THE SIGNIFICANCE OF NONLINEAR DAMPING TRENDS DETERMINED FOR CURRENT AIRCRAFT CONFIGURATIONS

By Harleth G. Wiley

NASA Langley Research Center
Langley Station, Hampton, Va., U.S.A.

Presented at the AGARD Flight Mechanics Panel's
Specialists' Meeting on Stability and Control

Cambridge, England
September 20-23, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON

[redacted]

THE SIGNIFICANCE OF NONLINEAR DAMPING TRENDS DETERMINED FOR CURRENT AIRCRAFT CONFIGURATIONS

By Harleth G. Wiley
Head, Vehicle Dynamics Section
Full-Scale Research Division
NASA Langley Research Center

ABSTRACT

The basic features and accuracy of the rigidly forced dynamic-stability technique used in wind tunnels at the Langley Research Center of the National Aeronautics and Space Administration for measuring pitch- and yaw-damping derivatives at subsonic, transonic, and supersonic speeds are reviewed. The ability of the equipment to permit investigations at high angles of attack where separated flow may be present and in regions of large aerodynamic instabilities is discussed. The effects of sting mounting on the measured derivatives are included. Representative results of experimental research performed for several current and proposed aircraft configurations are presented. The effects of angle of attack, wing-sweepback angle, horizontal-tail size and incidence angle, and nacelle placement on damping are discussed. The results of high angle-of-attack damping investigations of a T-tail transport configuration are presented. The significance of pitch-damping levels to stall entry and recovery for a typical T-tail transport airplane, as determined by analytical and simulator studies, is discussed.

L-5068

[redacted]

THE SIGNIFICANCE OF NONLINEAR DAMPING TRENDS DETERMINED FOR CURRENT AIRCRAFT CONFIGURATIONS

By Harleth G. Wiley
Head, Vehicle Dynamics Section
Full-Scale Research Division
NASA Langley Research Center

SUMMARY

This paper reviews the basic features and accuracy of the rigidly forced dynamic-stability technique in use in wind tunnels at the Langley Research Center of the National Aeronautics and Space Administration for investigations of the pitch- and yaw-damping characteristics of aircraft configurations from subsonic to supersonic speeds. The equipment is especially useful for research at high angles of attack where separated flow may be present and in regions of large aerodynamic instabilities.

Representative research results show that aircraft configurations with moderately swept, subsonic-type wings have sharply decreased or negative pitch damping near the primary stall. Analytical longitudinal-response studies of a T-tail transport airplane show that this negative damping can cause divergence to a deep-stall attitude. The levels and trends of pitch damping with angle of attack are functions of wing-sweepback angle, nacelle placement, and horizontal-tail size and incidence angle. Increased horizontal-tail size decreased the pitch damping at the primary stall and at the deep stall for a T-tail transport configuration. Analytical and piloted simulator studies of a T-tail transport show that this decreased pitch damping near the deep stall can be beneficial to recovery.

INTRODUCTION

The efficient and effective design of airframes and control systems for modern aircraft requires knowledge of the levels and trends of the aerodynamic damping, or so-called rotary derivatives. These damping derivatives are

L-5068

equally important as inputs to pilot-training simulators. However, the prediction of the damping derivatives for configurations with swept wings, large jet-engine packages, and complex fuselage shapes is often difficult. This is especially true at the higher angles of attack and the higher Mach numbers where the mechanics of the aerodynamic phenomena involved may be largely unknown. Consequently, the damping derivatives often must be determined by experimental means. Experimental results, of course, can be obtained by full-scale flight tests, if the airplane is available and if the required tests do not jeopardize aircraft safety. However, controlled dynamic testing in the wind tunnel is still one of the best methods for determining damping derivatives, as well as for performing fundamental research on dynamic phenomena. Therefore, efforts have continued within the National Aeronautics and Space Administration to develop and improve specialized wind-tunnel techniques for investigating damping derivatives.

This paper will review the basic features and the accuracy of the technique used in wind tunnels at the Langley Research Center of NASA to determine the oscillatory pitch- and yaw-damping derivatives at transonic and supersonic speeds. A discussion of sting effects on the measured parameters is included. Representative results of some of the experimental research performed for various current and proposed aircraft configurations will be presented. Emphasis will be placed on those aerodynamic and configuration factors that cause unstable or grossly nonlinear damping trends which are not predictable by the usual computing methods. The significance of some of these damping trends to stall entry and recovery for a representative aircraft type, as determined by analytical and simulator studies, also will be discussed.

EXPERIMENTAL TECHNIQUE

Basic Principles and Features

A rigidly forced oscillatory dynamic-stability technique has been developed and is in use at the Langley Research Center of NASA for measuring pitch- and yaw-damping derivatives in wind tunnels at transonic and supersonic speeds. A detailed description of the technique is reported in references 1, 2, and 3. However, this paper will review the concept and construction of this test equipment, as these factors strongly influence the type of research that can be performed, and the accuracy of the results.

The device illustrated in Fig. 1 is a sting-mounted, rigidly forced, oscillating mechanism which provides small-amplitude sinusoidal oscillations in pitch or in yaw. The oscillatory motion of the balance is provided by a motor-driven eccentric and crosshead assembly completely contained within the balance. Amplitude is maintained constant by the fixed throw, or stroke, of the eccentric crank at $1/2^{\circ}$, 1°, or 2°. A cantilevered mechanical spring is mounted between the fixed sting and the oscillating balance to aid in tuning, or balancing, the higher frequency inertia loads of the oscillating model and balance assembly. This spring provides a frequency range of about 3 to 20 cycles per second.

The torque required to oscillate the model and balance assembly and the resulting displacement of the model are sensed by strain gages. The oscillating torque and displacement signals are then fed through coupled sine-cosine resolvers which rotate at the fundamental frequency of model oscillation. These resolvers, with suitable electronic circuitry, convert the alternating torque and displacement signals into orthogonal components, the average values of which are read out on damped, digitized voltmeters. The calibrated orthogonal torque components, when precisely alined and phased with the calibrated model displacement readings, can easily be converted to the usual aerodynamic damping and stiffness or static-stability parameters.

The rigid mechanical drive system illustrated in Fig. 1 provides positive control of oscillation amplitude and frequency. Therefore, these test variables are not affected by the aerodynamic or inertia loads on the model.

Since oscillation amplitude and frequency are independent of the aerodynamic loads on the model, tests can be made to high angles of attack. At transonic and supersonic speeds, angles of attack up to about 25° can be attained. At lower speeds, investigations can be made up to an angle of attack of 55°. This capability has been especially useful for research of the stability characteristics for T-tail airplanes in the so-called deep-stall region.

The system is independent of model aerodynamic trim. Thus, auxiliary aerodynamic trimming devices such as those required for free-decay or spring-forced dynamic-stability systems are not needed.

Aerodynamic instabilities do not cause model divergence. Consequently, regions of static and dynamic instabilities, which are of primary importance, can be investigated, and tail-off tests can be made to determine the tail contributions to damping.

Accuracy

An important characteristic is the high accuracy of the technique. High frequencies are necessary to obtain realistic values of the reduced-frequency parameter at transonic and supersonic speeds. The high frequencies result in high model inertia loads which would ordinarily be sensed by the torque strain gages. However, as explained previously, a mechanical tuning spring is installed between the oscillating model and the fixed sting to counteract these inertia loads. Thus, the relatively small damping moments which are of primary importance are not masked by the high inertia loads. It is important to emphasize that this spring does not drive the model but is simply a tuning device. The best accuracy for damping measurements, of course, is obtained at the resonant frequency of the mechanical-aerodynamic system. Consequently, most tests are made at these resonant conditions unless frequency effects are of interest.

