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RESEARCH MEMORANDUM

for the

U. S. Air Force

THEORETICAL INVESTIGATION OF THE EFFECTS OF THE ARTIFICIAL-FEEL SYSTEM ON THE MANEUVERING CHARACTERISTICS OF THE F-89 AIRPLANE

By Marvin Abramovitz, Stanley F. Schmidt,
and Steven E. Belsley

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SUMMARY

The possibility of overshooting the anticipated normal acceleration as a result of the artificial-feel characteristics of the F-89C airplane at a condition of minimum static stability was investigated analytically by means of an electronic simulator. Several methods of improving the stick-force characteristics were studied. It is shown that, due to the lag in build-up of the portion of the stick force introduced by the bobweight, it would be possible for excessive overshoots of normal acceleration to occur in abrupt maneuvers with reasonable assumed control movements. The addition of a transient stick force proportional to pitching acceleration (which leads the normal acceleration) to prevent this occurring would not be practical due to the introduction of an oscillatory mode to the stick-position response. A device to introduce a viscous damping force would improve the stick-force characteristics so that normal acceleration overshoots would not be likely, and the variation of the maximum stick force in rapid pulse-type maneuvers with duration of the maneuver then would have a favorable trend.

INTRODUCTION

The Ames Aeronautical Laboratory was requested to undertake an investigation to determine the feasibility of adding a stick force proportional to the pitching acceleration to the artificial-feel system of the F-89C airplane to serve as a normal-acceleration warning signal. A series of structural failures in flight have been attributed in part to excessive normal-acceleration overshoots caused by a condition of very low static stability at about a Mach number of 0.75 and sea level, together with the characteristics of the spring and bobweight artificial-feel system. It was felt that an additional stick force proportional to the pitching acceleration, a quantity which leads the normal acceleration, would provide a warning of excessive normal acceleration prior to its occurrence in rapid maneuvers, thus allowing the pilot to take corrective action in time to eliminate the overshoot.

In view of the results of a flight investigation of another airplane at this Laboratory in which an undesirable oscillation was introduced to the control system when an additional stick force proportional to the pitching acceleration was included in a test airplane, it was decided to study the effects on the F-89C analytically using the Ames high-speed electronic simulator. Aerodynamic and control-system data for the F-89C were furnished by Northrop Aircraft, Inc., for the analytical investigation.

In addition, since the control and artificial-feel systems would be set up on the simulator, it was decided to investigate in a little more detail the influence of the artificial-feel system on the maneuvering characteristics.

NOTATION

$\Delta a_Z/g$	change in normal acceleration from level flight trim, g's
F_S	change in stick force from trim, lb
F_{S_B}	portion of stick force due to bobweight, lb
F_{S_T}	portion of stick force introduced by torque servo, lb
$F_{S_{\theta_S}}$	portion of stick force due to bellows spring, lb
g	acceleration of gravity, 32.2 ft/sec^2
K_B	steady-state stick force due to bobweight per g, lb/g
K_T	stick force introduced by torque servo per unit pitching acceleration, lb/radian/sec^2
K_{θ_S}	stick force due to bellows spring per unit stick deflection, lb/deg
l_B	distance between bobweight and airplane center of gravity, ft
M.A.C.	mean aerodynamic chord, ft

M	Mach number
q_c	impact pressure, lb/ft^2
t	time, sec
t_{man}	duration of pulse-type maneuver, time from start of maneuver until elevator angle returns to trim position, sec
$\Delta\delta_e$	change in elevator angle from trim, deg
$\Delta\theta_S$	change in stick position from trim, deg
$\ddot{\theta}$	pitching acceleration, radians/sec^2

METHOD AND CONDITION OF ANALYSIS

The F-89C is equipped with power-operated, irreversible control surfaces. Artificial feel for the longitudinal control system is provided by a bellows and linkage arrangement, to produce a spring force proportional to the dynamic pressure, and a bobweight, to produce a satisfactory stick-force gradient. The total pilot-applied stick force, then, is composed of two components: the bellows spring force $F_{S_{\theta_S}}$ and the bobweight force F_{S_B}. The spring force is a function of both the dynamic pressure and the airplane maneuver margin since the airplane response per unit stick deflection depends on the stick-fixed maneuver margin. Since the airplane response depends on stick position which is proportional to the spring force, and the bobweight force depends on the airplane response, the system is a closed-loop system defined by the following equations:

$$\left.\begin{aligned}
& & F_S &= F_{S_{\theta_S}} + F_{S_B} \\
&\text{or} & F_S - F_{S_B} &= F_{S_{\theta_S}} \\
&\text{where} & F_{S_B} &= K_B\left(\frac{\Delta a_z}{g} + \frac{l_B}{g}\ddot{\theta}\right) \\
&\text{and} & &\frac{\Delta a_z}{g} \text{ and } \ddot{\theta} \text{ are functions of } F_{S_{\theta_S}}
\end{aligned}\right\} \qquad (1)$$

The solid lines of the block diagram of figure 1 represent the airplane control and artificial-feel system as defined by equation (1). The broken lines indicate the method of introducing an additional stick force proportional to the airplane pitching acceleration by means of a torque servo.

The system was set up on the Ames high-speed electronic simulator and responses in stick position, elevator position, and normal acceleration to a unit step input of stick force were recorded. In addition, provision was made so that a step input in stick position of the same magnitude as the steady-state position due to the unit force input could be applied and the elevator position, normal acceleration, and stick force could be recorded. Since the system is considered linear, responses for different magnitudes of the input can be obtained by simply expanding or contracting the scales.

Conditions of Analysis

Characteristics of the control-system components are summarized in reference 1. In the analysis, the stick and artificial-feel-system inertia has been neglected. Briefly, the bobweight applies a steady-state stick force of 4.5 pounds per g and is located approximately 40 inches ahead of the leading edge of the mean aerodynamic chord. The bellows spring produces a stick force defined by the following equation:

$$F_{S_{\theta_S}} = (4.81 + 0.027\ q_c)(\Delta\theta_S) \tag{2}$$

The control servo is approximated by a first-order lag function with a break point at 20 radians per second.

