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SUMMARY

A piloted simulator study was conducted to investigate the stalling characteristics of transport-type airplanes with localized instabilities associated with the pitching-moment variations at the stall. Pitching-moment variations of this general class were found to be conducive to the development of serious stalls whether the unstable "bump" in the pitching-moment variation was large or small, the important factors being, respectively, inability to check the motion, and lack of indication of the stall penetration. The stability level at angles of attack above the unstable bump was of primary importance in defining the depth of stall penetration. Factors that had previously been identified as significant to the problem of controlling the deep stall of T-tail airplanes (i.e., the inadequacy of attitude information and the importance of prompt and sustained recovery control application) were also considered significant for the pitching-moment characteristics investigated here.

INTRODUCTION

In recent years there has been considerable concern over the effects on transport-type airplanes of longitudinal instabilities at angles of attack above the stall. Gross longitudinal instabilities beyond the stall cause large angle-of-attack excursions, with catastrophic results if longitudinal control is inadequate for recovery. The results of several NASA investigations of this "Deep-Stall" problem are presented in references 1-3. There has been no ambiguity in deducing these deep-stall characteristics from the airplane pitching-moment curves, and effective safeguards against inadvertent penetrations into areas of deep stall have been sought.

A somewhat milder form of longitudinal instability at the stall, the stall "pitch-up," is more difficult to evaluate than the deep stall. There was no rational basis for assessing the seriousness of different forms of such pitching-moment curves as applied to commercial transport design. Accordingly, a piloted simulation investigation of this problem, as it might appear in the landing configuration, was conducted at the Ames Research Center. The objectives of this test program were to gain a clearer understanding of the operational problems associated with these lesser instabilities, and to define what, if any, magnitudes of these instabilities might be acceptable. The results of this simulator investigation are presented in this report.

NOTATION

b	wing span, ft
$\bar{c}$	mean aerodynamic chord, ft
I_Y	moment of inertia about Y axis, slug-ft^2
p	roll rate, rad/sec
S	wing area, sq ft
V	velocity, ft/sec
C_D	drag coefficient
C_L	lift coefficient
C_l	rolling-moment coefficient
C_{l_β}	$\frac{\partial C_l}{\partial \beta}$
$C_{l_{\delta_a}}$	$\frac{\partial C_l}{\partial \delta_a}$
C_{l_p}	$\frac{\partial C_l}{\partial (pb/2V)}$
C_m	pitching-moment coefficient
C_{m_q}	$\frac{\partial C_m}{\partial (\dot{\theta}\bar{c}/2V)}$
$C_{m_{\dot{\alpha}}}$	$\frac{\partial C_m}{\partial (\dot{\alpha}\bar{c}/2V)}$
$C_{m_{\alpha_B}}$	slope of pitching-moment curve at angles beyond pitch-up bump (fig. 8)
C_n	yawing-moment coefficient
C_{n_β}	$\frac{\partial C_n}{\partial \beta}$
α	angle of attack

$\dot{\alpha}$ rate of change of angle of attack, rad/sec

β sideslip angle

δ_a aileron deflection

δ_r rudder deflection

φ bank angle

$\dot{\theta}$ rate of change of pitch angle, rad/sec

SIMULATION

The Ames five-degree-of-freedom simulator (fig. 1) was operated in pitch and roll for the studies. The pitching motion was confined to positive (nose up) pitch angles to avoid having the pilot supported unrealistically on the restraint harness in nose-down attitudes. The roll motion was not modified.

To simulate instrument flight, the cockpit was closed. The instrument panel, which included the basic instruments for such flight, and the cockpit controls are shown in figure 2.

The longitudinal cockpit control was usually adjusted to travel 4 inches forward and 8 inches aft from the position for zero control deflection. Stick forces were a linear function of control deflection (approximately 5 pounds per inch of deflection). The airplane responses were computed on analog computers with six degrees of freedom included in the equations of motion. The variations of C_L, C_D, and C_m with α were supplied as nonlinear functions; in some tests certain lateral-directional derivatives provided were also nonlinear functions of α, but in most tests lateral derivatives were constants.

TESTS

Tests were conducted for the various pitching-moment curves shown in figure 3; the curves were divided into three sections:

(1) The section for angles of attack up to stall was maintained constant for all configurations,

(2) The pitch-up "bump" was varied in amplitude, angle-of-attack range, and detailed shape, and

(3) The section above the pitch-up bump was a straight line of C_m against α; the magnitude of the slope was varied.

To form a complete $C_m - \alpha$ curve for simulator operation, the particular pitch-up bump was inserted between the sub-stall curve and the post-bump straight line to make a continuous curve. The combinations of curves tested are listed in table I. An identification code for the curves is based on the designations in figure 3.

For most of the tests lateral-directional stability and control derivatives were assumed constant at a satisfactory level for both prestall and poststall angles of attack. Limited tests with representative variations of these derivatives for poststall angles are discussed separately.

The basic lift and drag curves are shown in figure 4(a); the longitudinal control effectiveness is shown in figure 4(b). Values of C_{m_q} and $C_{m_{\dot{\alpha}}}$ of -1.41 and -0.88, respectively, were used.

The geometric, weight, and inertial parameters used in the tests are listed in table II. Except for changes in $S\bar{c}/I_y$, that were assumed to be associated with changes in I_y, the physical characteristics of the simulated airplane were maintained constant.

The tests were generally conducted by first trimming the airplane in level flight at 1.3 times the stall speed and then steadily approaching the stall at a rate of 1 knot per second with thrust held constant. The several techniques used for recovery are described later. Two variations in piloting technique examined initially but omitted from the main part of the test program were as follows:

(1) Approaching stall at 4 rather than 1 knot per second always resulted in higher angles of attack before corrective action could be taken, but since this technique did not contribute to understanding of the problem, it was eliminated from the test schedule.

(2) "Wind-up turns" on the simulator did not generate the asymmetric effects or other dynamic response effects that might make them useful in flight tests. They were, therefore, also discarded as a test technique.

No attempt was made to examine the effects of either atmospheric turbulence, stall buffeting, or artificial stall-warning cues in this program. Their interrelated effects would merit consideration in a more comprehensive test program, but were considered beyond the scope of this study.

Most of the tests were made by one NASA test pilot who has extensive experience in the operation of transport-type, as well as fighter-type, airplanes. The main observations of the study were demonstrated to and verified by three other NASA test pilots, four airplane manufacturers' test pilots, and two FAA pilots experienced in transport certification.

RESULTS AND DISCUSSION

Before discussing the present results it would be helpful to review briefly the character of the deep stall as defined by the earlier studies of gross instabilities; the current discussion of the effect of localized instabilities can then be interpreted more easily in terms of similarities and differences from the effects of gross instabilities.

As demonstrated in the earlier studies (refs. 1 and 3) a significant element of the deep-stall problem is the inadequacy of pitch attitude to warn of stall entry, and to indicate the development of the stall and the recovery from it. Basic to this problem is the fact that high sink rates develop in stall as a result of drag increases, and these may not be recognized or properly interpreted as deep-stall angles of attack. Consequently, the airplane tends to remain at deep-stall angles of attack for a prolonged time. This is obviously undesirable because it requires a sustained effort to control against lateral-directional instabilities and a steep nose-down attitude for recovery. The latter results in large losses of altitude and increases in speed. It is obviously important to recognize stall early and to begin recovery promptly.

The present studies indicate, generally, that localized pitching-moment instabilities at the stall are also conducive to the development of deep stalls in which most of the undesirable elements noted above are apparent. The responses of the airplane in the present tests differed from those of airplanes with gross instabilities mostly in the initial stall development, and these differences were more a matter of degree than character. Once the stall was well established, the responses associated with the gross and the localized instabilities with low post-bump stability were qualitatively similar; in both situations drag increases in the stall produced steep rates of descent that, in turn, led to further increases in angle of attack. With this similarity identified, the remainder of this report will deal with the additional operational factors noted in the present study.

The effects of variations in pitching-moment curves may be discussed in terms of two operational factors that are of significance in characterizing the stall: (1) stall warning, and (2) severity of motions throughout the stall. These factors are difficult to assess independently because the nature or strength of one actually affects the assessment of the other. For example, pilots would be inclined to assess the adequacy of a given warning not only on the basis of how forcefully it was manifested, but on the consequences of missing or ignoring the warning. In the following discussion the interdependence of the two factors will become more apparent.

Stall Warning

A number of cues, such as buffeting, "g break," wing drop, etc., may indicate stall, but in this paper stall warning is confined to the longitudinal responses of the airplane that would be associated with the pitching-moment curves being studied. These are mainly pitch-attitude changes shown by the pitch-attitude indicator and, secondarily, by cockpit pitching motions. These are among the primary cues by which a pilot flies an airplane, the former being particularly important for the instrument flight conditions which were selected as the basis for this study.

Lack of indication of stall penetration on the pitch-attitude indicator was observed to be a potential problem for many of the cases studied in the present program. This same factor had been noted in reference 1, and other sources, to contribute to the original deep-stall problem. In the earlier studies it was shown that pitch-attitude changes were minimized in the stall because the flight-path angle was steepening (due to drag increases) at a rate essentially equal to the rate of increase of angle of attack. The same general phenomenon, modified only in degree, was observed in this study. In the following sections the inadequacy of pitch motion as a deep-stall warning is discussed separately for the curves having small and large pitch-up bumps because the reasons are basically different for the two cases. Bumps A, C, D, and I were intuitively classed as large and the others as small.