Another very important requirement is that the measured damping be independent of the effects of wind-tunnel turbulence. Because of the rigid mechanical drive just described, the model cannot physically respond to turbulence. The signals caused by turbulence and other inputs of a random nature, however, are obviously superimposed on the oscillating torque signal. But when this random signal is passed through the sine-cosine resolvers operating at the fundamental model oscillation frequency, and then impressed upon suitably damped voltmeters, the effects of turbulence and noise are filtered out as explained in references 1, 2, and 3.

The internal mechanical or tare damping is maintained at a minimum in three critical areas. First, the torque strain gages are mounted at the model ahead of all moving elements of the oscillating balance. The measured damping, therefore, is not subjected to inputs from the friction of bearings and other drive components. Second, the tuning spring and its mounting flexures, which are located ahead of the torque strain gages and therefore could contribute to the measured mechanical damping, are electron-beam welded in place after assembly. Thus, the damping of bolted fittings is eliminated. Finally, model components are built of metal, with integral-welded construction where possible.

(Wood and foamed-plastic materials have been found unsuitable because of high internal damping.) These construction procedures have resulted in very low mechanical or tare damping levels of less than 1 percent of the measured aerodynamic pitch damping for typical airplane models.

High strain-gage-balance sensitivity is necessary in order to measure the relatively small damping moments in the presence of very large static pitching moments at the higher angles of attack. To accomplish this, the strain-gage-balance elements are designed for maximum element surface strain with minimum total structural deflection. In addition, the balances are now equipped with semiconductor strain gages which provide about 60 times the sensitivity of the usual foil or wire strain gages. (Although these semiconductor strain gages provide large increases in sensitivity of measurement, the gages also are very sensitive to heat and light. However, temperature-controlled, balance-heating elements and proper light shielding have solved these problems.) As a result of these techniques, the most recent balance is capable of sensing about 0.05 inch-pound of damping moment in the presence of 1600 inch-pounds of static pitching moment.

All oscillating mechanisms and drive components are located within the model and sting. Thus, shock interference from externally mounted drive linkages is eliminated.

Sting Effects

One of the first questions that usually arises is whether or not the sting mounting affects the experimentally measured damping results. Consequently, damping investigations have been made for a four-jet subsonic transport airplane model with three grossly different sting-mounting arrangements. Sketches of this model with the three sting-mounting systems are presented in Fig. 2.

For system A, the model was mounted with the sting entering through the top of the fuselage at an angle of 16°. The vertical tail was removed to provide sting clearance. The sting itself was short and rather large in diameter, with a blunt conical section immediately behind the model. This blunt sting design was required for high-angle-of-attack investigations. System B utilized the same sting as system A. The aft portion of the fuselage was modified as shown to permit sting entry parallel to the model longitudinal axis. For system C, the sting was relatively long and slim and entered the bottom of the fuselage at an angle of -10° in order to preserve the geometry of the afterbody and tail assembly (ref. 4).

The experimentally measured pitch-damping characteristics of the transport airplane model at a Mach number of 0.2 for the three different sting arrangements are presented in Fig. 3. Some of the results presented are published in reference 4. The pitch-damping parameter is plotted on the ordinate and the angle of attack is plotted on the abscissa. (Positive damping is indicated by the arrow.) As shown in Fig. 3, the most noticeable effect occurred at high angles of attack for system B, which had the modified model afterbody and the blunt sting. The modified afterbody, as indicated by the dotted outline (Fig. 3), was then tested on system A. Although the data are not presented in this figure, the results showed no significant effects of the afterbody modifications when tested on system A. The differences at high angles for system B, therefore, apparently result from flow distortions caused by the blunt sting located immediately behind, and in the plane of, the horizontal tail. At low to moderate angles of attack, however, the grossly different sting arrangements did not materially affect the measured pitch damping for the subsonic transport model. As shown in Fig. 3, a pronounced decrease in pitch damping occurred near an angle of attack of 18° for this transport-airplane model. This decreased damping characteristic is independent of sting-mounting arrangement and will be discussed in the section on experimental results.

DISCUSSION OF RESULTS

The dynamic-stability equipment just described has been used for research on the rigid-body pitch- and yaw-damping characteristics of aircraft and spacecraft configurations at the Langley Research Center at Mach numbers from 0.2 to 4.6. The system has proven to be very reliable and accurate. It has been especially useful for investigations of the theoretically unpredictable damping parameters at high angles of attack where separated flow may be present and in regions of large aerodynamic instabilities.

A broad range of aircraft configurations has been investigated. Both fixed-wing and variable-sweep proposals, suitable for supersonic military and transport use, have been investigated at subsonic, transonic, and supersonic speeds. Extensive experiments have been made on the effects of angle of attack on the damping characteristics of typical contemporary swept-wing jet-transport configurations at subsonic and transonic speeds. This paper will present some selected results from these many experimental investigations and will discuss the significance of these damping trends to the flight response of a representative aircraft type.

General Experimental Results

Effect of primary stall.- The effects of angle of attack on the pitch damping of three aircraft models with moderately swept, subsonic-wing configurations have been investigated and representative results are presented in Fig. 4.

The characteristics of the typical swept-wing subsonic transport with four wing-mounted jet engines (which were previously discussed and are reported in ref. 4) and the characteristics of a subsonic T-tail transport research model with two aft-fuselage-mounted jet engines are presented for a Mach number of 0.2. The pitch-damping characteristics of a variable-sweep configuration with wings swept 20° are presented for a Mach number of 0.4. (For this test, the highly swept inboard leading edge, or chord extension, was removed. This resulted in a relatively thick subsonic-type wing, with a straight leading edge which extended to the fuselage.) Computed values of the pitch damping at an angle of attack of 0° for the two transport models are indicated by symbols and show good agreement with the experimental values at 0°. The pitch damping for the three configurations remains about constant with angle of attack at first, but decreases sharply and becomes negative near the primary stall region. Incorporation of the highly swept inboard wing extension on the variable-sweep model appreciably increased the damping near the stall.

Three significant points can be made from these results. One is that the levels of pitch damping determined at an angle of attack of 0° cannot reasonably be extrapolated to the higher angles of attack. Second, a rigidly forced test mechanism is required for investigations of unstable regions such as those illustrated in Fig. 4. Finally, the sharply decreased or negative pitch damping near the stall for these subsonic, swept-wing configurations may well expedite entry into the stall and/or intensify a pitch-up tendency. This subject will be discussed subsequently in this paper.

Effects of wing-sweep angle.- Fig. 5 presents the pitch-damping characteristics at a Mach number of 0.8 for a variable-sweep research model for several wing-sweep angles. For wing-sweep angles Λ of 20° and 50°, the level of damping is approximately the same at angles of attack near 0°. Above 0°, however, there was a sharp decrease in pitch damping for the wing with 20° sweep, and a contrasting increase in damping for a sweep angle of 50°. For a sweep angle of 70°, the damping was nearly independent of angle of attack. These results show that wing-sweep angle can appreciably affect the levels and trends of pitch damping.