The mass and aerodynamic characteristics of the airplane are summarized in reference 2. A condition of very low static stability and small maneuver margin exists at a Mach number of 0.75 at sea level. The analysis covered a range of center-of-gravity positions from 23-percent M.A.C. to 27.8-percent M.A.C. at this condition. In going from 23-percent M.A.C. to 27.8-percent M.A.C., the stick-force gradient varies from 13.9 to 6.9 pounds per g and the elevator-angle gradient varies from 0.59° to 0.15° per g as calculated from the data of reference 2 modified by recent flight-test results. Dynamic characteristics of the airplane were determined by deriving the transfer functions connecting $(\Delta a_z/g)$ and $\ddot{\theta}$ with δ_e from the usual two-degrees-of-freedom longitudinal equations of motion.

The operation of the torque servo, used to determine the effect of an additional stick force proportional to pitching acceleration, is explained in reference 3. In the present analysis, the dynamic effects of the servo have been neglected. However, the pitching accelerometer has been represented as a second-order system with a natural frequency of 9 cycles per second and a damping ratio of 0.7 to correspond to the characteristics of instruments available at this Laboratory.

RESULTS AND DISCUSSION

Normal Airplane

Figure 2(a) presents time histories of $\Delta\delta_e$, $\Delta a_z/g$, and stick force due to a step input of $\Delta\theta_s$ for the aft center-of-gravity condition (27.8-percent M.A.C.). Figure 2(b) presents the responses to a step in stick force. In figures 3(a) and 3(b) are the corresponding responses for the forward center-of-gravity location (23-percent M.A.C.). It should be noted that ordinate scales of both the position and force responses are for a unit steady-state stick force. A comparison of the responses to the step in stick position (figs. 2(a) and 3(a)) indicates quite clearly the effect of the very low static stability with the aft center-of-gravity position on the control and feel-system characteristics. The normal acceleration per unit control deflection is, of course, larger and the portion of the stick force due to the spring is much smaller, being only about 35 percent of the total steady-state stick force. Because of the delay in stick-force build-up due to the action of the bobweight, it might be expected that an appreciable g overshoot would occur for a constant-force input. However, referring to figure 2(b), it is seen that with a step in stick-force input there is no g overshoot even though stick-position and elevator-position overshoots of 200 percent to 300 percent occur.

Responses resulting from various assumed pilot's reactions and control movements were calculated by superposition from the responses to step inputs in stick position in order to reveal circumstances which might lead to excessive g overshoots.

One interesting result is illustrated in figure 4. Figure 4(a) shows computed time histories of an abrupt pull-up at a Mach number of 0.6 at sea level where the airplane has greater static stability than at a Mach number of 0.75. In this maneuver, it was assumed that the pilot first imposes an initial step input in stick position of a magnitude that results in an initial stick force due to the spring equivalent to what the pilot correctly anticipates will be the total steady-state stick force after steady acceleration is reached (0.105 g/lb). For the solid curves, he holds the constant stick position (regardless of the stick-force increase due to the bobweight) until the anticipated normal acceleration is reached, and then abruptly reduces the stick deflection to that value which corresponds in the steady state to the desired acceleration. Because of the lag in the bobweight force build-up, the g overshoot is about 20 percent. For the dashed curves, he delays 0.2 second before making the correction. In this case, the overshoot is about 40 percent. In figure 4(b) are time histories of similar maneuvers at a Mach number of 0.75 where the airplane has a minimum maneuver margin. However, here it is assumed that the pilot's reactions and control movements are heavily conditioned by extensive flight experience at lower Mach numbers where the stability and stick-force gradients are higher. For figure 4(b), the pilot applies the same initial force input as for figure 4(a), anticipating that the resulting steady-state acceleration will be the same (0.105 g/lb). However, because of the lower stability, this force actually corresponds to a larger steady-state acceleration so that when the pilot reverses the stick at 0.105 g larger overshoots occur. It is seen that if he corrects the stick deflection at 0.105 g, the overshoot is 50 percent. When he delays correction for 0.2 second, the overshoot increases to about 100 percent.

The assumed pilot's reactions and step-control movements of figure 4 were necessarily oversimplified for ease in computation. However, the results do indicate that, due to the low stability and stick-force gradient and the lag in the bobweight force, excessive normal-acceleration overshoots might occur in abrupt pull-ups at high Mach number, especially if (as appears reasonable) the pilot's reactions are strongly influenced by the normal behavior in the more familiar low Mach number range.

If the pull-out is initiated at a higher speed, say at a Mach number of 0.85, and the speed decrease during the maneuver is considered, the amount of overshoot might be even more serious. In this case, at the start of the maneuver the airplane has a larger maneuver margin and, as the speed decreases to $M = 0.75$, the margin drops off rapidly to a minimum. The normal acceleration corresponding to the initial stick deflection, then, will increase rapidly during the maneuver.

Effect of Pitching-Acceleration Signal

In figures 5(a) and 5(b) are the responses to a step in deflection and force, respectively, with an additional stick force proportional to the airplane pitching acceleration included. It can be seen from figure 5(a) that the stick force is more nearly in phase with the stick position than was the case for the normal control system. However, for a constant force input (fig. 5(b)) the response in stick position is oscillatory and would probably be considered unsatisfactory by a pilot. This effect is due to the dynamic characteristics of the pitching accelerometer. Similar difficulties were experienced in a flight investigation at this Laboratory in which an additional stick force was provided for a conventional propeller-driven fighter airplane to serve as a normal-acceleration warning signal. To remedy these difficulties, the effect of a filter or shaping network in the loop was investigated, but it has not yet been determined whether an appreciable amount of additional stick force proportional to pitching acceleration can be provided and still maintain a satisfactory stick-position response. Figure 5(c) shows the effect of a perfect accelerometer (i.e., one which measures the pitching acceleration exactly). It is seen that the response is no longer oscillatory. In view of the effect of the accelerometer dynamics, it is not considered feasible to incorporate this signal in the control system.