Small pitch-up bumps.- For pitching-moment curves having small pitch-up bumps (i.e., B, E, F, G, and H in fig. 3), only minimal indications of initial stall penetrations, lasting a very short time, would be apparent on the pitch-attitude indicator. Figure 5 shows a typical time history of a stall entry. The increase in pitch attitude at the stall (between 27 and 30 sec) is quite small. Similarly small values are noted for the other small-bump cases listed in table III. For these cases it is doubtful whether, in actual operations, when the pilot was not consciously alert to stall cues, he would properly interpret the indicated attitude changes as stall entries. The lack of stall warning from the pitch-attitude indicator was even more apparent for the curve that had no bump (i.e., neutral stability for a range of angle of attack above the stall); for such a case the angle of attack tended to drift to deep stall angles with no obvious attitude cues at all.

This phenomenon is not completely new to aeronautics, but has been observed by pilots who have flown fighter aircraft with low-aspect-ratio wings and poorly defined maximum lift coefficients. Its existence is less likely to be anticipated on an airplane with a well-defined maximum lift coefficient (see fig. 4) and is considered a serious factor for transport operation.

Large pitch-up bumps.- For the larger pitch-up bump there was some change in attitude associated with stall (see fig. 6 between 27 and 30 sec). If the pilot were looking for this attitude information or cockpit motion as indicative of an expected stall, the magnitude of these bumps is large enough to be significant. However, again, in a normal operational situation, complicated perhaps by turbulence effects, the pilots judged that even these motions might be overlooked.

An additional, and equally important, factor that discounted the slightly greater warning effect of a large bump was the fact that the airplane was projected into deep stall angles more quickly. This effect will be discussed further in a later section of the report.

In general, then, for the range of conditions examined in these tests, none of the pitching-moment curves provide, of themselves, warning-pitch motions that would prevent penetration to deep-stall angles once the stall began.

Severity of Motions in the Stall

The severity of the stall may be described in terms of the depth of angle-of-attack penetrations. This parameter is of significance from two standpoints. First, at large poststall angles of attack, the lateral-directional stability and control derivatives frequently become erratically nonlinear and tend to cause unstable motions that present a serious control problem, and that could, in extreme cases, develop into a spin. So that the study could concentrate on the longitudinal aspects of the problem, the satisfactory lateral-directional characteristics used for unstalled flight were assumed initially to persist unchanged in the stall. Second, the larger the angle of attack attained, the longer the airplane is committed to stalled flight before recovery can be completed. This prolonged commitment is undesirable not only because of lateral control problems, but also because of the steep nose-down attitudes, rapid airspeed build-up, and altitude losses that occur before recovery can be completed.

Control techniques for recovery.- Angle-of-attack penetrations are affected by piloting technique as well as by the shape of the pitching-moment curve. References 1 and 3 show that for the gross pitching-moment instabilities associated with the deep stall a delay in applying longitudinal control for recovery, which would, of course, be related to the nature of the stall warning, was very important in promoting deeper stall penetration. Similar observations can be made on the basis of the present studies.

Another aspect of piloting technique, which was examined as a variable in these tests, was the nature of the recovery control used. The following four different control motions were examined; all represent possible pilot reactions:

(1) Immediate recovery with full forward stick (fig. 7(a)). This maneuver would represent the reaction of the pilot performing a stall test as a deliberate maneuver. Such a maneuver would represent an optimum test, where the pilot being alert and forewarned or being provided with an unmistakable cue was able to detect the stall and react immediately and positively.

(2) Recovery by release of stick to trim deflection (fig. 7(b)). Pilots have used this maneuver when, because of unstable lateral-directional motions in the stall, they have been engrossed in maintaining the wings level, and have neglected to maintain more positive longitudinal control for recovery.

(3) Maintaining of constant control deflection (fig. 7(c)). This action has been described as one that might naturally occur in actual operations when the pilot does not immediately recognize that the stall is entered and

consequently delays taking any corrective action. The effects of turbulence in obscuring the nature of the observed airplane reactions would be significant in this regard.

(4) Continuing aft motion of the stick after the stall (fig. 7(d)). The practicality of this maneuver is controversial. As part of a deliberate stall investigation, this maneuver appears illogical - why should the pilot deliberately aggravate a serious situation? It has been suggested in answer that the circumstances under which pilots inadvertently stall airplanes are not nice rational situations; rather, they occur when a series of cockpit troubles have accumulated to put the pilot under stress or subject him to loss of vital information. From this standpoint the maneuver may not be so illogical as it first appears. Additional information on the circumstances of stalls in actual operations is needed to clarify this question. Lacking such clarification it was considered prudent to include this control technique in this study.

Stall penetrations.- The results of the tests indicate that, insofar as the depth of stall penetration is concerned, the most important feature of the pitching-moment variations was the static stability at angles of attack above the pitch-up bump $C_{m_{\alpha_B}}$. The combined effects of piloting technique and static stability above the pitch-up bump are demonstrated quantitatively in figure 8, where the maximum angles of attack are plotted for one bump. The data show that for large values of $C_{m_{\alpha_B}}$, the effects of control technique were not significant. Despite prompt corrective action by the pilot with full forward stick the minimum overshoot in α shown in the figure occurred before the motion could be arrested. And, on the other hand, these large values of stability offset even a continued aft stick movement, and the net effect was the indicated small differences in stall penetration.

At lower values of $C_{m_{\alpha_B}}$, there was considerable variation in the depth of stall penetration with differing piloting techniques. It was not possible to determine from the deliberate stall tests used here the critical technique which would be most suitable for actual flight assessments. Determining the probability of pilots using one or the other of these techniques in operational practice would require the inclusion of mission-oriented tasks, more realistic cockpit environment, and situations that involved an element of surprise.

In situations where moderately strong positive stability existed beyond the pitch-up bump, the airplane tended to pitch down eventually and recover from the stall even with fixed elevator. In fact, when the stability beyond the bump was large or when the control effectiveness diminished greatly at high angles of attack this inherent recovery tendency was evidenced even with an aft control movement. The existence of this effect for any particular design would have to be determined by analysis. Such an effect might very well be significant in the overall assessment of the stall characteristics.

Other variables in the pitching-moment curves (the size and shape of the unstable bump) were found to be of secondary importance. One reason indicated earlier was that failure of the pilot to recognize a stall cancelled the relative benefits of a smaller bump. A second reason was that the pilots normally tended to use an amount of recovery control proportional to the severity of the pitch-up cue. That is, for the larger bumps, larger corrective control applied promptly would tend to check the pitch-up; for the smaller bumps, the cues, being imperceptible, would not prompt a corrective control, and the airplane would still progress well into the stall, unchecked by the pilot.

The net result of these compensating effects was that the airplane would penetrate into the stall by an amount at least equal to the angle-of-attack extent of the bumps. This is demonstrated by the data of figure 8 (Technique of fig. 7(a), immediate recovery) which shows that the angle-of-attack increase in the pitch-up maneuver could not be held to less than about 10° above the stall. The bump associated with the data of figure 8 had a width of about 7° (pitching-moment curve C, fig. 3).

Use of thrust for recovery.- Since drag increase figures so strongly in developing deep stalls, it would be natural to consider using increased thrust as an aid to recovery. Potentially this could be a very effective aid in speeding recovery and minimizing altitude loss, but in practice there are several factors that can offset the potential benefits. First, if the nose-up pitching moments resulting from thrust application are very large, they tend to cancel the recovery control moments from the aerodynamic controls and delay or even prevent recovery. Second, in actual practice, it must be recognized, the pilot may increase thrust only very slowly to assure that an accidental thrust asymmetry does not upset the airplane laterally. Consequently, this effective time delay and any additional delay that might result from basic thrust-response dynamics may compromise the conservation of speed and altitude in the presence of a large pitching moment due to thrust. Failure to maintain airspeed would magnify the problem since the nose-up pitching moments due to thrust would not be reduced with decreasing airspeed while the nose-down control moments would. As an illustration of the order of magnitude of this effect, in simulation tests of an airplane with available thrust-weight ratios corresponding to those of a supersonic transport in the landing approach, the vertical distance from thrust line to center of gravity had to be reduced to one foot before the full thrust could be used effectively for recovery. A third factor that could compromise the use of power for recovery is the possible existence of flow asymmetries in the engine inlet at the high angles of attack in the stall, which might prevent the attainment of large thrust levels.

In general, then, it appears that full reliance cannot be placed on the theoretical benefits from the use of thrust for recovery, and that aerodynamic control should probably be counted on as the primary means for recovery.

Variation of parameter $S\bar{c}/I_y$.- Values of $S\bar{c}/I_y$ equal to 0.033 were used in the major portion of this test program, but certain pitching-moment curves (see table I) were tested with $S\bar{c}/I_y$ equal to 0.016. In comparative time histories for two stalls with different values of $S\bar{c}/I_y$ (fig. 9) the pitching motions in the stall entry were small when $S\bar{c}/I_y$ was small, as would be expected. For the larger pitch-up bumps this effect might be considered favorable because the angles of attack before recovery control could be applied would be smaller than they would be with a larger value of $S\bar{c}/I_y$. However, the pitch response to control for recovery was also reduced with smaller $S\bar{c}/I_y$.

On the whole, larger values of $S\bar{c}/I_y$ were considered preferable, mainly because of the rapid response to recovery control which for the larger bumps would compensate for the rapid stall entry. These observations, however, refer only to relative values; it is not suggested that the differences noted result in satisfactory stalling characteristics for any case examined.

Lateral-Directional Characteristics

In the previous discussions of longitudinal characteristics it was noted that lateral-directional characteristics were artificially held at satisfactory values beyond the stall. In general, of course, it has been established from flight experience that lateral-directional control of the airplane beyond the stall may be extremely difficult, depending on the airplane design.

