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RESEARCH MEMORANDUM

SIMULATOR STUDIES OF JET REACTION CONTROLS FOR USE AT HIGH ALTITUDE

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Edwards, Calif.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SIMULATOR STUDIES OF JET REACTION CONTROLS FOR USE AT HIGH ALTITUDE*

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SUMMARY

An investigation was conducted into the use of jet reaction forces for vehicle attitude control in regions of flight at extremely low dynamic pressures where aerodynamic controls would be ineffective. Analog computer and mechanical simulator studies were made of the use of manually controlled jet reaction forces. The effects of various control configurations, control magnitudes, control techniques, dynamic pressure, and the amount of aerodynamic stability were investigated. The investigation was limited to acceleration command controls; that is, controls in which the pilot controlled the thrust directly with no feedback loops.

The results of the investigation indicate that satisfactory attitude control can be maintained with acceleration command jet reaction controls at dynamic pressures up to 20 pounds per square foot.

Control techniques are somewhat different from those used with aerodynamic controls at normal flight speeds. Because of the ease of overcontrolling with large control powers, much lower control power than that required for aerodynamic controls was preferred. Pilots' comments indicated only small differences existed between the ease of control for proportional control and for full-on, full-off type of control.

Moderate values of effective dihedral produced a noticeable increase in the amount of roll control required to maintain trim at dynamic pressures up to 20 pounds per square foot because of the rolling produced by small sideslip angles. Changes in longitudinal or directional stability had little effect on the ease of control.

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*Title, Unclassified.

INTRODUCTION

With the large values of jet-engine and rocket-engine thrust now available, man-carrying vehicles can attain altitudes and airspeeds where aerodynamic controls, which depend on dynamic pressure, are essentially ineffective. The general flight areas where this loss of control may occur are at extremely high altitude and during the take-off and early transition phases of vertical take-off aircraft. For these areas the dynamic pressure may be as low as zero.

The actual level of dynamic pressure below which aerodynamic controls have insufficient effectiveness cannot be stated definitely; however, it is probably on the order of 5 to 10 pounds per square foot. The shaded area of figure 1 illustrates the variation of Mach number and altitude for this range of dynamic pressure. This area, then, indicates the general combination of Mach number and altitude at which aerodynamic controls must be replaced by controls which do not rely upon aerodynamic forces for effectiveness. Two types of controls are suitable for use in the transition region and the reaction control region. One type depends on jet reaction forces; the other depends on the reaction to changes in the angular momentum of a rotating flywheel within the airplane. These controls are not intended for maneuvering, that is, changing the flight path, but only for controlling attitude. Also, since aerodynamic stability is nonexistent, the controls must be utilized to provide static and dynamic stability.

In general, the jet control method would be of interest to vehicles, such as research airplanes, designed to operate for only brief periods at low dynamic pressure. The momentum-type of control would be applicable to space operations of longer duration. For long-duration operation at altitudes considerably above the transition boundary it might be practical to use other control means which depend on the outside environmental factors such as solar radiation pressure, gravity, or magnetism.

The NACA High-Speed Flight Station has initiated a study of reaction controls for flight at high altitudes. This study, which includes both simulator investigations and flight tests, will investigate both types of reaction controls. The jet-type control was selected as the subject of the first investigation since it is of more immediate interest. This paper describes the results of analog computer and mechanical simulator studies of various control configurations, control magnitudes, control techniques, and the effects of jet thrust lag, dynamic pressure, and aerodynamic stability. Although the airplane characteristics selected for the investigation were those of the X-1B, it is believed that the results will provide general information pertinent to jet reaction controls.

This investigation was limited to acceleration command controls; that is, controls in which the pilot controlled thrust directly with no feedback loops. The results of a brief investigation of jet reaction controls incorporating angular velocity and attitude angle feedback are presented in reference 1.

SYMBOLS

b	wing span, ft
C_l	rolling-moment coefficient, $\frac{\text{Rolling moment}}{\frac{1}{2}\rho V^2 Sb}$
C_m	pitching-moment coefficient, $\frac{\text{Pitching moment}}{\frac{1}{2}\rho V^2 S\bar{c}}$
C_n	yawing-moment coefficient, $\frac{\text{Yawing moment}}{\frac{1}{2}\rho V^2 Sb}$
$C_{l_\beta}, C_{m_\alpha}, C_{n_\beta}$	indicates derivative with respect to subscript
$\bar{c}$	wing mean aerodynamic chord, ft
h_p	pressure altitude, ft
M	Mach number
p	rolling velocity, radians/sec or deg/sec
q	pitching velocity, radians/sec or deg/sec
R	control effectiveness ratio, $\frac{\text{Roll control effectiveness}}{\text{Pitch or yaw control effectiveness}}$
r	yawing velocity, radians/sec or deg/sec
S	wing area, sq ft
t	time, sec

V	true airspeed, ft/sec
α	angle of attack, radians or deg
β	angle of sideslip, radians or deg
θ	pitch angle, deg
ρ	mass density of air, slugs/cu ft
φ	bank angle, deg
ψ	yaw angle, deg

Dot over a symbol indicates derivative with respect to time.