Effects of horizontal-tail incidence.- The effects of horizontal-tail incidence on the pitch and yaw damping of the variable-sweep model are presented in Fig. 6. In the upper plot, the pitch damping is shown for a Mach number of 1.70, a wing-sweep angle of 70°, and horizontal-tail incidence angles i_t of 0° and -20°. Deflection of the horizontal tail to an incidence angle of -20° (leading edge down) appreciably decreased the available pitch damping for angles of attack below 10°. The lower plot presents the yaw damping of the same configuration for a Mach number of 1.20 and for the same wing-sweep angle. As shown, deflection of the horizontal tail to an incidence angle of -20° caused an appreciable, and favorable, increase in yaw damping at angles of attack below about 10°.

These results illustrate two important points. One is that seemingly minor configuration changes, such as the decrease in horizontal-tail incidence angle discussed here, can appreciably affect the pitch and yaw damping. It is also apparent that use of horizontal-tail incidence to provide auxiliary model trim for tests with free-decay or spring-driven dynamic-stability mechanisms may produce misleading results. Thus, the rigidly forced technique is of considerable advantage for tests of this type.

T-Tail Transport Studies

Effects of nacelle placement.- Extensive investigations are being made at Langley of the damping characteristics of the previously discussed generalized research model of a subsonic transport airplane with two aft-fuselage-mounted jet engines and a T-tail. The model is typical of the family of short- and medium-range transports in use throughout the world. This model has been investigated on the short, blunt sting previously described as system B in order to provide very high angles of attack (Fig. 3). Although the effects of this blunt sting have not as yet been evaluated at very high angles of attack, it is believed that the high T-tail is located sufficiently far above the sting that the trends of the measured damping can be considered representative.

Fig. 7 presents the pitch-damping characteristics of the complete T-tail model and an indication of the contributions of the engine nacelles for a Mach number of 0.4 and at angles of attack up to 52°. The pitch damping for the model without engine nacelles is compared to that of the complete configuration. The typical decrease in damping near the stall is evident at angles of attack between 15° and 20°. The added area of the nacelles near the rear of the model caused large increases in pitch damping above the primary stall. An appreciable decrease in damping occurred near an angle of attack of 45° for both configurations. Previous research indicates that decreased damping tends to accompany flow separation. This decreased pitch damping, therefore, is probably caused by immersion of the high T-tail in the separated wake of the wing at these extreme angles of attack.

Effects of horizontal-tail size.- The effects of horizontal-tail size on pitch damping at 0.4 Mach number are indicated in Fig. 8. (The pitch damping of the complete basic T-tail model is repeated from Fig. 7.) For this basic configuration, the horizontal tail is considered to have an area of unity, as indicated by the solid sketch. An alternate tail of 37 percent greater area, but with the same span and sweep, is outlined in the dotted sketch. Although increased pitch damping was provided below the stall and at intermediate angles of attack, the large horizontal tail decreased the damping at the stall and near an angle of attack of 45°. It appears, therefore, that the increased area of the large tail, when subjected to the effects of separated flow, causes greater negative damping contributions.

Longitudinal-response studies.- Analytical and flight simulator studies have been made at Langley of the significance of these nonlinear decreased pitch-damping levels to stall entry and recovery for transport airplanes.

An analytical study of the importance of damping to the longitudinal response of a T-tail transport airplane has been made with a three-degree-of-freedom digital computer program. The airplane was considered to be a representative medium-range transport of 75,000 pounds gross weight with typical inertia characteristics. Level flight was assumed at an altitude of 5000 feet at a Mach number of 0.28 and in the clean configuration to represent a holding condition. The pitch damping as determined by wind-tunnel tests was introduced as a function of angle of attack as shown by the solid curve at the top of Fig. 9. The typical low damping near the primary stall is evident. The static pitching-moment characteristic, which was determined in the wind-tunnel investigations reported in reference 5, is shown by the center plot of Fig. 9. (A nose-down moment is of negative sign.) The airplane was initially trimmed at an angle of attack of about 7°. This pitching-moment variation is typical of many T-tail configurations and indicates the possibility of a second stable trim point at a deep-stall angle of attack of 39°. In the study, an initial upward pitching rotation was introduced by a longitudinal-control deflection of -3° for about 3 seconds and return to neutral. The predicted time history of the angle-of-attack response of the airplane is shown as the solid curve at the bottom of the figure. With initial rotation, and the low damping level near the primary stall, the airplane quickly diverged and "locked in" at the deep-stall trim position at an angle of attack of 39°. Recovery from a so-called deep-stall, as is generally known, is often difficult.

The study was then repeated but with assumed positive pitch damping near the primary stall region, as indicated by the dotted line in the top plot of Fig. 9. All other conditions were the same. The results of this study are indicated by the dotted curve in the bottom plot of Fig. 9. The airplane pitched up to a maximum angle of attack of about 21° and then returned to the initial flight trim point at an angle of attack of 7°.

Although some of the assumed conditions just described are admittedly unique, the results of this study illustrate several important points. One is that pitch damping can significantly affect the longitudinal response of a T-tail airplane. Since pitch damping is significant, especially if unpredictably low or negative levels are present, wind-tunnel tests should be made throughout the angle-of-attack range for use in stability analyses. It is also possible that an automatic pitch damper may prove useful for T-tail airplanes to decrease the possibility of entry into a deep-stall attitude.

The second area of interest is the effect of pitch damping on recovery from a deep-stall attitude. The effects of the damping level on the recovery of a T-tail transport from a trimmed deep stall were studied on a piloted fixed-base simulator at Langley and reported in reference 6. Results of this study show that assumed levels of positive damping near the deep stall prevented recovery of the simulated airplane. However, decreased damping levels near the trimmed stall, as indicated by the wind-tunnel damping results of Figs. 7, 8, and 9, were favorable to recovery. Subsequent studies of recovery techniques were made using phase-plane trajectories for fixed elevator deflections and were reported in reference 7. These studies verified that pitch damping is significant to recovery and showed that decreased damping can aid the pilot in effecting dynamic recovery by rocking the airplane out of the deep stall with alternate fore and aft deflections of the stick. Thus, it appears from these studies that the seemingly adverse decreased damping near the deep stall, as determined by wind-tunnel investigations, is actually beneficial to the recovery of a T-tail airplane.

CONCLUDING REMARKS

A rigidly forced dynamic-stability technique is in use at the Langley Research Center of NASA for wind-tunnel investigations of the pitch- and yaw-damping characteristics of aircraft configurations from subsonic to supersonic speeds. The equipment has been especially useful for research at high angles of attack where separated flow may be present and in regions of large aerodynamic instabilities.

Research results show that aircraft configurations with moderately swept, subsonic wings have sharply decreased or negative pitch damping near the primary stall. Analytical longitudinal-response studies of a T-tail transport show that this negative damping can intensify a pitch-up tendency and cause divergence to a deep-stall attitude. Research also shows that the levels and trends of pitch damping with angle of attack are functions of wing-sweepback angle, nacelle placement, and horizontal-tail size and incidence angle.

Increased horizontal-tail size decreased the pitch damping at the primary stall and at the deep stall for a T-tail transport configuration. Analytical and piloted simulator studies of a T-tail transport show that this decreased pitch damping near the deep stall can be beneficial to recovery.

REFERENCES

1. Wiley, Harleth G.; and Braslow, Albert L.: A Method of Accurately Measuring Dynamic Stability Derivatives in Transonic and Supersonic Wind Tunnels. AGARD Rept. 345, April 1961.