In the present studies, representative variations of lateral-directional stability and control derivatives at poststall angles of attack were included in some simulation runs. The term "representative" as used here needs some clarification. There are very few data on the lateral-directional characteristics of transport-type airplanes at the deep-stall angles of attack, either for specific airplanes or in general. Furthermore, what data do exist are usually a combination of raw wind-tunnel static data, and estimated dynamic derivatives that are necessarily crude in the present state of the art. Their lack of consistency is shown in figure 10 where available estimates for several transport-type configurations are plotted. The significant conclusion from the simulator operations was that these types of variations presented a real problem in maintaining wings-level flight. This, of course, corresponds closely with the classical stalling problem that has historically concerned pilots; that is, prevention of a wing drop and large sideslip angles leading to a spin.

From the standpoint of piloting technique, it was indicated that tight lateral and directional control had to be used in order to maintain lateral control. If the sideslip were allowed to build up as a result of loose control either of yawing motions or rolling motions, the large dihedral effect would rapidly overcome the lateral control and result in complete loss of control. These results were qualitatively confirmed in unreported flight tests of a swept-wing fighter-type airplane at Ames a number of years ago. There, too, it was noted that if the pilot used vigorous control to maintain wings level and zero sideslip it was possible to penetrate to deep-stall angles of attack, but if the stall were entered with a little sideslip or if sideslip were allowed to increase after the stall was penetrated, the pilot usually lost control of the airplane temporarily. In normal operations, it should be noted, the pilot would not have the benefit of the sideslip indication that was provided in both the simulation and the flight-test airplane.

One additional point should be made regarding the simulator tests. A considerable difference in the pilot's ability to maintain lateral control was noted when the simulator cab was fixed and when roll motion was provided. When roll motion was provided the pilot was much better able to control the roll motions, and to maintain control in some cases where complete loss of control occurred with a fixed cab. It is apparent, then, that simulation studies with a fixed cab may give a pessimistic answer as to the controllability of an airplane. This point and the general character of the problem are indicated in figure 11 by typical time histories of attempts to maintain control in the stall for a fixed and moving simulator. The most significant conclusion to be drawn from these tests is that the poststall lateral-directional characteristics may have a first-order effect on the acceptability of deep-stall tendencies. This is essentially a restatement of the well-known fact that stalling characteristics can be considered unacceptable solely on the basis of lateral instabilities. With reference to these lateral-directional instabilities one new element introduced in the present studies is that once the deep-stall region is penetrated, the pilot tends to be committed to this stalled region for a considerable period of time, roughly of the order of 30 seconds. Simulation experience would indicate that situations that are marginally controllable for a short period of time, can frequently become uncontrollable when it is necessary to cope with them for this length of time. Furthermore, when the pilot is preoccupied with lateral-directional characteristics he tends to use only a portion of the available longitudinal control for recovery and consequently prolong the stall.

With regard to lateral-directional characteristics, one other significant point has been observed that requires consideration. In all wind-tunnel data seen thus far, a large change in rolling and yawing moment has been indicated at zero sideslip angle for a range of angles of attack slightly above the stall (fig. 12). The magnitude of these indicated moments and the rapidity of their onset are such that in simulation operations it has been found almost impossible to control them if angle of attack changes rapidly. It has been customary in the past to attribute such indicated moments for wind-tunnel models to slight asymmetries resulting from tolerances in construction. There are, however, limited indications from flight tests that such moments do exist, although perhaps at reduced values, and this fact, coupled with the consistency with which such moments appear in the wind-tunnel data (fig. 12), suggests that it may be unrealistic to neglect these moments as wind-tunnel oddities. Further wind-tunnel investigations would be desirable to establish the reliability of such moment measurements.

Stall Safeguards

The indications from the present study were that none of the pitching-moment curves examined would be considered satisfactory from the standpoint either of stall warning or of avoiding the tendency to develop deep stalls. Under these circumstances it is apparent that alternative forms of stall warning, either natural or artificial, would be needed when the airplane had these characteristics. In reference 1, a safeguard philosophy was proposed for transport airplanes with gross deep-stall instabilities; this philosophy suggested the need for two successive levels of safeguard at different angles of attack below the stall. In view of the deep-stall tendencies observed in the present study for pitching-moment curves with localized instabilities, it is suggested that the safeguard philosophy proposed in reference 1 be applied to this class of instability. For convenience, the figure illustrating this philosophy, which is largely self-explanatory, is reproduced here as figure 13; additional supporting description will be found in reference 1.

CONCLUSIONS

Simulator studies have been conducted of the stalling characteristics of transport-type airplanes with localized instabilities in the pitching-moment variations at the stall. The simulator provided pitch and roll motion. The following conclusions have been reached, some of which are a reaffirmation of those given in reference 1:

(1) Considered from the standpoint of whether a deep stall could develop following stall penetration, there were different operational considerations that resulted in a high degree of susceptibility for a wide class of pitching-moment variations. With large bumps, the airplane tended to be projected to deep-stall angles of attack before the pilot could check the motion. And with small unstable bumps the airplane tended to drift into deep-stall angles with no obvious cues to the pilot.

(2) The longitudinal stability at angles of attack above the unstable bump was of primary importance in defining the depth of stall penetration.

(3) In both the entry into and the recovery from the stall, the lack of positive information regarding stall status from the standard instrument display of pitch attitude compromised the ability of the pilot to regain unstalled flight expeditiously.

(4) The tendency of the pilot to adjust the magnitude of the corrective control to the severity of the motions in stall entry compensated for differences in rate of stall entry associated with different pitching-moment bumps.

(5) Available data on lateral-directional characteristics at deep-stall angles of attack indicated that maintaining wings-level flight and avoiding a spin would be a serious problem. This problem, which was recognized in the past as a limiting factor for conventional stalls on many airplanes, has increased importance in relation to the deep stall because of the prolonged commitment to stalled flight.

(6) In view of the probable serious consequences of penetration into a deep stall, it is considered mandatory that adequate safeguards be provided against inadvertent stall entries. A philosophy of stall safeguard featuring two levels of stall warning, originally proposed for use with gross instabilities in the deep stall, is considered applicable with localized instabilities.

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720-04-00-01-00-21

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TABLE I.- CONFIGURATIONS TESTED IN SIMULATOR PROGRAM

Configuration no.	Pitching-moment curve[a]	$S\bar{c}/I_y$
1	A-1	0.033
2	A-3	.033
3	B-1	.033
4	B-2	.033
5	B-3	.033
6	C-1	.033
7	C-2	.033
8	C-3	.033
9	C-3	.016
10	C-4	.033
11	C-5	.033
12	D-6	.033
13	D-3	.033
14	E-3	.033
15	F-3	.033
16	G-3	.033
17	H-3	.033
18	I-3	.033
19	I-3	.016
20	I-3	.008
21	J-3	.016

[a]See figure 3.

TABLE II.- PHYSICAL CHARACTERISTICS OF TEST CONFIGURATIONS

Gross weight, lb	244,000
Wing area, S, sq ft	4,684
Wing span, b, ft	86.33
Wing mean aerodynamic chord, $\bar{c}$, ft . .	64.52
Moment of inertia about Y-axis, I_y, slug-ft^2	9.25×10^6 18.50×10^6 37.00×10^6

TABLE III.- INCREASE IN PITCH ATTITUDE IN STALL ENTRY

[Longitudinal control fixed at $C_{L_{max}}$]

	Bump configuration[a]	Increase in pitch attitude, deg
Small bumps, $S\bar{c}/I_y = 0.033$	B	2 to 4-1/2
	E	3-1/2
	F	3
	G	2
	H	2
	J	2
Large bumps, $S\bar{c}/I_y = 0.033$	A	4 to 5-1/2
	C	6 to 7
	D	5
	I	6-1/2
Large bump, $S\bar{c}/I_y = 0.016$	C	4-1/2

[a]See figure 3.

