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SIMULATOR INVESTIGATION OF THE CONTROL REQUIREMENTS OF A TYPICAL HYPERSONIC GLIDER

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Edwards, Calif.

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SIMULATOR INVESTIGATION OF THE CONTROL REQUIREMENTS OF A TYPICAL HYPERSONIC GLIDER*

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SUMMARY

The handling qualities of a typical hypersonic glider were investigated with a flight simulator at Mach numbers of 0.26, 1.0, 3.5, 8, and 20 over an angle-of-attack range of 0° to 50°. Inasmuch as flight conditions influencing the control of the glider can be expected to change relatively slowly, a five-degree-of-freedom mechanization was used. Pilots assessed the controllability of the glider without augmentation, with fixed gain dampers, and with an adaptive control system. The investigation was limited to aerodynamic control.

The pilots considered the control characteristics of the basic glider to be satisfactory only at lower Mach numbers and low angles of attack. Control coupling severely restricted the effectiveness of normal control techniques at high angles of attack, and extremely light damping was apparent over much of the flight envelope. The technique of using rudders to control bank angle was effective, especially at high angles of attack.

Dampers greatly improved the vehicle handling qualities; however, special control techniques were required, especially at high angles of attack.

The adaptive control system with a special rudder interconnect and lateral-acceleration feedback provided acceptable control at all test conditions, including those at which the unaugmented glider was unstable.

*Title, Unclassified.

INTRODUCTION

Providing satisfactory stability and control for a piloted hypersonic glider with orbital and controlled landing capability poses many problems in the design of the glider and its control system. Although the ultimate evaluation of the design must be made in flight, flight simulators have been used successfully to evaluate and predict the handling qualities of airplanes (refs. 1 to 3). To investigate the handling qualities of a typical hypersonic glider, a fixed-base flight simulator was mechanized with five-degree-of-freedom equations of motion (constant velocity). The flight conditions investigated were Mach numbers of 0.26, 1.0, 3.5, 8, and 20 over a range of angle of attack from 0° to 50° and dynamic pressure from approximately 6 lb/sq ft to 400 lb/sq ft.

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An investigation was made of the handling qualities of the glider without augmentation, with fixed gain dampers, and with an adaptive control system. Also, the effects of changes to some stability and control parameters and the effects of pilot's display quickening on the vehicle handling were evaluated. Only the control of the glider with aerodynamic controls was considered. The results of these tests, which were conducted at the NASA Flight Research Center, Edwards, Calif., are summarized in this paper.

SYMBOLS

g acceleration due to gravity, ft/sec^2

I_X moment of inertia about the principal X-axis, slug-ft^2

I_Y moment of inertia about the principal Y-axis, slug-ft^2

I_Z moment of inertia about the principal Z-axis, slug-ft^2

$j\omega$ imaginary part of a root

K_{n_y} lateral-acceleration-feedback gain to the rudder

K_p,K_q,K_r,K_i control-system gain of the roll axis, pitch axis, yaw axis, and rudder interconnect, respectively

L $\frac{\text{Rolling moment}}{I_X}$, per sec^2

M Mach number

M	$\frac{\text{Pitching moment}}{I_Y}$, per sec^2
M_o	$\frac{\text{Pitching moment due to angle of attack}}{I_Y}$, $(\delta_e = 0°)$, per sec^2
N	$\frac{\text{Yawing moment}}{I_Z}$, per sec^2
n_y	lateral acceleration, g units
p	roll rate, radians/sec
q	pitch rate, radians/sec
$\bar{q}$	dynamic pressure, lb/sq ft
r	yaw rate, radians/sec
s	Laplace transform variable
t	time, sec
Y	$\frac{\text{Side force}}{mV}$, per sec
Z	$\frac{\text{Normal force}}{mV}$, per sec
α	angle of attack, deg or radians
α_i	angle of attack displayed to the pilot, deg
α_0	trim angle of attack, deg
β	angle of sideslip, deg or radians
β_i	angle of sideslip displayed to the pilot, deg
Δ	incremental quantity
δ_a	total aileron deflection, left elevon minus right elevon, (positive for right roll), deg
δ_e	elevator deflection, deg
δ_{e_t}	trim elevator deflection, deg
δ_p	angular displacement of pilot's controller, deg

δ_r rudder deflection, positive for left yaw, deg

ζ damping ratio

$2\zeta_\theta \omega_{n_\theta}$ damping of the short-period longitudinal mode

$2\zeta_\psi \omega_{n_\psi}$ damping of the short-period (Dutch roll) lateral-directional mode

θ pitch attitude, deg or radians

σ real part of a root

τ_φ time constant in roll, sec

φ bank angle, deg or radians

φ_i angle of bank displayed to the pilot, deg

ψ yaw angle, deg or radians

$\omega_{n_\theta}^2$ static stability of the short-period longitudinal mode

$\omega_{n_\psi}^2$ static stability of the short-period (Dutch roll) lateral-directional mode

Subscripts:

max maximum

The subscripts p, q, r, α, β, δ_a, δ_e, and δ_r indicate the partial derivative with respect to the specific subscript.

A dot above a variable indicates a derivative with respect to time; two dots denote a second derivative with respect to time.

CONTROL TASK AND SCOPE OF THE INVESTIGATION

The handling qualities of the vehicle were evaluated by several research pilots and engineers at each test Mach number and dynamic pressure. The piloting tasks included rolls to a bank angle of 45° at several rates of roll and the control of intentionally induced disturbances. Control tasks were rated by the pilots on a rating scale similar to that presented in reference 4. System stability was evaluated by using sharp control inputs. Also, the response of the unaugmented glider to step control deflections was recorded.

Figure 1 presents a summary of ranges of dynamic pressure investigated at each test Mach number. In the hypersonic regions (M = 8 and M = 20) dynamic pressures as low as 6 lb/sq ft were investigated.

Several supplemental evaluations were also made during the program. The stability derivatives L_β and N_β and control derivatives N_{δ_a} and L_{δ_r} were varied to determine their effects on the handling qualities of the glider. A side-located three-axis controller (ref. 5) was used with several values of control gearing. The use of pilots' display quickening (attitude plus the rate of change of attitude) to enable easier control of the unaugmented glider was evaluated. The quickening studies were performed at a Mach number of 20 and dynamic pressures from 6 lb/sq ft to 100 lb/sq ft.

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SIMULATION

Inasmuch as Mach number and dynamic pressure during reentry of a typical hypersonic glider are expected to change relatively slowly, a five-degree-of-freedom (speed invariant) simulation was programed on the analog computer.

Equations of Motion

The equations of motion used for this investigation were

$$\dot{p} = \left(\frac{I_Y - I_Z}{I_X}\right) qr + L_{\delta_a}\delta_a + L_{\delta_r}\delta_r + L_p p + L_\beta \beta$$

$$\dot{q} = \left(\frac{I_Z - I_X}{I_Y}\right) pr + M_{\delta_e}\delta_e + M_q q + M_o(\alpha)$$

$$\dot{r} = \left(\frac{I_X - I_Y}{I_Z}\right) pq + N_{\delta_r}\delta_r + N_r r + N_\beta \beta + N_{\delta_a}\delta_a$$

$$\dot{\beta} = -r + \alpha p + Y_\beta \beta$$

$$\dot{\alpha} = q - p\beta + Z_\alpha \alpha$$

The Euler angles were generated by solving

$$\dot{\varphi} = p + \dot{\psi} \sin \theta$$

$$\dot{\theta} = q \cos \varphi - r \sin \varphi$$

$$\dot{\psi} = \frac{q \sin \varphi + r \cos \varphi}{\cos \theta}$$

Presented in table I and in figures 2(a) to 2(e) are the derivatives for the five Mach numbers investigated. The primary stability derivatives L_{β}, N_{β}, and M_{α} were programed as functions of angle of attack; the other derivatives were invariant with angle of attack.

Pilot's Display and Control

For the pilot's display, angle of attack, angle of sideslip, and roll rate were presented on meters. In addition, angle of attack, angle of sideslip, and angle of bank were presented on the oscilloscope as shown in figure 3. Several values of control gearing were investigated for the unaugmented glider (see fig. 4); however, two values, basic and 1/10 basic, were used during most of the program. The dynamics of each surface actuator were mechanized as a first-order system having a time constant of 0.15 second. In addition, the surfaces were rate-limited to 25 deg/sec, and the total travel of the pitch-roll surfaces was limited to 75° (22° down and 53° up). The rudder was limited to ±37.5°. These limits provided a simulation of the effect of surface limiting, which results in pitching moments when roll is commanded near the limit of longitudinal surface deflection.

Dampers

Simple rate dampers were mechanized as shown in figure 5. Throughout this portion of the program, the damper gains in pitch and roll were constant and equal to 1; that is, 1 deg/sec of pitch or roll rate commanded 1° of elevon deflection. In yaw, the gain was 5.

Adaptive System

Figure 6 is a block diagram of the adaptive system investigated. The system, which was similar to that used in the study of reference 6, was basically a rate command system with a variable gain in the forward loop. The gains K_p, K_q, and K_r labeled "variable" were variable only in that they were manually changed for each change in Mach number and dynamic pressure. For this study, the critical gain was determined by calculating the root loci (ref. 7) as a function of gain (fig. 7) for each flight condition. The actual system would employ an automatic gain changer to keep the pitch gain at a critical level, thus obtaining maximum performance.

From the root-loci calculations it was determined that the critical gains were

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$$K_{q_{critical}} = \frac{102}{M_{\delta_e}} \qquad K_q < 60$$

The gains of the remaining two axes were not critical, but were proportional to K_q.

$$K_p = 0.13K_q = \frac{13.6}{M_{\delta_e}} \qquad K_q < 8$$

$$K_r = 0.17K_q = \frac{17.0}{M_{\delta_e}} \qquad K_q < 10$$

The interconnect gain K_i (shown in fig. 6) was variable only in that it was proportional to the trim elevator deflection

$$K_i \sim \delta_{e_t}$$

The maximum vehicle rolling and pitching rates that could be commanded by the pilot were

$$p_{max} = 0.5 \text{ radian/sec} = 28.6 \text{ deg/sec}$$

$$q_{max} = 0.2 \text{ radian/sec} = 11.5 \text{ deg/sec}$$

Characteristic of the mechanization of one type of adaptive system is the use of a model or filter having the desired response. For this program, a first-order-lag model with a time constant of 1.3 seconds was used in roll. In pitch, the system was compared to a second-order model having an undamped natural frequency of 0.32 cps and a damping ratio of 1. These characteristics were chosen as a compromise between a model that would provide good responses and one that provided sufficient filtering of the pilot inputs to minimize airplane disturbances from pilot control inputs. The pilot was provided with conventional roll and pitch controls but no yaw control. Rather, the vehicle was stabilized in yaw by a yaw damper with a washout circuit having a 2-second time constant and a lateral-acceleration loop which commanded lateral acceleration to zero. A rudder control was provided during the system evaluation for disturbing the glider in yaw.

Quickened Display

During a brief investigation of quickening, the basic display was altered to include angular-rate information by summing the angular velocity with the displacement and presenting the combined signal to the pilot in place of the normal angles shown in figure 3. Thus, in the pitch axis, the angle displayed to the pilot was

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$$\alpha_i = \alpha + \dot{\alpha}$$

Two different quickening techniques were used to present the lateral and directional vehicle motions. The first method, referred to as normal quickening, was consistent with that used for the pitch axis; that is

$$\beta_i = \beta + \dot{\beta}$$

$$\varphi_i = \varphi + p$$

A second method was attempted in an effort to take into account the coupling of the lateral-directional motions. With this technique, the preceding quickened bank-angle and sideslip-angle information was altered by adding roll rate to sideslip angle and yaw rate to bank angle. This resulted in the following quantities being displayed

$$\beta_i = \beta + \dot{\beta} + 0.25p$$

$$\varphi_i = \varphi + p + 2\dot{\beta}$$

After a few exploratory tests, the values of $0.25p$ and $2\dot{\beta}$ were found to be acceptable for this investigation. This type of quickening is referred to as roll-yaw coupled quickening.

RESULTS AND DISCUSSION

The results of the investigation were, primarily, qualitative. They are presented as pilot opinion of the handling characteristics of the vehicle as a function of angle of attack, dynamic pressure, and Mach number. Although both research pilots and engineers participated in the investigation, all significant findings were checked by one or more of the pilots. The rating scale used during the investigation (table II) was similar to that presented in reference 5.

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The variation in pilot ratings for a particular test condition is presented in figure 8. These data were obtained near the end of the program to better define the pilot rating of the control of the vehicle after special control techniques had been developed. Although the principal pilots were thoroughly familiar with the piloting task and with the special control techniques, all of the pilots were briefed on the special techniques, but were permitted to use any technique they desired. The spread in pilot ratings increased with the number of pilots, as might be expected; however, much of the difference in pilot opinion at the lower ratings may be attributed to pilot familiarity and degree of confidence in the alternate control techniques. The high ratings for the basic vehicle were obtained with the alternate techniques; the lower ratings indicate a reluctance of most of the pilots to fully accept the alternate techniques. The data presented represent average ratings for the pilots evaluating the condition.

Unaugmented Control Characteristics

Response characteristics.- Although the handling qualities of a typical glider were investigated over a wide range of Mach number and dynamic pressure, the most thorough evaluation was made at $M = 8$ and $\bar{q} = 100$ lb/sq ft. The longitudinal motion of the vehicle at this test condition was lightly damped ($\zeta \approx 0.01$), as shown in figure 9. Elevator step inputs of 10° amplitude were made at angles of attack of 0°, 15°, 30°, and 50°. The control effectiveness was invariant with angle of attack, but the increased stability with angle of attack resulted in an apparent decrease in control effectiveness. At subsonic speeds, vehicle damping was somewhat higher. An uncontrollable pitch-up occurred at an angle of attack of about 13°.

Directional damping at supersonic speeds was light. Static directional instability made control impossible at low angles of attack. In addition, roll-control effectiveness decreased markedly with increased angle of attack because of control coupling. Figures 10(a) and 10(b) show the transient response to aileron and rudder steps of 10°

at angles of attack of 15°, 30°, and 50°. A decrease in roll-control effectiveness with increasing angle of attack is shown in contrast to the more nearly constant effectiveness of the rudder as a roll-control device. Aileron effectiveness is reduced as the yaw due to aileron produces sideslip which counteracts the rolling moment of the ailerons. In figure 11 the roll-control-reversal boundary is presented for the flight envelope of the hypersonic glide vehicle; that is, right aileron gives left roll in the steady state at conditions beyond the boundary. At hypersonic speeds, at both high and low angles of attack, the vehicle without augmentation and with dampers was susceptible to this roll-control reversal caused by control coupling. At subsonic speed the problem existed down to $\alpha \approx 10°$.

Normal control characteristics.- Because of light damping, control of the basic vehicle with normal control technique required precise, well-timed control inputs. In figure 12 one of the control problems, that of overcontrolling the vehicle, is illustrated for the $M = 8$, $\bar{q} = 100$ lb/sq ft condition with basic control gearing. At an angle of attack of 15° (fig. 12(a)) the nonmaneuvering stabilizing task was not too difficult; however, maneuvering the vehicle with the low inherent damping ($\zeta \approx 0.008$) usually resulted in large overshoots and sustained vehicle oscillations. Figure 12(b) shows a typical attempt to bank to 45° and back to -45° at an angle of attack of 30°. An attempt to coordinate aileron and rudder to arrest the roll rate resulted in overcontrol and large rolling motion. Light damping and easily sustained oscillatory motions are apparent. At high angles of attack (fig. 12(c)), attempts to control normally with aileron often resulted in loss of control because of control coupling.

In general, at supersonic and hypersonic speeds the basic control-stabilization task was difficult and normal maneuvers were almost impossible. The pilots rated the overall controllability of the vehicle (fig. 13(a)) at the $M = 8$, $\bar{q} = 100$ lb/sq ft condition as unacceptable to uncontrollable. The investigation at higher speeds indicated similar results; however, at subsonic speeds (fig. 13(b)) where vehicle inherent damping was higher, the controllability of the vehicle with reduced control gearing was improved.

Effect of control gearing.- Except at dynamic pressures below 50 lb/sq ft, control of the basic vehicle was sensitive at all Mach numbers investigated when normal control techniques were used. At high Mach numbers ($M \geqq 3.5$) a reduction in gearing was desirable at $\bar{q} = 100$ lb/sq ft, but at sonic and subsonic Mach numbers the gearing reduction was essential because of the increased control effectiveness. The improved controllability of the basic vehicle with the control gearing for pitch, roll, and yaw reduced to 1/10 basic is reflected in the pilot ratings shown in figures 14(a) and 14(b). The 1/10 gearing was selected as an effective compromise value of gearing for most

Mach numbers. Other gearings were investigated briefly; for example, a gearing of 1/2, 1/2, 1/8 in pitch, roll, and yaw, respectively, was preferred by one pilot at hypersonic speeds at a dynamic pressure of 100 lb/sq ft.

Special control techniques.- Figure 11 indicated that the ailerons become ineffective at high angles of attack. The rudder, however, proved to be an effective roll control (fig. 15) except at low angles of attack. Therefore, it became expedient to use the rudder as the primary roll control for much of the angle-of-attack range. This method of control also had the advantage of not exciting the lightly damped lateral-directional oscillatory mode.

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As another technique, the pilot used ailerons only to control both bank angle and sideslip. Control was effected by using precisely timed aileron pulses to damp the excursions in sideslip. Bank angle was controlled with repeated pulses in the direction of the desired bank.

One pilot's evaluation of the three control techniques at $M = 8$ and $\bar{q} = 100$ lb/sq ft is shown in figure 16. Control tasks rated marginally controllable by the pilot using normal control techniques were rated as high as acceptable with the special control techniques. It is apparent that this pilot developed a high degree of confidence in his ability to use the special control techniques.

At a Mach number of 1.0 (fig. 17) the normal control technique and special rudder control techniques were rated as more nearly comparable. At an angle of attack of about 20° the techniques resulted in similar ratings; however, at an angle of attack of 0°, only the normal technique could be used. The pilot ratings of the control task reflect the variation in effectiveness of the roll control with angle of attack. The effectiveness of the rudder as a roll control decreases rapidly at low angles of attack, whereas the effectiveness of the aileron increases.

Effect of derivatives.- To determine the effect of some of the more important derivatives on the handling qualities of the vehicle, pilot evaluations were made at $M = 8$ and $\bar{q} = 100$ lb/sq ft. Four of the basic derivatives N_{δ_a}, L_β, N_β, and L_{δ_r} were varied from 0 to twice their basic values. Although there were noticeable effects from some of the derivative changes, the overall handling qualities of the basic vehicle remained low, and, thus, unacceptable with normal control techniques. Only derivative changes which made the vehicle characteristic motion divergent made the handling characteristics markedly different from those of the basic vehicle.

The effect of changing N_{δ_a} on the vehicle response in roll is documented at $M = 8$ and $\bar{q} = 100$ lb/sq ft in figures 18(a) to 18(c).

It is apparent that an increase in N_{δ_a} reduces the roll-control effectiveness and, therefore, makes the normal control technique less effective. In addition, when ailerons are used N_{δ_a} disturbs the vehicle in yaw which, with light damping, can aggravate the control problem.

Inasmuch as N_{δ_a} appeared to be the derivative responsible for much of the adverse pilot comment when normal control techniques were used, and, since normal control techniques are preferred for landing, a brief investigation was conducted to determine the change in N_{δ_a} required to insure good handling qualities. Figure 19 shows the results of this program. A reduction in N_{δ_a} to one-fourth the original value resulted in acceptable-to-desirable handling qualities at angles of attack below pitch-up.

The effects of changes in L_β on roll control, illustrated for $M = 20$ and $\bar{q} = 25$ lb/sq ft in figures 20(a) to 20(c), were similar to the effects of N_{δ_a}. At $L_\beta = 0$ the vehicle was directionally unstable at high angles of attack, and at high values of L_β roll-control effectiveness was reduced.

Low values of N_β resulted in an unstable vehicle except at high angle of attack where αL_β provided stability; increased N_β increased the directional static stability. The pilot, however, found this increase in stability to be objectionable because of the short period and low inherent damping of the vehicle. Although L_{δ_r} was also varied to as great as twice the basic value, the basic control characteristics were not changed sufficiently to be noted by the pilot. The effects on the vehicle motions resulting from rudder step inputs were negligible.

Quickening.- Quickening was investigated at $M = 20$ by evaluating the controllability of the unaugmented glider at various angles of attack over a range of dynamic pressure from 6 lb/sq ft to 100 lb/sq ft. Figures 21(a) to 21(c) present time histories showing control with a conventional display and with the two types of quickened display. It can be seen that the quickened displays resulted in more precise control of bank angle and sideslip. It was found that considerable practice was required to fully appreciate and effectively use a quickened display. The time histories presented are representative of the control techniques of an experienced pilot. The quickened displays offered no improvement in the controllability of the glider when the special control techniques were used; in fact, control effectiveness was reduced.

Presented in figure 22 are pilot ratings for the two types of quickened displays as a function of dynamic pressure. The data show that control was acceptable with the roll-yaw coupled quickening over a larger dynamic-pressure range than with the normal quickening. Control with the normal quickening was only slightly less satisfactory.

The roll-yaw coupled quickening was preferred by most pilots since, in addition to permitting the use of conventional control techniques, it provided an earlier indication of the lateral-directional motions. It might be noted that all conditions evaluated could be satisfactorily controlled with the roll-yaw coupled display. Although the test conditions were not duplicated exactly, the ratings are comparable to those for the special control techniques shown in figure 23.

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Figure 23 shows, as a function of dynamic pressure, the pilot ratings for both the special and normal control techniques used to control the basic glider. Maneuvering and stabilizing tasks were difficult over the dynamic-pressure range with the normal technique; however, with the special technique, ratings improved to "acceptable" with increasing dynamic pressure. As might be expected, at low dynamic pressures control was unacceptable with the aerodynamic controls.

Comparison with criteria.- In many areas of the flight regime, the control of the unaugmented glider was marginal. Some of the vehicle control and stability characteristics are compared with available handling criteria for entry vehicles in figures 24 to 27. Figure 24 compares the longitudinal-control sensitivity of the glider with the criteria of reference 8 for entry vehicles. The longitudinal-control sensitivity reported by the pilots at the sonic condition agrees favorably with the criteria, whereas that at the subsonic condition does not. The control gearing at supersonic and hypersonic speeds was in the desired range.

The roll control and response characteristics of the glider are compared to the criterion of reference 9 in figure 25. The criterion has been modified to account for the effect of coupling on the steady-state roll rate. Again, the control is predicted to be sensitive at subsonic speeds, but the reduction in gearing results in a satisfactory roll control. Little correlation exists between the roll characteristics and the criterion at greater than supersonic speeds because of the transient behavior due to the extreme coupling.

Figure 26 compares the longitudinal dynamic characteristics with the criterion of reference 10. The basic stability and damping of the glider are predicted to be acceptable only at the subsonic Mach number. At the higher speeds the prediction is "acceptable for short time emergency operation". Lateral dynamic characteristics are compared to the criterion of reference 10 in figure 27. Throughout the Mach number range (except $M = 0.26$ and $\alpha < 15^\circ$) the dynamics are considered unsatisfactory or "acceptable for short time emergency operation". Although, initially, the pilots felt that the control task was acceptable for emergency only, with experience and the special techniques developed, the pilots could control the vehicle for extended periods.

Dampers

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Inadequate damping over much of the operating envelope is characteristic of high-performance vehicles. Inasmuch as this problem has been alleviated on most airplanes by the use of rate feedback to the control surface to provide auxiliary damping, rate dampers, which are simple and reliable, were considered for the hypersonic glider. Although the extreme ranges of the control and stability parameters of the glider might indicate that changes in gain would be required, such changes were not necessary. A partial explanation of this unexpected result is given in the following example. Consider the steady-state roll rate per aileron deflection (single degree of freedom)

$$\frac{p}{\delta_a} = \frac{-L_{\delta_a}}{L_{p_{basic}} + L_{p_{damper}}}$$

For a large part of the flight envelope $L_{p_{damper}}$ is much greater than the L_p of the basic vehicle. Thus

$$\frac{p}{\delta_a} \approx \frac{-L_{\delta_a}}{L_{p_{damper}}} \approx \frac{-L_{\delta_a}}{-K_p L_{\delta_a}} \approx \frac{1}{K_p}$$

Effectiveness of dampers.- The dampers provided acceptable-to-satisfactory handling qualities over much of the flight envelope of the vehicle (fig. 28); however, the static instabilities of the vehicle were still uncontrollable (fig. 29). The dampers did eliminate the need for changing control gearing.

Except at low angles of attack, the rudder was as effective for roll control with dampers as without dampers. This technique offered the additional advantage of not requiring a washout circuit in the yaw axis. The washout circuit would be required otherwise, inasmuch as rolling at high angle of attack produced a yaw rate (body axis) which would cause adverse rudder inputs by the dampers. Washout somewhat reduces the damping, especially at low dynamic pressure, because of the low natural frequency in yaw.

Control-system characteristics which are sometimes considered unimportant can compromise the effectiveness of the simplest control system. In this investigation, for example, control-surface rate limiting restricted the amount of damping realized from the damper system. Figures 30(a) to 30(c) show responses in pitch for three values of rate limiting at $M = 8$, $\bar{q} = 50$ lb/sq ft, and $\alpha = 30^\circ$. The response is essentially deadbeat for the infinite surface rate, whereas more than one cycle is required to damp to one-half amplitude for a surface rate limit of 12.5 deg/sec.

