CURRENT STATUS OF LONGITUDINAL STABILITY

By Charles J. Donlan

Langley Memorial Aeronautical Laboratory

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.

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 Committee's high-speed wind tunnels and at transonic Mach numbers up to 1.2 utilizing the NACA wing-flow method and the associated wind-tunnel transonic-bump technique. These investigations are contained in references 1 to 15, and some of the configurations investigated together with the Mach number range for which data are available are summarized in figure 1.

For the tailless configuration (a), Langley high-speed 7- by 10-foot tunnel data for a sting supported model and for a semispan model exist up to a Mach number of 0.95, and wing-flow data are available up to a Mach number of 1.20. 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 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. 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.

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

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 $M = 0.6$ are typical of the behavior before force break, and some comments regarding the predicability of the characteristics in this range is 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 16). 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 17 and 18). 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 is apparent at a Mach number of 0.905 and 0.933, and the appearence 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 $M = 0.7$ 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 (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 (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 2 or 3 g's 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 variations 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-fulselage-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.

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 tho 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

Static Stability in High Lift Range

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 conter of the wing can be estimated fairly reliably, and a paper entitled "Prediction of the Aerodynamic Characteristics of Wings of Arbitrary Plan Form" by Victor I. Stevens dealing with this subject

has already been presented. 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 19. 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 on 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 on 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 20 to 24).

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 20 and 21) 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 21). 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.- Thus far we have discussed only the characteristics of the basic wing-fuselage combination. 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 (reference 22).

A study of these data indicate 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 greatly reduce 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.

[redacted]

REFERENCES

Complete Model Investigations

1. Mattson, Axel T.: Force and Longitudinal Control Characteristics of a 1/16-Scale Model of the Bell XS-1 Transonic Research Airplane at High Mach Numbers. NACA RM No. L7A03, 1947.

2. Mattson, Axel T., and Loving, Donald L.: Force, Static Longitudinal Stability, and Control Characteristics of a 1/16-Scale Model of the Bell XS-1 Transonic Research Airplane at High Mach Numbers. (Prospective NACA paper)

3. Wright, John B., and Loving, Donald L.: High-Speed Wind-Tunnel Tests of a 1/16-Scale Model of the D-558 Research Airplane. Lift and Drag Characteristics of the D-558-1 and Various Wing and Tail Configurations. NACA RM No. L6J09, 1946.

4. Wright, John B.: High-Speed Wind-Tunnel Tests of a 1/16-Scale Model of the D-558 Research Airplane. Basic Longitudinal Stability of the D-558-1. (Prospective NACA paper)

5. Wright, John B.: High-Speed Wind-Tunnel Tests of a 1/16-Scale Model of the D-558 Research Airplane. Longitudinal Stability and Control of the D-558-1. (Prospective NACA paper)

6. Goodson, Kenneth W., and Myers, Boyd C., II: An Investigation of the Aerodynamic Characteristics of an 0.08-Scale Model of the Chance Vought XF7U-1 Airplane in the Langley High-Speed 7- by 10-Foot Tunnel. Part IV - Aileron Characteristics - TED No. NACA DE308. NACA RM No. L7H22, Bur. Aero., 1947.

7. Kuhn, Richard E., and Myers, Boyd C., II: An Investigation of the Aerodynamic Characteristics of an 0.08-Scale Model of the Chance Vought XF7U-1 Airplane in the Langley High-Speed 7- by 10-Foot Tunnel. Part V - Wing-Alone Tests and Effect of Modifications to the Vertical Fins, Speed Brakes, and Fuselage. TED No. NACA DE308. NACA RM No. L7J09, Bur. Aero., 1947.

8. Sawyer, Richard H., and Trant, James P., Jr.: Longitudinal Stability and Control Characteristics of a Semispan Model of the XF7U-1 Tailless Airplane at Transonic Speeds by the NACA Wing-Flow Method. NACA RM No. L7I08, Bur. Aero., 1947.