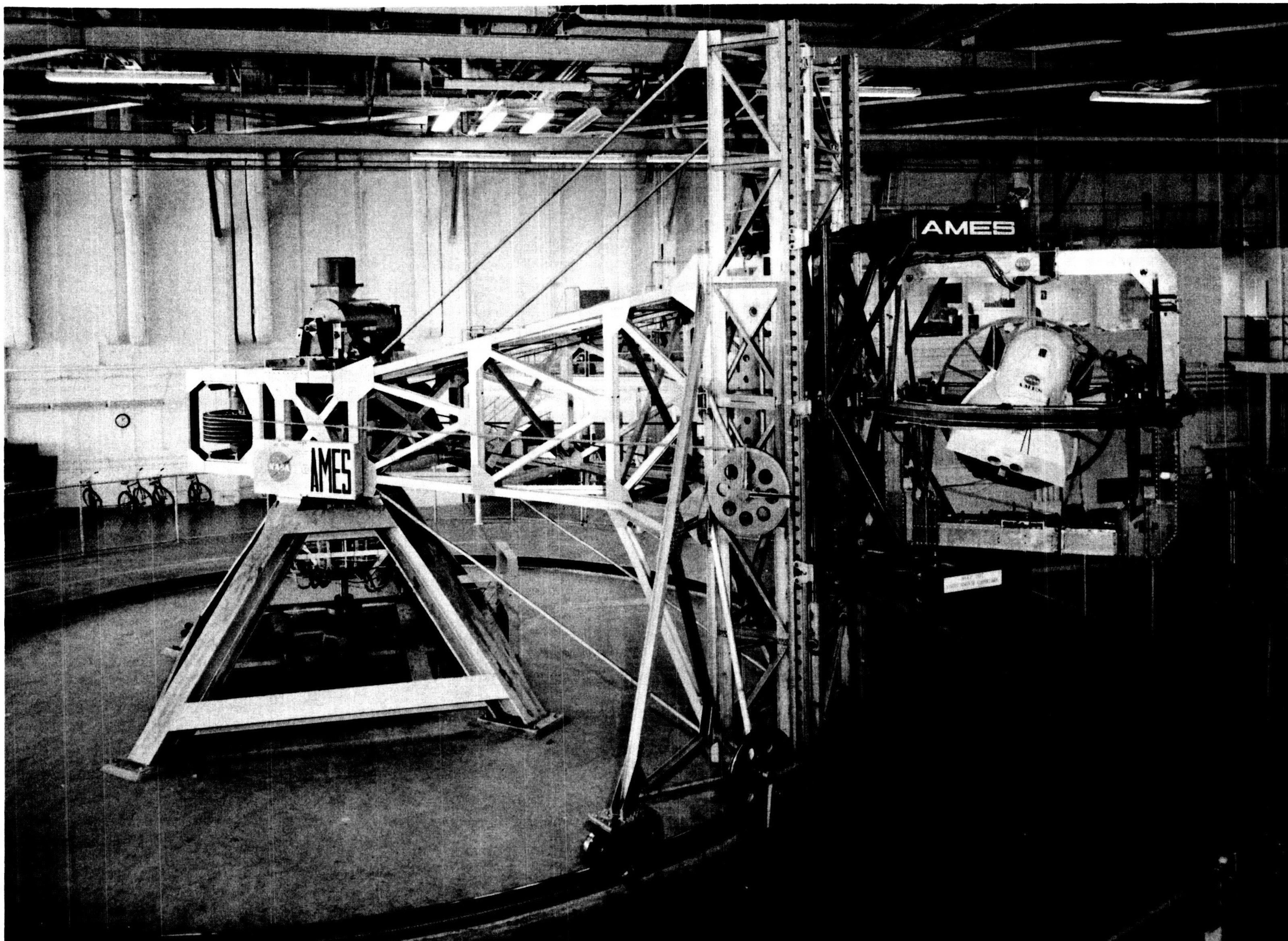

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Figure 1.- Five-degree-of-freedom simulator.

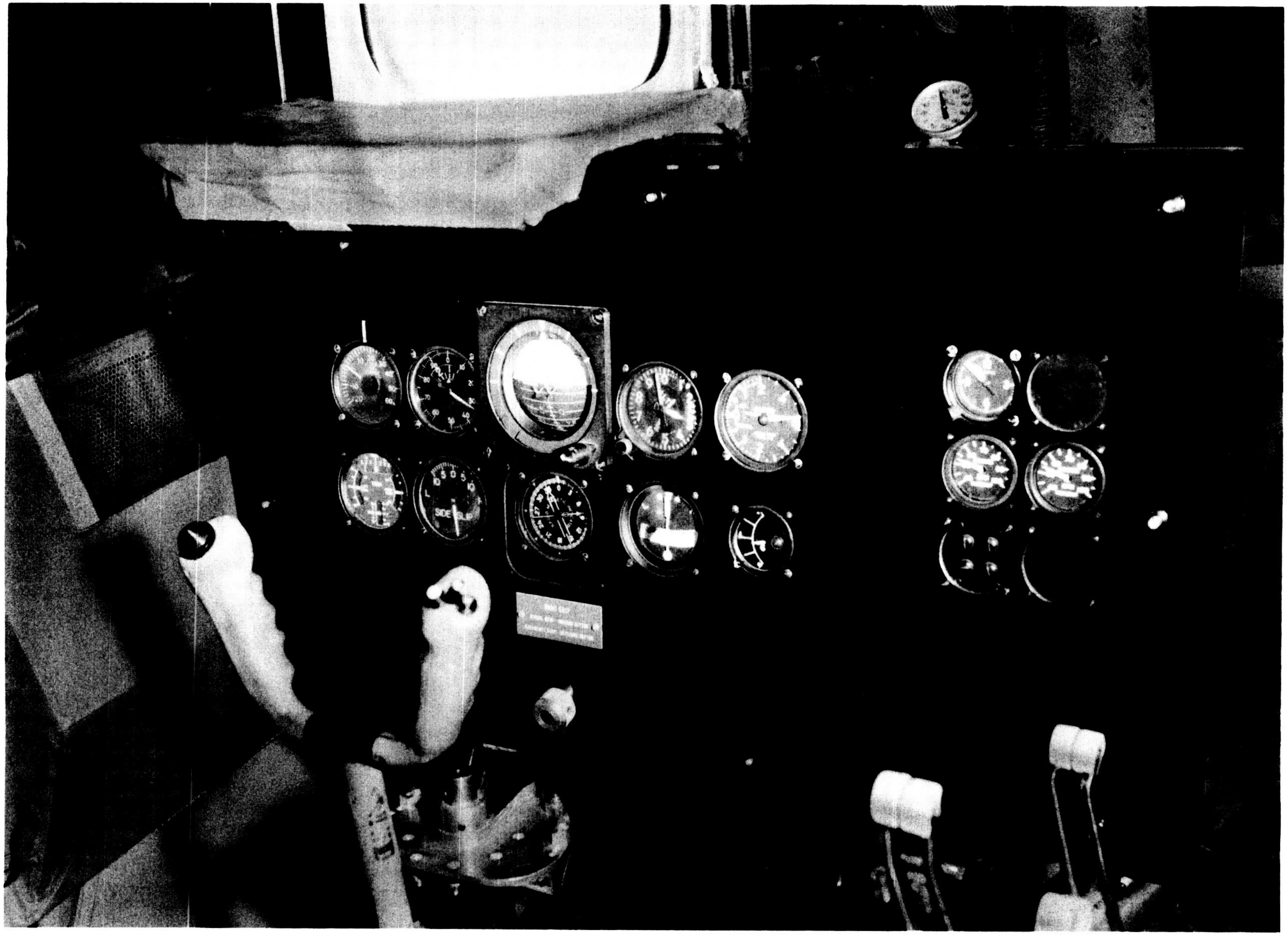

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Figure 2.- Simulator instrument panel.