Effect of the Addition of Viscous Damping

In reference 4, the control characteristics of a bobweight-equipped airplane were investigated. It was found that the addition of viscous damping to the control system improved the characteristics in rapid maneuvers. The device to produce this effect can be described in a simplified manner as a dashpot connected to the control stick through a spring. Figures 6(a) and 6(b) show the effect of this device on the responses to both a stick-position and a stick-force input for the F-89C control system. The values of the spring force and damping force are 50 pounds of stick force per degree and 50 pounds of stick force per degree per second of stick movement, respectively. It is seen that with additional transient forces of this magnitude, the stick force follows the stick movement very closely so that the overshoots that occurred in the previous figures are no longer present.

The effects of a bobweight in the control system can be assessed in a different manner, as was done in reference 4. This is by examining the maximum stick force per maximum g occurring in a pulse-type maneuver. Figure 7 shows the stick-force characteristics of the F-89C for pulses of various durations at both the forward and aft center-of-gravity positions. It is seen that for the forward center of gravity the stick force becomes lower than the steady-state value. This characteristic was considered undesirable in reference 4 and the U. S. Air Force and Navy Specifications now include a requirement that this condition should not occur (ref. 5). For both the forward and aft centers of gravity, the stick force begins to increase rapidly at maneuver times much smaller than those of the satisfactory airplane of reference 4. It is apparent from the figure that the addition of the viscous damping device should improve the control characteristics greatly in this respect.

CONCLUSIONS

The possibility of overshooting the anticipated normal acceleration as a result of the artificial-feel characteristics of the F-89C airplane at a condition of minimum static stability was investigated analytically. Several methods of improving the stick-force characteristics were studied. Results of the electronic simulator studies indicated that:

1. Due to the lag in build-up of the portion of the stick force introduced by the bobweight (which, at the condition of low static stability, comprises about 65 percent of the total steady-state stick force), it would be possible for excessive overshoots in normal acceleration to occur in abrupt maneuvers with reasonable assumed control manipulations.

2. The addition of a transient stick force proportional to pitching acceleration (which leads the normal acceleration) would not be practical because the stick-position response would become oscillatory.

3. A device to introduce a viscous damping force would improve the stick-force characteristics so that normal-acceleration overshoots would not be likely and the variation of the maximum stick force in rapid pulse-type maneuvers with duration of the maneuver would have a favorable trend.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Dec. 31, 1952.

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FIGURE LEGENDS

Figure 1.– Artificial-feel system.

Figure 2.– Responses for normal airplane – aft center-of-gravity location. (a) Step-position responses. (b) Step-force responses.

Figure 3.– Responses for normal airplane – forward center-of-gravity location. (a) Step-position responses. (b) Step-force responses.

Figure 4.– Responses for normal airplane in theoretical abrupt maneuver – aft center of gravity. (a) $M = 0.60$.

Figure 4.– Concluded. (b) $M = 0.75$.

Figure 5.– Responses with angular acceleration signal included. Accelerometer natural frequency equals 9 cycles per second. (a) Step-position responses. (b) Step-force responses.

Figure 5.– Concluded. (c) Step-force-response, perfect accelerometer.

Figure 6.– Responses with viscous damping force included. (a) Step-position responses. (b) Step-force responses.

Figure 7.– Stick-force characteristics in rapid maneuvers.

Note: Torque servo not part of normal system.