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Directional stabilization.- Several attempts were made to improve the handling characteristics of the vehicle with dampers, for example, stabilizing the glider directionally with a lateral-acceleration feedback loop. The glider could be stabilized at the most unstable condition, but the allowable gain range of the n_y feedback was much too critical to be used with a fixed-gain system. A lower limit of gain was required for control of the directional instability of the vehicle, and an upper limit of gain was determined by system stability. With high gain, a very small disturbance in sideslip caused the rudder to rate limit, thus producing phase lag and system instability.

Adaptive Control System

In an attempt to obtain a control system which would provide excellent handling qualities for the hypersonic glider, several mechanizations of an adaptive control system were investigated. The desirable features of this system, as well as some of the designs which proved to be ineffective, are considered in the following discussion.

Description of the system.- The adaptive control system which was mechanized for this study was basically a rate-command system with a model of the desired response characteristics in the forward loop. Both the pitch and roll systems commanded rate of change of vehicle attitude proportional to stick deflection. No trim was required. As the desired attitude was attained, the controller was returned to its neutral position.

No provision was made for pilot control in yaw; rather, the glider was stabilized with rate and acceleration feedback loops. Also, a rudder interconnect was mechanized to control sideslip and allow normal roll control.

Directional stabilization.- The effectiveness of the lateral-acceleration feedback in yaw is indicated in figure 31. The typical time histories are for $M = 8$ and $\alpha = 0^\circ$, a directionally unstable case, with both rate and acceleration feedback and without acceleration feedback. The pilot was monitoring bank angle in both cases; however, the glider diverged directionally without the acceleration feedback.

Both the gain of the lateral-acceleration feedback loop and the control-surface rate limit were important factors in the directional stabilization of the vehicle. The allowable gain range of the acceleration feedback was sensitive to control-surface rate limiting to avoid directional divergence. To establish the gain range for stability, the allowable sideslip excursions to avoid divergence (fig. 32) were investigated as a function of acceleration-feedback gain ratio and control-surface rate limit. The gain range of acceleration feedback for stability varied with flight conditions, but with the adaptive feature of the adaptive control system, glider stability was assured at all flight conditions investigated. H226

Interconnect.- A rudder-to-aileron interconnect was required at all angles of attack to cancel the yawing moment of the ailerons and at high angles of attack to reduce the sideslip due to angle of attack of the principal axis of the vehicle during the initiation of roll.

The interconnect design problem is presented in figure 33. The boundaries shown indicate the area in which a control reversal occurs and reflect the requirement that $N_\beta > L_\beta \frac{N_{\delta_a}}{L_{\delta_a}}$. The shift of the boundary indicated at low angles of attack shows how the n_y feedback makes control possible at low values of $\frac{N_{\delta_a}}{L_{\delta_a}}$ by effectively increasing N_β. The diagonal line shows the value of $\frac{N_{\delta_a}}{L_{\delta_a}}$ which minimizes the sideslip excursions resulting from abrupt aileron inputs. The relationship between this value and α_0 was obtained by considering the initial trend in sideslip, that is, $\ddot{\beta} \approx -\dot{r} + \alpha_0\dot{p} = \left(-N_{\delta_a} + \alpha_0 L_{\delta_a}\right)\delta_a$. Equating $\left(-N_{\delta_a} + \alpha_0 L_{\delta_a}\right)\delta_a$ to zero gives the equation used to proportion N_{δ_a} and L_{δ_a} to minimize sideslip. As a result of these considerations, it would be ideal if $\left(\frac{N_{\delta_a}}{L_{\delta_a}}\right)_{effective}$ could be made proportional (through a rudder interconnect) to angle of attack to minimize the transient sideslip. A compromise constant-gain rudder interconnect proved to be inadequate, necessitating changes in interconnect gain with angle of attack. Rather than making the rudder-interconnect gain proportional to α_0, the gain was mechanized proportional to elevator deflection, since for the steady-state case $\alpha = K\delta$. The resultant rudder interconnect effectively avoided the problem areas and resulted in an acceptable control system.

A more straightforward interconnect of the form $\delta_a = K_r r$ was mechanized in an attempt to provide directional damping by using the large yawing moments due to aileron control. This interconnect reduced the sideslip excursions due to roll, but also reduced maximum steady-state rolling velocity to an undesirable level. This interconnect was, therefore, considered to be undesirable.

System evaluation.- Compared in figure 34 are responses to step roll-rate commands to the adaptive system to show the effect of various components on the performance of the system. The beneficial effects of the washout circuit in the yaw-rate channel are shown by comparing figures 34(a) and 34(b). Without the washout circuit, the rudder opposed the yaw rate produced by rolling at high angles of attack and caused sideslip which reduced the vehicle roll performance. The overall effect of the interconnect (figs. 34(a) and 34(c)) was to improve the roll performance and reduce the sideslip. At higher angles of attack without the interconnect, roll with the ailerons was impossible. The filtering effect of the model in the roll axis is shown in figure 34(d). For this application, the primary purpose of the model was not to make the response characteristics of the vehicle invariant, but to improve the dynamics of the vehicle by filtering the input of the pilot at the cost of lower roll response.

The possibility of either removing the model from the pitch axis or using a higher-performance model was investigated briefly. A higher-performance model was desirable at conditions of high control-surface effectiveness, but at low dynamic pressure the high gain of the system and low control-surface effectiveness caused the control surfaces to rate limit. The system lag caused by the surface rate limiting resulted in vehicle control-system instability. With a slower model, the pitch system remained operationally stable to a much lower dynamic pressure for a specified value of control-surface rate limiting. By selecting the model characteristics and the surface rate limiting, the instability was delayed to a very low dynamic pressure where reaction controls would normally be used. The lateral-directional system stability at low dynamic pressures required that the gains of the yaw and roll axes be kept subcritical. They were mechanized proportional to the critical pitch gain.

Adaptive system, single-axis failure.- A limited investigation was made of the handling qualities of the vehicle with one axis of the adaptive system inoperative. The results are compared in figure 35 with the all-axes-operative condition. With the pitch axis inoperative, the lateral-directional characteristics remained acceptable, but the longitudinal mode had no damping augmentation. The drop in rating at low angles of attack is attributed in part to the poor static stability. The loss of the roll axis resulted in system instability, which made the vehicle uncontrollable at all angles of attack. For the range of angles of attack indicated ($\alpha \approx 10^\circ$ to 30°), loss of yaw axis resulted in little deterioration of the vehicle handling, but, at other angles of attack, airplane or system instability precluded control. No attempt was made to modify the adaptive system to improve the performance with a single-axis failure.

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Summary of Handling Qualities

The handling qualities of the glider without augmentation, with dampers, and with the adaptive control system are compared in figures 36(a), (b), and (c), respectively, over the entire flight envelope at a dynamic pressure of 100 lb/sq ft. The control gearing was decreased to 10 percent of its basic value at Mach numbers below 3.5 when no augmentation was used.

At low speeds the basic glider (fig. 36(a)) possesses good handling qualities at low angles of attack, but, as pitch-up is reached ($\alpha \approx 15^\circ$), the vehicle becomes uncontrollable. Rudder is required, with or without aileron, for roll control because of control coupling. At supersonic speeds, the handling qualities are generally unacceptable without augmentation and uncontrollable at low angles of attack because of the directional instability. Control coupling dictated the use of the rudder for roll control at all but low angles of attack.

The handling qualities of the vehicle were greatly improved by the damper augmentation (fig. 36(b)). The pilots rated the vehicle handling qualities as desirable below $M = 2$ and acceptable over the higher angle-of-attack range at $M > 2$. Changes in the control gearing were not necessary or desirable with dampers. Rudders were required for roll control at all but the lower angles of attack. The areas of static instability remained uncontrollable.

The adaptive control system (fig. 36(c)) made the glider handling qualities good throughout the test Mach number and angle-of-attack range even in regions that were otherwise uncontrollable. The response in roll, however, was somewhat sluggish. A model with slow response was used to filter abrupt pilot inputs at the more critical flight conditions. Otherwise, it was possible for the pilot to trigger a system instability which might result in loss of control. Inasmuch as the pitch axis was a rate command system, it was necessary for the pilot to monitor the angle of attack to avoid drift.

A comparison is made of the handling qualities of the three glider configurations as a function of dynamic pressure in figure 37. The handling qualities of the unaugmented glider deteriorated at high dynamic pressures because of the shorter periods of the oscillations, which required more carefully timed control inputs. At low dynamic pressures, the handling qualities of all the configurations deteriorated because of the loss of control power. At very low dynamic pressure, the handling qualities with the adaptive control system became poorer than the handling qualities with dampers because the limit gain of the adaptive system was higher than the gain of the damper system. With the higher gain, surface rate limiting compromised the performance of the adaptive control system more than the damper system. However, in this region, reaction controls would probably be used.

CONCLUSIONS

The following results were obtained from a simulator investigation of the handling qualities of a typical hypersonic glider with basic aerodynamic controls, fixed gain dampers, and an adaptive control system at Mach numbers of 0.26, 1.0, 3.5, 8, and 20.

The control characteristics of the basic vehicle were considered to be satisfactory only at the lower Mach numbers and low angles of attack with reduced control gearing. Pitch-up precluded control at high angle of attack at the subsonic Mach number. At supersonic and hypersonic speeds, directional instability at low angles of attack made the vehicle uncontrollable. Control coupling severely restricted the effectiveness of normal control techniques, and extremely light damping made control difficult. The technique of using rudders to control bank angle was effective, especially at high angles of attack.

Dampers greatly improved the handling qualities of the vehicle, but the use of rudder was still required to roll above moderate angles of attack at most flight conditions. The use of dampers also removed the requirement for reduced control gearing. Flight conditions which were made uncontrollable because of static instability, however, remained uncontrollable.

The adaptive control system with a special rudder interconnect and lateral-acceleration feedback provided good control at all test conditions, including those at which the unaugmented glider was unstable. Vehicle instabilities were satisfactorily controlled. This system was rated desirable by all pilots at all flight conditions investigated.

Flight Research Center
National Aeronautics and Space Administration
Edwards, Calif., December 14, 1961

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TABLE I.- GLIDER DIMENSIONAL DERIVATIVES

($\bar{q}$ = 100 lb/sq ft)

Mach number	Derivatives									
	Y_β, 1/sec	M_{δ_e}, 1/sec^2	M_q, 1/sec^2	L_{δ_a}, 1/sec^2	L_p, 1/sec^2	N_{δ_r}, 1/sec^2	N_{δ_a}, 1/sec^2	N_r, 1/sec^2	Z_α, 1/sec	L_{δ_r}, 1/sec^2
0.26	-0.231	-9.4	-2.25	14.9	-0.752	-3.29	-0.496	-0.218	-0.976	2.68
1.0	-.066	-11.0	-.724	16.8	-.242	-3.90	-.512	-.056	-.253	2.68
3.5	-.0128	-3.0	-.25	2.85	-.40	-1.03	-.007	-.014	-.0412	.320
8.08	-.0048	-3.4	-.02	1.15	-.010	-.82	-.026	-.006	-.014	.320
20.0	-.002	-3.4	-.004	1.05	-.0014	-.752	-.017	-.002	-.0056	.320

TABLE II.- PILOT RATING SCALE[1]

General classification	Numerical rating	Handling qualities
Desirable	1	Easy to control precisely; little corrective control required.
	2	Good response, but necessitates attention for precise control.
	3	Acceptable controllability, but more than desired attention generally needed.
Acceptable	4	Submarginal for normal use; requires excessive pilot attention.
	5	Controllability poor; demands constant pilot attention and continuous control inputs.
	6	Can be controlled, but pilot must exercise considerable care.
Unacceptable	7	Difficult to control and demands considerable pilot concentration.
	8	Controllable only with a high degree of pilot concentration and large control inputs.
	9	Extremely dangerous; can be controlled only with exceptional piloting skill.
Uncontrollable	10	Uncontrollable.

[1]Adapted from reference 4.

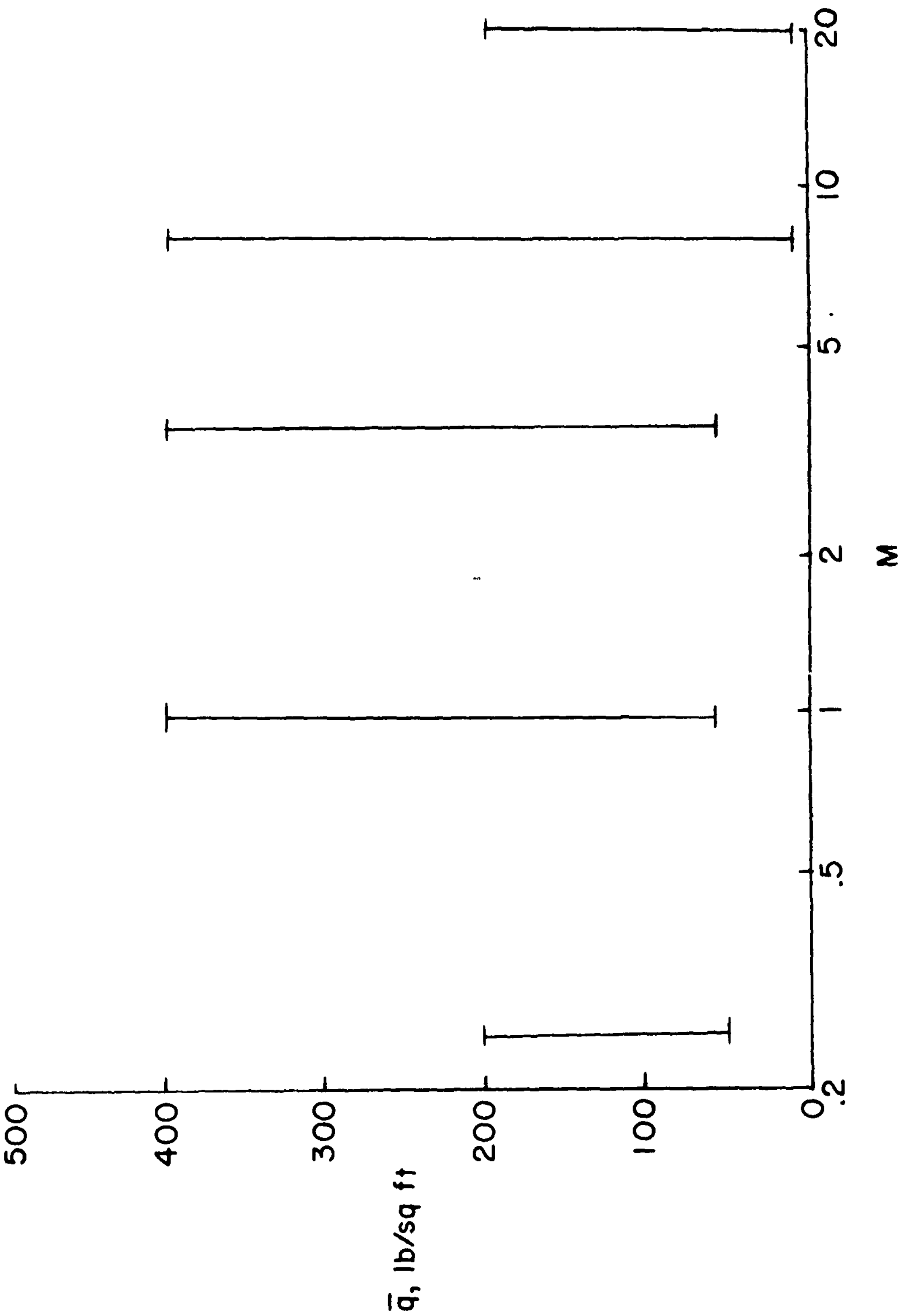

Figure 1.- Test Mach numbers and ranges of dynamic pressure.

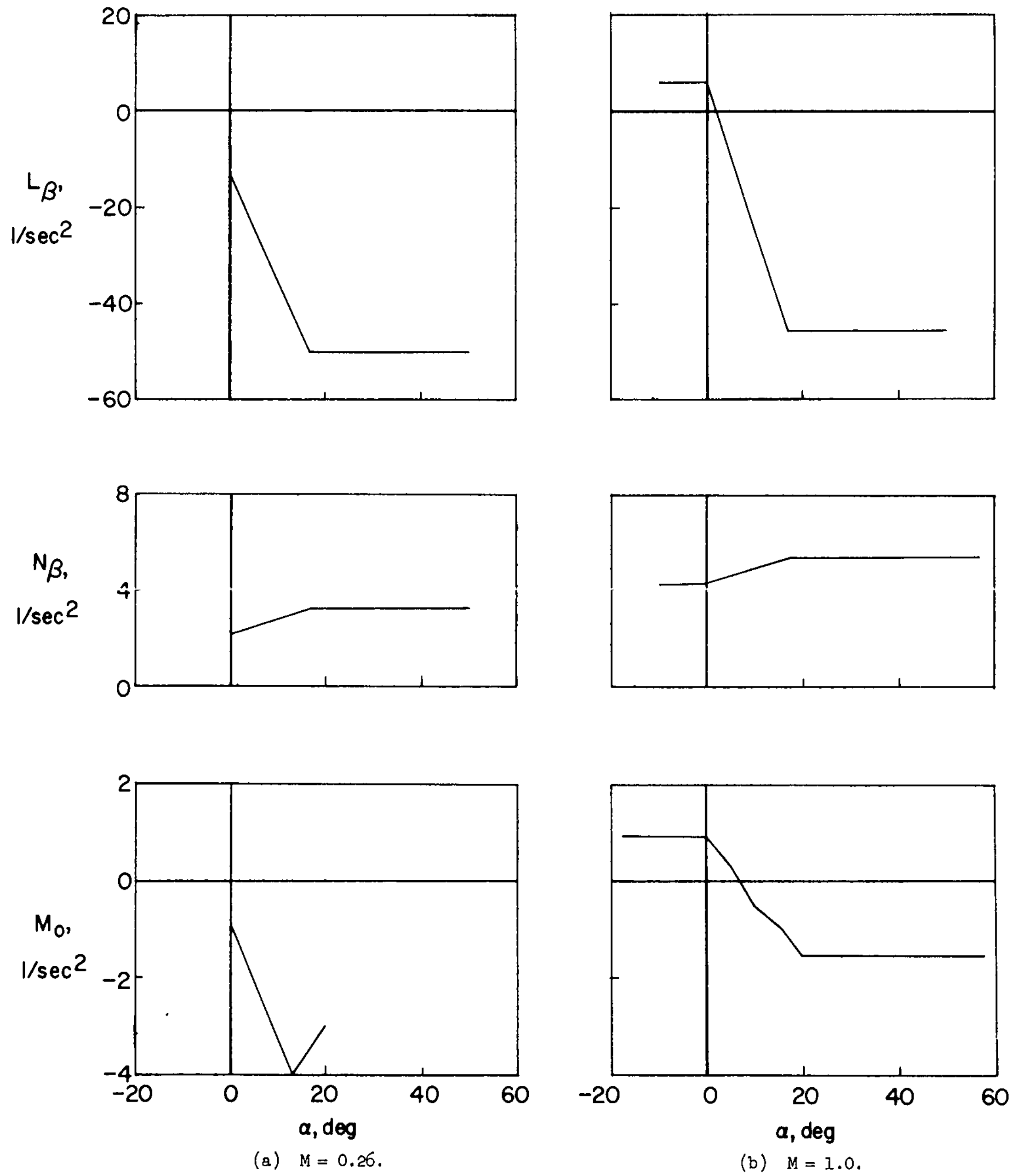

Figure 2.- Glider dimensional derivatives programed as a function of angle of attack.

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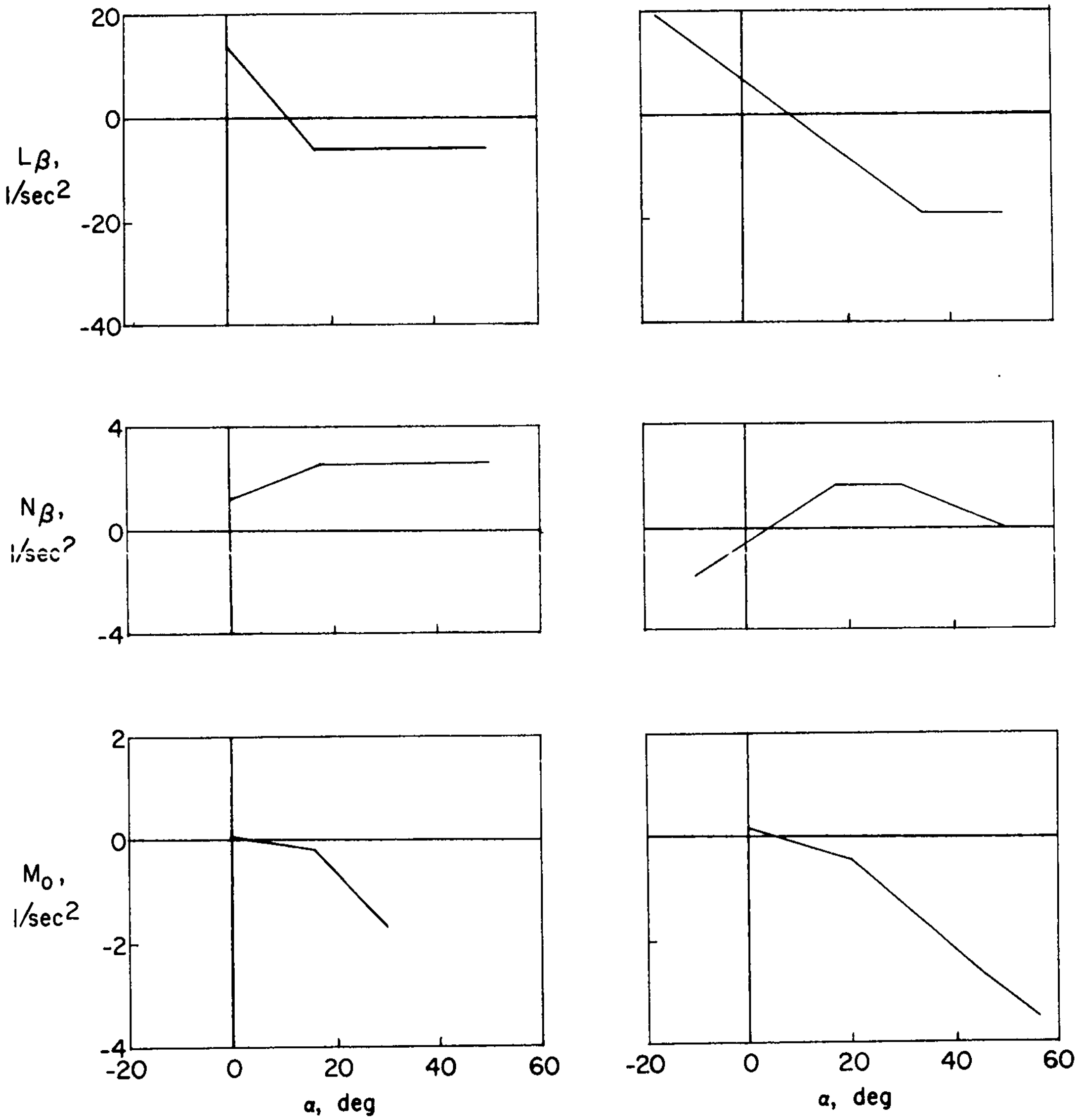
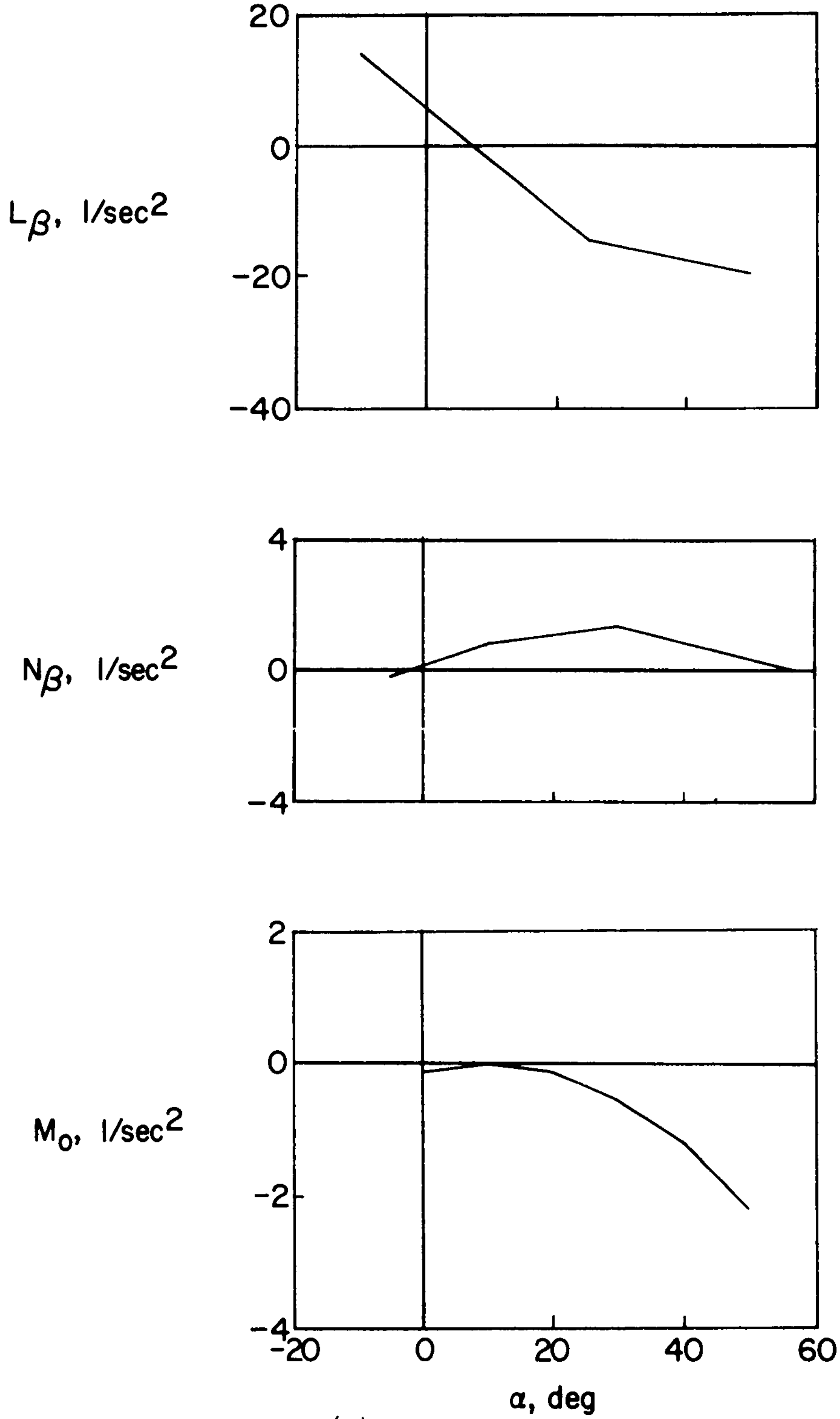


(c) M = 3.5.