9. Goodson, Kenneth W.: An Investigation of an 0.08-Scale Semispan Model of the Chance Vought XF7U-1 Airplane in the Langley 7- by 10-Foot Wind Tunnel. (Prospective NACA paper)

[redacted]

10. Spearman, M. Leroy: Longitudinal Stability and Control Characteristics at Transonic Speeds of a Model Equipped with a 45° Swept Wing and Tail by the Transonic-Bump Method. (Prospective NACA paper.)

11. Zalovcik, John A., and Sawyer, Richard H.: Longitudinal Stability and Control Characteristics of a Semispan Airplane Model at Transonic Speeds from Tests by the NACA Wing-Flow Method. NACA ACR No. L6E15, 1946.

12. Weil, Joseph, and Spearman, M. Leroy: Longitudinal Stability and Control Characteristics of a Semispan Airplane Model at Transonic Speeds as Obtained by the Transonic-Bump Method and a Correlation with Results Obtained by the NACA Wing-Flow Method. (Prospective NACA paper)

13. Zalovcik, John A., and Sawyer, Richard H.: Longitudinal Stability and Control Characteristics of a Semispan Airplane Model with a Swept-Back Tail From Tests at Transonic Speeds by the NACA Wing-Flow Method. NACA MR No. L6G09, 1946.

14. Boddy, Lee E., and Morrill, Charles P., Jr.: The Aerodynamic Effects of Modifications to the Wing and Wing-Fuselage Intersection of an Airplane Model with the Wing Swept Back 35°. NACA RM No. A7J02, 1947.

15. Morrill, Charles P., Jr., and Boddy, Lee E.: Stability and Control Characteristics of a Fighter Airplane Model with a Sweptback Wing and Tail. (Prospective NACA paper)

Theoretical Investigations

16. Jones, Robert T.: Properties of Low-Aspect-Ratio Pointed Wings at Speeds below and above the Speed of Sound. NACA TN No. 1032, 1946.

17. Owen, P. R.: The Effect of Compressibility on Longitudinal Stability below the Shock Stall. Rep. No. Aero 1829, British R.A.E., March 1944.

18. Nielsen, Jack N., and Sweberg, Harold, H.: Note on Compressibility Effects on Downwash at the Tail at Subcritical Speeds. NACA CB No. L5C09, 1945.

Low-Speed Investigations

19. Shortal, Joseph A., and Maggin, Bernard: Effect of Sweepback and Aspect Ratio on Longitudinal Stability Characteristics of Wings at Low Speeds. NACA TN No. 1093, 1946.

20. Neely, Robert H., and Conner, D. William: Aerodynamic Characteristics of a 42° Sweptback Wing with Aspect Ratio 4 and NACA 64_1-112 Airfoil Sections at Reynolds Numbers from 1,700,000 to 9,500,000. NACA RM No. L7D14, 1947.

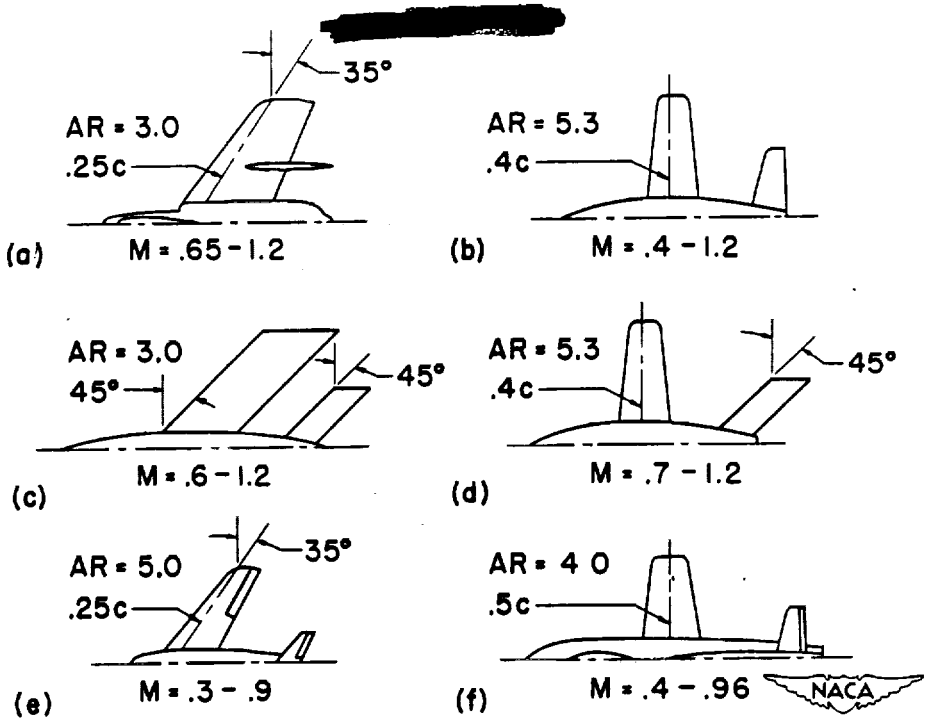
21. Conner, D. William, and Neely, Robert H.: Effects of a Fuselage and Various High-Lift and Stall-Control Flaps on Aerodynamic Characteristics in Pitch of an NACA 64-Series 40° Swept-Back Wing. NACA RM No. L6L27, 1947.