2. Braslow, Albert L.; Wiley, Harleth G.; and Lee, Cullen Q.: A Rigidly Forced Oscillation System for Measuring Dynamic-Stability Parameters in Transonic and Supersonic Wind Tunnels. NASA TN D-1231, 1962.

3. Bielat, Ralph P.; and Wiley, Harleth G.: Dynamic Longitudinal and Directional Stability Derivatives for a 45° Sweptback-Wing Airplane Model at Transonic Speeds. NASA TM X-39, 1959.

4. Wright, Bruce R.; and Brower, Margaret L.: Aerodynamic Damping and Oscillatory Stability in Pitch for a Model of a Typical Subsonic Jet-Transport Airplane. NASA TN D-3159, 1966.

5. Ray, Edward J.; and Taylor, Robert T.: Effect of Configuration Variables on the Subsonic Longitudinal Stability Characteristics of a High-Tail Transport Configuration. NASA TM X-1165, 1965.

6. Lina, Lindsey J.; and Moul, Martin T.: A Simulator Study of T-Tail Aircraft in Deep Stall Conditions. AIAA Paper No. 65-781, 1965.

7. Montgomery, Raymond C.; and Moul, Martin T.: Analysis of Deep-Stall Characteristics of T-Tailed Aircraft Configurations and Some Recovery Procedures. AIAA Paper No. 66-13, 1966.

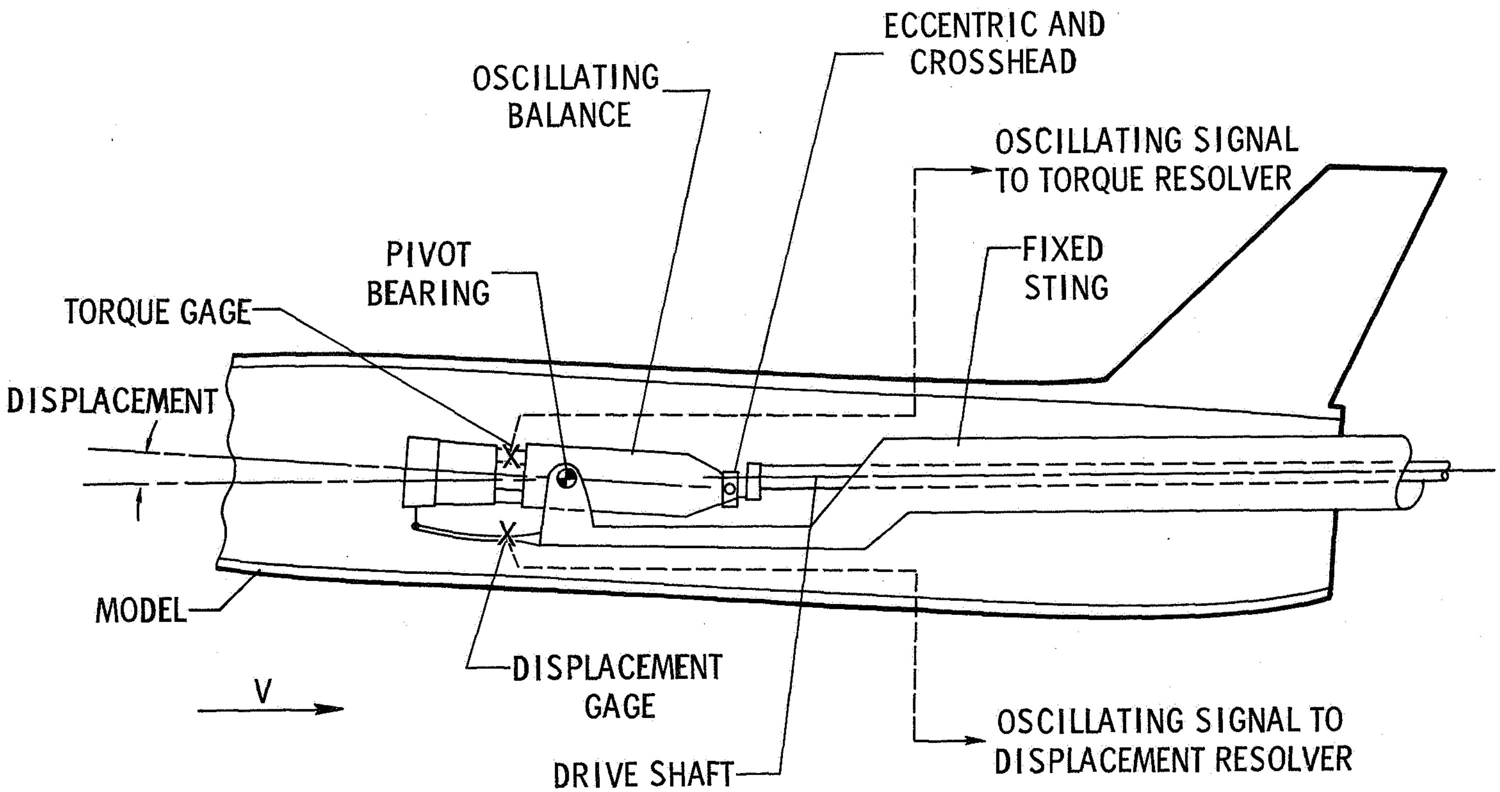

Figure 1.- Schematic of oscillating balance assembly.