(d) M = 8.08.

Figure 2.- Continued.



(e) M = 20.

Figure 2.- Concluded.

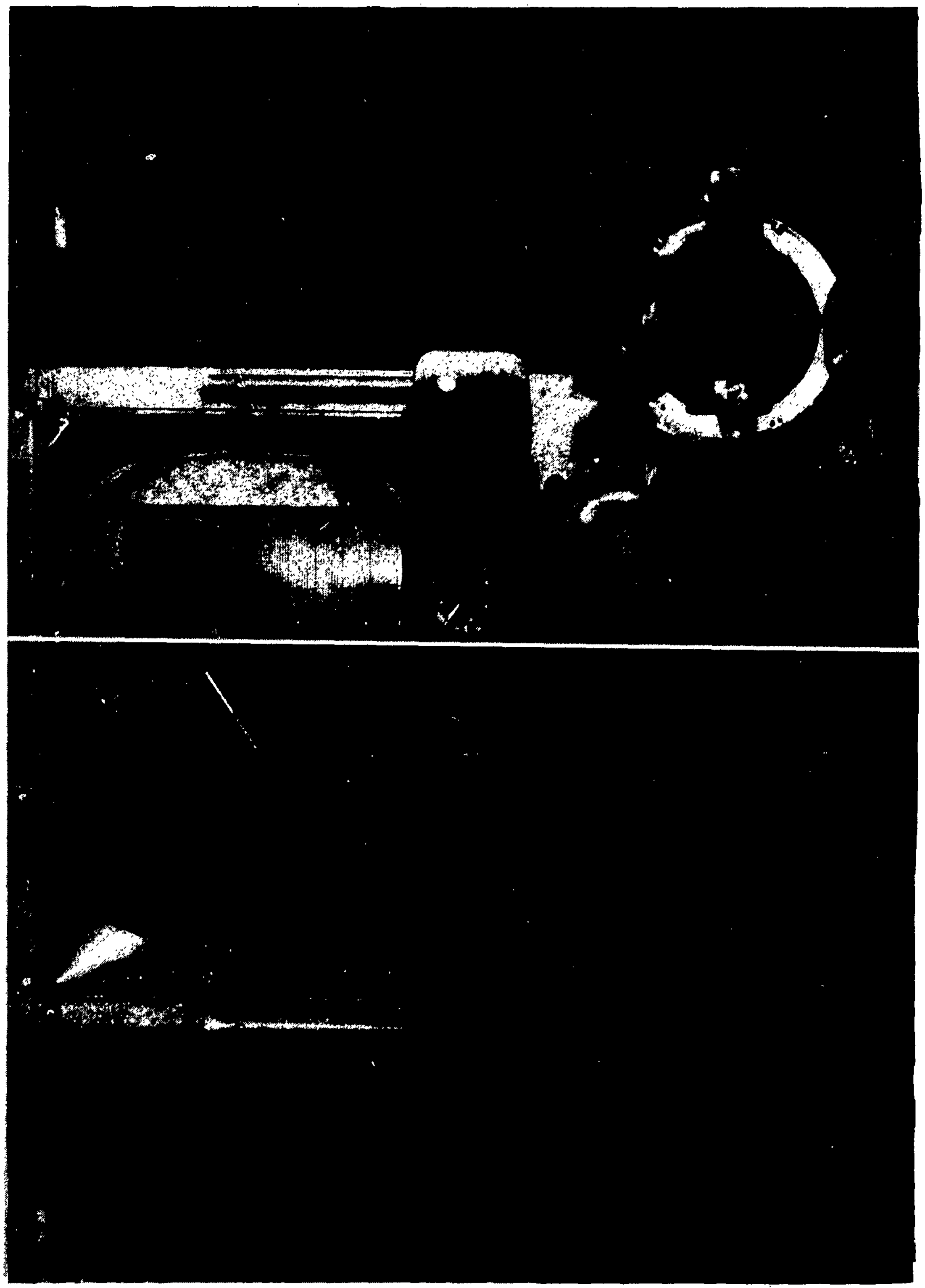


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Figure 3.- Photograph of the flight-simulator presentation and controller.

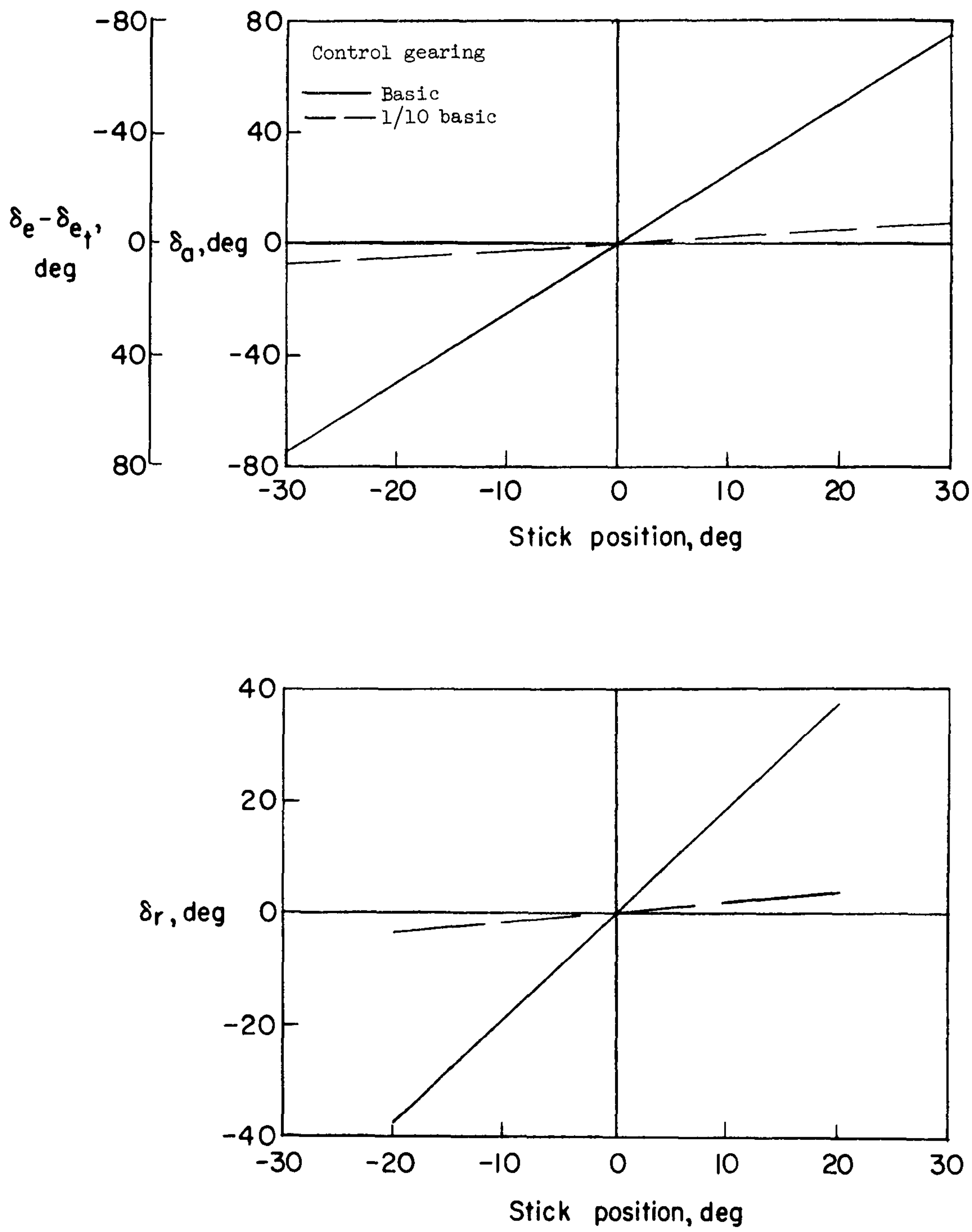

Figure 4.- Control gearing used in the investigation. Aileron and elevator deflections are limited so that the individual pitch-roll surface deflections range from 22° to -53°.

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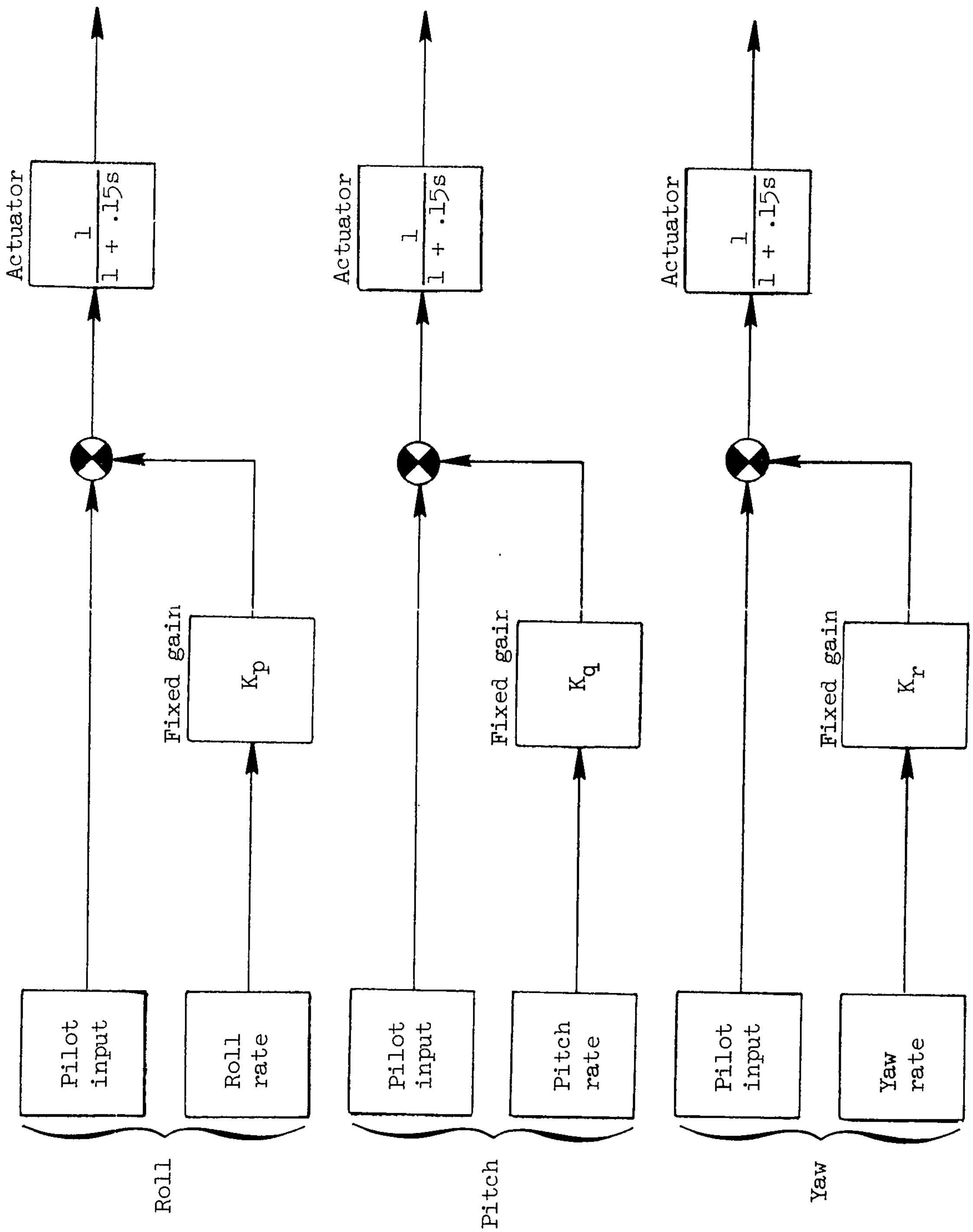

Figure 5.- Block diagram of the damper system.

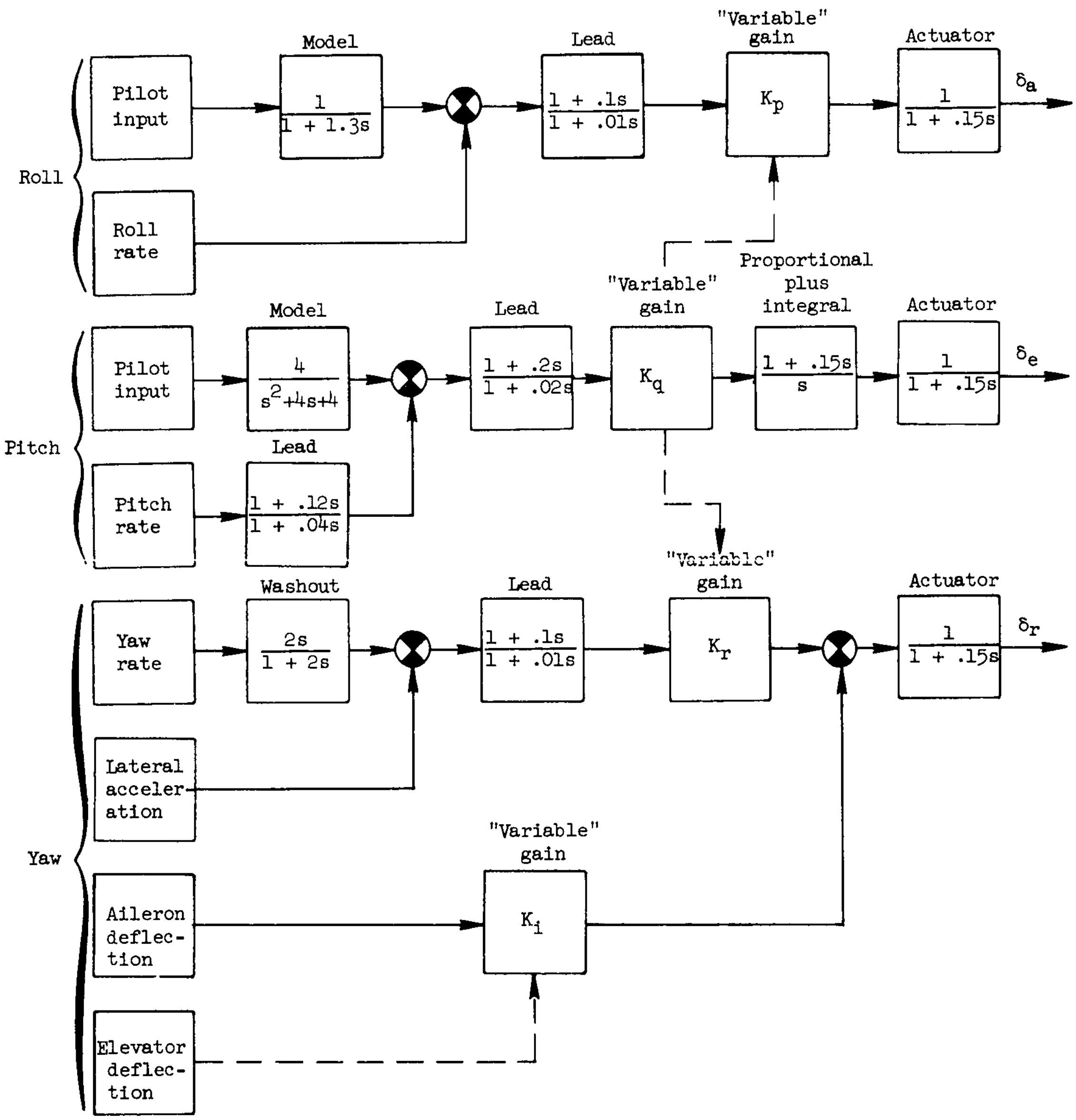

Figure 6.- Block diagram of the adaptive control system.

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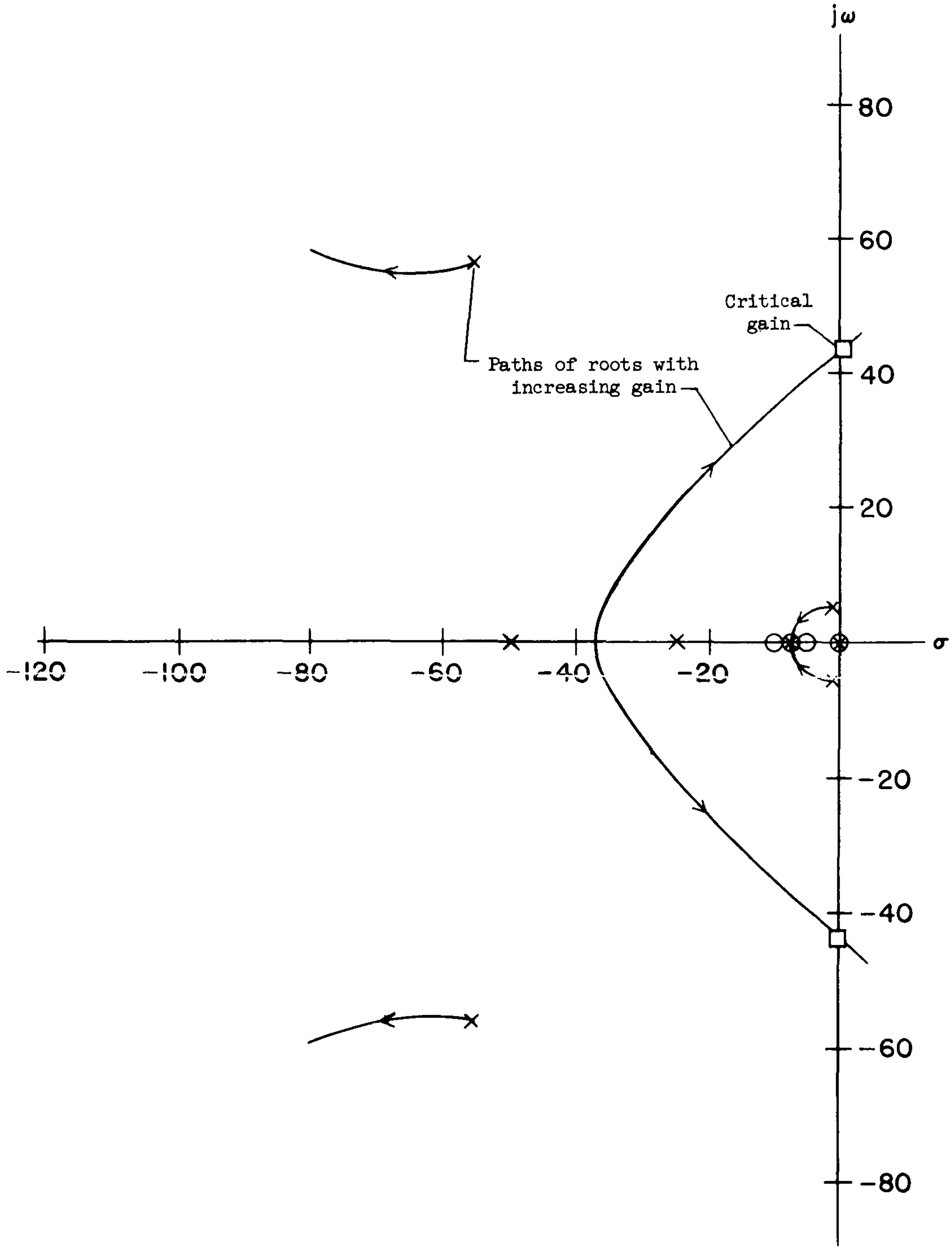

Figure 7.- Example root-locus plot used to determine the critical gain of the adaptive system.

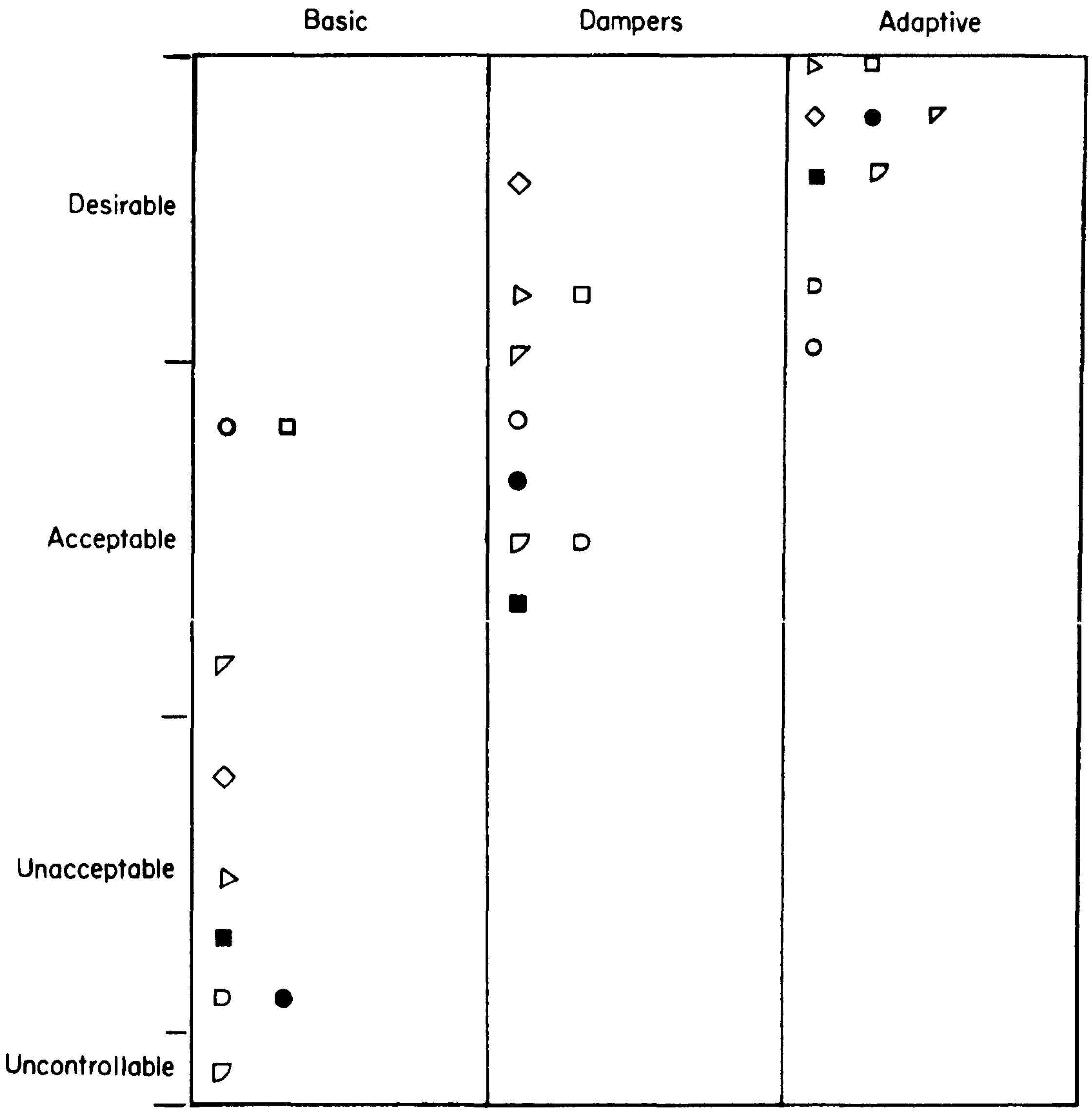

Figure 8.- Variation in pilot opinion of the vehicle controllability. Open symbols denote pilots; solid symbols refer to engineers. $M = 20$; $\bar{q} = 100$ lb/sq ft; $\alpha = 30°$.