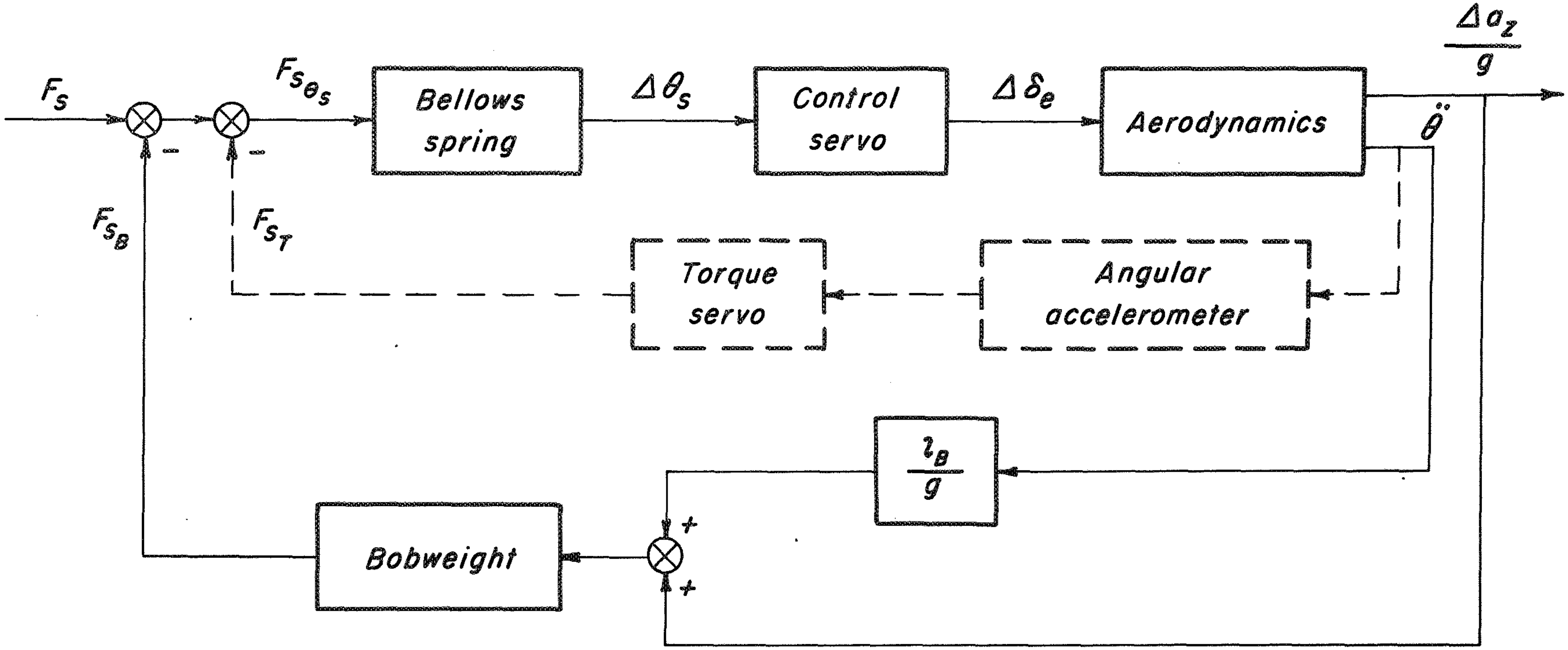
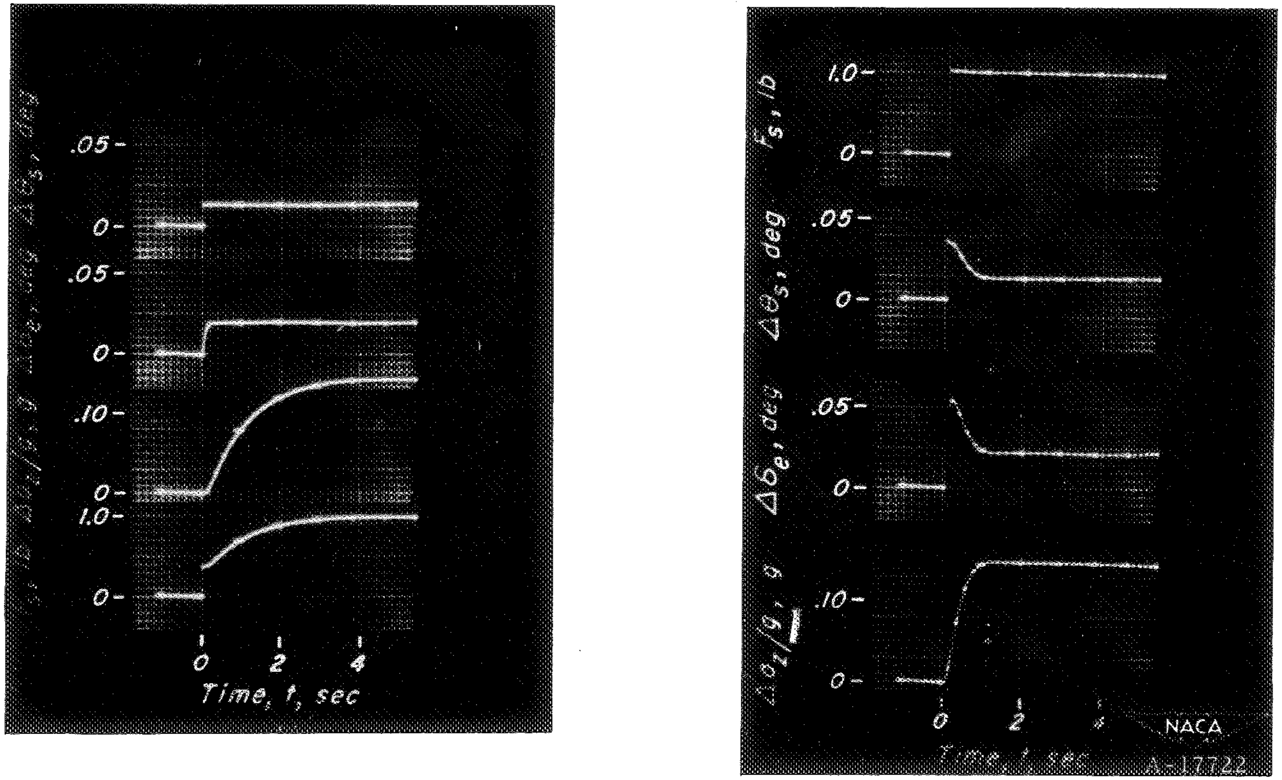