22. Spooner, Stanley H.: Longitudinal Stability Characteristics of a 42° Sweptback Wing and Tail Combination. (Prospective NACA paper)

23. Weil, Joseph, Comisarow, Paul, and Goodson, Kenneth W.: Longitudinal Stability and Control Characteristics of an Airplane Model Having a 42.8° Sweptback Circular-Arc Wing with Aspect Ratio 4.00, Taper Ratio 0.50, and Sweptback Tail Surfaces. NACA RM No. L7G28, 1947.

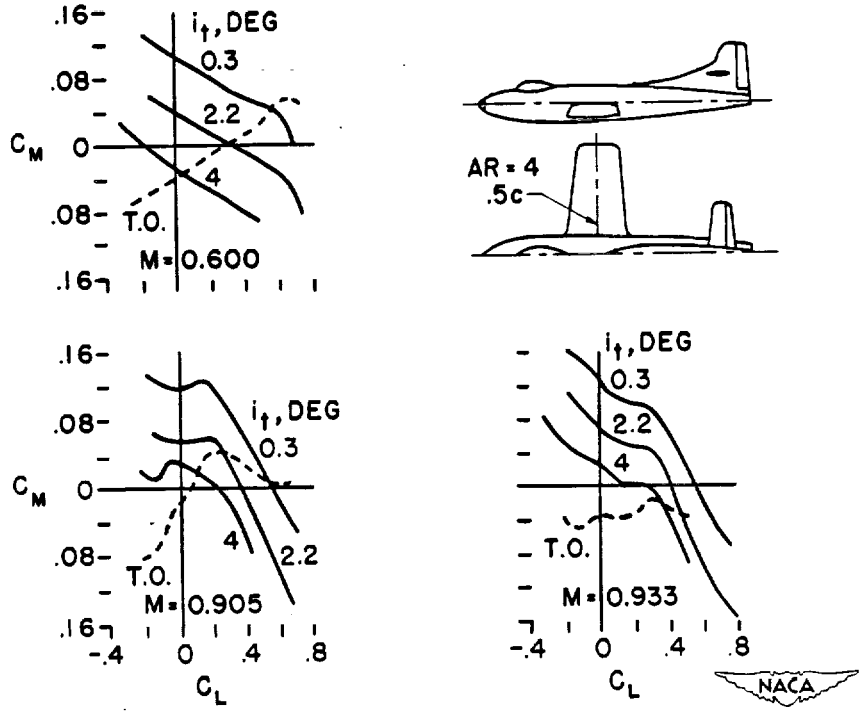
24. Schuldenfrei, Marvin, Comisarow, Paul, and Goodson, Kenneth W.: Stability and Control Characteristics of an Airplane Model Having a 45.1° Swept-Back Wing with Aspect Ratio 2.50 and Taper Ratio 0.42 and 42.8° Swept-Back Horizontal Tail with Aspect Ratio 3.87 and Taper Ratio 0.49. NACA RM No. L7B25, 1947.