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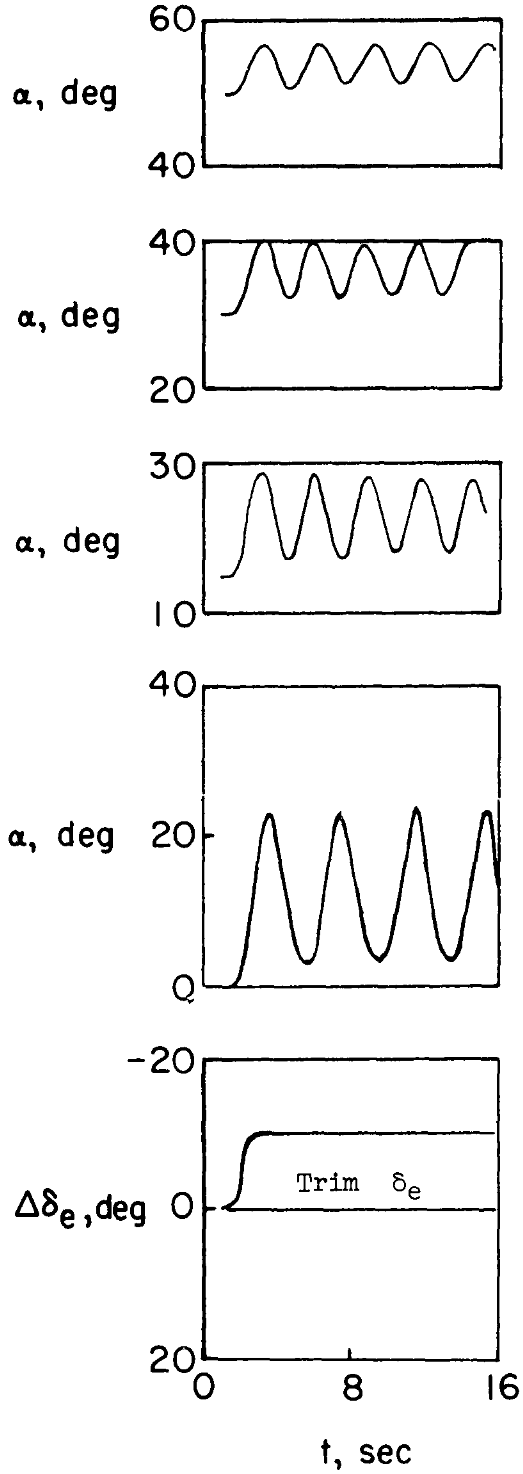

Figure 9.- Vehicle response characteristics in pitch. M = 8; $\bar{q}$ = 100 lb/sq ft.

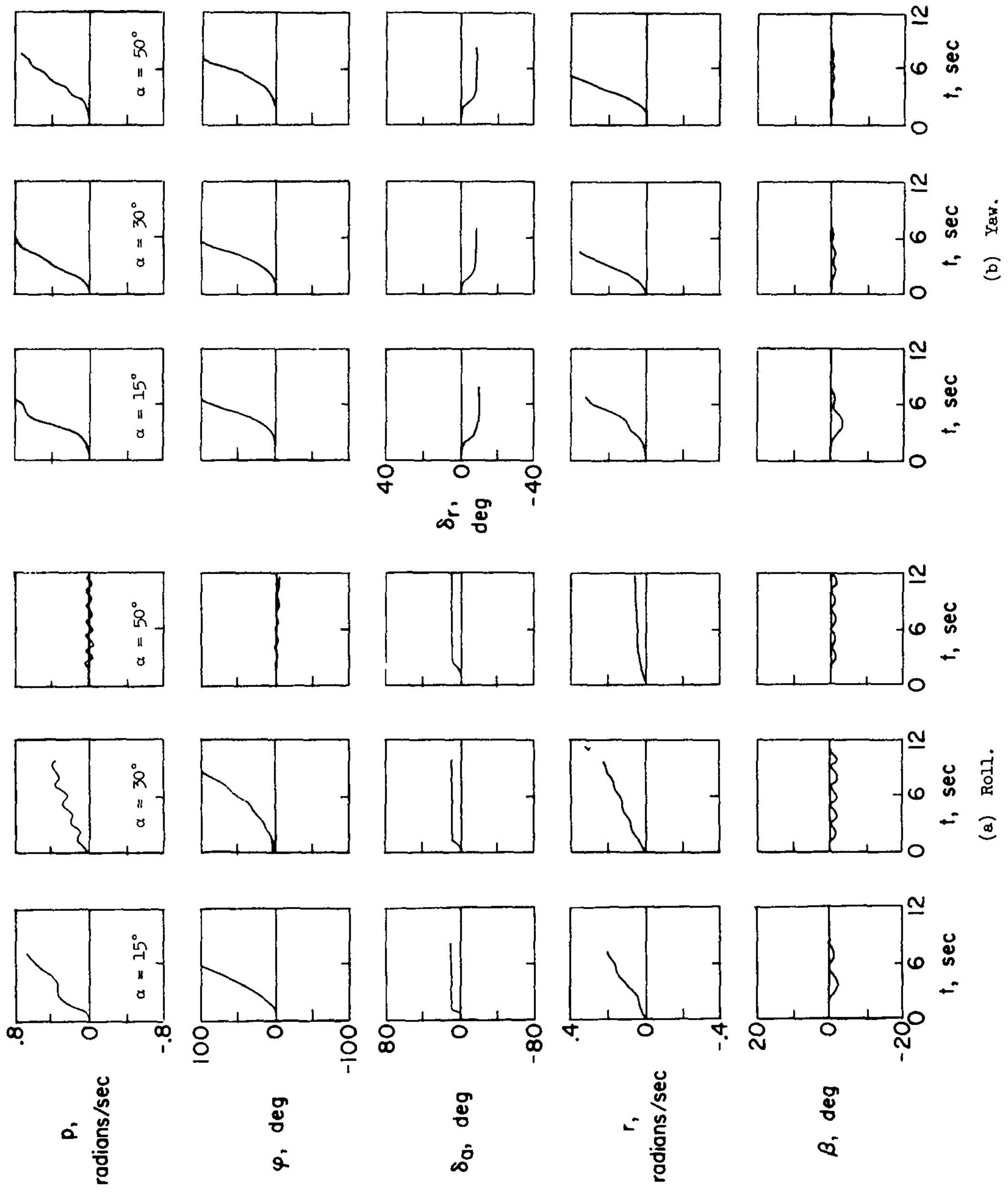

Figure 10.- Vehicle response in roll and yaw. M = 8; $\bar{q}$ = 100 lb/sq ft.

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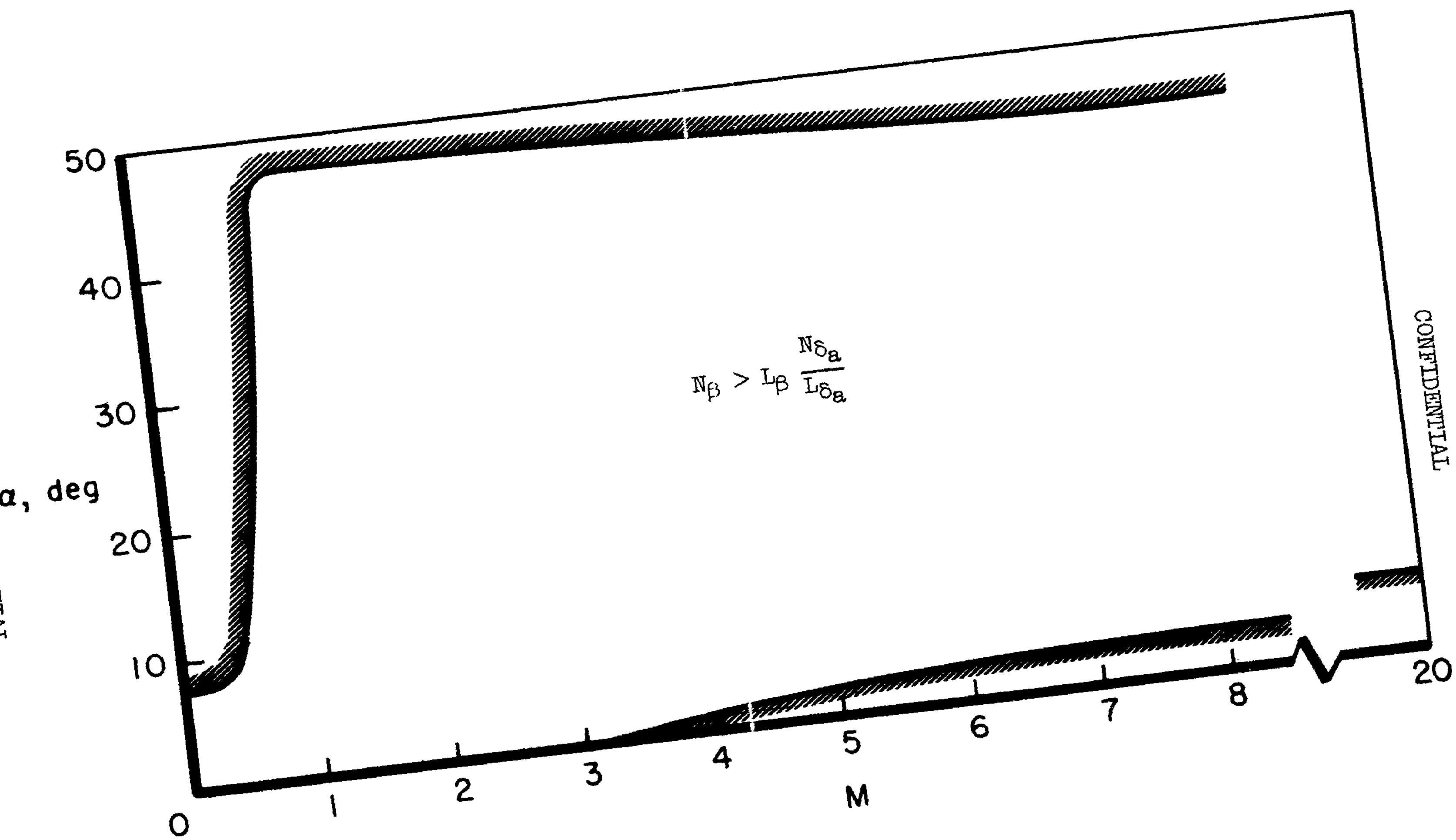

Figure 11.- Roll-control-reversal boundary.

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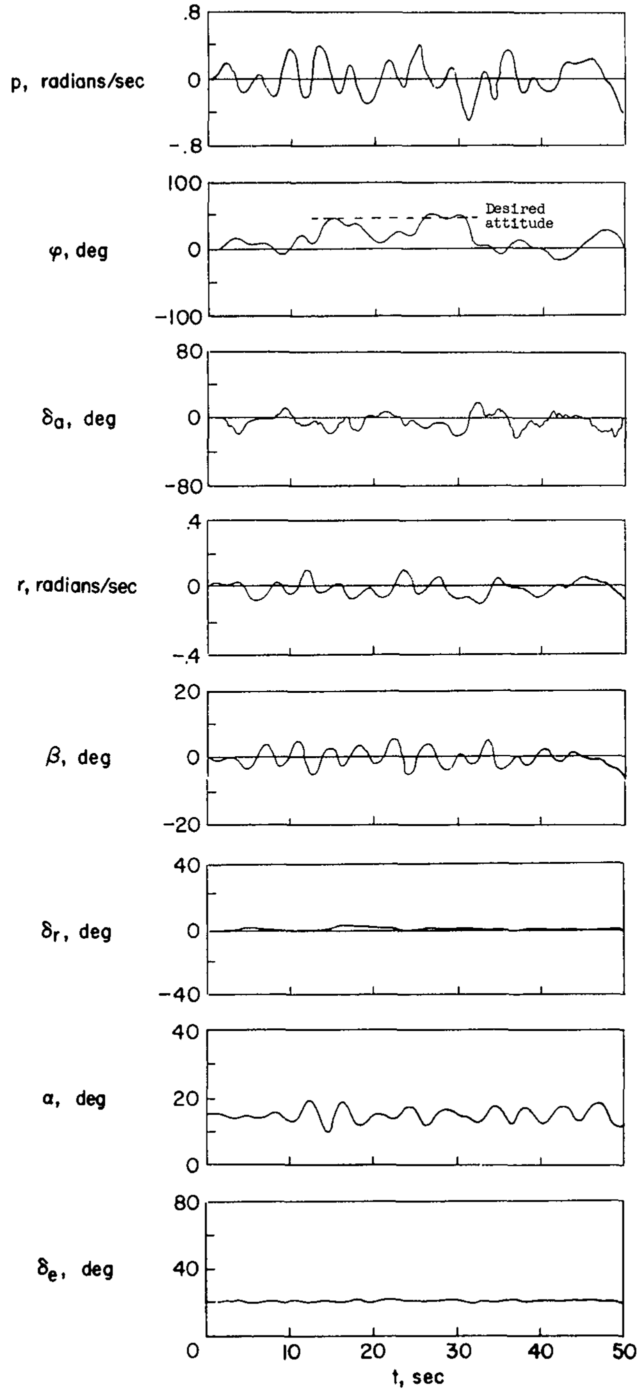

(a) $\alpha = 15°$.

Figure 12.- Typical examples of use of normal control technique. Basic control gearing; M = 8; $\bar{q}$ = 100 lb/sq ft.

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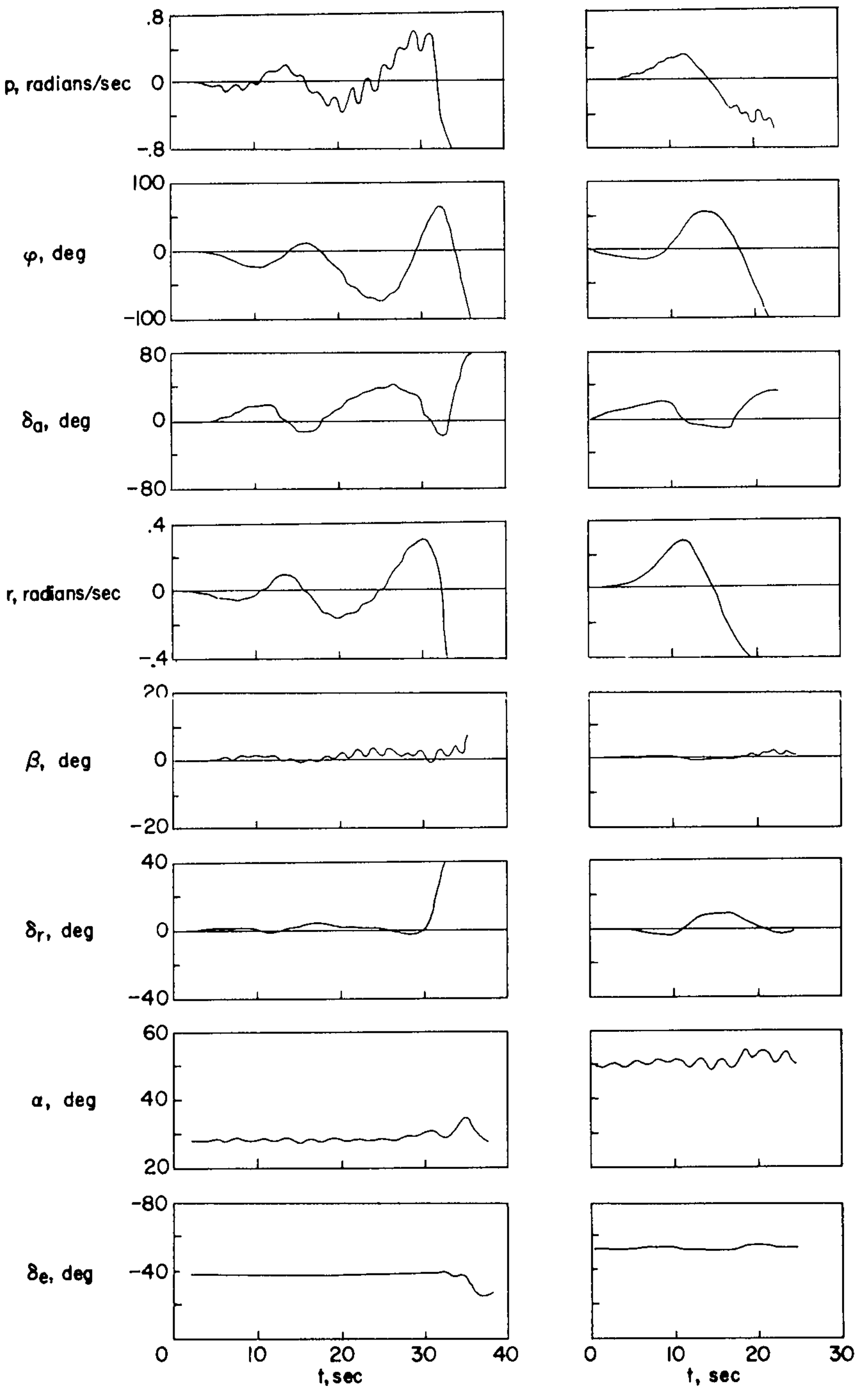
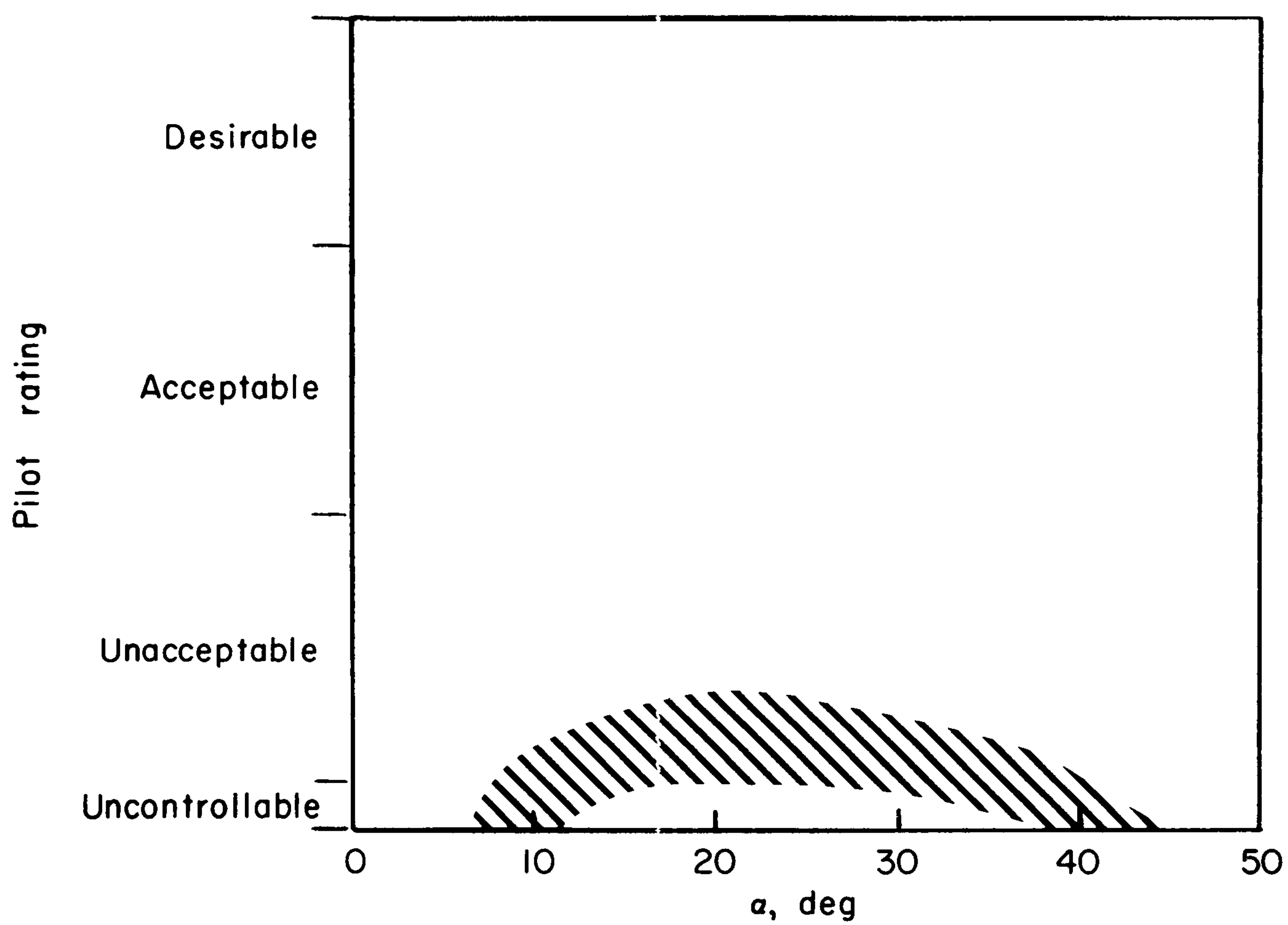


(b) $\alpha = 30^\circ$.

(c) $\alpha = 50^\circ$.

Figure 12.- Concluded.



(a) Basic control gearing; M = 8; $\bar{q}$ = 100 lb/sq ft.

Figure 13.- Pilots' rating of the basic vehicle using normal control technique.

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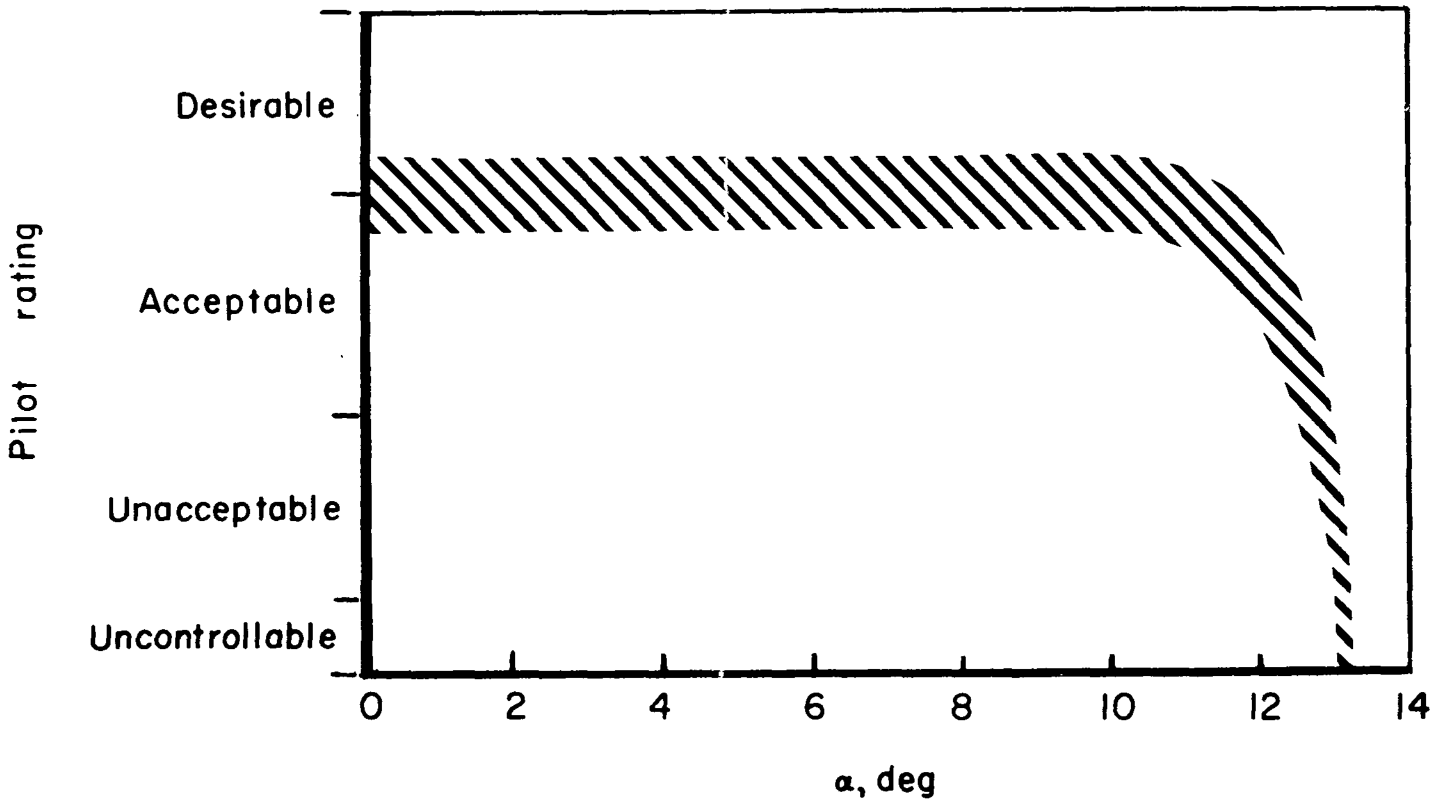
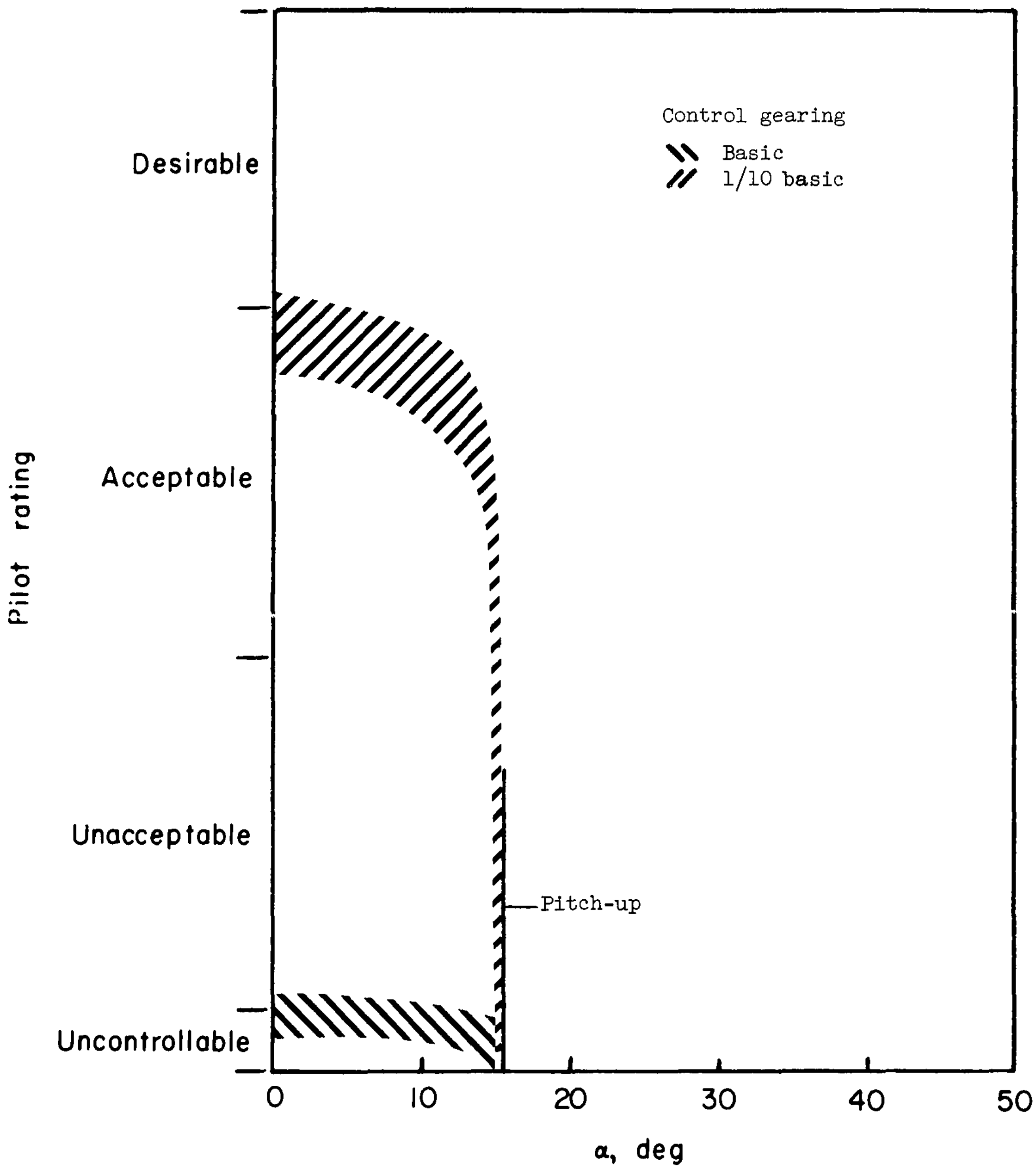