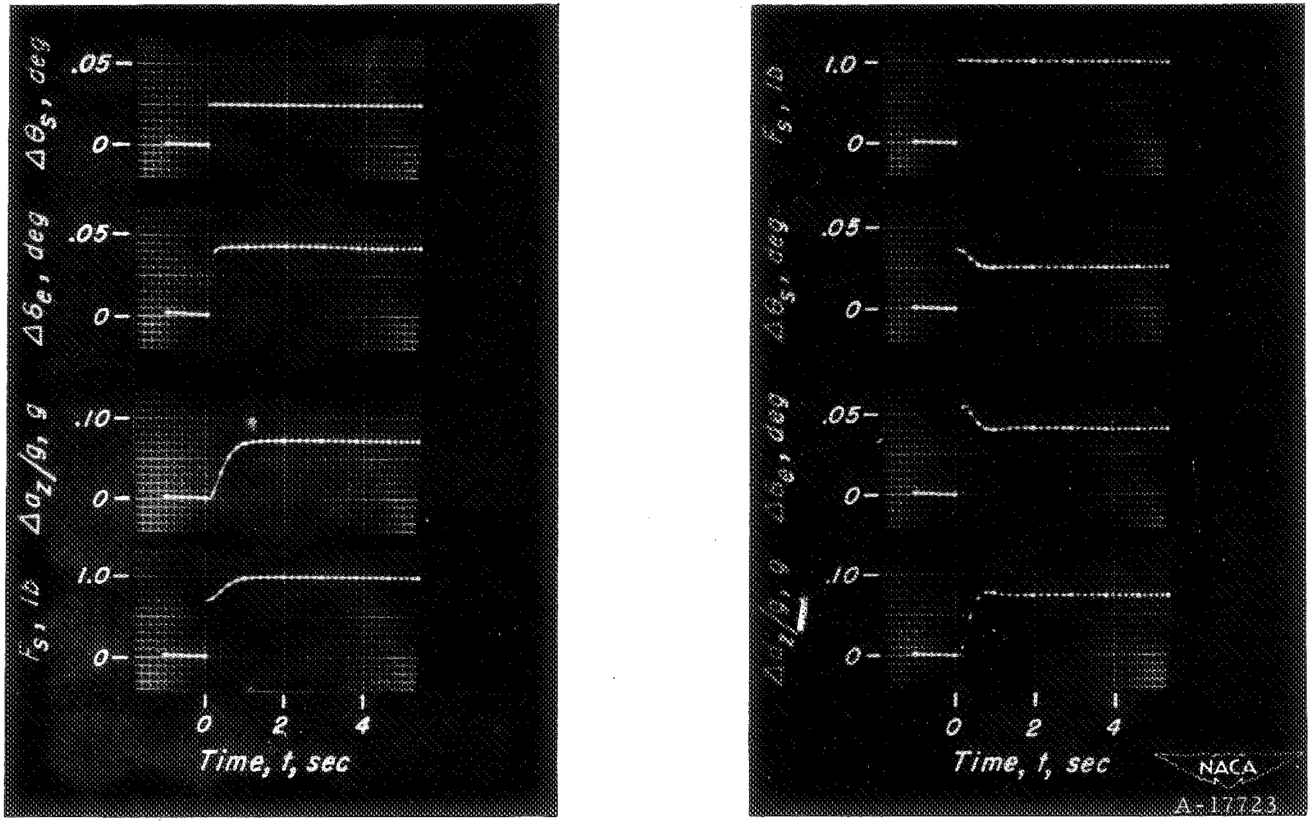
Figure 1.– Artificial-feel system.



(a) Step-position responses.

(b) Step-force responses.

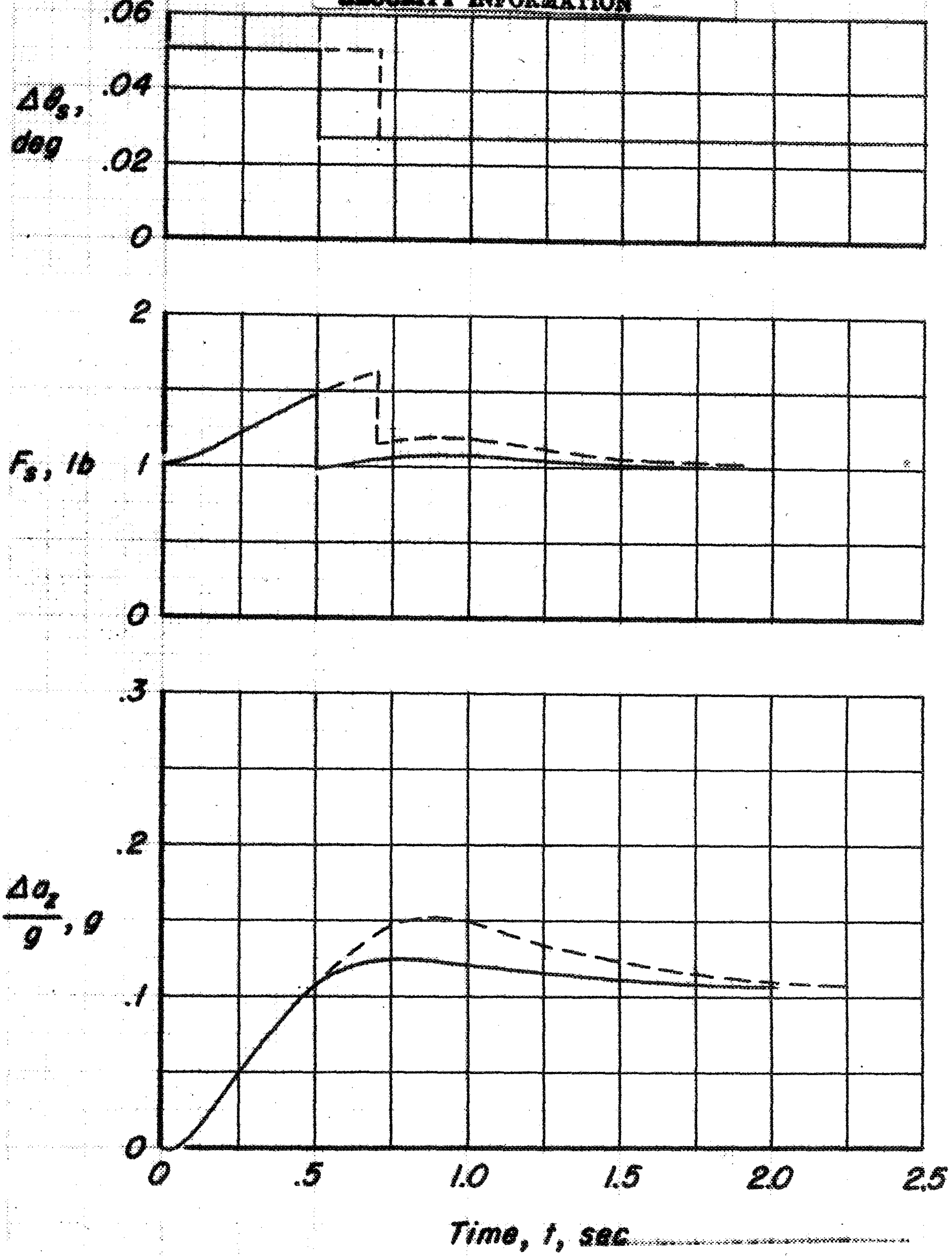
Figure 2.- Responses for normal airplane - aft center-of-gravity location.