Donlan



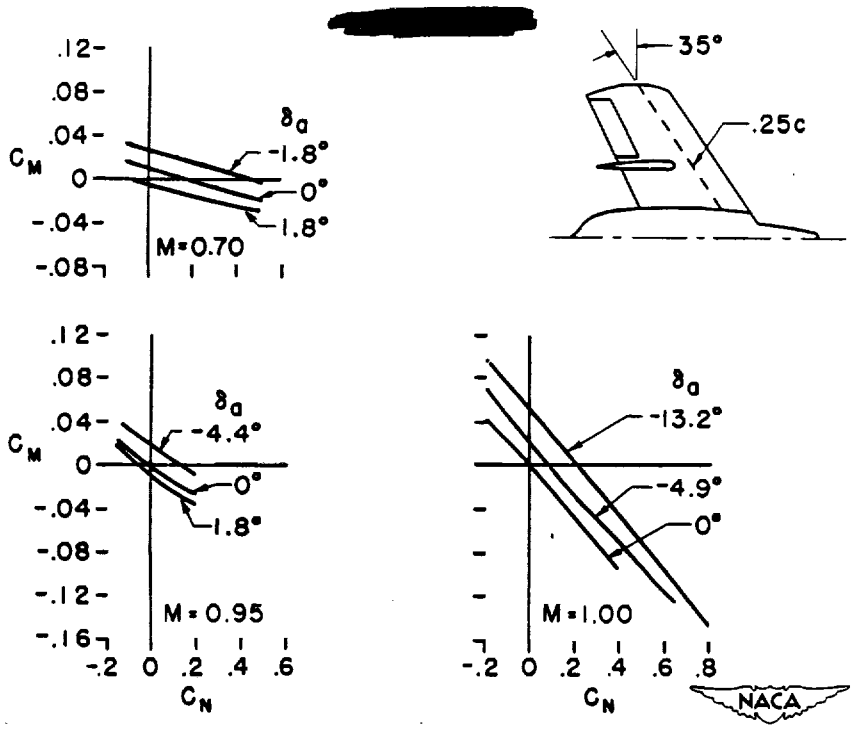
COMPLETE MODEL INVESTIGATIONS

Figure 1.