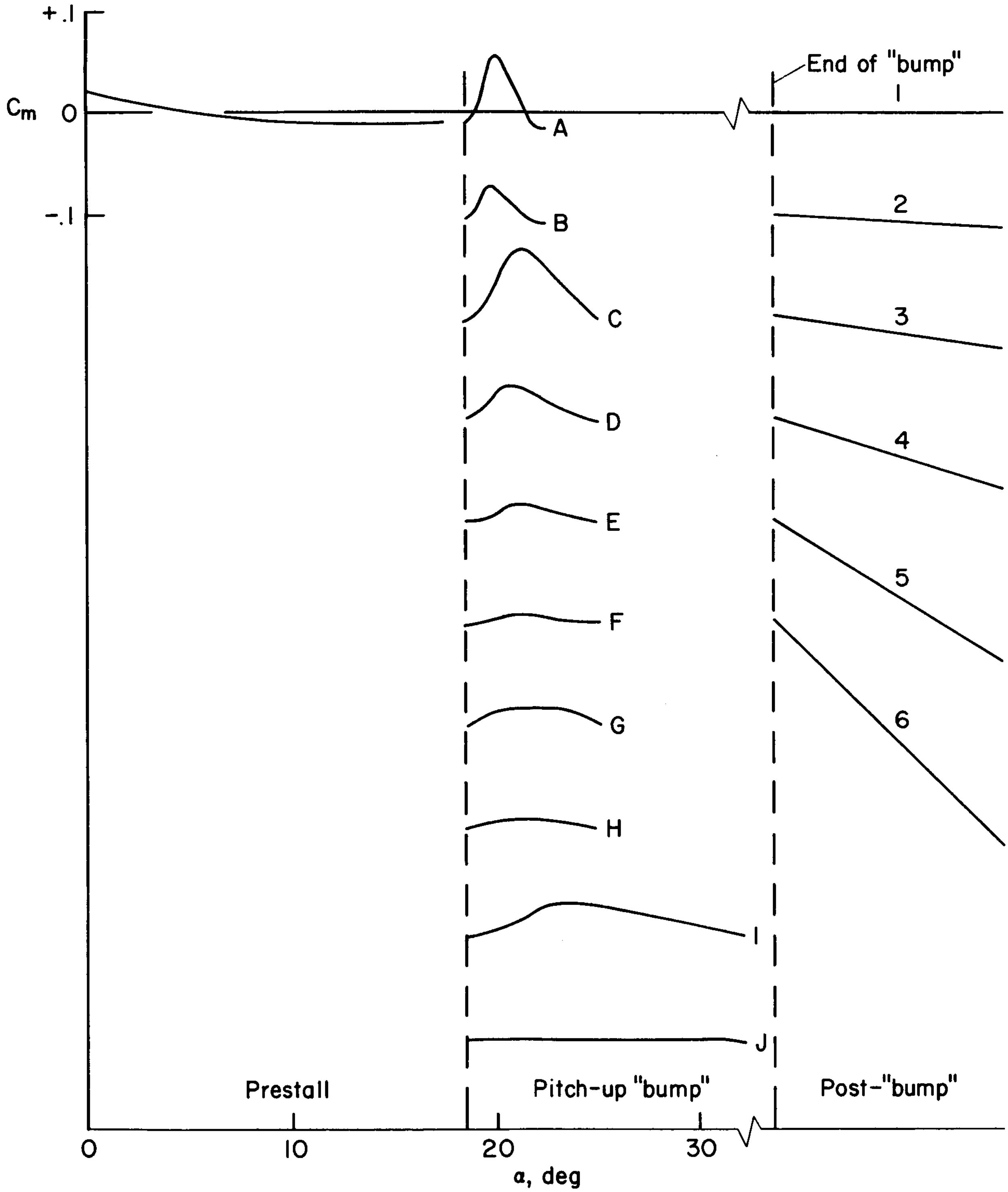
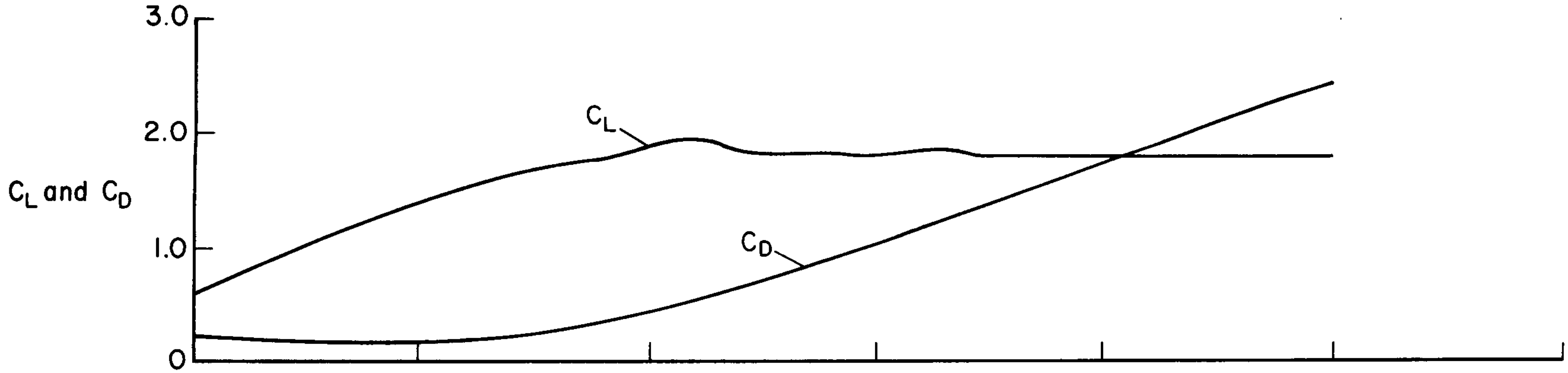
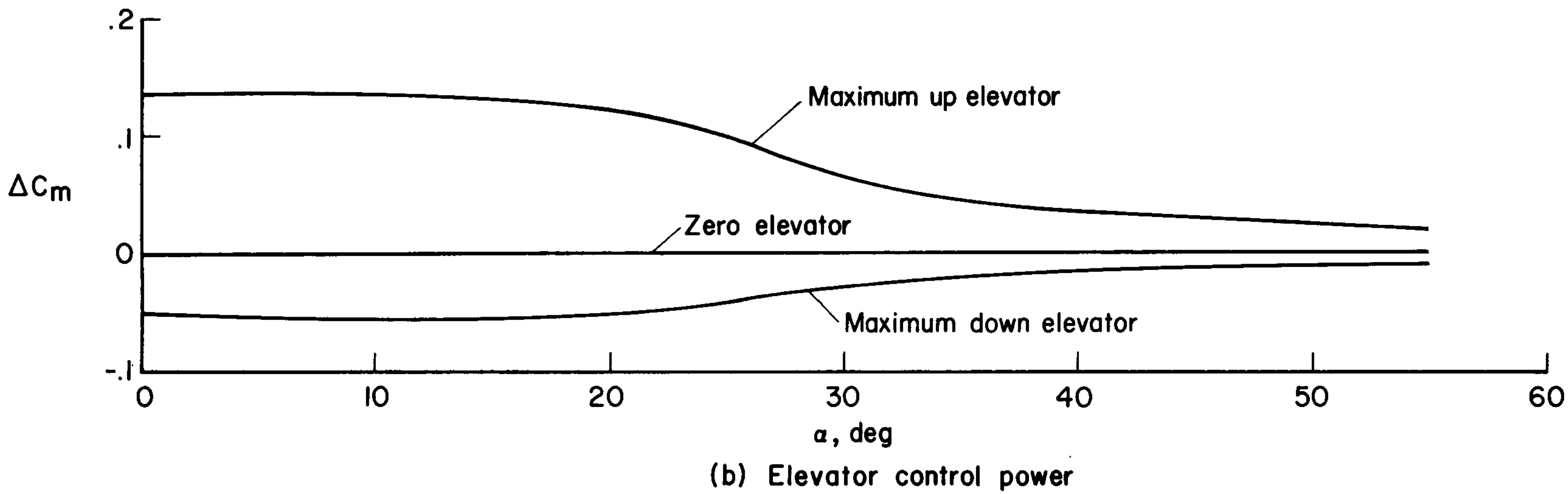


Figure 3.- Pitching-moment-curve variations investigated.



(a) C_L and C_D



(b) Elevator control power.

Figure 4.- Variation of C_L, C_D, and elevator control power with α, as used in simulation.

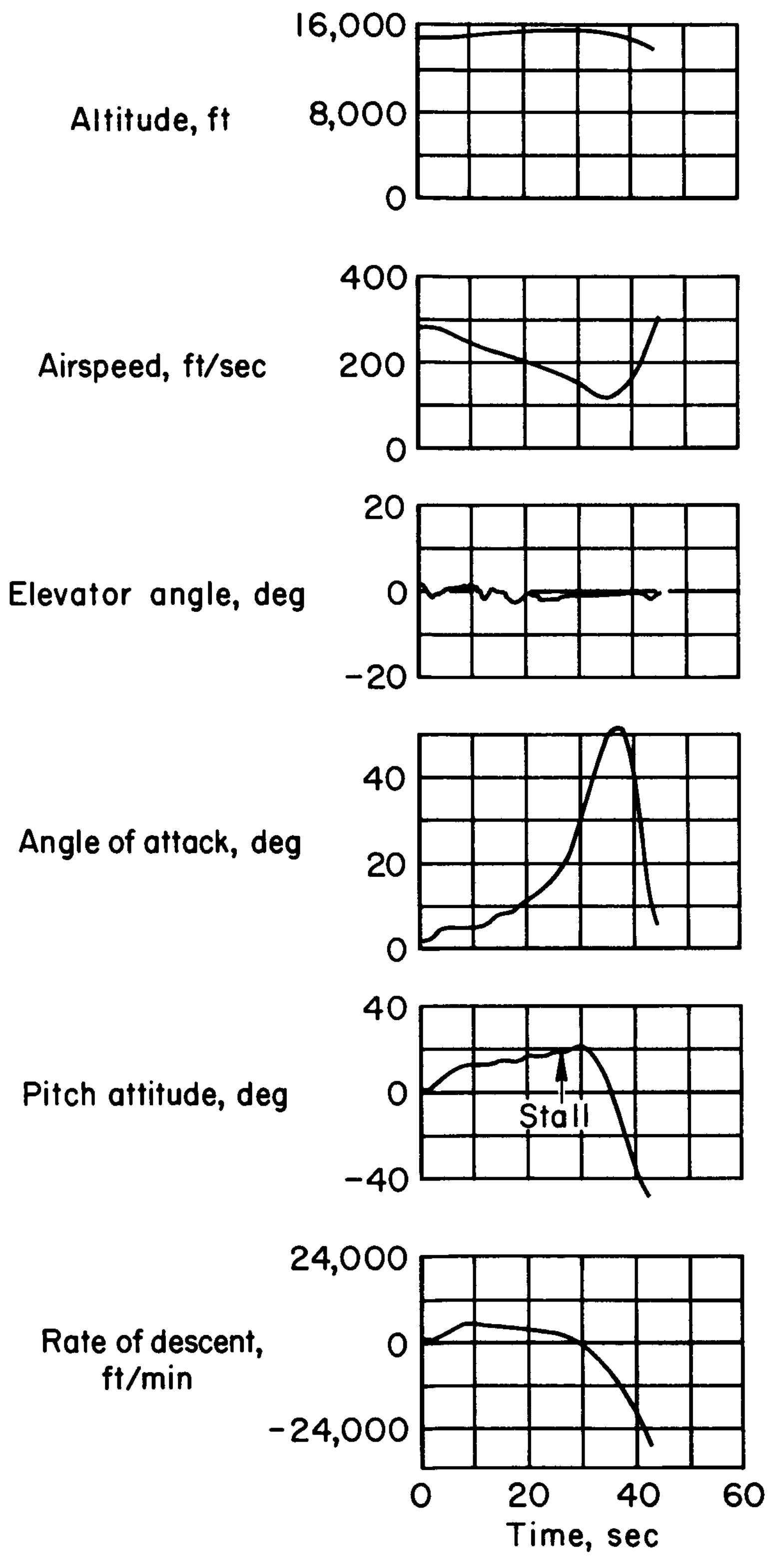


Figure 5.- Time history of typical stall; small bump, configuration 16 (see table I); controls held fixed at stall.