METHODS AND EQUIPMENT

The present study was performed with closed-loop circuits consisting of presentation, pilot, control stick, and simulated airplane motions. One method utilized a fixed-base setup with an analog computer to solve the equations of motion; the other method utilized a three-degree-of-freedom mechanical simulator with which the pilot actually experienced the airplane motions.

Analog Computer

The analog computer represented the airplane in five degrees of freedom with control provided by signals from the pilot's control stick. The computer also provided the signals for the presentation and the recorded data. The investigation was conducted with the computing equipment of the Air Force Flight Test Center and the NACA High-Speed Flight Station at Edwards, Calif. The equipment differed only in computing capacity and quantities recorded.

Equations of motion.- The five-degree-of-freedom equations of motion used are shown in the appendix. For zero dynamic pressure, eliminating all terms containing dynamic pressure and assuming $\dot{\alpha} = q$ and $-\dot{\beta} = r$ resulted in three-degree-of-freedom equations containing the inertia terms and control terms of the $\dot{p}$, $\dot{q}$, and $\dot{r}$ equations. Aerodynamic derivatives and mass characteristics of the X-1B research airplane were used during the study, except as noted.

Pilot presentation.- Presentations were varied during the tests because of the differences in analog equipment and as a result of observations as the tests progressed. Throughout the study, emphasis was placed upon presentations that were easy to learn and to interpret.

Figure 2(a) shows a sketch of the presentation in which all three displacement angles were presented on an oscilloscope. This presentation is similar to the "inverted T" presentation of reference 2 except for yaw angle, which for the present study was indicated by movement of the short vertical oscilloscope trace across the trace used to indicate bank angle.

A second presentation shown in figure 2(b), was used for most of the tests. An oscilloscope trace consisting of a short horizontal line indicated roll and pitch angle; yaw angle was indicated on a voltmeter centered below the oscilloscope.

The pilots indicated that both presentations were easy to learn and, after practice, there was little tendency toward misinterpretation.

Control stick.- The control stick used for most of the study evolved from a brief investigation of types that could be installed in the X-1B airplane. For research purposes it was believed that a separate control stick for the reaction controls would be desirable. Since it would be necessary for the pilot to control the airplane about three axes through one control, a rather unconventional control stick was envisioned. Several rather short sticks were investigated with pitch and roll control movements similar to conventional control-stick movements and with a means of rotation for yaw control. Shown in figure 3 is the control stick that was used during the investigation. Movement of the thumb rotates the curved thumb rest at the top of the stick, which applies yaw control. Although manipulating this type of thumb control was awkward at first, with practice it was not difficult to become proficient in its use. All control forces were provided by springs.

Mechanical Simulator

A photograph of the three-degree-of-freedom simulator is presented in figure 4. The simulator consists, essentially, of two steel I-beams mounted on a supporting strut by means of a universal joint that permits rotation about three axes. At first, an attempt was made to duplicate exactly the moments of inertia of the X-1B airplane; however, in order to maintain a reasonable weight the simulator was ballasted to the same inertia ratios as those of the X-1B. The simulator was balanced on the supporting strut by proper weight distribution and by adjusting the vertical center of gravity until it coincided with the pivot point. In this condition the only forces acting on the simulator, other than those from the reaction controls, arose from the mechanical friction of the universal joint. A blind-flying hood over the cockpit of the simulator was normally used during the tests.

The simulator was operated by forces developed from nitrogen gas expanding from jet nozzles at the right wing tip and aft end to apply roll control, and pitch and yaw control, respectively. Nitrogen gas was piped from a storage tank to the nozzles, and two-position solenoid-actuated valves at the nozzles provided on-off control of the nitrogen jet. The reaction forces were varied by adjusting the nozzle size to produce the desired jet thrust.

Presentation.- A photograph of the instrument panel is shown in figure 5. Conventional gyro-horizon and directional-gyro instruments were used to indicate roll, pitch, and yaw angle. The turn and bank indicator was included, since it is normally one of the primary blind-flying instruments.

Control stick.- The control stick shown in figures 3 and 4 was used during the initial simulator tests; however, later tests led to the development of a different type of control stick for the X-1B airplane. This later type, shown in figure 5, was used for most of the tests. With this stick, pitch control was applied by moving the stick up or down, yaw control by moving the stick left or right, and roll control by rotating the hand grip. Control forces were provided by springs operating on cams.