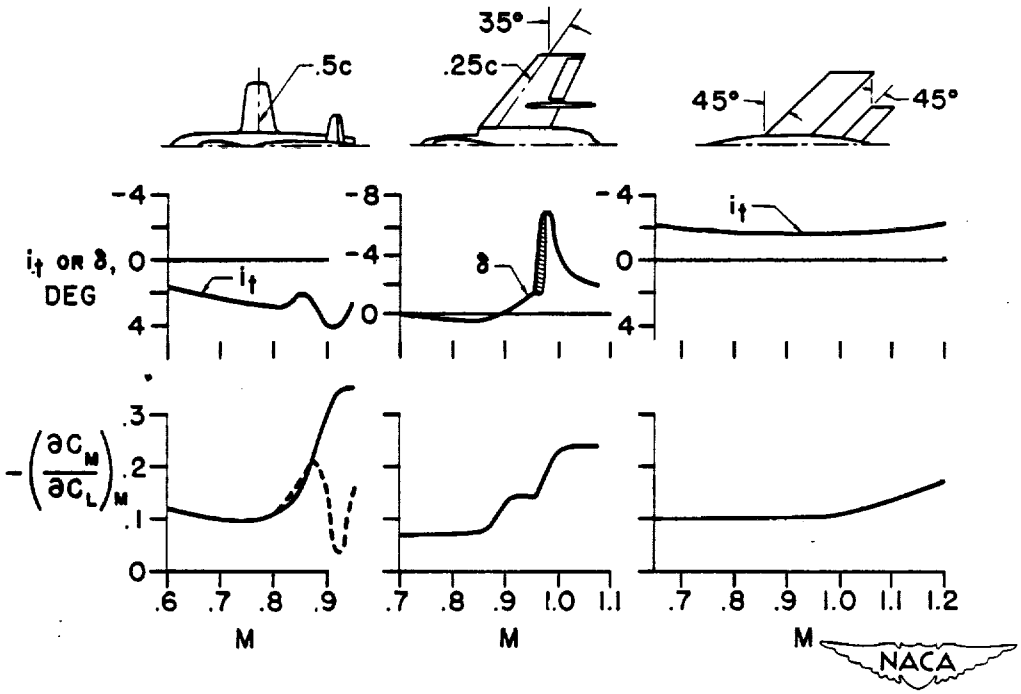
PITCHING CHARACTERISTICS OF A STRAIGHT-WING DESIGN

Figure 2.



PITCHING CHARACTERISTICS OF A TAILLESS DESIGN

Figure 3.

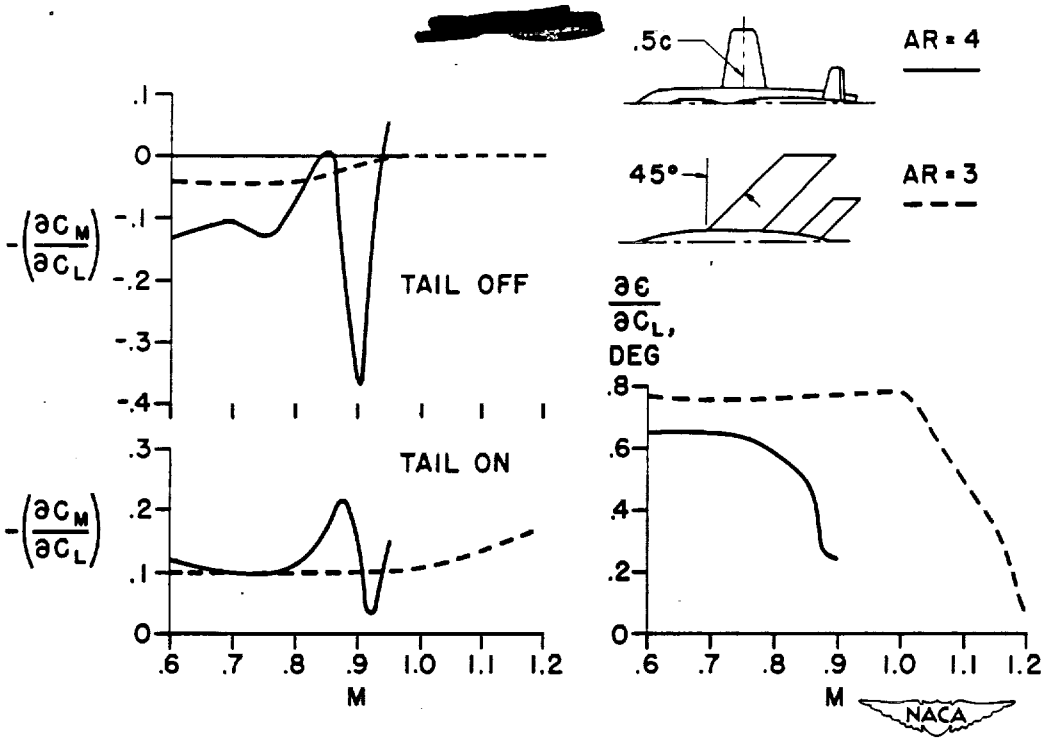


LONGITUDINAL STABILITY OF THREE TRANSONIC DESIGNS

Figure 4.