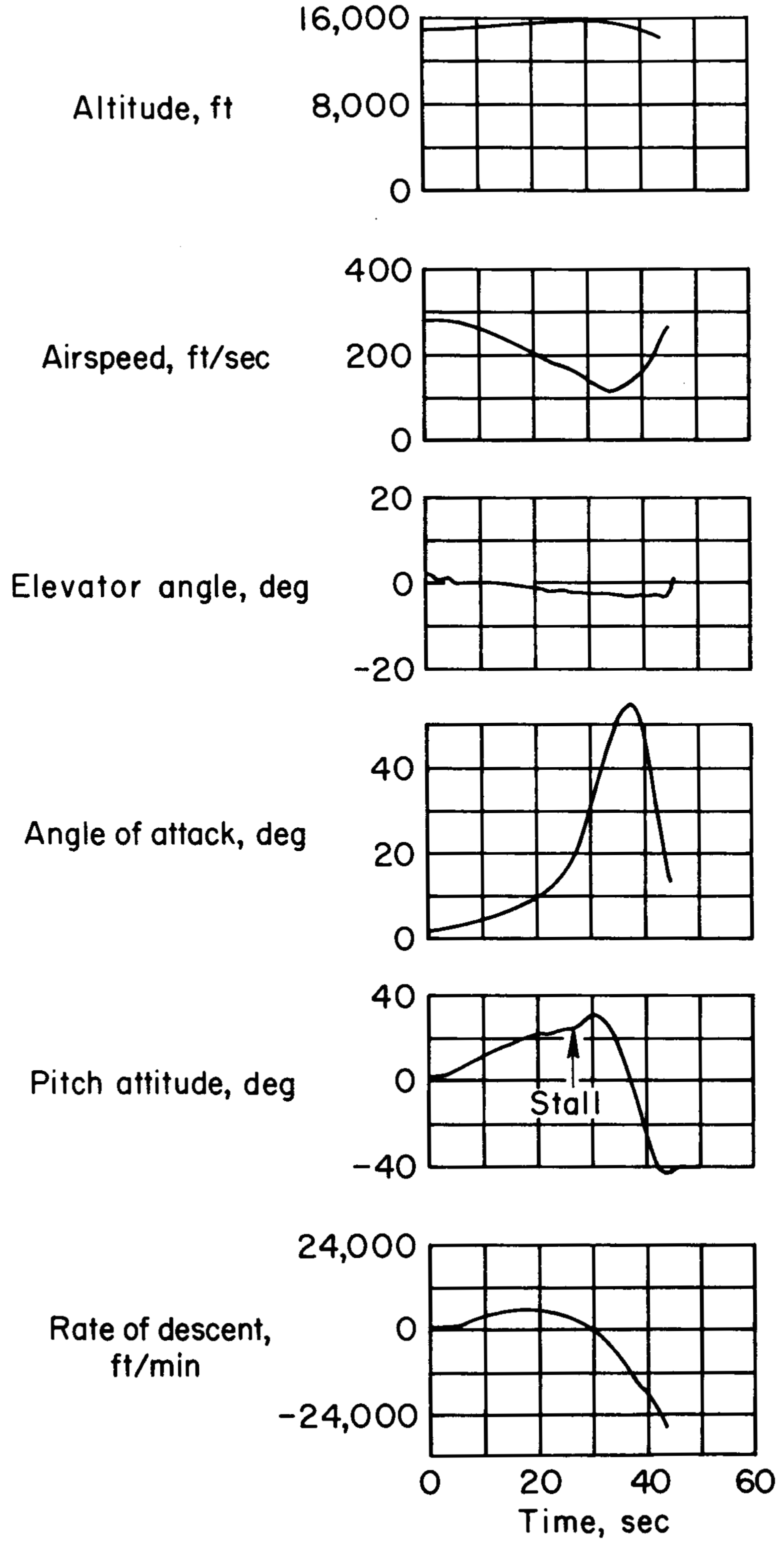


Figure 6.- Time history of typical stall; large bump, configuration 8 (see table I); controls held fixed at stall.

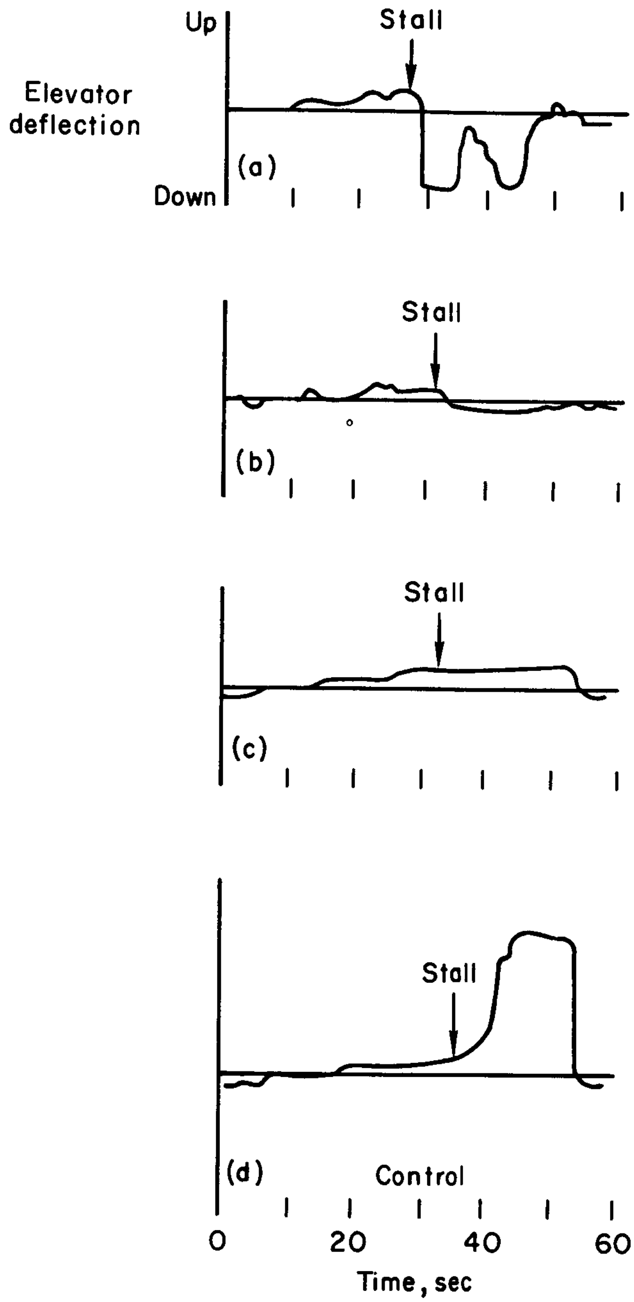


Figure 7.- Illustrative time histories of various pilot control techniques used in stall investigations.

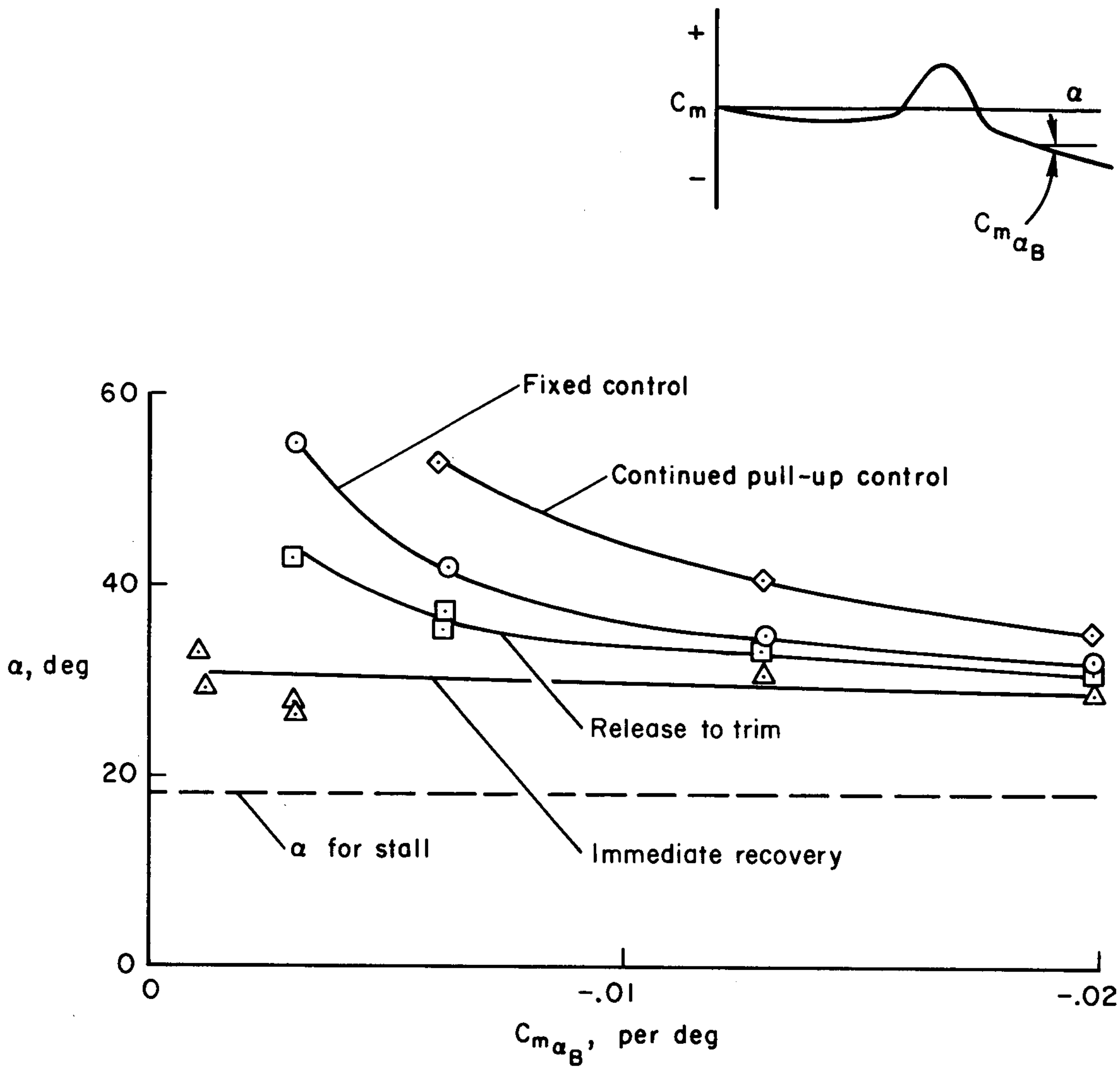


Figure 8.- Variation with static stability (beyond pitch-up) of maximum angle of attack developed for several different piloting techniques; pitching-moment curve C.