Recording instruments.- Standard NACA flight recorders were used to record control-stick positions and roll, pitch, and yaw angle and rate.

TESTS

Analog

The capacity of the computing equipment placed some limitations on the number of variables that could be investigated simultaneously. Therefore, an initial investigation was made to evaluate overall control characteristics of various reaction control configurations for zero dynamic pressure. The more promising configurations were then used to investigate control characteristics at low dynamic pressures.

The primary task of a pilot during flight in regions where reaction controls are required would be to stabilize the airplane on the flight trajectory. This type of flying was simulated during two-minute test runs in which the pilot was instructed to maintain zero roll, pitch, and yaw angle after a small initial disturbance in rolling, pitching, and yawing velocity was applied. The second task was concerned with the pilot's ability to control high rates of rotation. This task was evaluated by imposing initial disturbances about three axes and successively increasing the magnitude of the disturbances until the motions could not be controlled. These runs were made primarily for pilot familiarization, since it is expected that external disturbances during space flight will be small.

The reaction control characteristics were evaluated from pilot comments and from the total thrust-impulse requirements for the two-minute runs. In addition to providing information concerning the fuel requirements of jet-type reaction controls, thrust-impulse information was also used as an indication of control efficiency, since it is a measure of the amount of control used.

Tests were conducted with four NACA research pilots and one NACA engineer as simulator pilots. Although an attempt was made to have several pilots fly each condition studied, each pilot did not fly every condition. Differences in the control techniques of the operators were noted, with large variations for one operator sometimes evidenced. In general, the thrust-impulse data presented herein show trends common to several operators and do not indicate maximum or minimum impulse levels.

Mechanical Simulator

The tests with the mechanical simulator were conducted to evaluate reaction control characteristics qualitatively under conditions more closely approximating flight than were available with the analog computer. The results of the analog studies were used to establish the range of control effectiveness to be investigated. Various control effectiveness levels within this range were evaluated on the simulator by making test runs and comparing the ease of control for each level. The pilots' control task during these runs was to maintain a stabilized attitude while small external disturbances were applied.

RESULTS AND DISCUSSION

Analog

To familiarize the reader with some of the peculiarities of flight with reaction controls, the control characteristics of conventional aerodynamic controls at normal speeds are compared with the control characteristics of reaction controls at a dynamic pressure of zero in figure 6. This figure shows the motions of an aircraft following lateral and longitudinal control inputs with aerodynamic and reaction controls. The difference in response is not caused by the difference in the controls, but arises from the lack of aerodynamic stabilizing or damping forces during flight at zero dynamic pressure. Thus, the response to reaction control input is an angular acceleration rather than an angular velocity or attitude angle as with aerodynamic control. For the zero dynamic-pressure condition the pilot would be required to provide stability and damping with the reaction controls.

An initial exploratory investigation was made with this type of control for familiarization purposes, followed by a more detailed study of various conditions. As a result of the exploratory investigation, the general characteristics of flight with reaction controls were found to be different from those with aerodynamic controls because of overshoot or overcontrol tendencies. Since all motions were undamped, it was difficult to reduce angular velocities to exactly zero, and desired trim angles were usually undershot or overshot. However, control was not too difficult, and only a relatively short learning period was required to become proficient with reaction controls. Constant attention to the control task was required. Satisfactory control could be maintained for a large range of effectiveness levels and control configurations, but large differences were encountered in the ease of control for the various conditions. Therefore, the determination of optimum control configurations and effectiveness levels became the primary objective of the study. The investigation also included studies of the effects of dynamic pressure up to 20 pounds per square foot, rocket thrust lag, pilot technique, and inertial coupling. The results of the various studies are presented in the following sections.

Control configuration.- The investigation was first concerned with the choice of control configuration or proportioning of thrust (or control effectiveness) to control stick deflection. The three control configurations investigated (shown in fig. 7) are: proportional control, with a linear variation of thrust to control-stick deflection; on-off control, with full thrust being applied when the control stick is moved to a certain position (90-percent travel); and two-step on-off control, with thrust being applied in two levels of on-off operation (50-percent and 90-percent travel).

A control problem was initially encountered with the proportional control because of the difficulty in avoiding small amounts of inadvertent control application when the control stick was neutralized. This problem was eliminated either by the provision of positive centering through centering cams or by a deadspot in thrust at the center of control travel. The results of a brief separate investigation to determine the desired amount of deadspot showed that a deadspot of at least 18 to 20 percent of control travel is required. A deadspot of 25 percent, shown in figure 7, was used for the proportional-control tests reported herein.

