacted]



PITCHING-MOMENT BEHAVIOR OF SWEPTBACK WINGS

Figure 7.



EFFECT OF HIGH-LIFT AND STALL CONTROL DEVICES ON PITCHING MOMENT

Figure 8.

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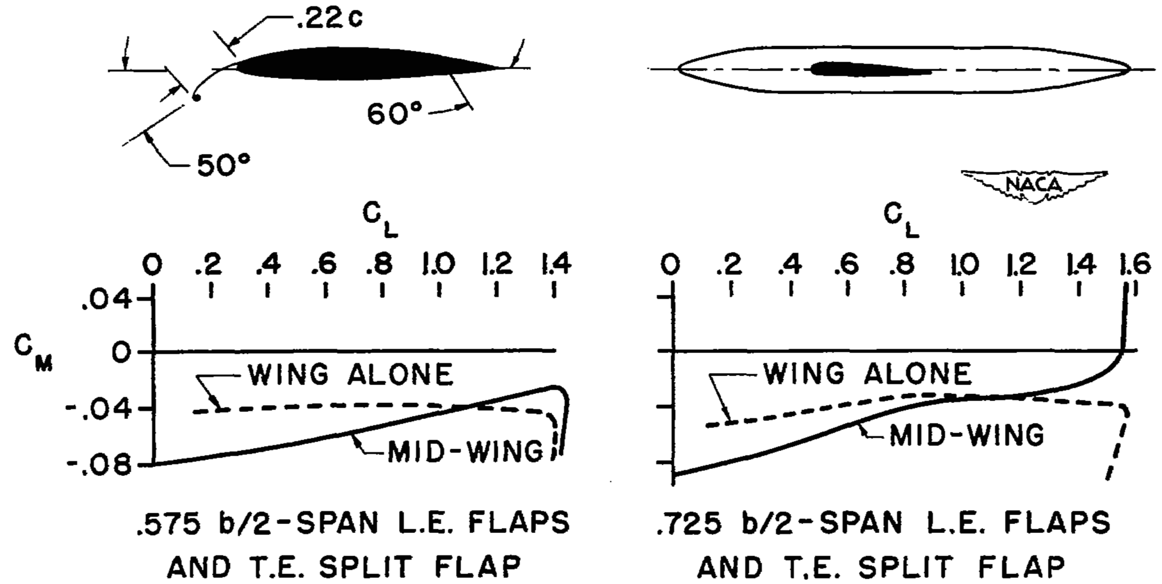
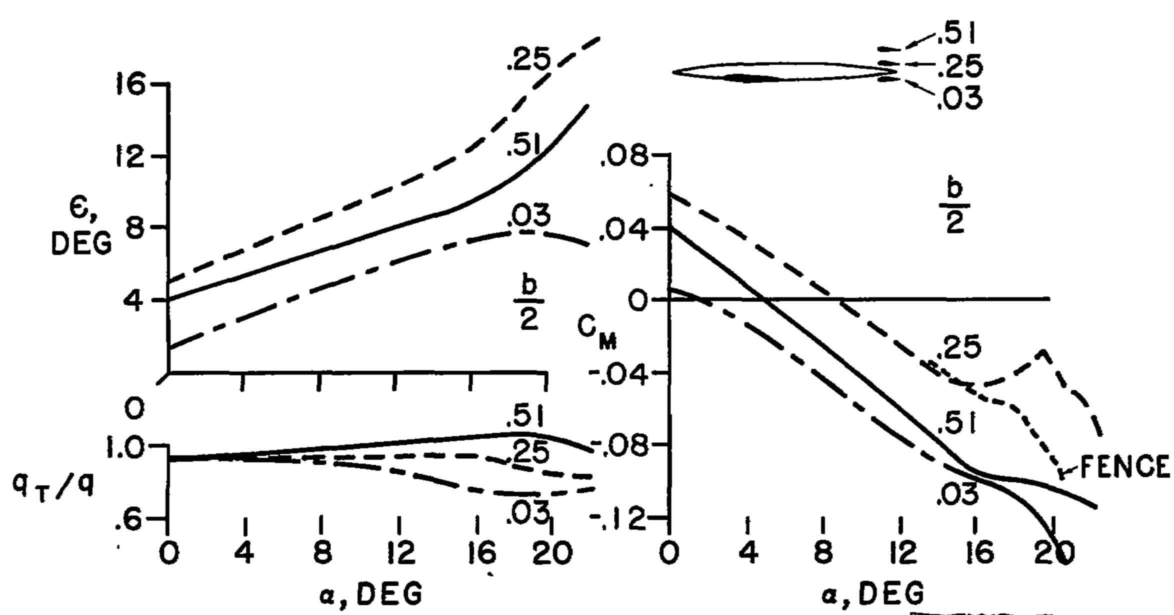
[redacted]



EFFECT OF FUSELAGE ON PITCHING MOMENT

Figure 9.



EFFECT OF TAIL LOCATION

Figure 10.

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