(a) Step-position responses.

(b) Step-force responses.

Figure 3.- Responses for normal airplane - forward center-of-gravity location.



(a) $M = 0.60$.

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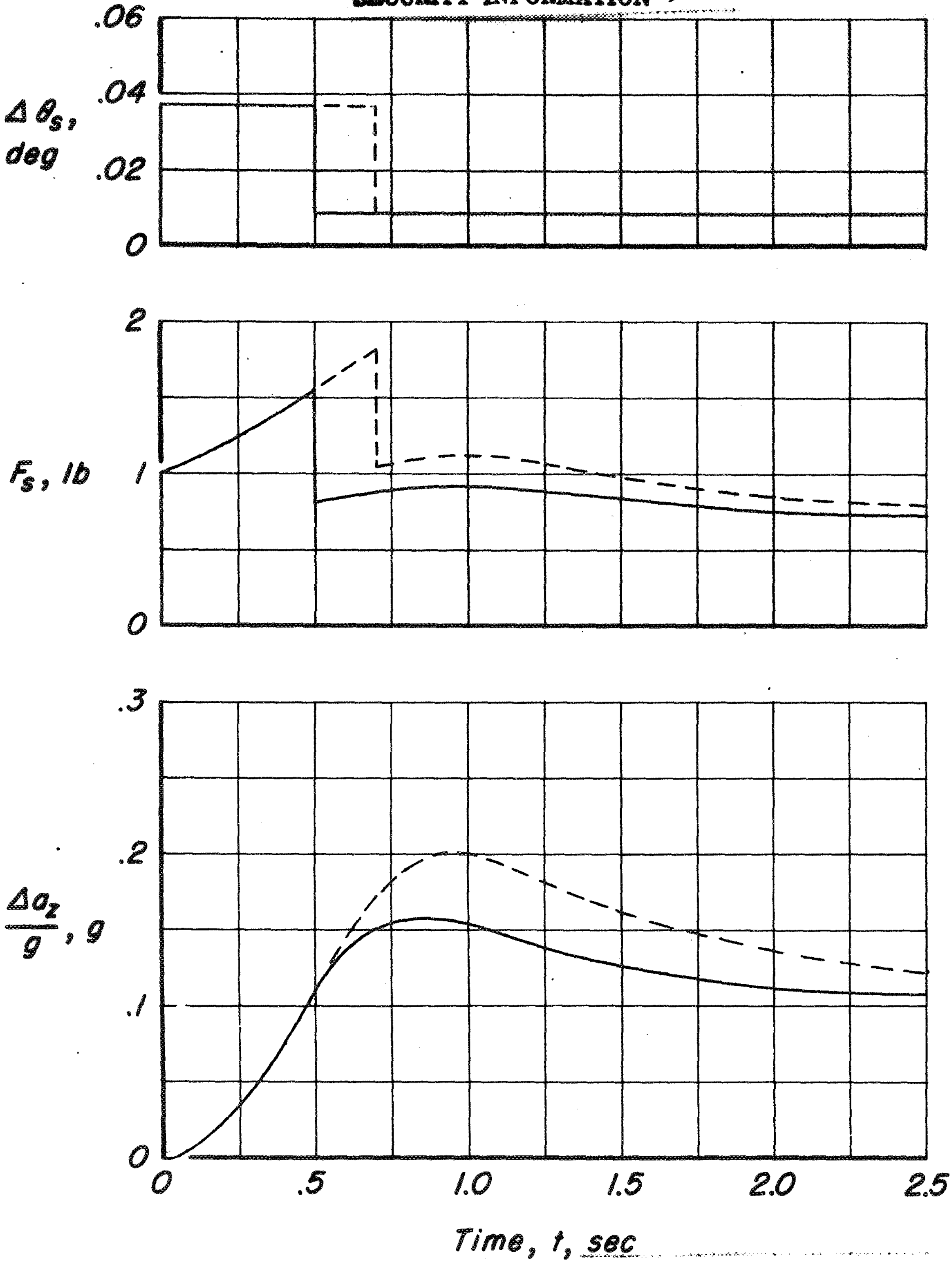
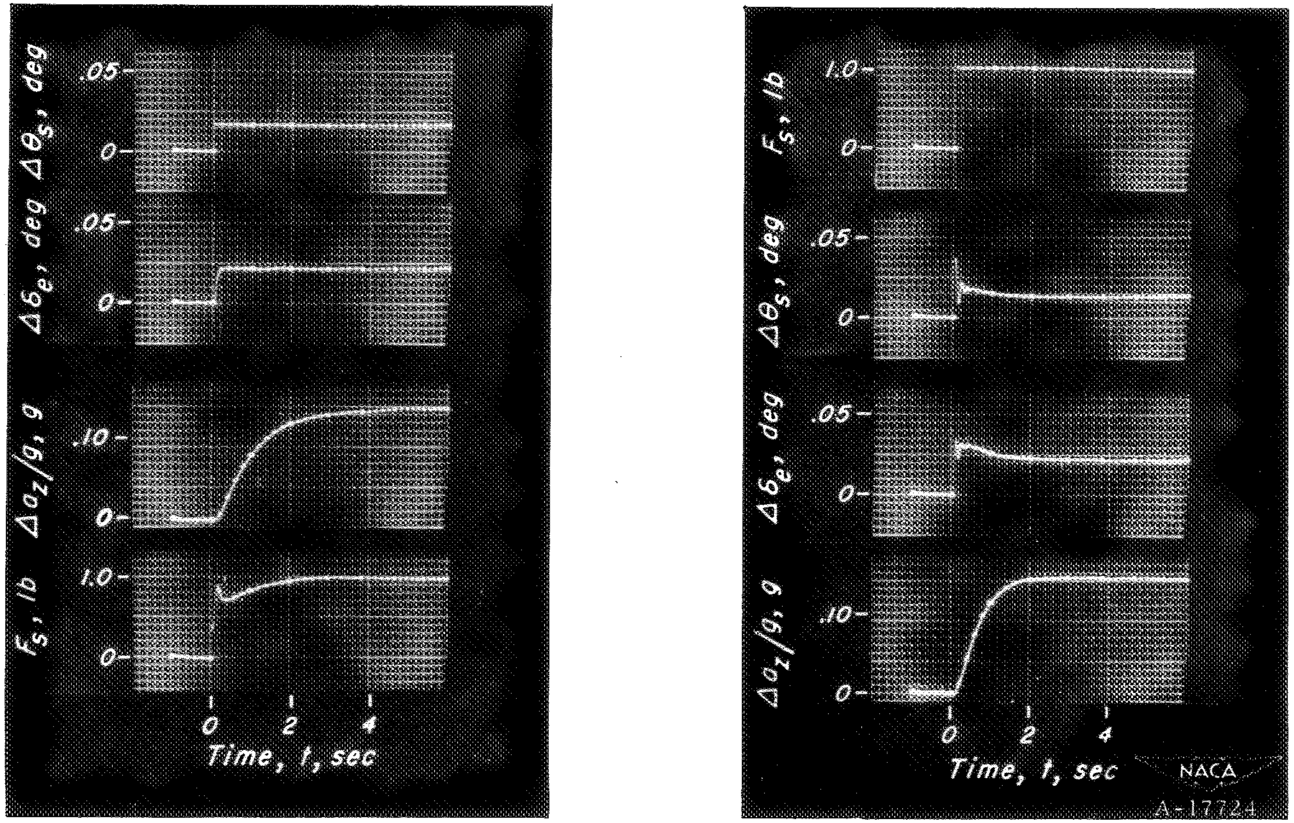
Figure 4.— Responses for normal airplane in theoretical abrupt maneuver — aft center of gravity.