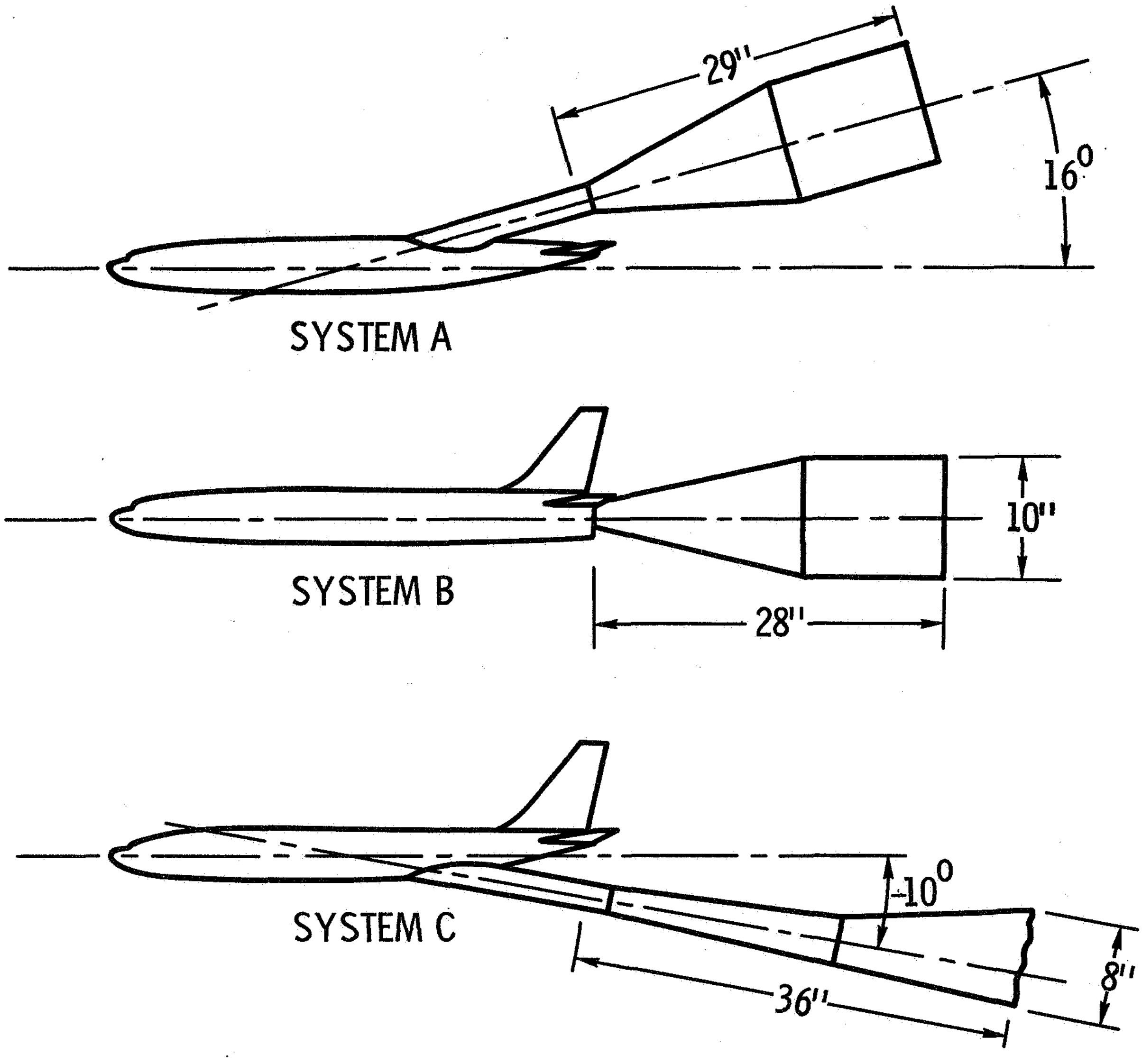

Figure 2.- Sting arrangements.

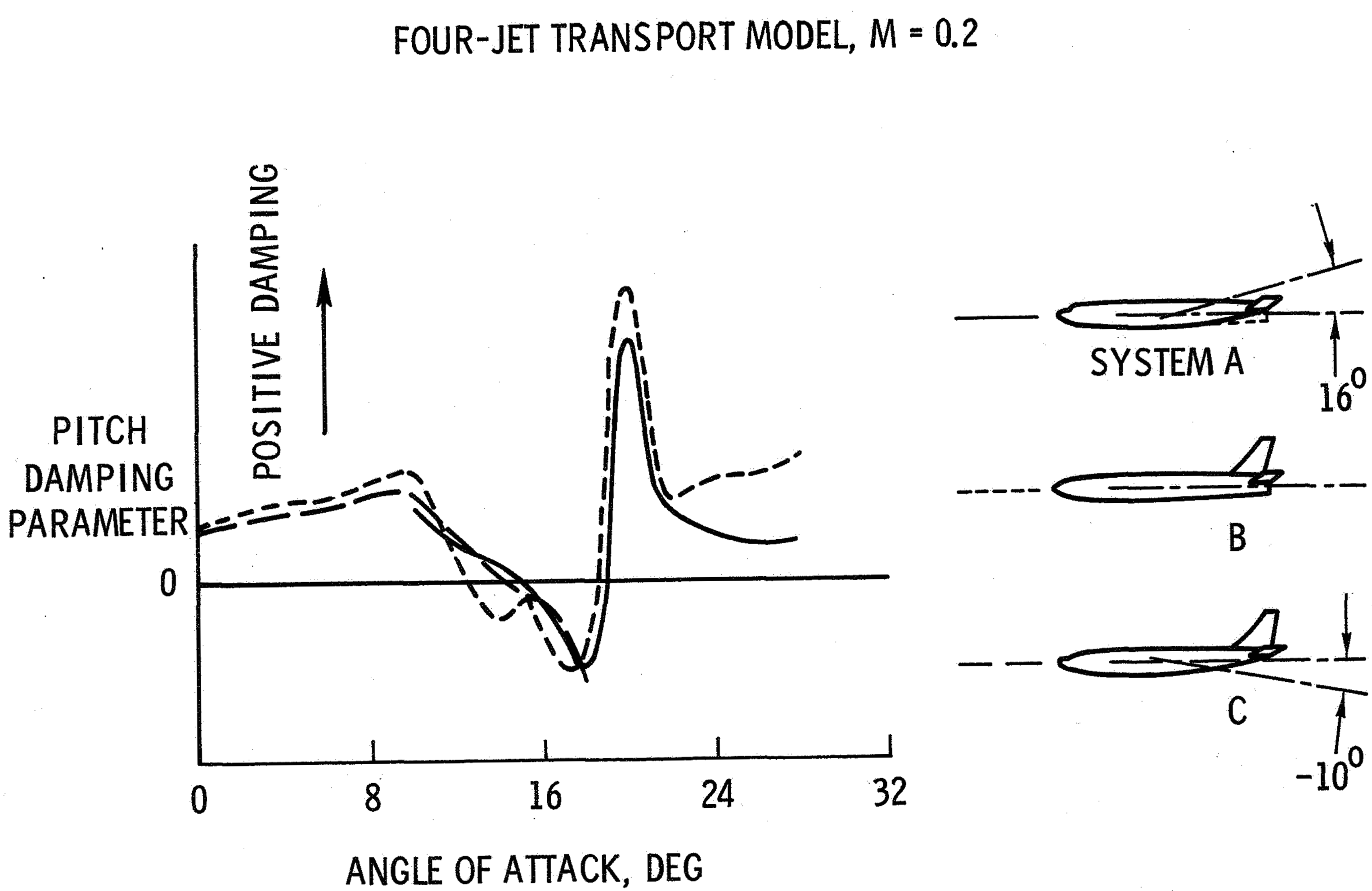

Figure 3.- Effect of sting on measured pitch damping.