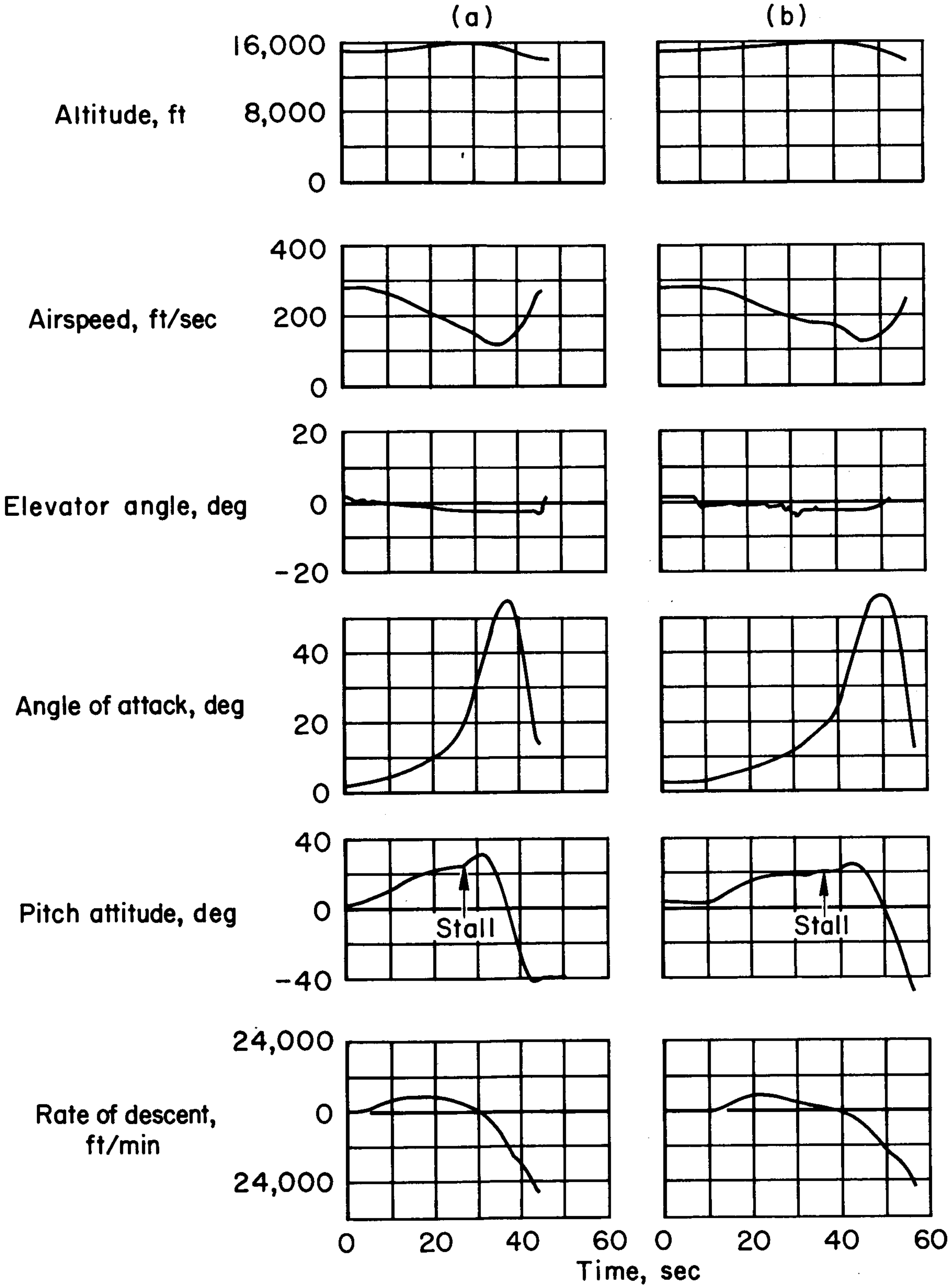


Figure 9.- Effect of parameter $S\bar{c}/I_y$ on stall entry; pitching-moment curve C-3; controls held fixed at stall entry.

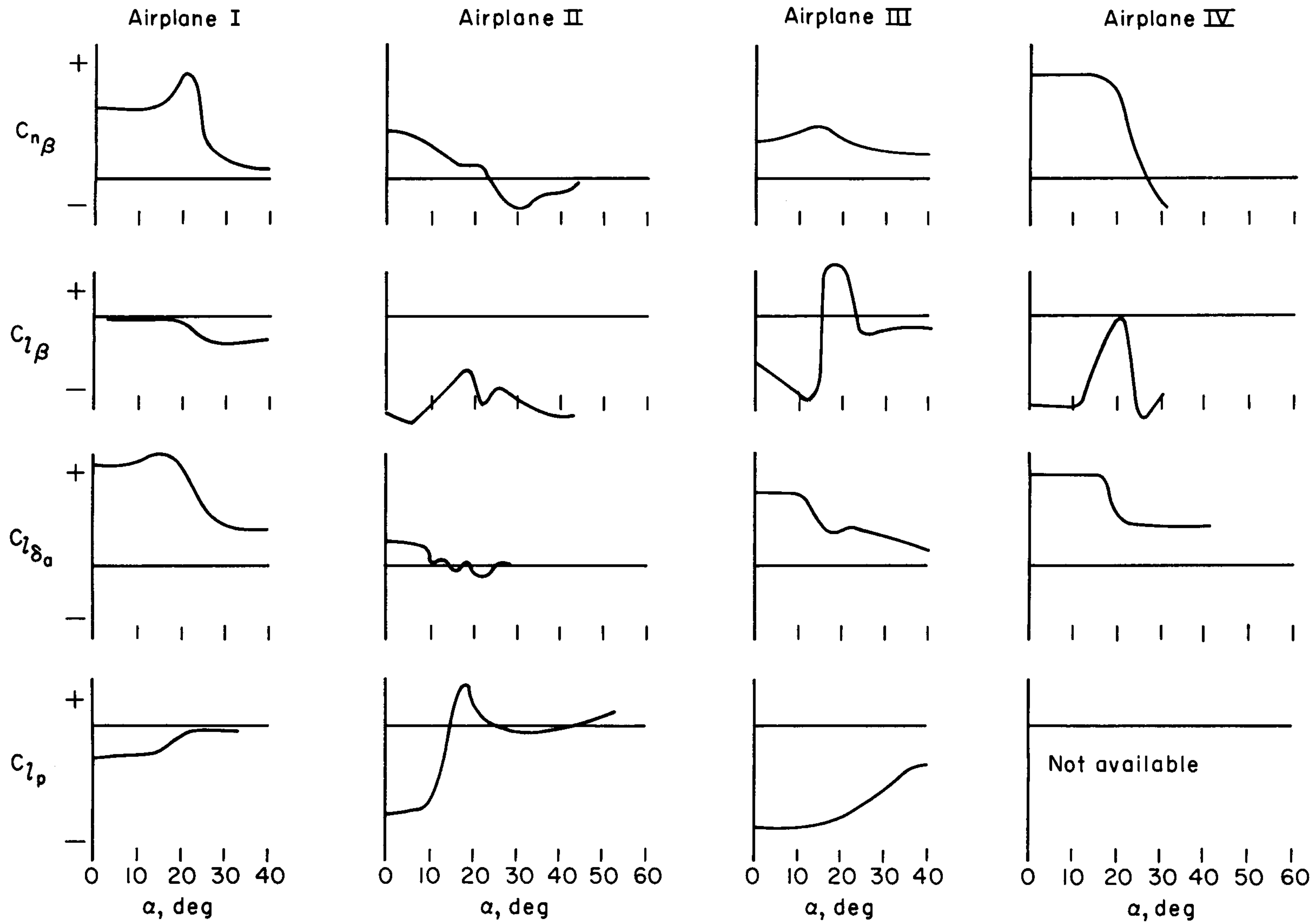


Figure 10.- Representative variations of lateral-directional derivatives at high angles of attack for several transport-type airplane models.