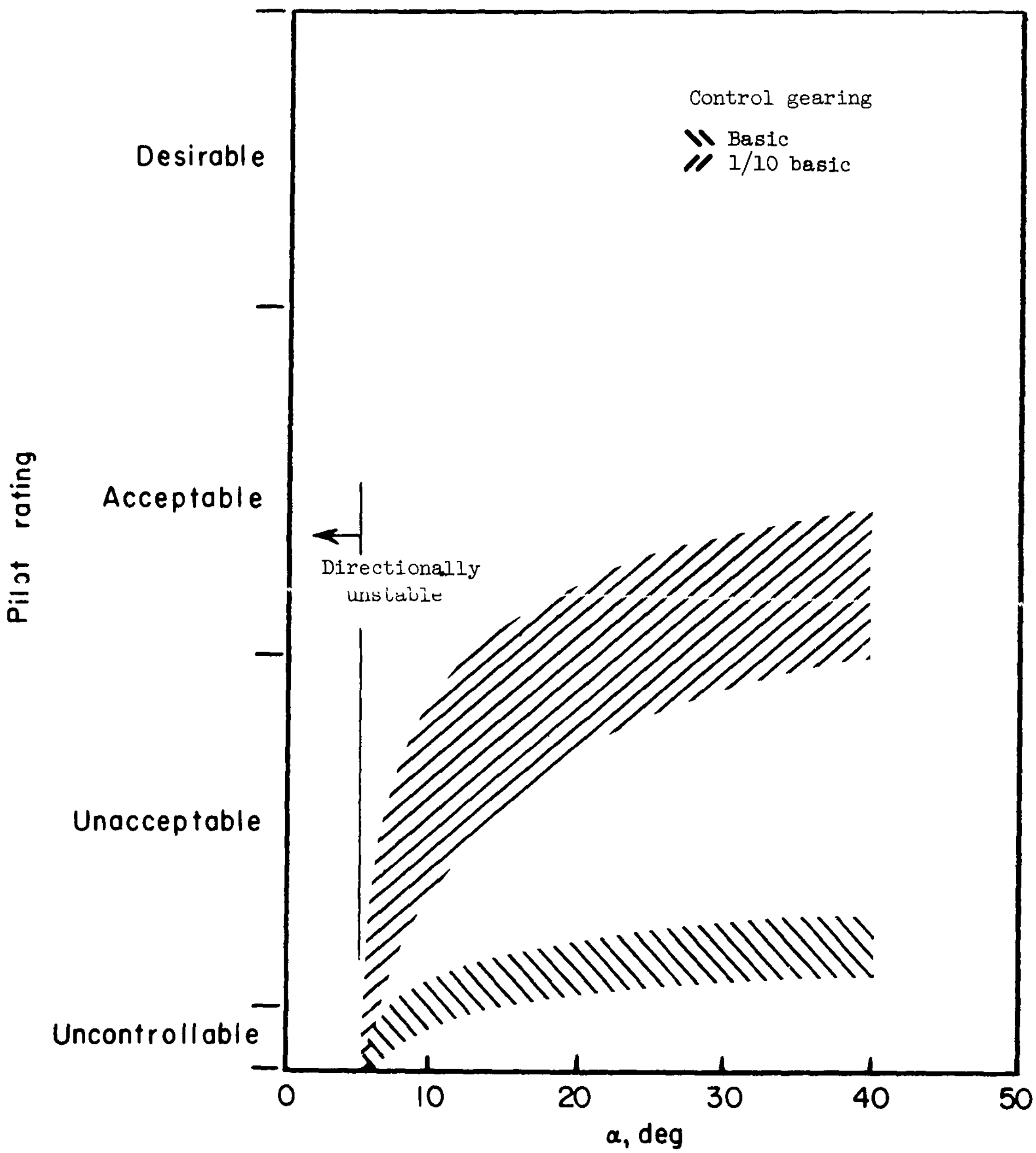
(b) One-tenth control gearing; M = 0.26; $\bar{q}$ = 100 lb/sq ft.

Figure 13.- Concluded.



(a) M = 0.26; $\bar{q}$ = 50 to 100 lb/sq ft.

Figure 14.- Effect of control gearing on vehicle controllability.



(b) M = 3.5; $\bar{q}$ = 100 to 400 lb/sq ft.

Figure 14.- Concluded.

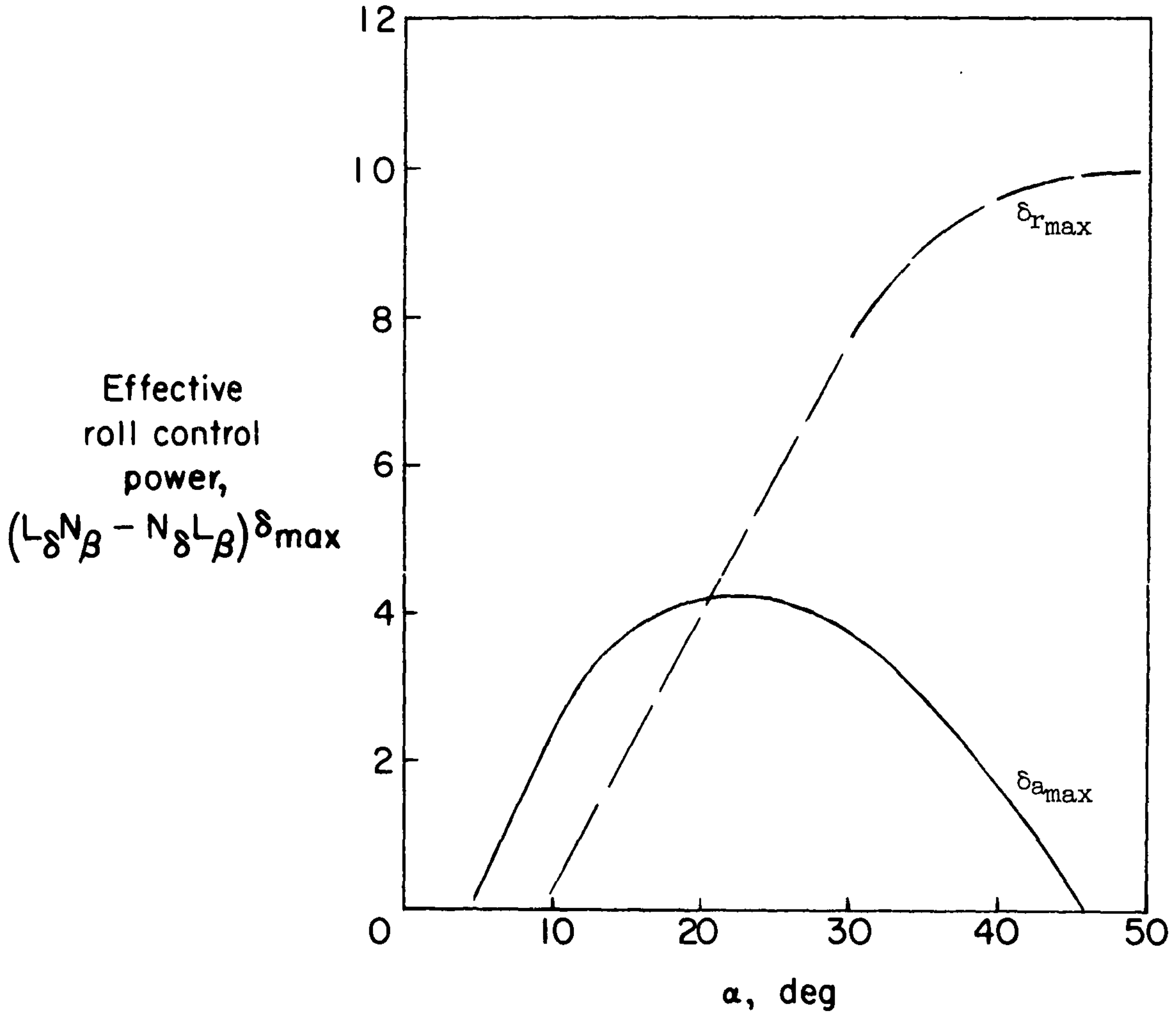


Figure 15.- Comparison of the effective roll control of the ailerons and the rudder. $M = 8$; $\bar{q} = 100$ lb/sq ft.

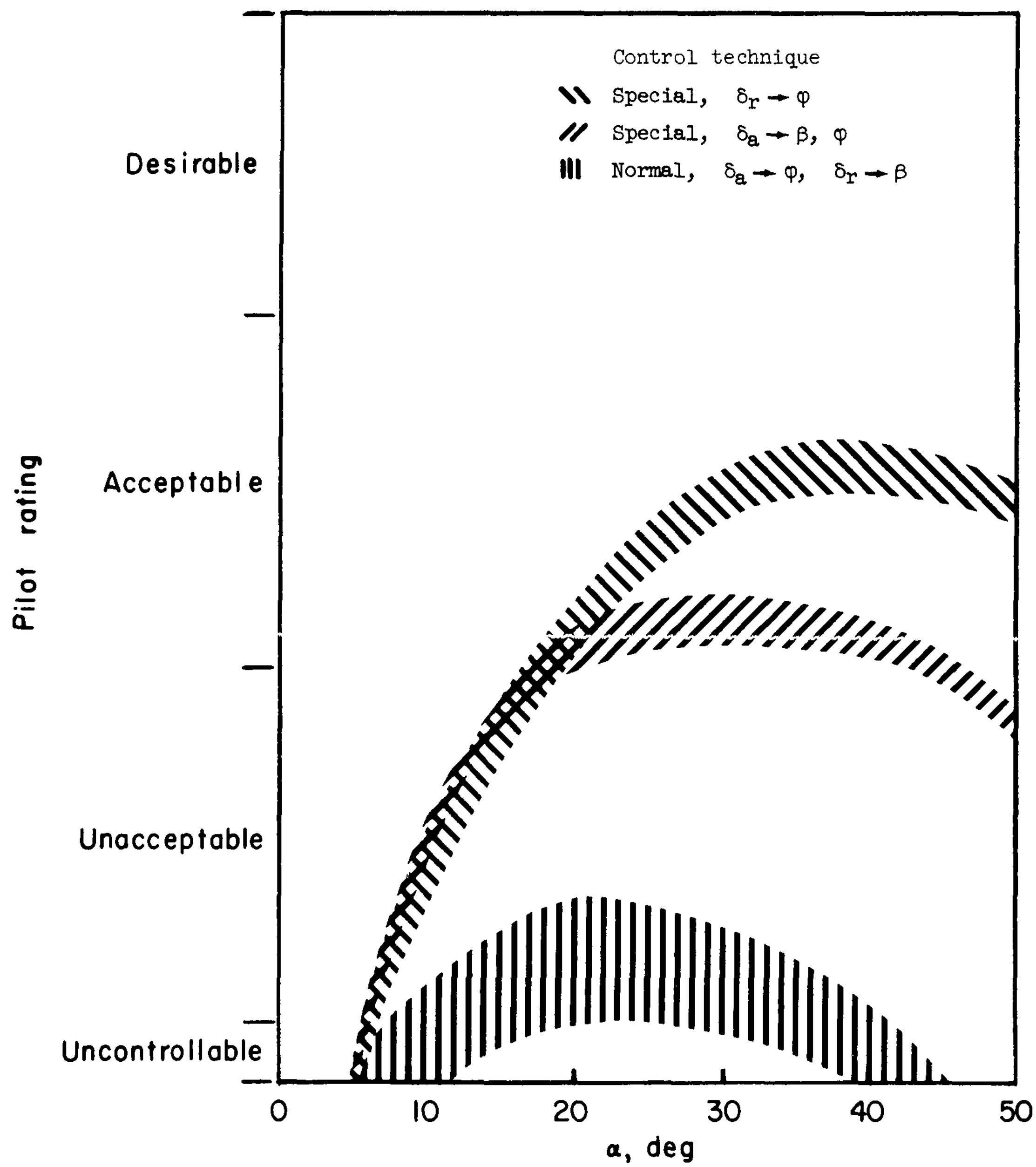


Figure 16.- Vehicle controllability using various control techniques. Basic control gearing; M = 8; $\bar{q}$ = 100 lb/sq ft.

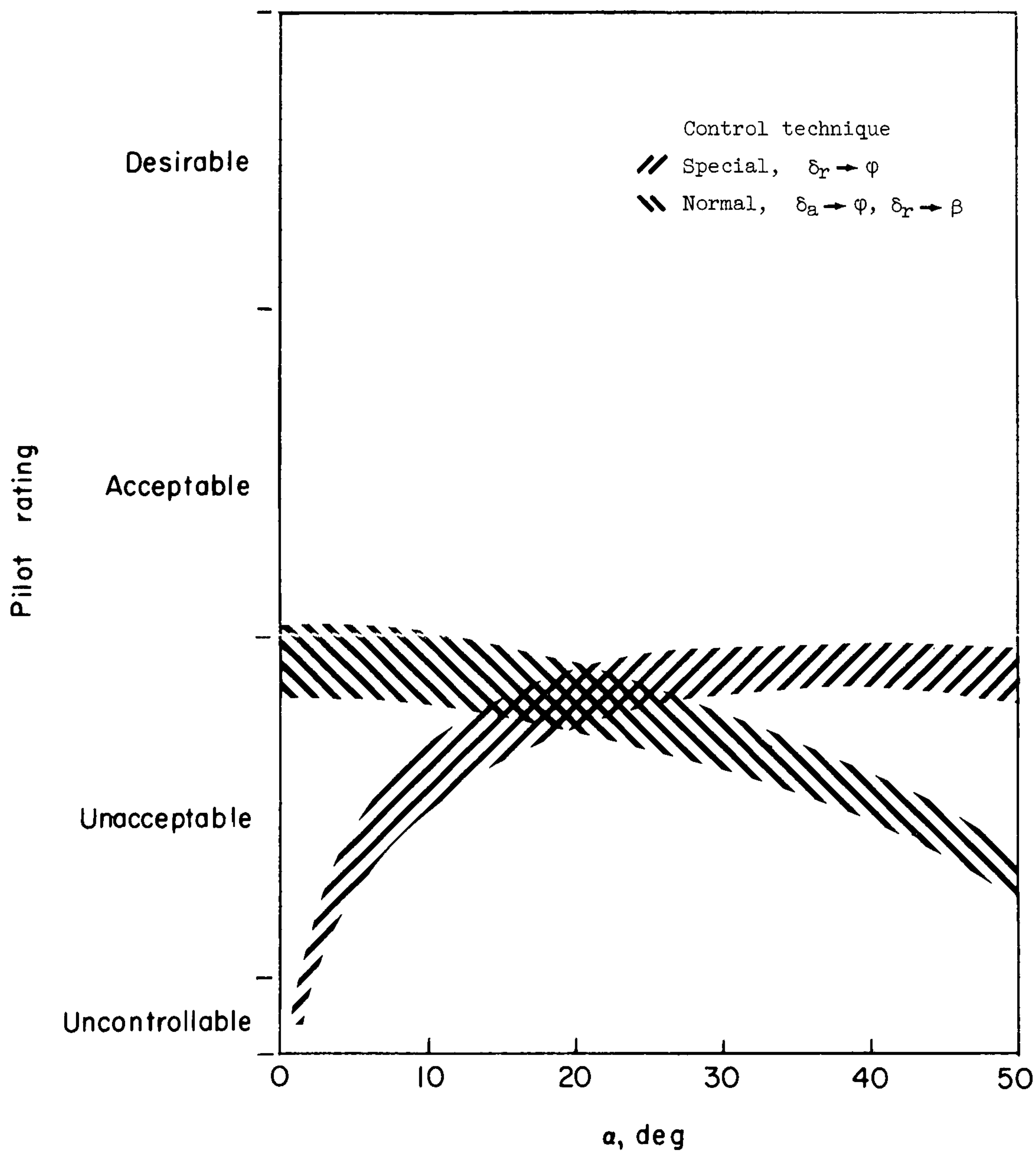


Figure 17.- Comparison of control techniques at low Mach number. One-tenth basic control gearing; M = 1.0; $\bar{q}$ = 100 lb/sq ft.

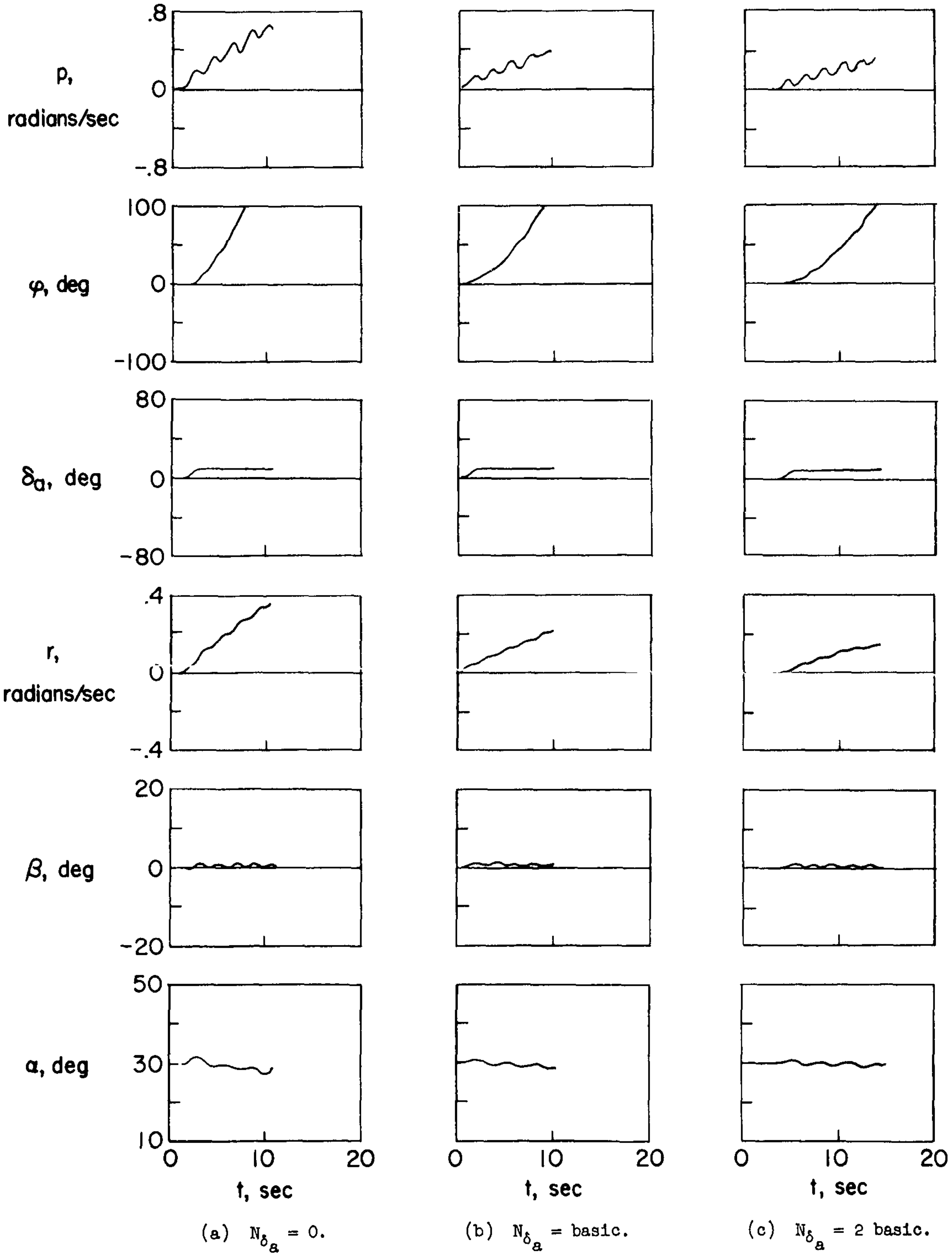


Figure 18.- The effect of N_{δ_a} on the roll capability of the ailerons. $M = 8$; $\bar{q} = 100$ lb/sq ft.

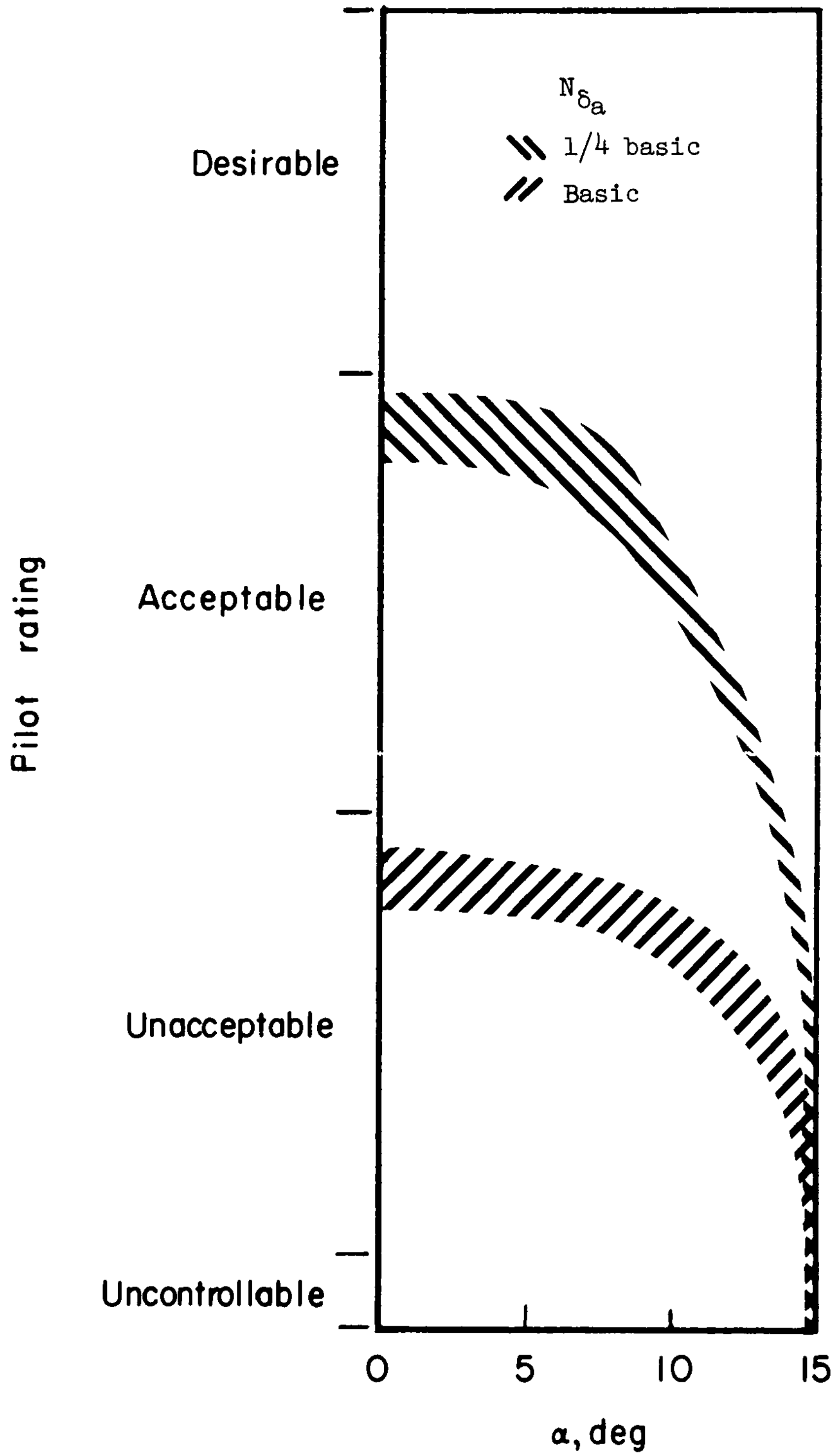


Figure 19.- The effect of N_{δ_a} on vehicle controllability. Normal control technique with 1/10 basic control gearing; M = 0.26; $\bar{q}$ = 50 lb/sq ft.