(b) M = 0.75.

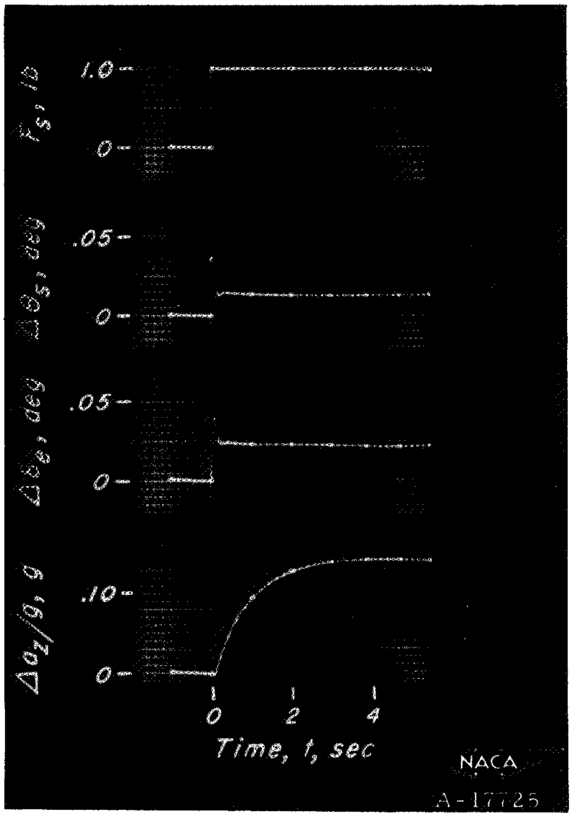
Figure 4.— Concluded.



(a) Step-position responses.

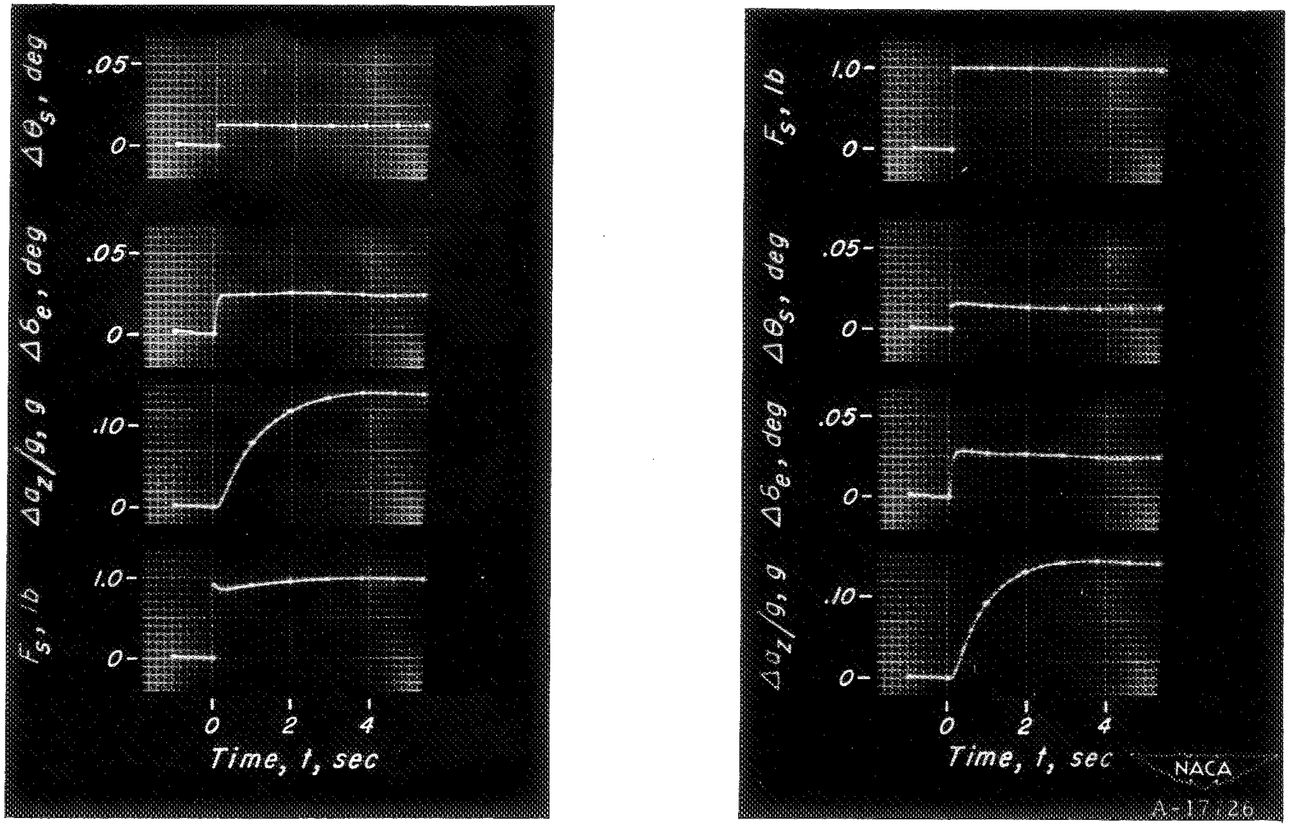
(b) Step-force responses.