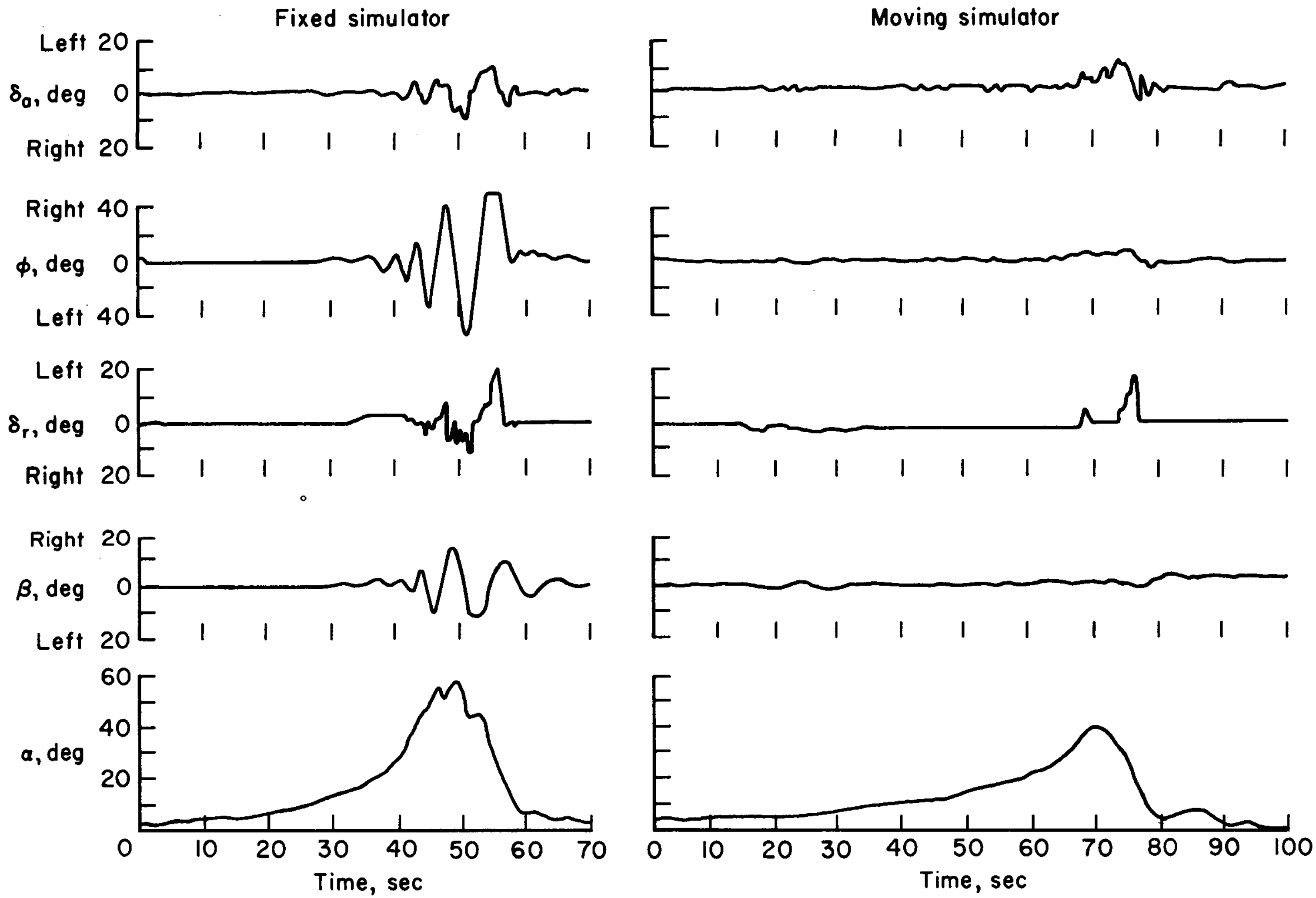


Figure 11.- Comparison of lateral-directional control of deep stall in fixed and moving simulators.

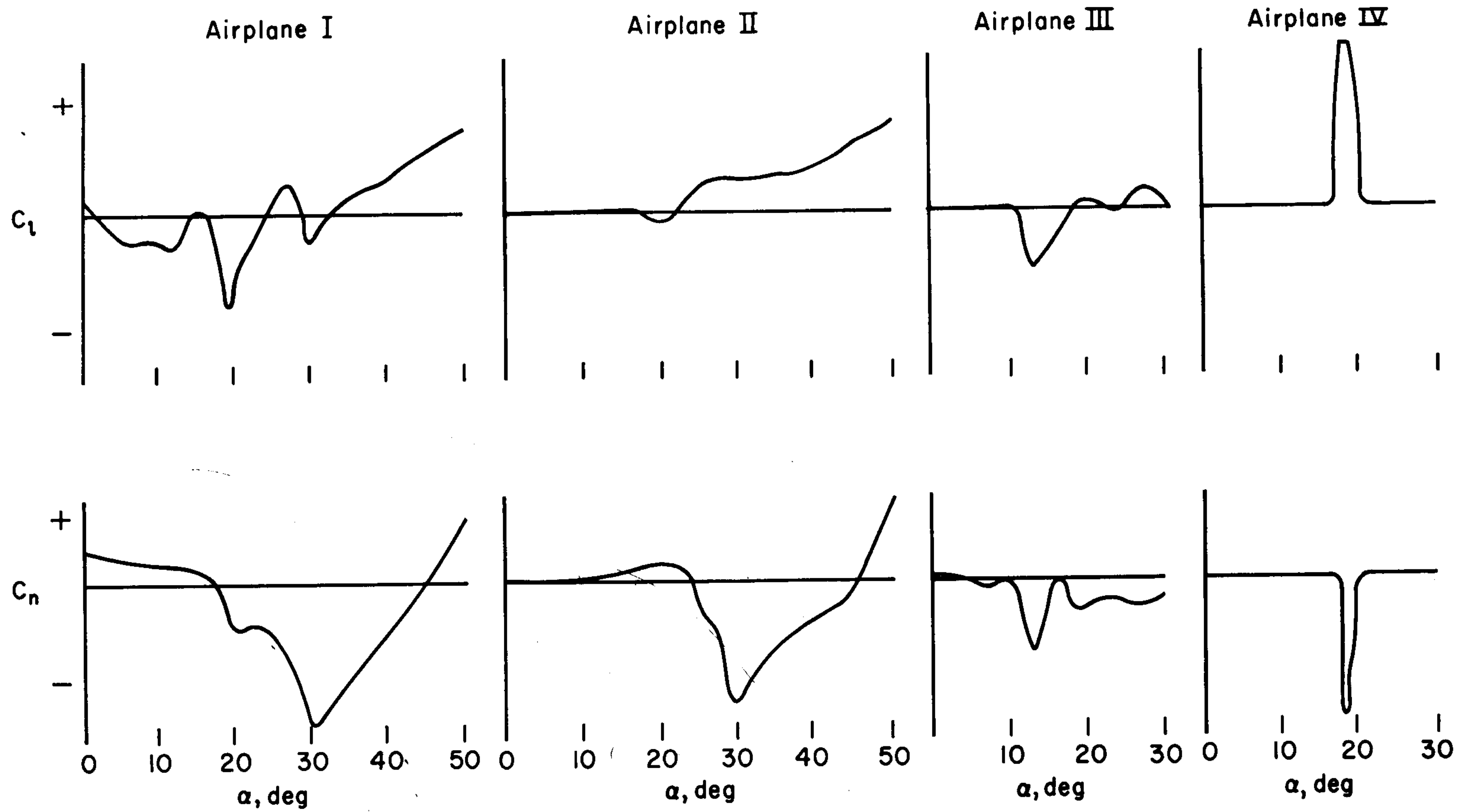
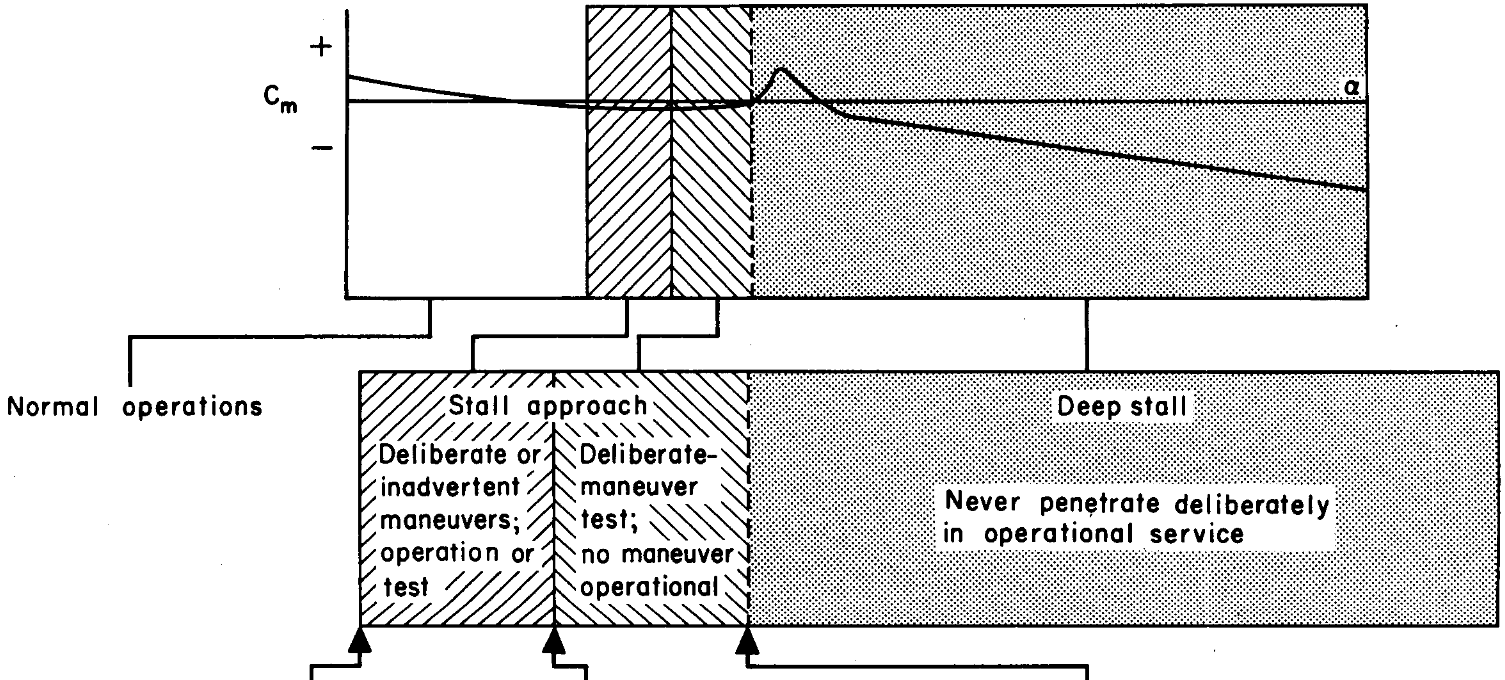


Figure 12.- Representative variations of rolling- and yawing-moment coefficients at zero sideslip for several transport-type airplane models.



Operation	Warning required (typical)	Positive cue required (typical)	Recovery augmenter required (typical)
Operational service	Buffet	Unmistakable stability increase	Not applicable
	Stick shaker	Stick pusher	
Development flight test	Buffet	Unmistakable stability increase	Tail parachute
	Stick shaker	Angle of attack indicator	

Figure 13.- Suggested operational philosophy for airplanes with deep-stall tendencies.