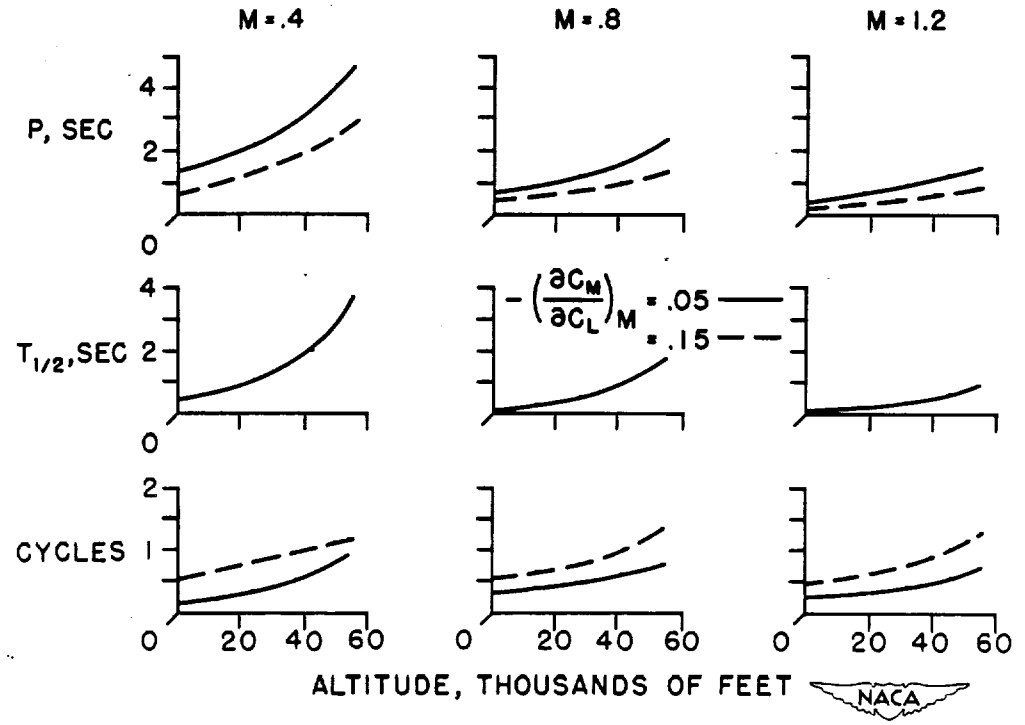
[redacted]

112(a)



EFFECT OF SWEEP ON STABILITY COMPONENTS

Figure 5.

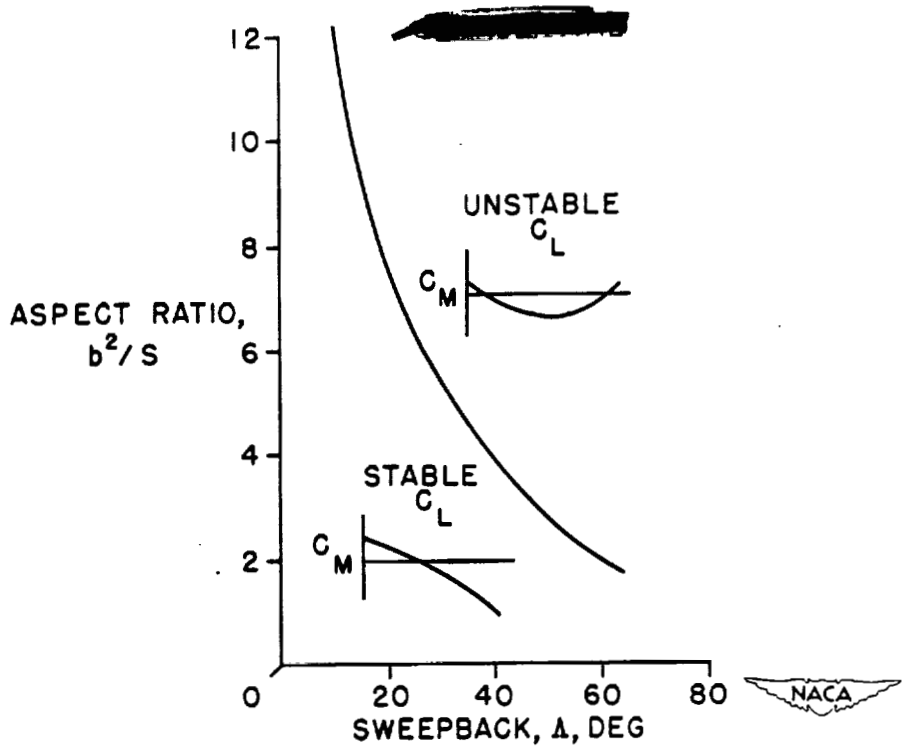


DYNAMIC STABILITY OF A TAILLESS DESIGN W/S = 28.0

Figure 6.