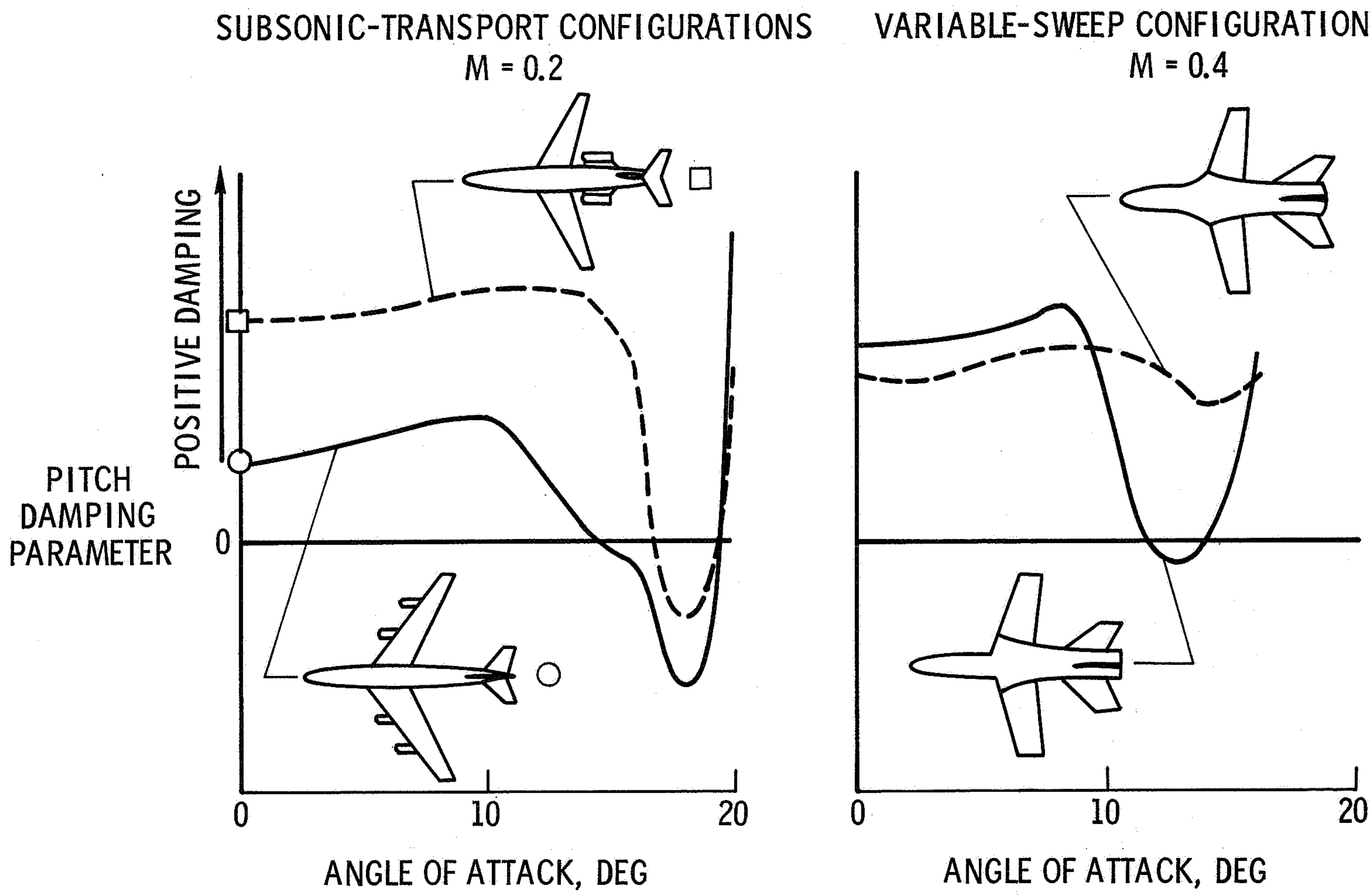

Figure 4.- Pitch-damping characteristics near stall.

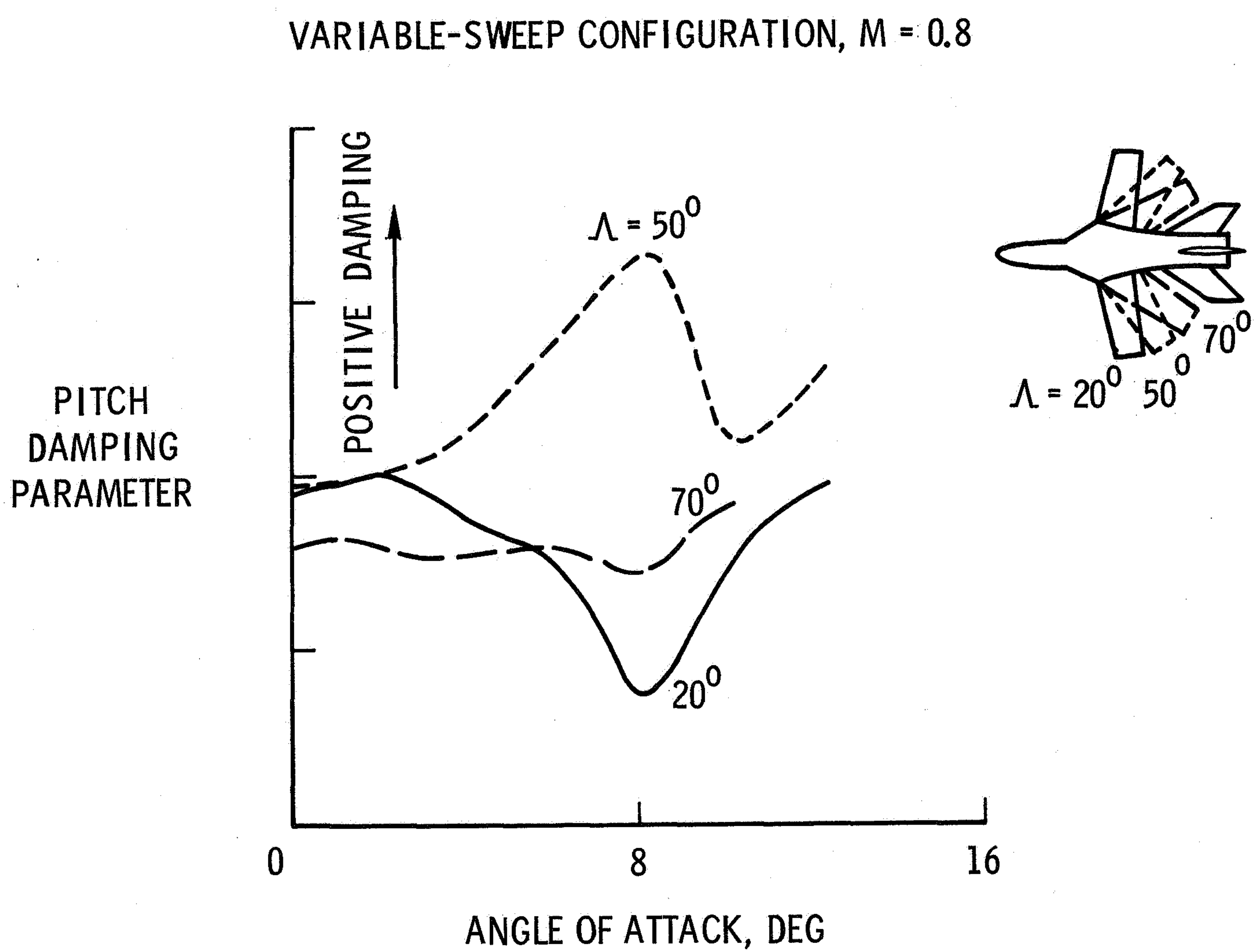

Figure 5.- Effect of wing sweep on pitch damping.