Figure 5.- Responses with angular acceleration signal included. Accelerometer natural frequency equals 9 cycles per second.



(c) Step-force-response, perfect accelerometer.

Figure 5.- Concluded.



(a) Step-position responses.

(b) Step-force responses.

Figure 6.- Responses with viscous damping force included.

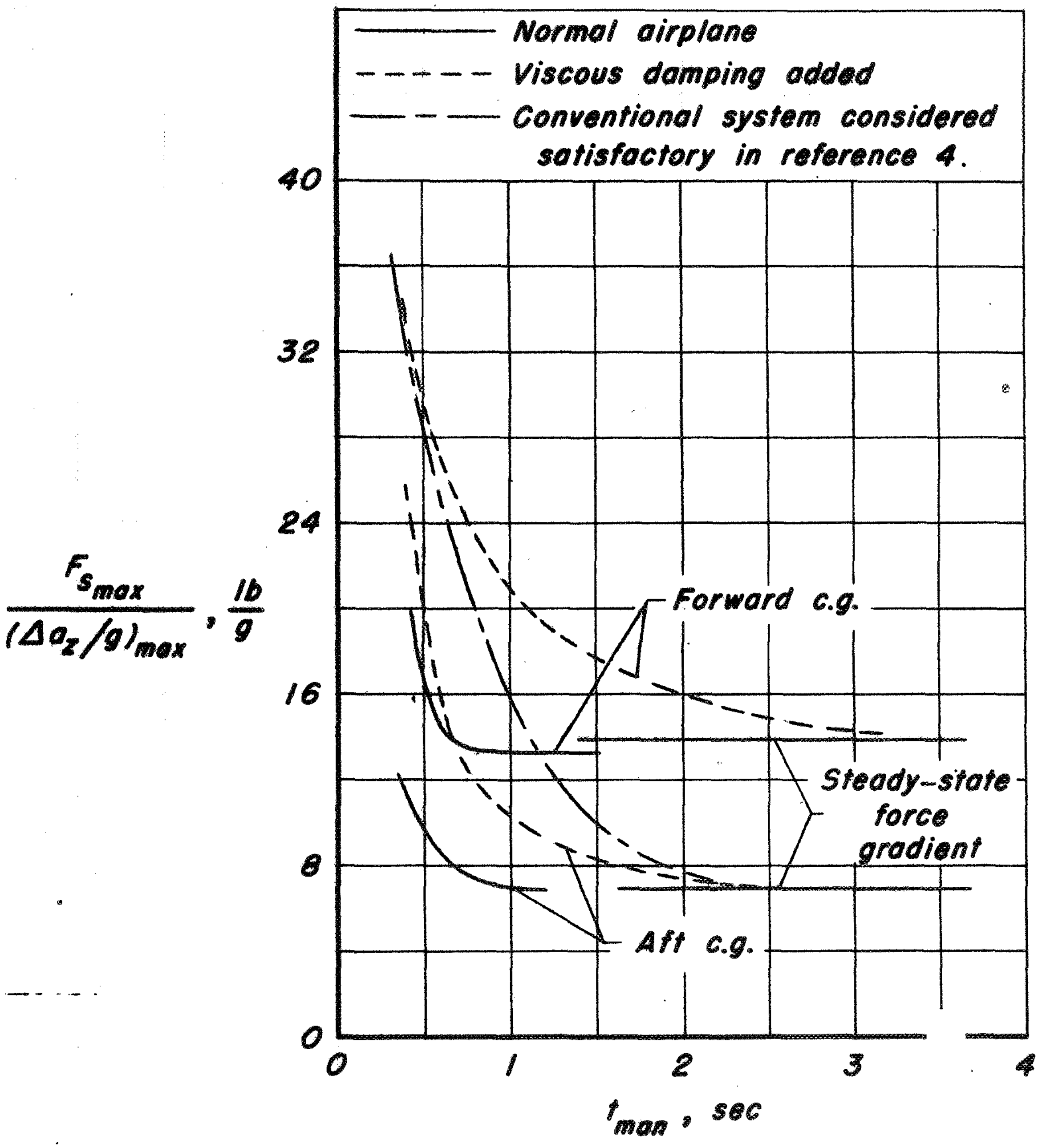


Figure 7.— Stick-force characteristics in rapid maneuvers.