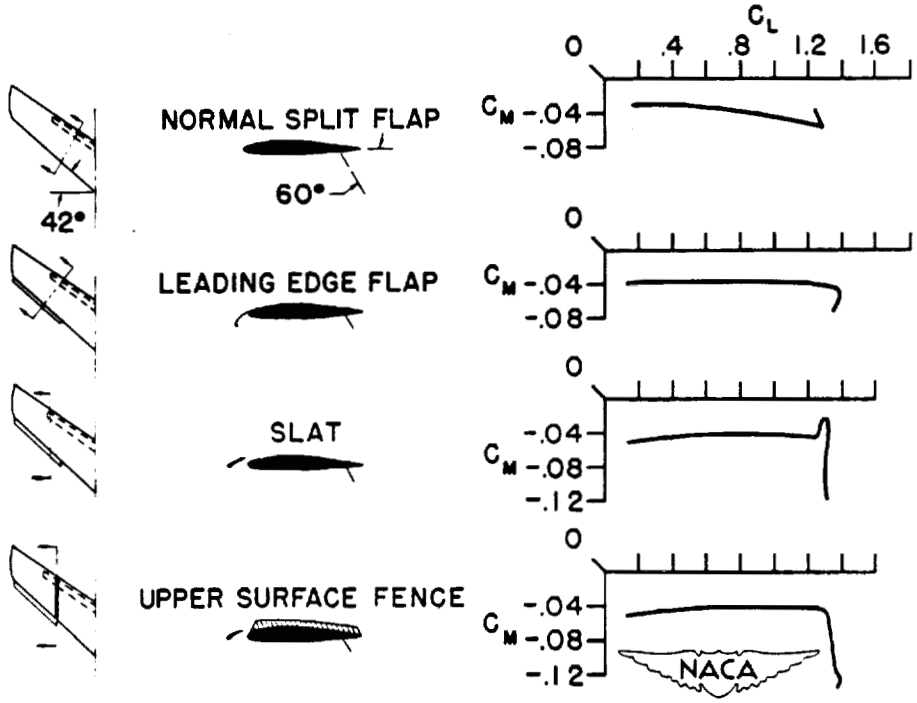
[redacted]

114(a)