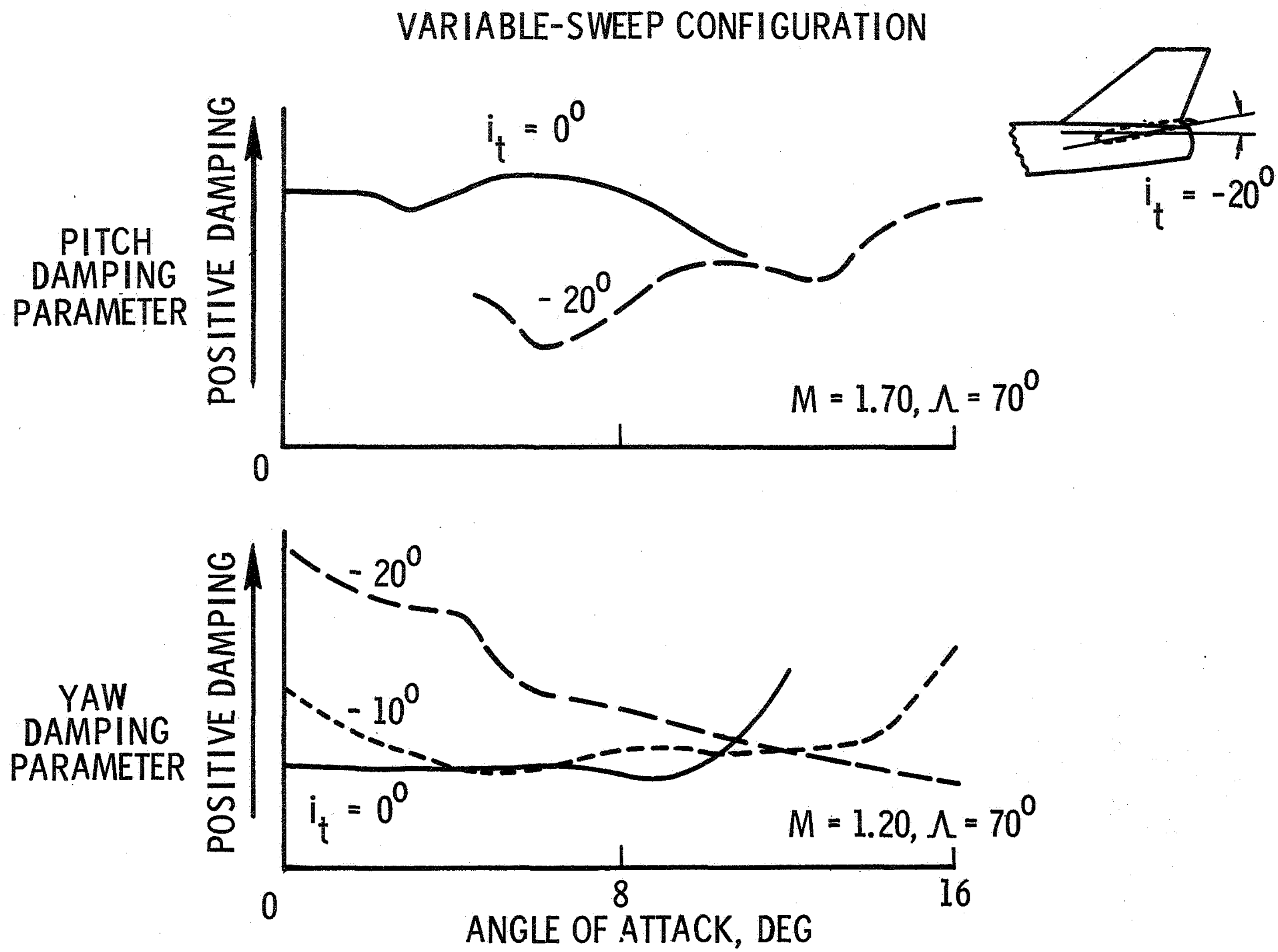

Figure 6.- Effect of tail incidence on pitch and yaw damping.

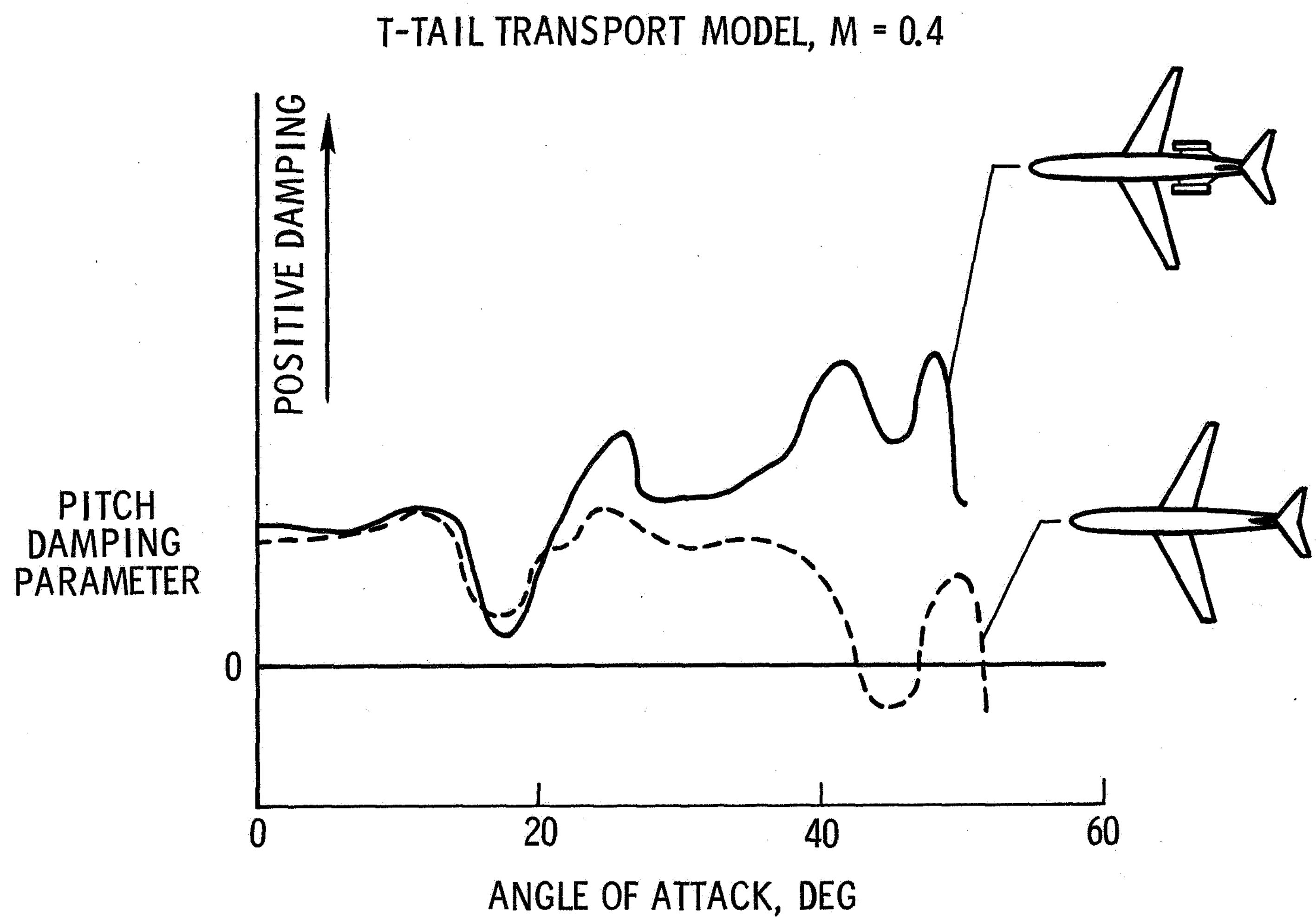

Figure 7.- Effect of nacelles on pitch damping.