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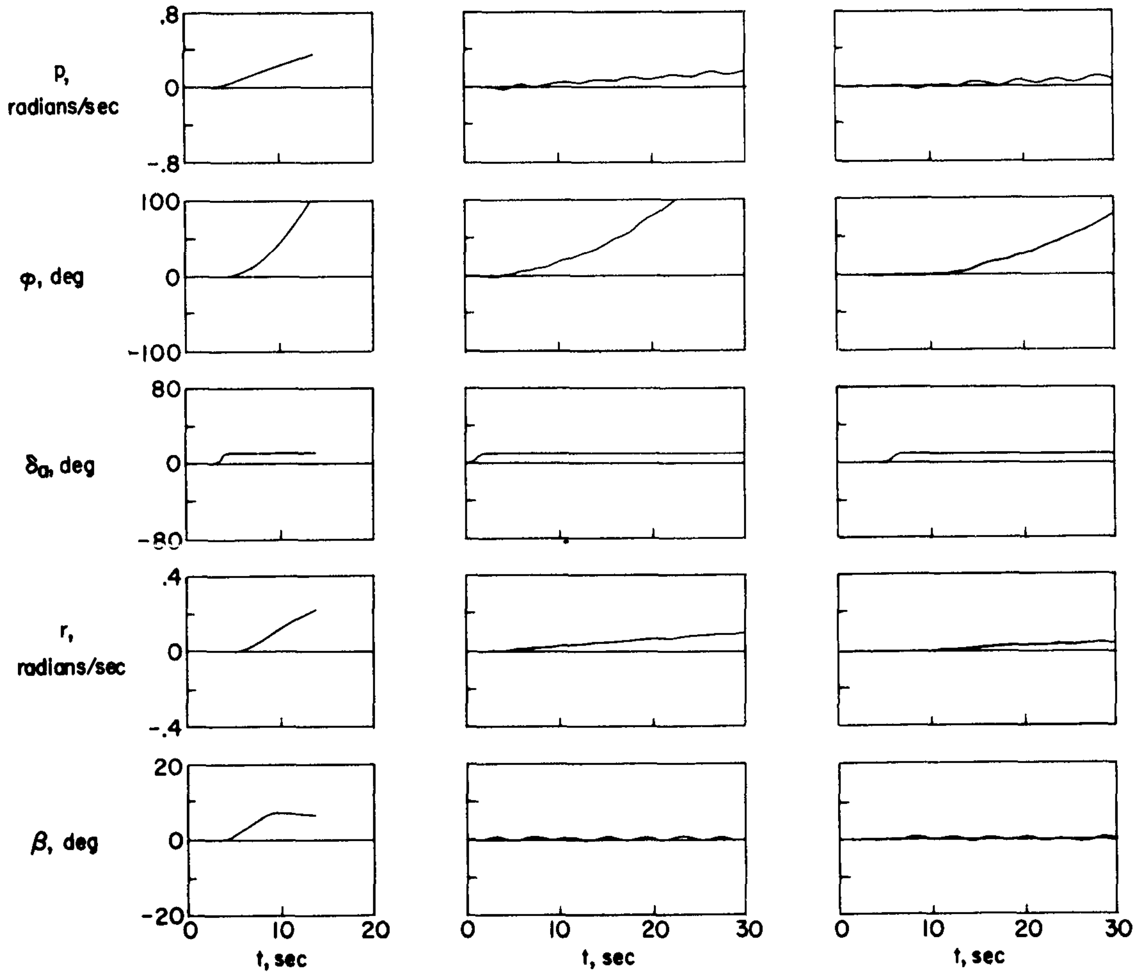
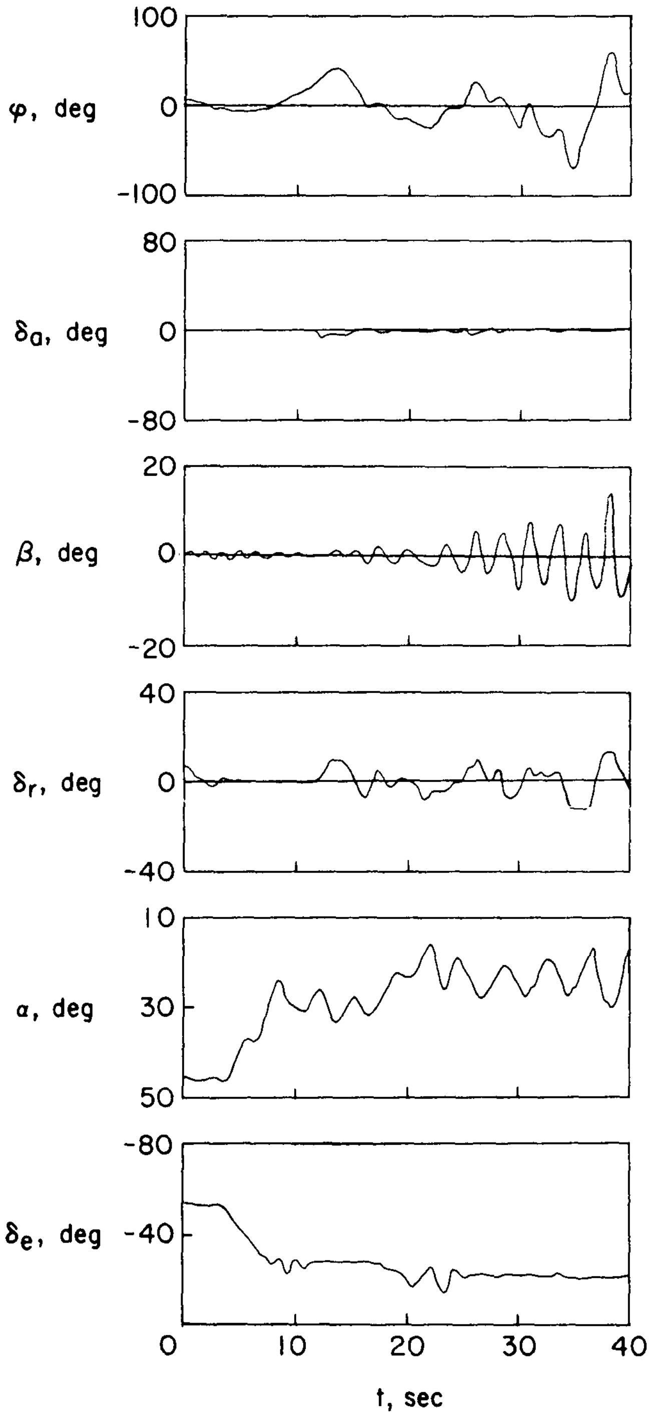


(a) L_β = 0. (b) L_β = basic. (c) L_β = 2 basic.

Figure 20.- Effect of L_β on the roll-control capability of the vehicle. M = 20; $\bar{q}$ = 25 lb/sq ft; α = 30°.



(a) Basic presentation φ, β, and α.

Figure 21.- Typical time history using three presentations. M = 20; $\bar{q}$ = 100 lb/sq ft.

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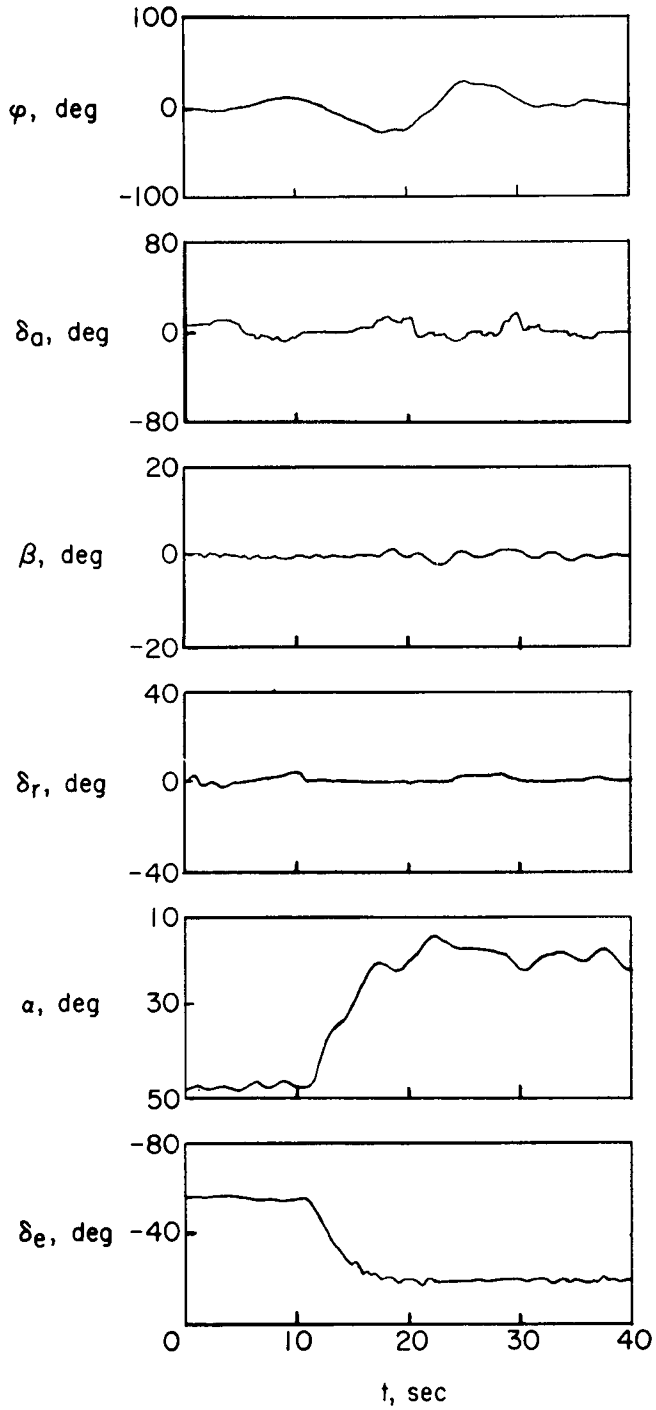
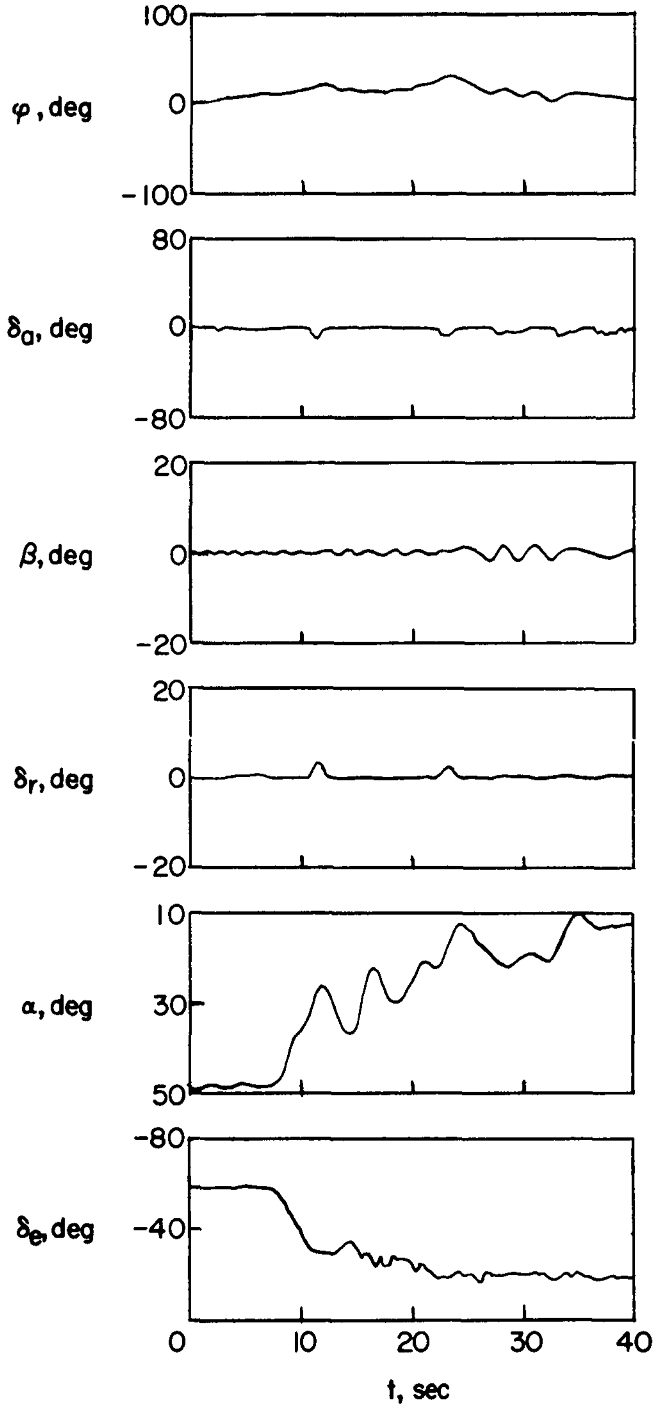


(b) Normal quickening $\varphi + p$, $\beta + \dot{\beta}$, and $\alpha + \dot{\alpha}$.

Figure 21.- Continued.



(c) Roll-yaw coupled quickening $\varphi + p + 2\dot{\beta}$ and $\beta + \dot{\beta} + 0.25p$.

Figure 21.- Concluded.

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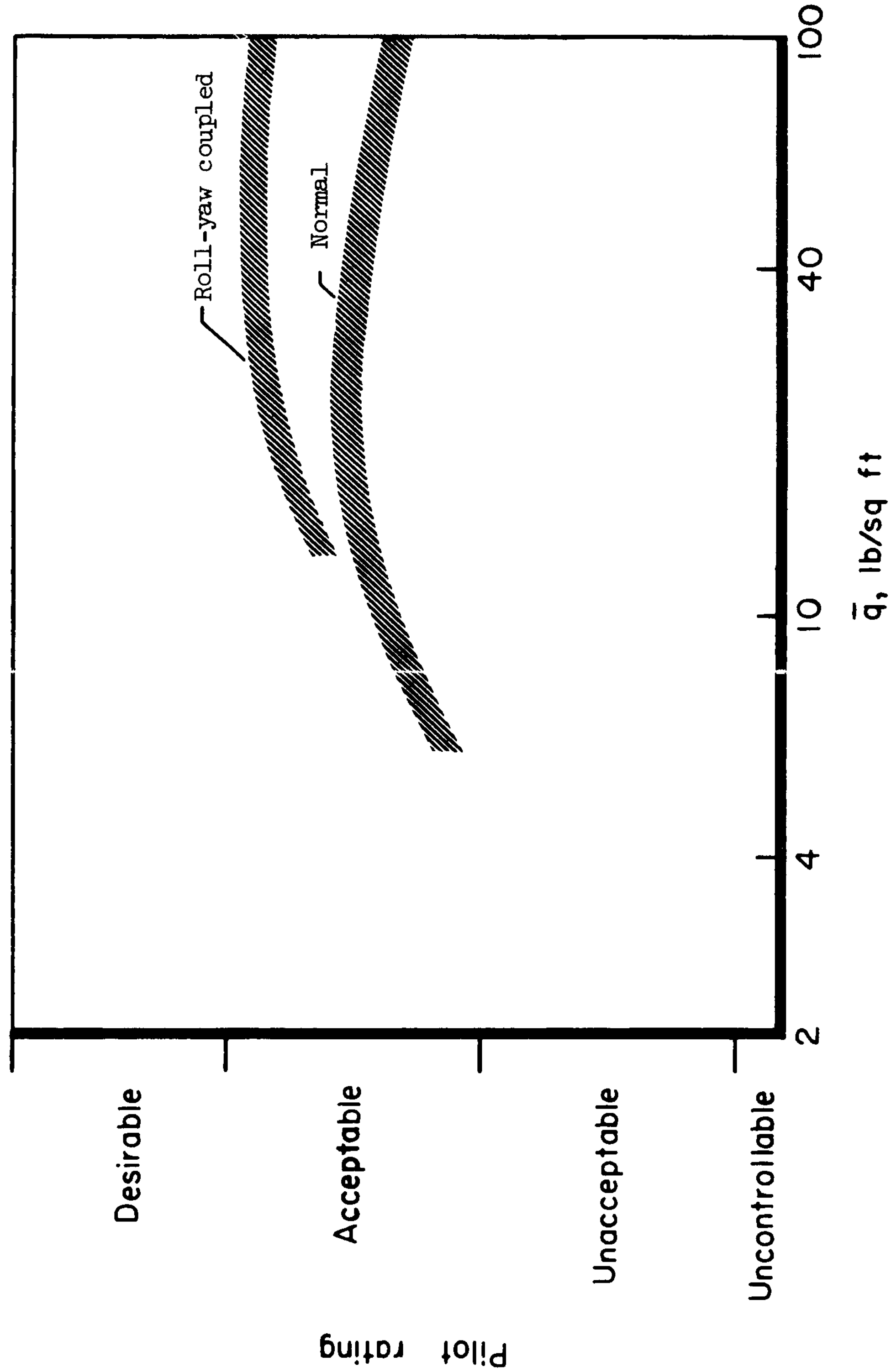

Figure 22.- Comparison of two types of quickened displays. M = 20.

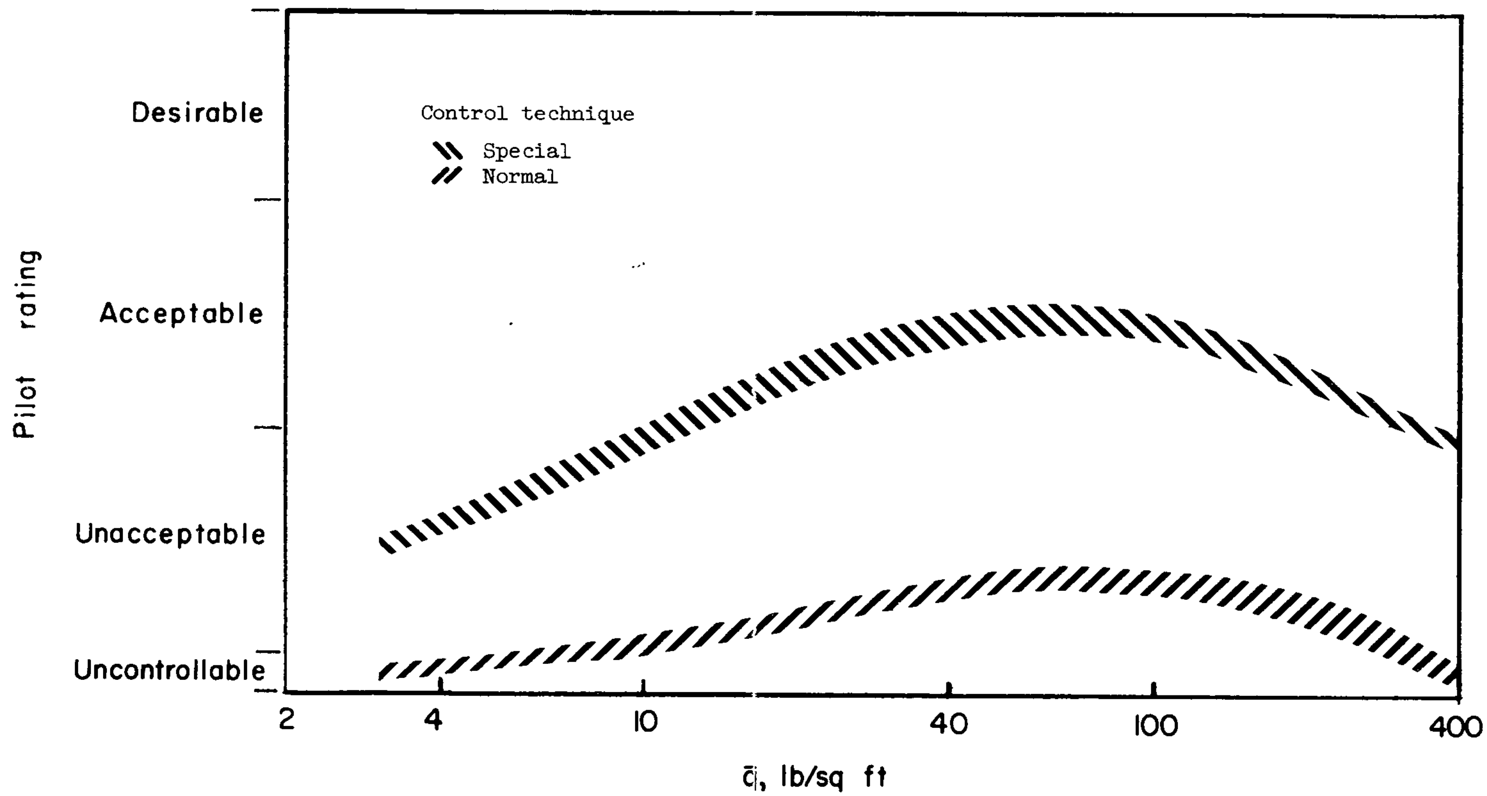

Figure 23.- Effect of dynamic pressure on the pilots' rating of the basic vehicle. Basic control gearing; M = 8; α = 30°.

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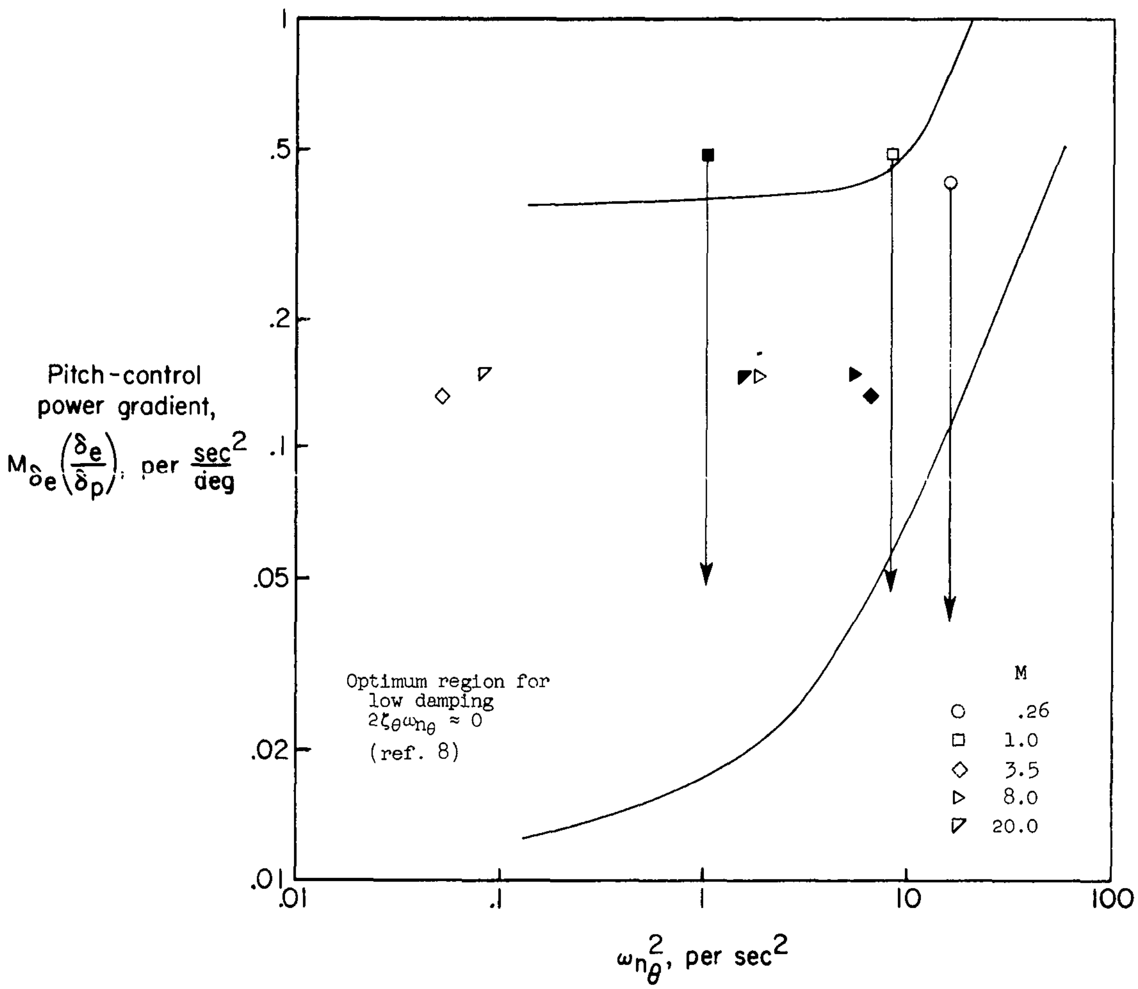

Figure 24.- Comparison of pitch-control power gradients. Solid symbols indicate an angle of attack greater than 20°. Arrows indicate effect of reduced control gearing. $\bar{q}$ = 100 lb/sq ft.