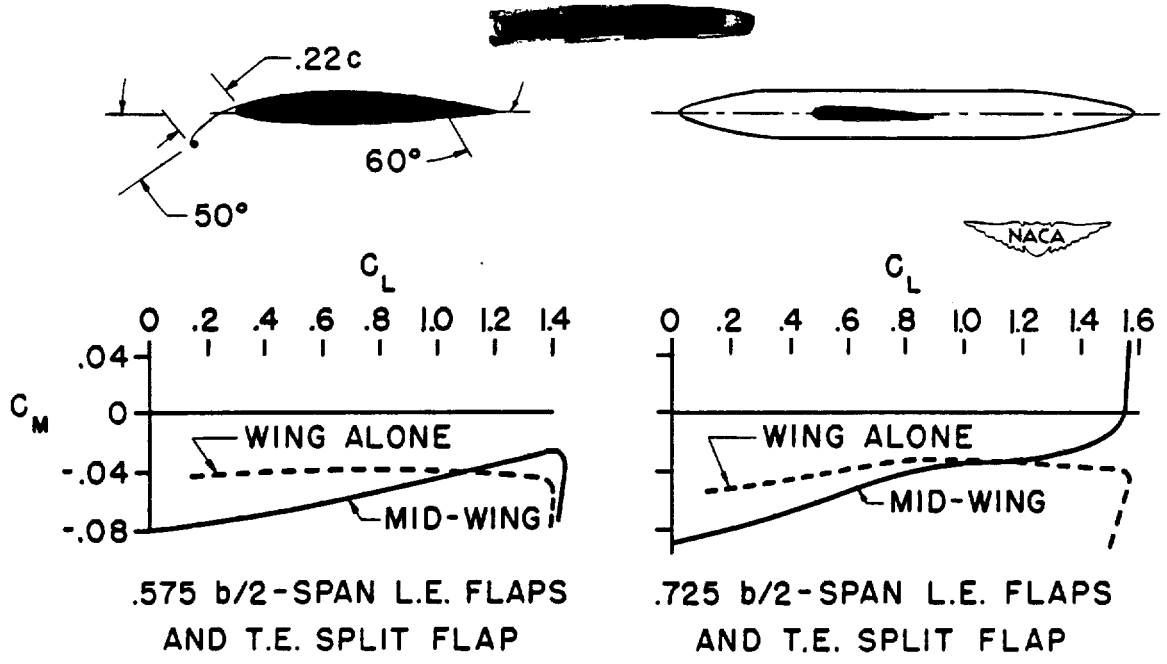
PITCHING-MOMENT BEHAVIOR OF SWEPTBACK WINGS

Figure 7.



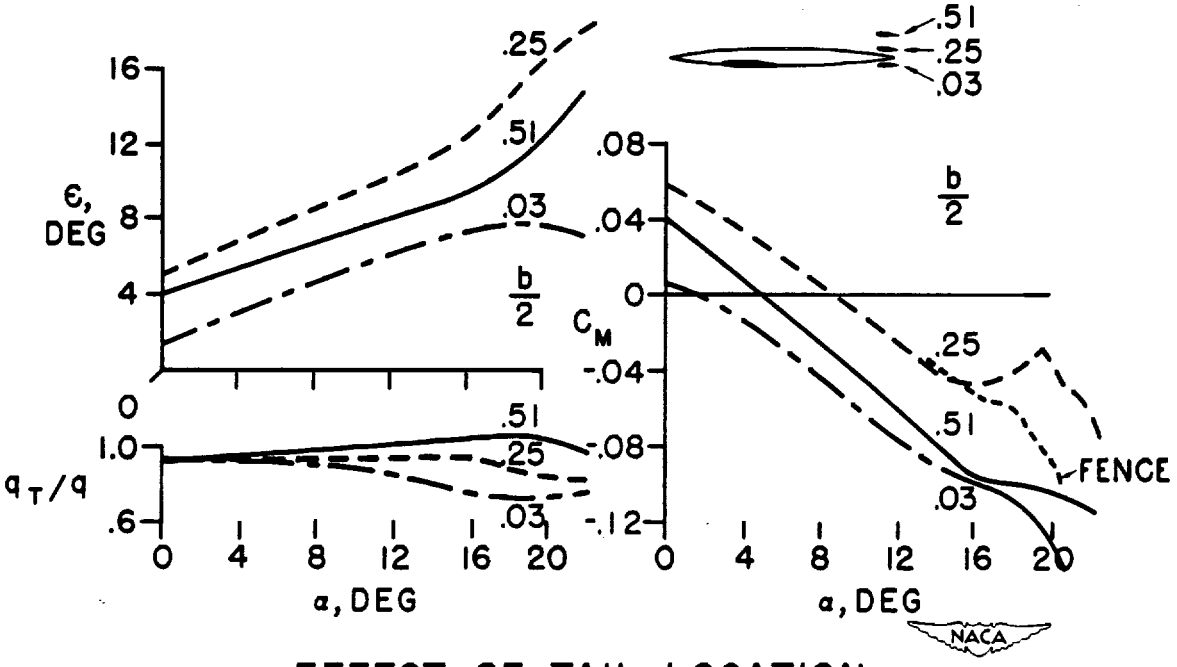
EFFECT OF HIGH-LIFT AND STALL-CONTROL DEVICES ON PITCHING MOMENT

Figure 8.



EFFECT OF FUSELAGE ON PITCHING MOMENT

Figure 9.



EFFECT OF TAIL LOCATION

Figure 10.

[redacted]

1:2(d)