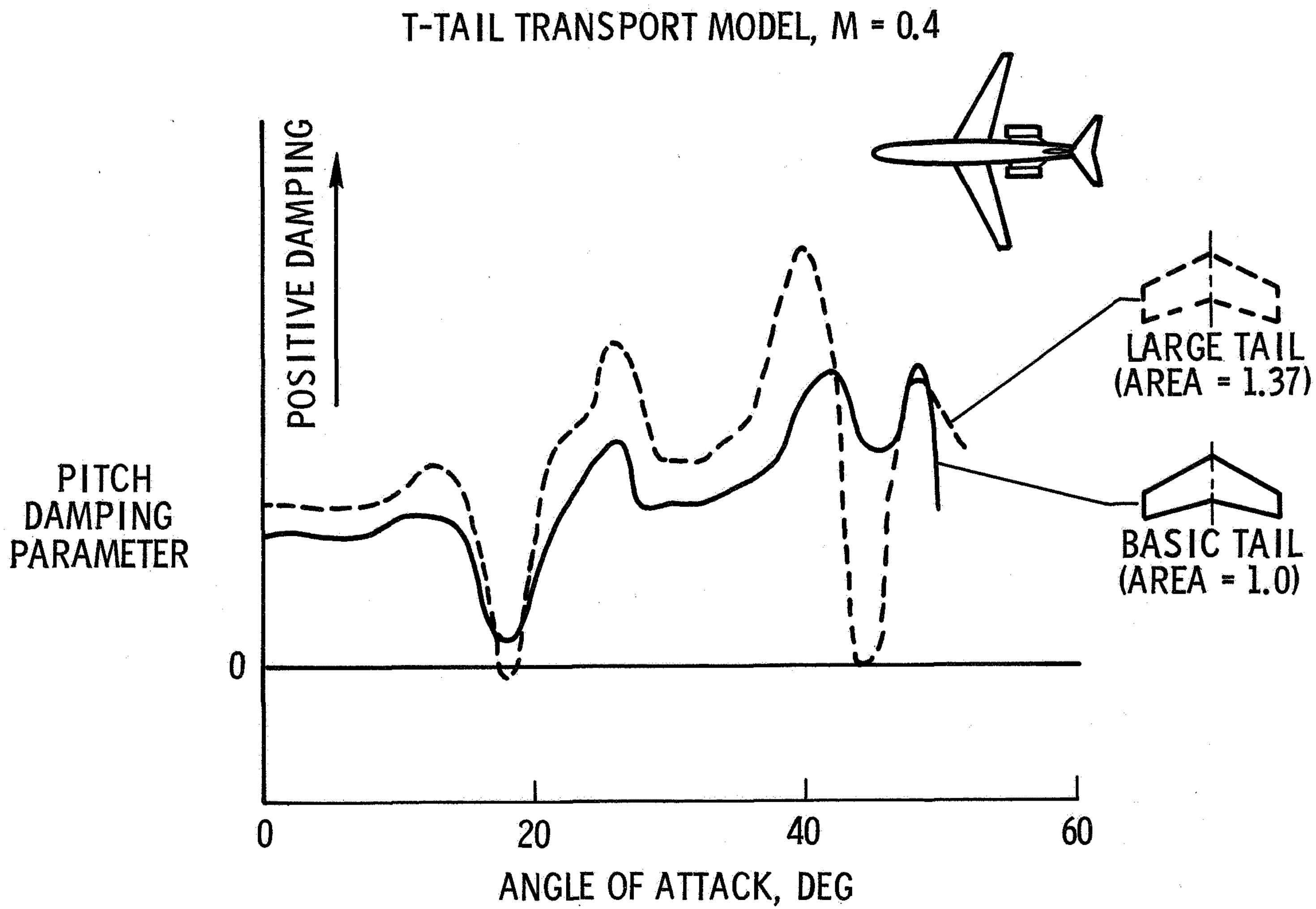

Figure 8.- Effect of horizontal-tail size on pitch damping.

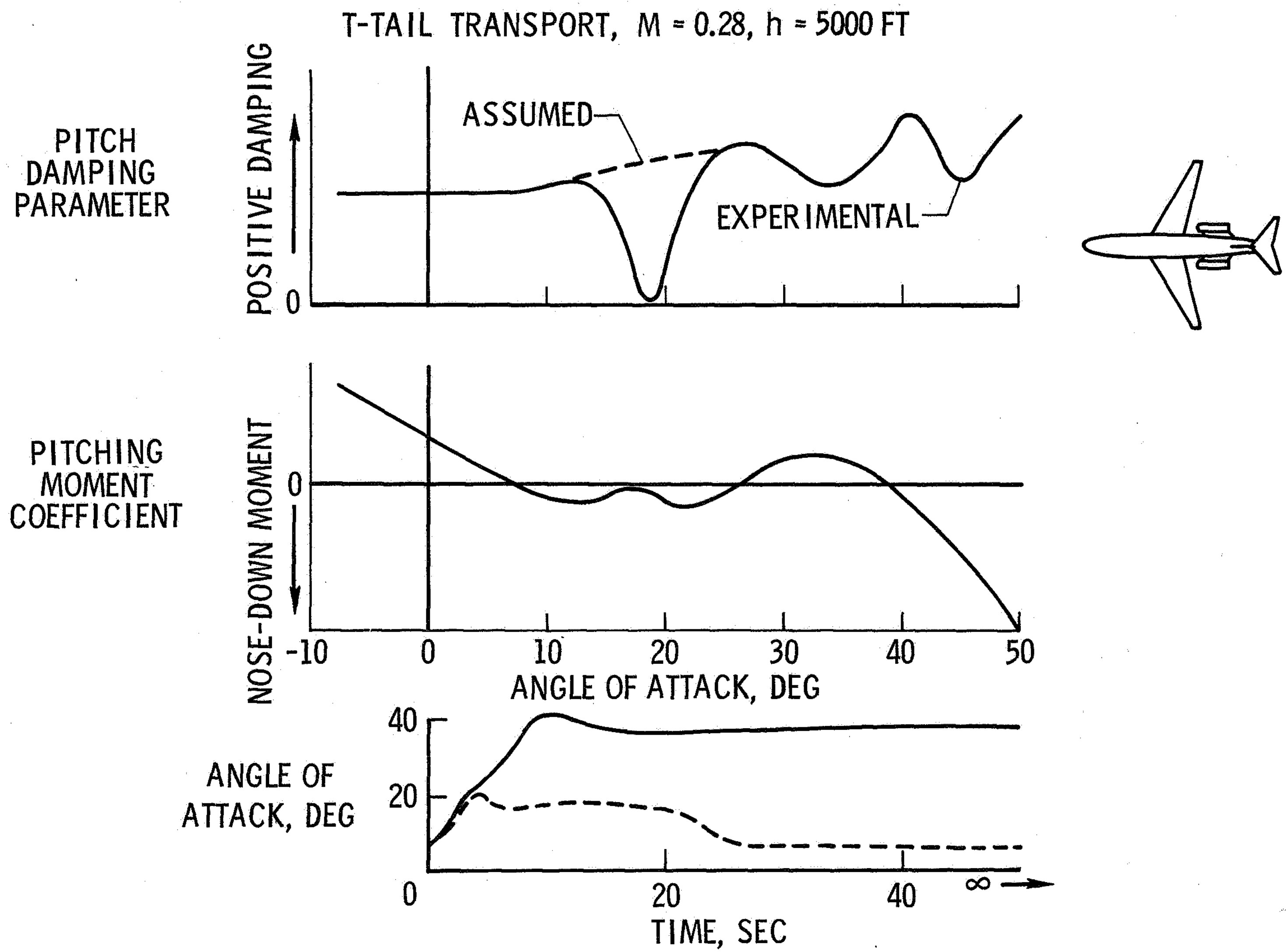

Figure 9.- Longitudinal stability characteristics and computed response.

NASA-Langley, 1966