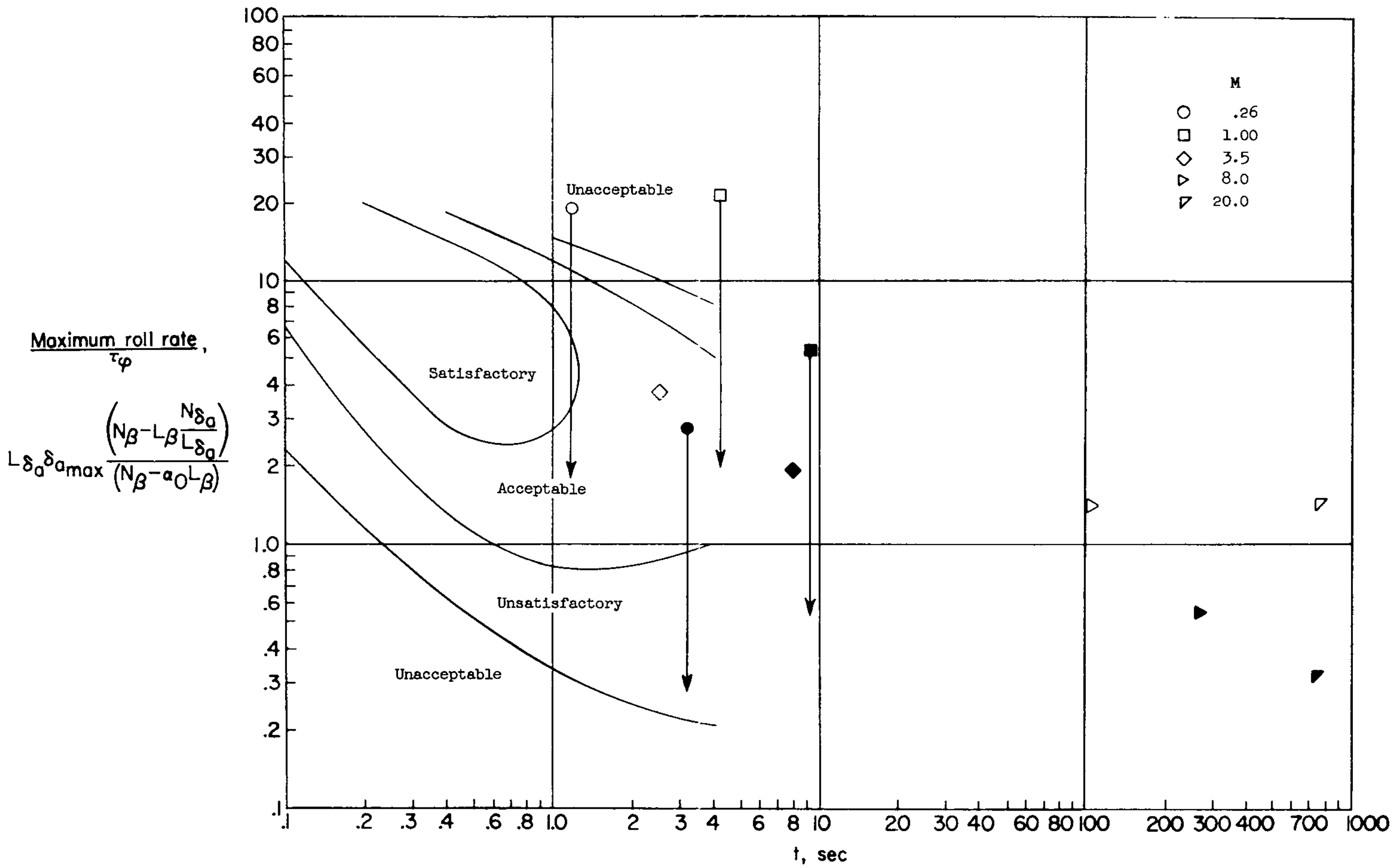

Figure 25.- Comparison of maximum steady-state roll rates with the criterion of reference 9. Solid symbols indicate angles of attack greater than 20°. Arrows show effect of reduced control gearing. $\bar{q}$ = 100 lb/sq ft.

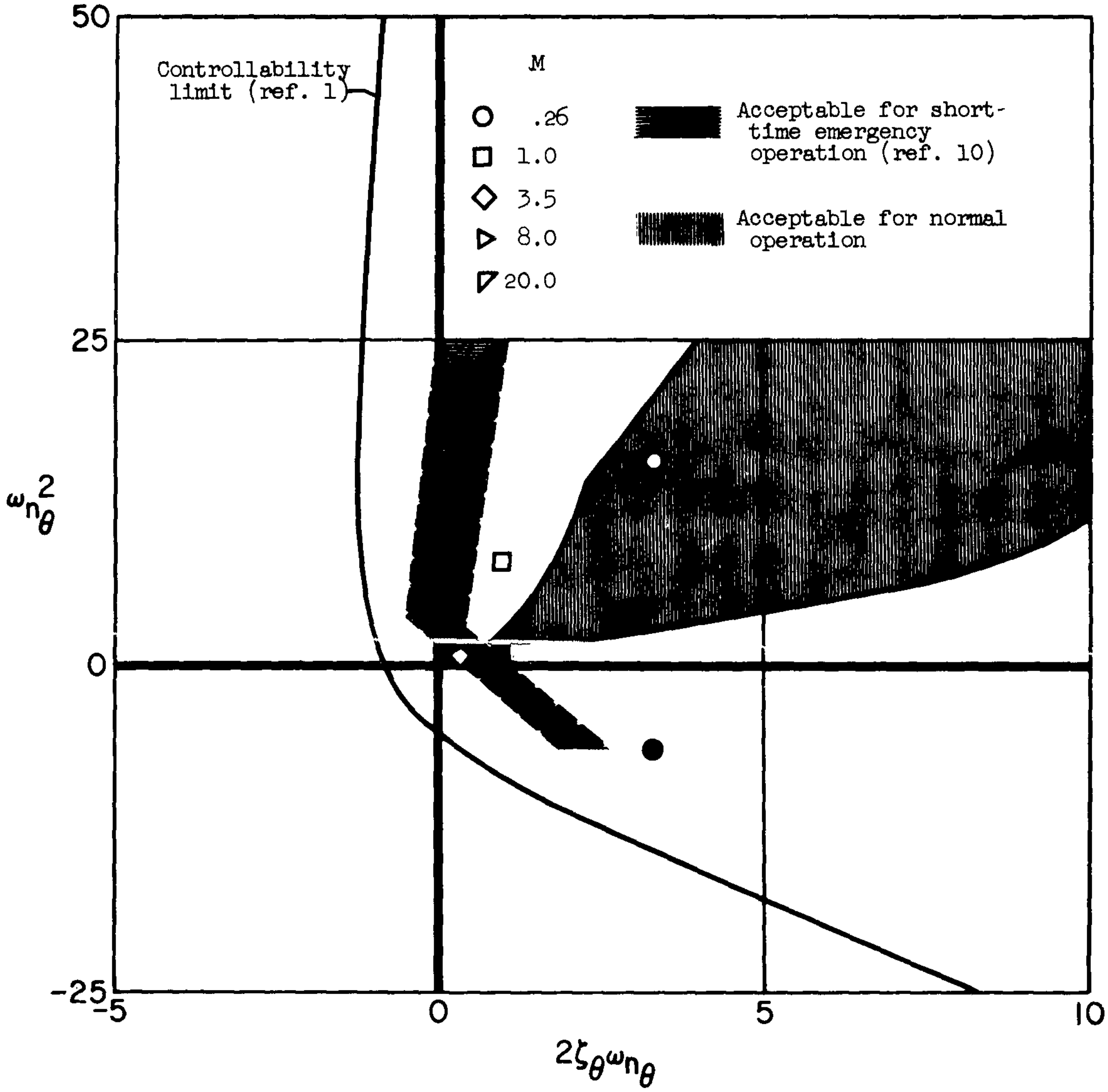

Figure 26.- Comparison of longitudinal dynamic characteristics with various control requirements. Solid symbols indicate an angle of attack greater than 20°. $\bar{q}$ = 100 lb/sq ft.

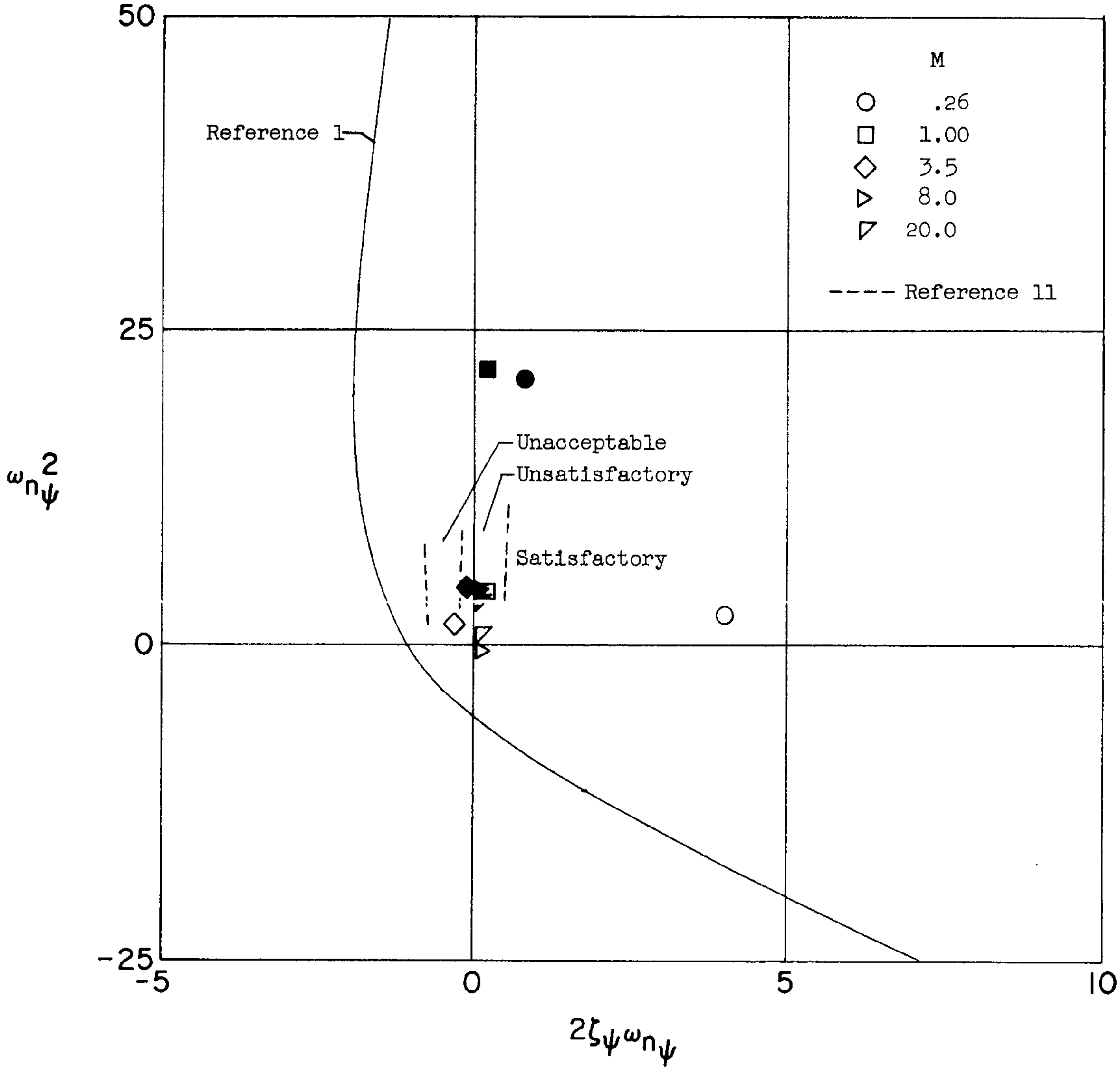

Figure 27.- Comparison of lateral dynamics with controllability limit. Solid symbols indicate an angle of attack greater than 20°. $\bar{q}$ = 100 lb/sq ft.

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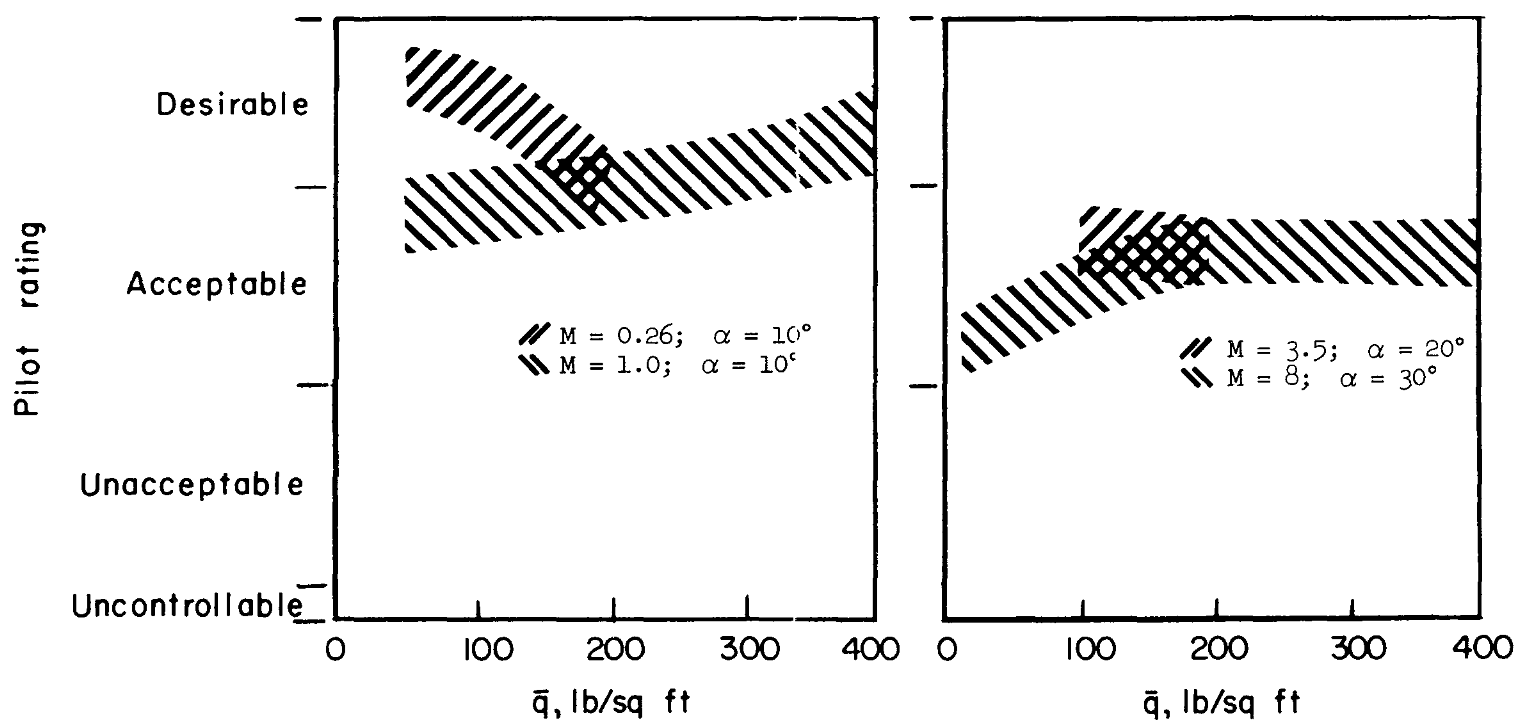

(a) $M = 0.26$ and 1.0; $\alpha = 10°$.

(b) $M = 3.5$, $\alpha = 20°$; $M = 8$, $\alpha = 30°$.

Figure 28.- Controllability of the vehicle with dampers as a function of dynamic pressure.

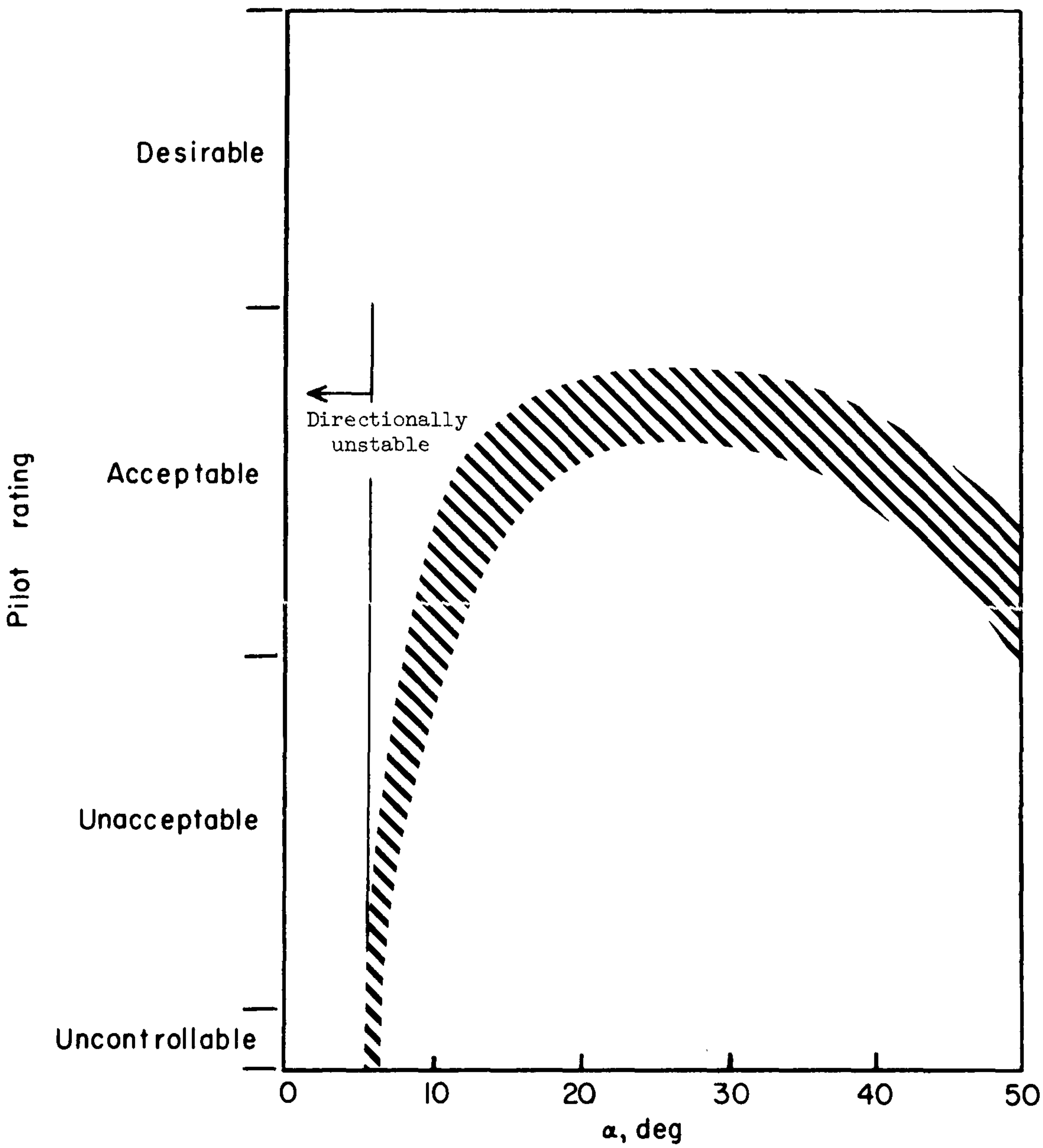

Figure 29.- Controllability of the vehicle with dampers as a function of angle of attack. Basic control gearing; M = 8; $\bar{q}$ = 100 lb/sq ft.

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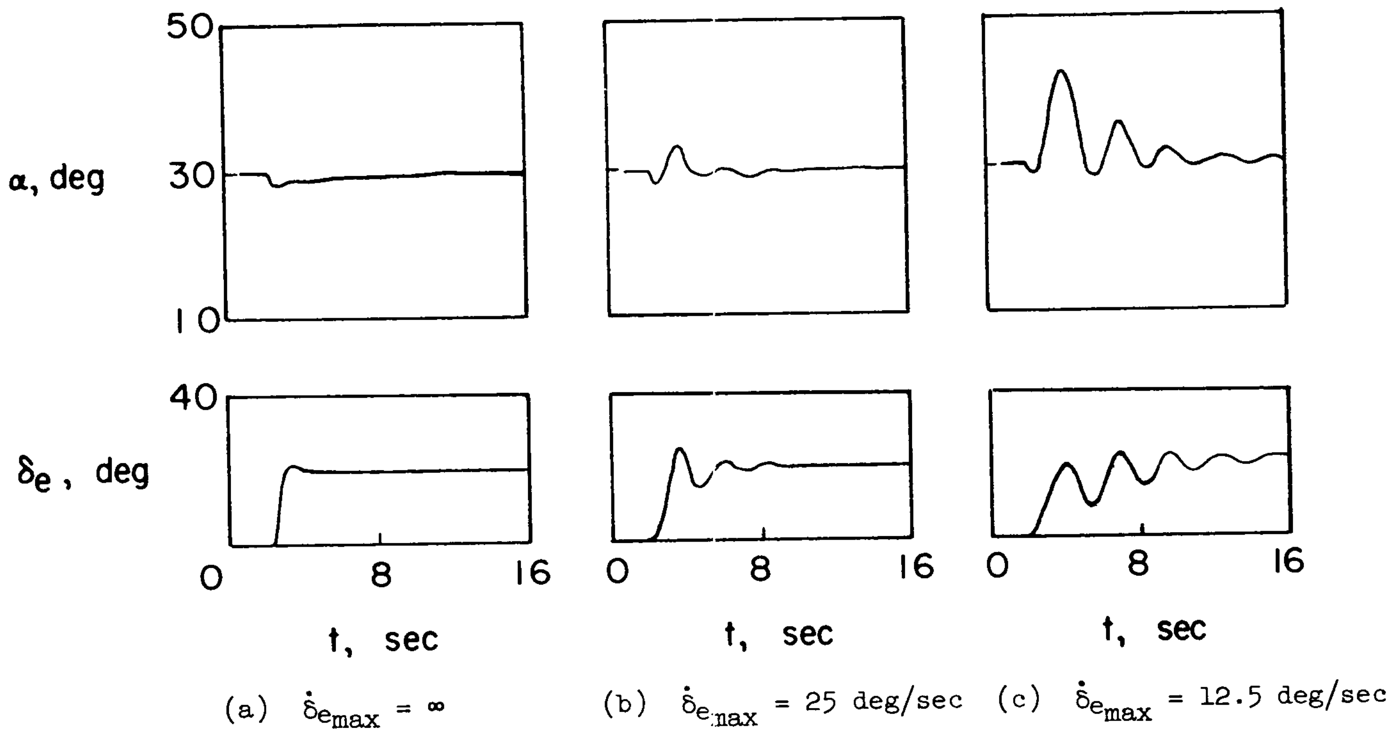
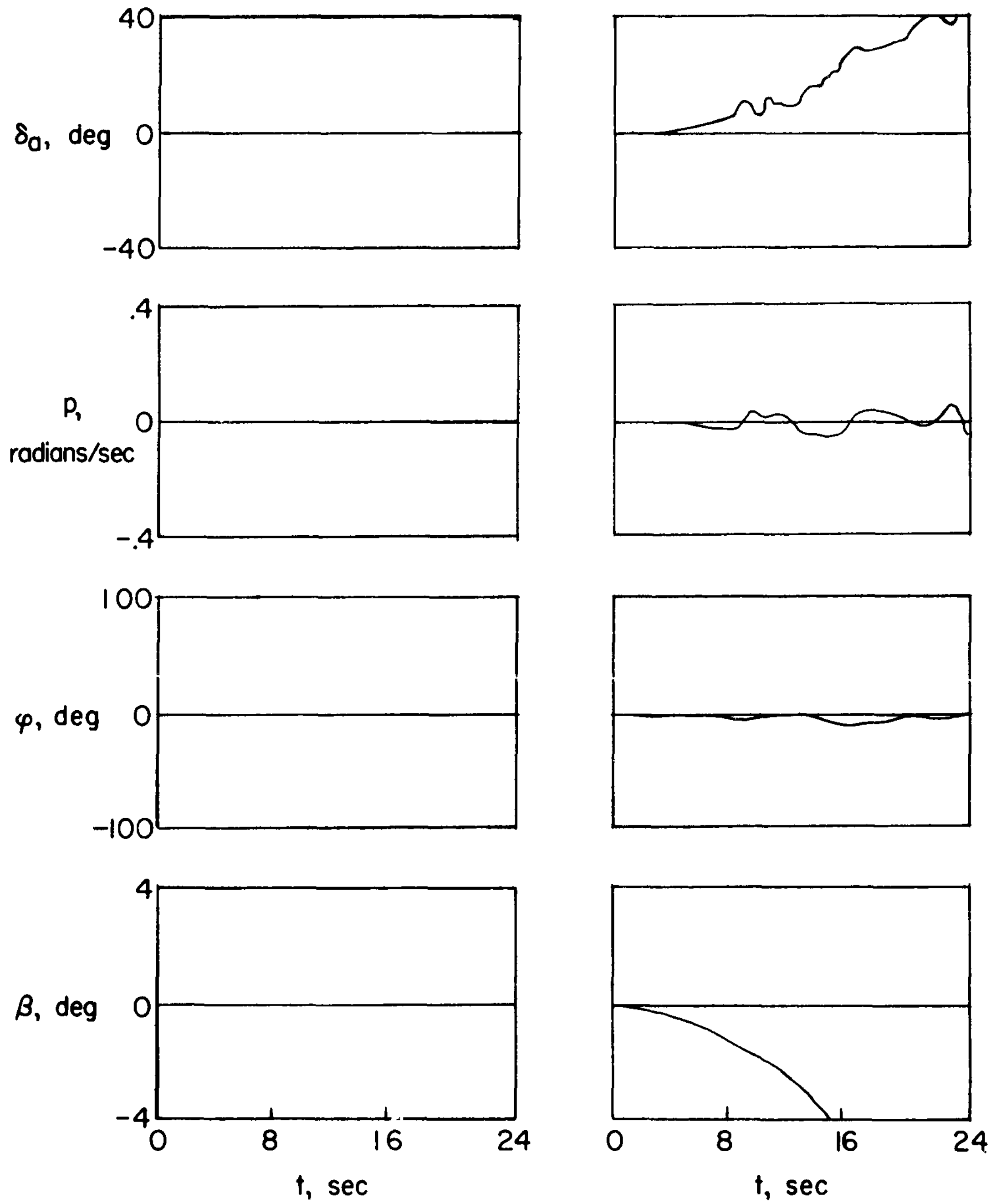


Figure 30.- The effect of surface rate limiting on vehicle damping. $M = 8$; $\bar{q} = 50$ lb/sq ft; $\alpha = 30^\circ$; $K_q = 2$.



(a) With n_y feedback. (b) Without n_y feedback.

Figure 31.- Stabilizing effect of lateral-acceleration feedback in the yaw axis of the adaptive system with pilot monitoring bank angle. $M = 8$; $\bar{q} = 100$ lb/sq ft; $\alpha = 0°$.

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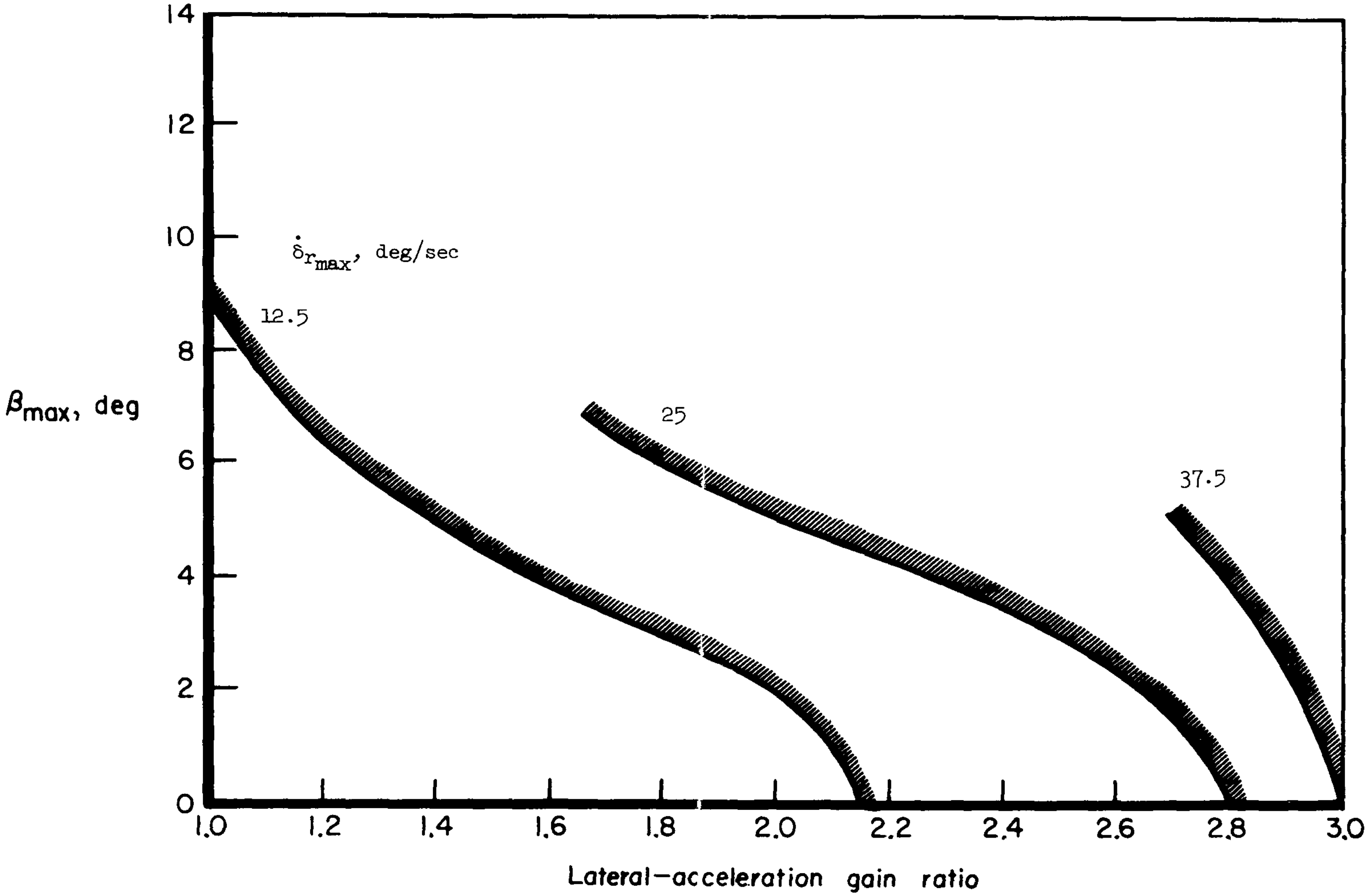

Figure 32.- Effects of lateral-acceleration gain and maximum surface rate on the allowable sideslip for stability. $M = 8$; $\alpha = 0°$; $\bar{q} = 100$ lb/sq ft; $K_{n_{y_{basic}}} = 3.0$.

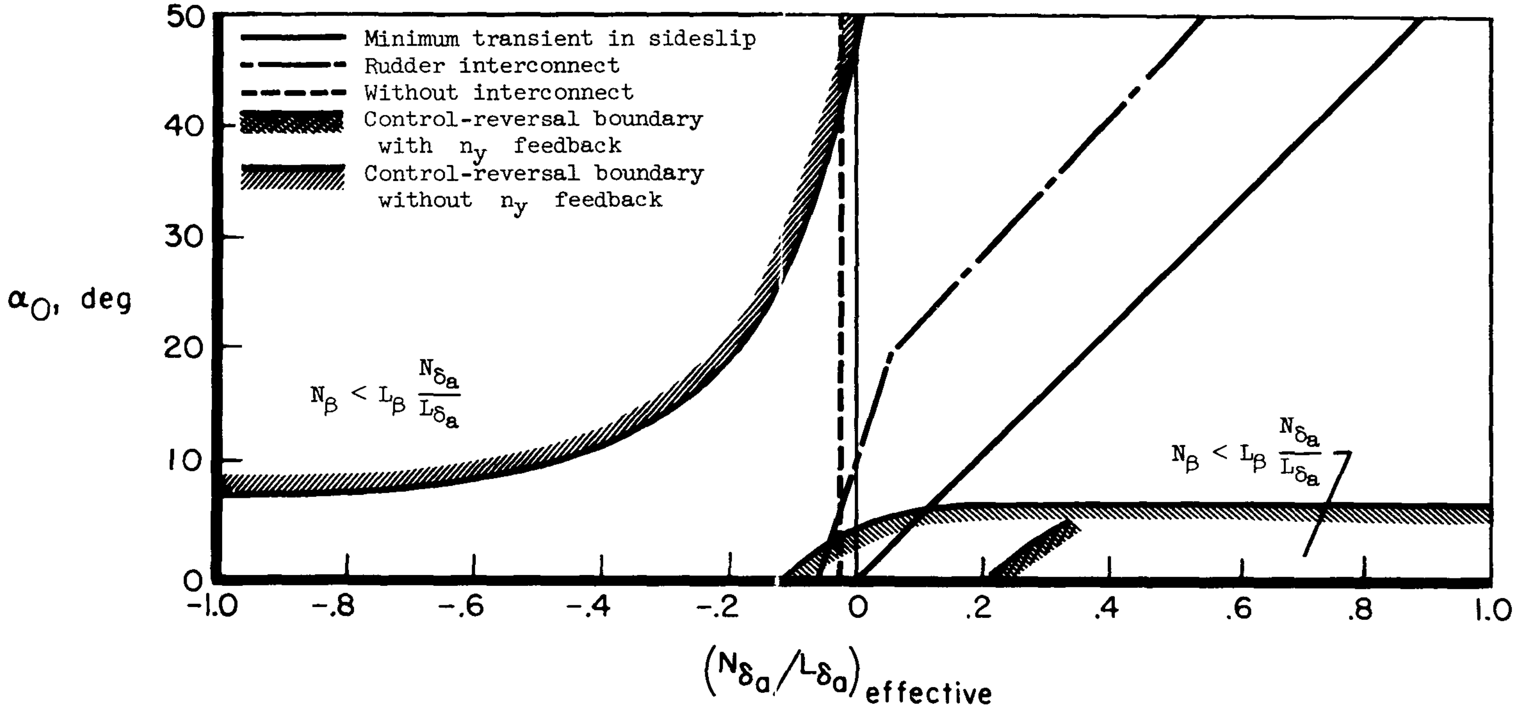

Figure 33.- Effective yawing-to-rolling moment of the aileron deflection used to design the rudder interconnect. M = 8.

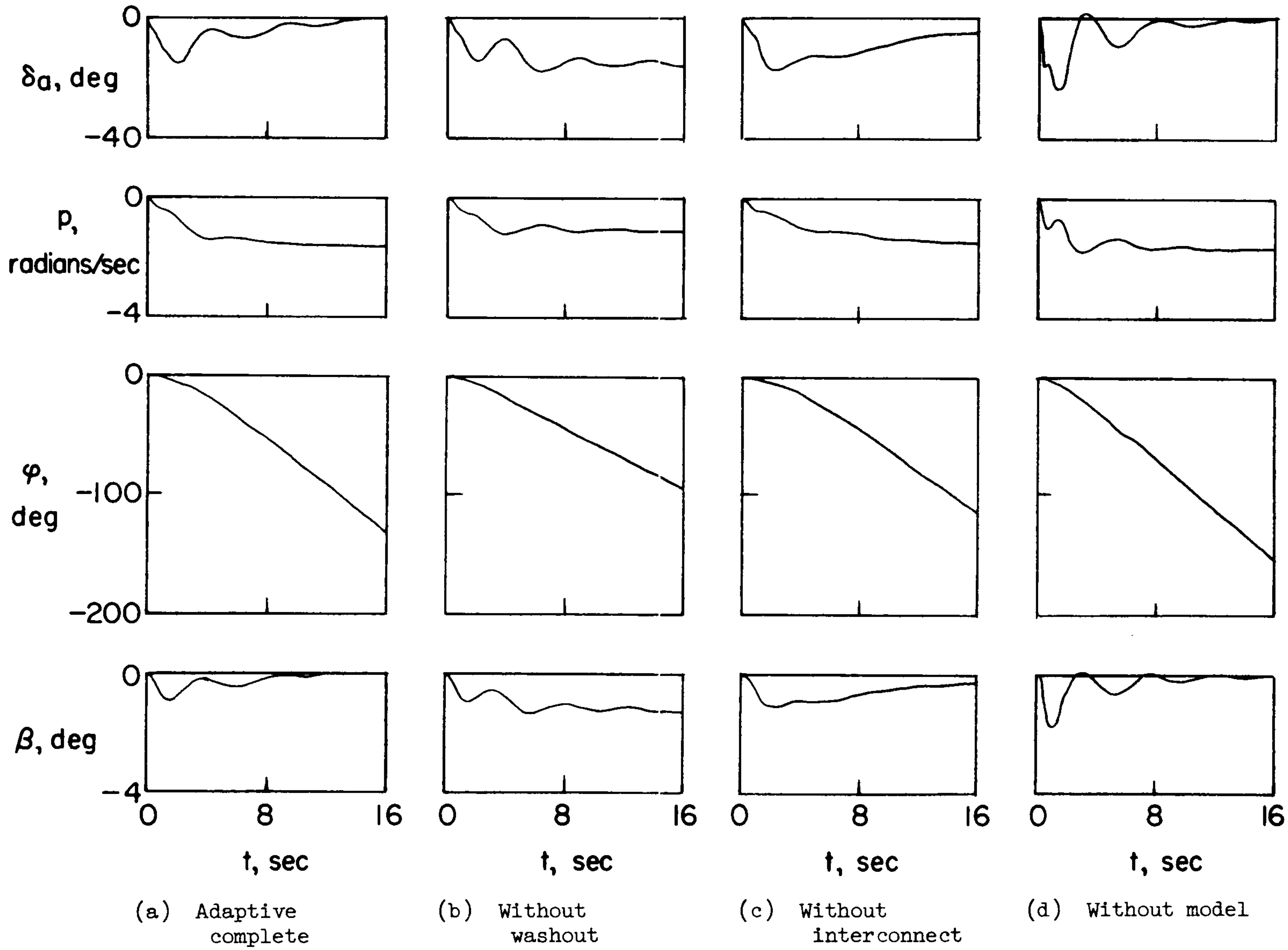

Figure 34.- Effects of washout in yaw rate, interconnect, and model shaping on the lateral step response of the vehicle with the adaptive system. $M = 8$; $\bar{q} = 100$ lb/sq ft; $\alpha = 30°$.

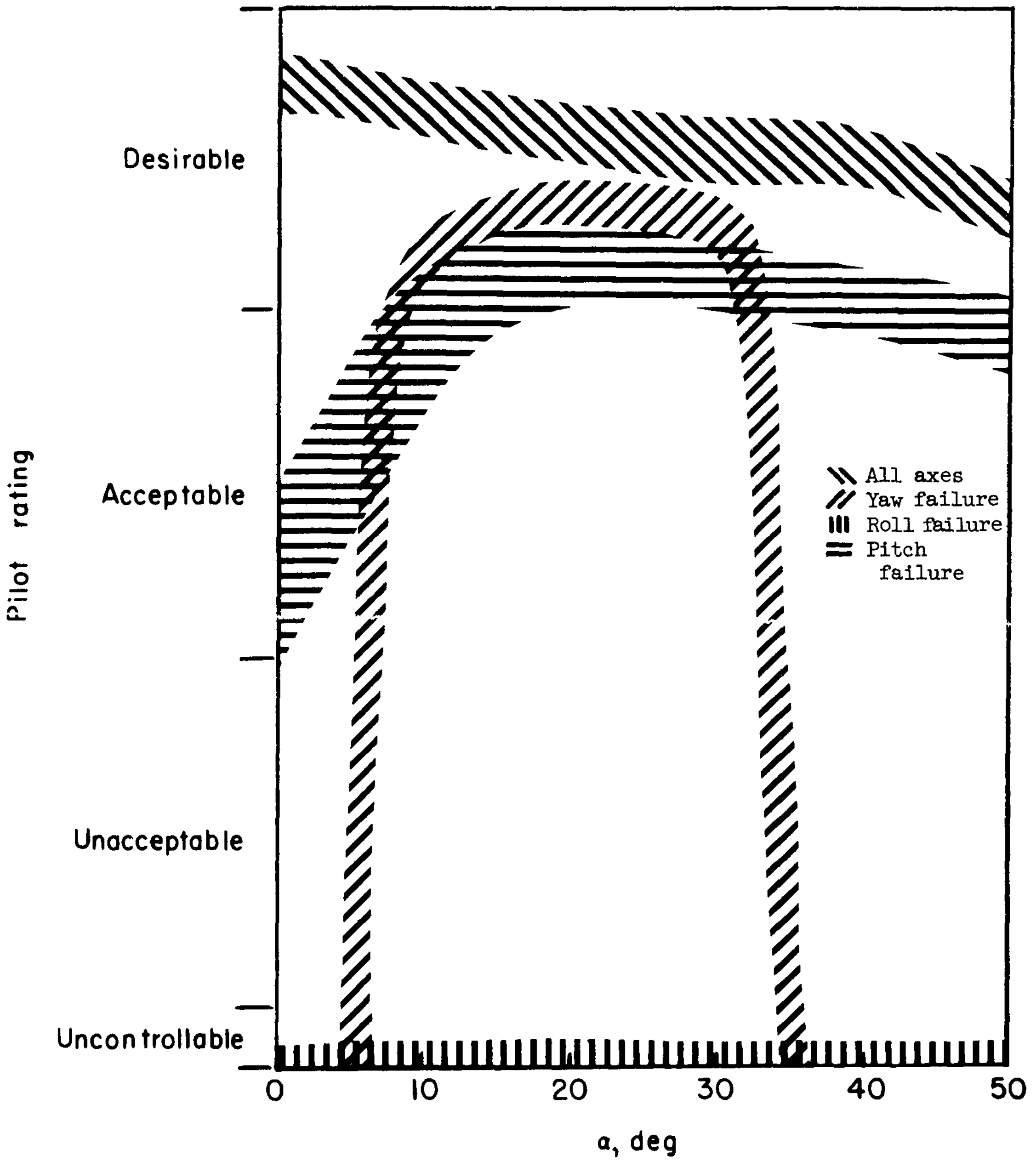

Figure 35.- Effect of mode failure on the controllability of the vehicle with the adaptive system. M = 8; $\bar{q}$ = 100 lb/sq ft.

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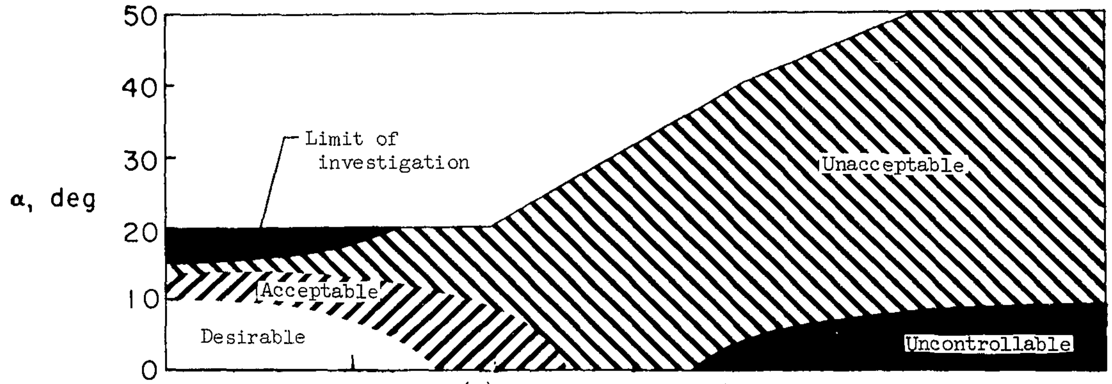
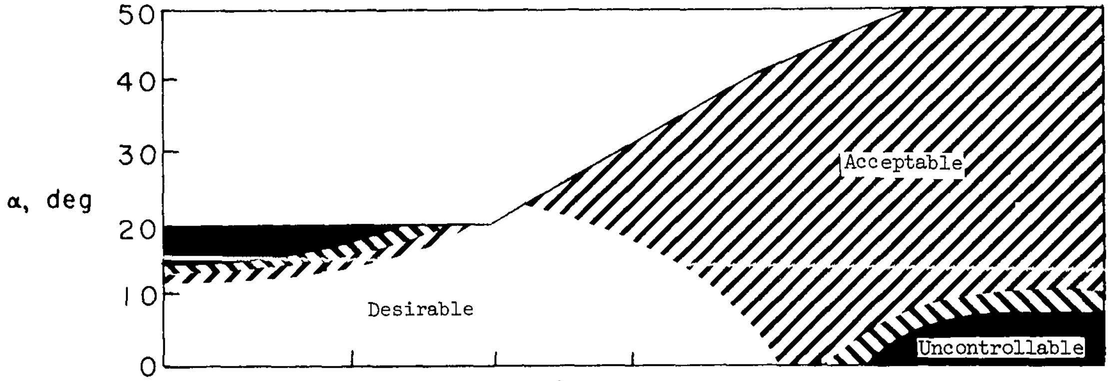
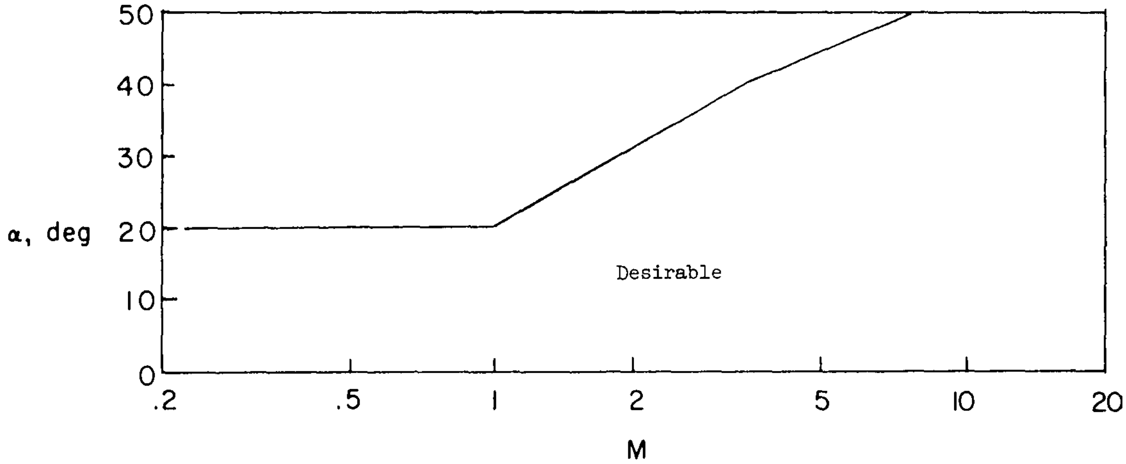


(a) Without augmentation.



(b) Dampers.



(c) Adaptive control system.

Figure 36.- Handling qualities of a hypersonic glider. $\bar{q}$ = 100 lb/sq ft.

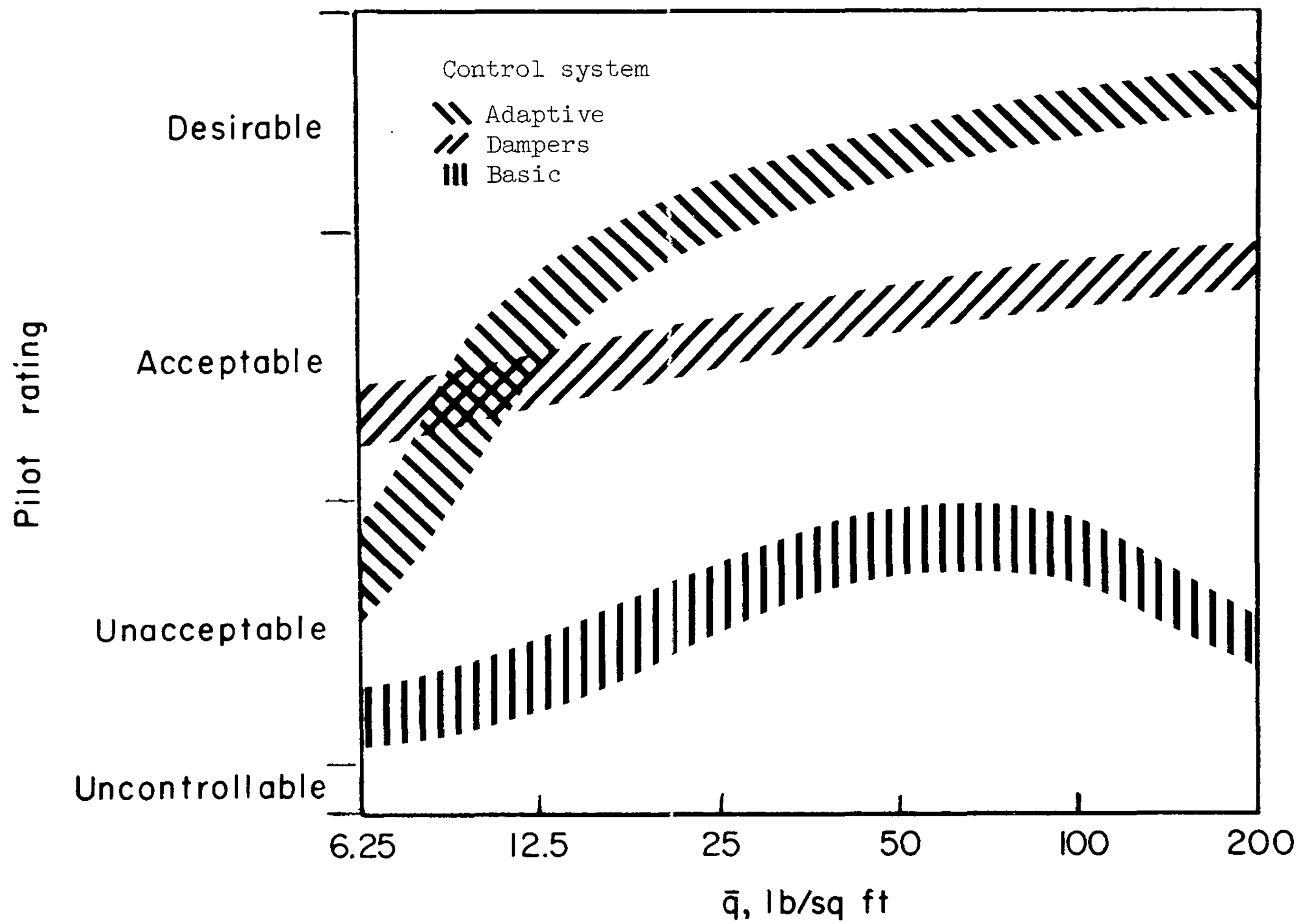


Figure 37.- Effect of dynamic pressure on the vehicle handling qualities. M = 20; α = 30°.

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SIMULATOR INVESTIGATION OF THE CONTROL REQUIREMENTS OF A TYPICAL HYPERSONIC GLIDER. Lawrence W. Taylor, Jr., James L. Samuels, and John W. Smith. March 1962. 66p. (NASA TECHNICAL MEMORANDUM X-635)
CONFIDENTIAL
(Title, Unclassified)

An investigation of the handling qualities of a typical hypersonic glider with basic aerodynamic controls, fixed gain dampers, and an adaptive control system was conducted with a fixed-base flight simulator. The controllability of the basic glider, which was marginal because of control coupling and light damping, was greatly improved through the use of dampers. Special control techniques, however, were required for precise control. The adaptive control system provided acceptable handling qualities over the entire flight envelope, including regions of vehicle static instability.

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