Typical time histories from the two-minute trim runs are shown in figure 8 for proportional control and on-off control configurations having equal control effectiveness. Control inputs for both configurations consist essentially of pulses of short duration. The control inputs and resulting motions are typical of the continuous control manipulations required for acceleration controls.

Some pilots tended to use proportional control as on-off control (that is, control inputs were short pulses of about maximum control power) and, therefore, found no appreciable advantage of proportional control over on-off control. Others indicated that control with the proportional control was easier, since it was possible to make very small control applications.

The two-step on-off control was of considerable advantage for control of large disturbances. However, the two-step control was of no advantage for the trim runs, since the second step was used only infrequently.

Figure 9 presents a comparison of thrust impulse for two-minute trim runs with proportional and on-off controls for various control effectiveness levels. Control effectiveness is expressed as the maximum angular acceleration produced by jet thrust. Roll control effectiveness was arbitrarily selected for comparative purposes. These data show slightly smaller impulse levels for the proportional control at low effectiveness levels, with larger differences shown at the higher effectiveness levels. However, since differences in impulse are small, and since there were varied opinions regarding the relative merit of proportional and on-off controls, it appears that for the stabilization task there is no marked advantage for proportional control. Because the on-off control configuration offered some advantage in simplifying the analog simulation, on-off controls were used throughout the remainder of the investigation.

Control effectiveness levels.- Since one of the objectives of the study was to establish desirable levels of control power, a range of control effectiveness for angular accelerations from 1.25 degrees per second^2 to 40 degrees per second^2 was investigated. Although the maximum angular acceleration of 40 degrees per second^2 might seem to be low in comparison with the effectiveness of aerodynamic controls at normal speeds, it was about the upper limit of reaction control effectiveness of interest because of large amounts of overshoot produced at higher levels.

A range of ratios of roll control to pitch or yaw control of from 1/2 to 8 were investigated to determine the desired proportioning between these controls. The tests indicated a preference for higher roll control effectiveness than pitch or yaw control effectiveness (R = 2 or 4).

Sample time histories from two-minute trim runs are shown in figure 10 for two control effectiveness levels. A simplified notation of 2.5, 1.25, 1.25 will be used to indicate control effectiveness in degrees per second^2 of angular acceleration about the roll, pitch, and yaw axes, respectively. In figure 10 the time histories for control effectiveness levels of 20, 10, 10 and 2.5, 1.25, 1.25 show the characteristic hunting of roll, pitch, and yaw angle, with the larger angles for the 20, 10, 10 control effectiveness indicating the increased overshoot tendency at the higher effectiveness level.

The effect of control effectiveness on impulse for the two-minute trim runs is presented in figure 11. The data are shown for ratios of roll to pitch or yaw control of 1/2, 1, 2, 4, and 8 as functions of roll control effectiveness. The data show a large increase in the impulse required as control effectiveness is increased. It might be expected that, if control could be as easily maintained with any level of control effectiveness, the impulse levels would be about the same. Thus, the increased impulse shown (for one control ratio) for higher control effectiveness indicates that more control is required for these conditions. It should be pointed out that the impulse values are for the moments of inertia and moment arms of the X-1B airplane, but the trends should be applicable to other configurations.

A summary of pilot opinion of the various control ratios and effectiveness levels investigated is shown in figure 12. Each condition was rated as satisfactory or unsatisfactory, and an indication was given of the best, or preferred, condition. The left boundary of the satisfactory region, in general, represents the region where control was described as sluggish or aircraft response was too slow. The curved boundary at the right of the satisfactory region shows the region where control was difficult because of excessive overshooting. The preferred conditions, as indicated, correspond to control effectiveness levels of 5, 2.5, 2.5 and 10, 2.5, 2.5.

Effects of disturbances.- Tests were made to determine the difficulty of controlling large external disturbances with reaction controls. The results are more qualitative than quantitative, since control depends upon such factors as pilot reaction time, pilot experience with the analog simulator, type of disturbance, and direction of motion of the disturbance. In addition, little is known about the magnitude of possible disturbances for low or zero dynamic pressure conditions.

For these tests an initial angular velocity was applied about all three axes and the thrust impulse required to control these imputs and return to trim conditions was measured. Control effectiveness levels varied from 5, 2.5, 2.5 to 20, 10, 10. A summary of the data obtained is presented in figure 13. The disturbances are expressed in terms of the product of the initial angular velocity inputs $p \times q \times r$. In general, the data show the increased impulse required to control the larger disturbances. An upper limit was established for the factor $p \times q \times r$

of 2,500 $(\text{deg/sec})^3$, above which combined disturbances could not be controlled within the limits of the computer simulation of ±40° pitch, ±40° yaw angle, and ±180° bank angle.

Effect of piloting technique.- As expected, control technique (pertaining to the method of maintaining precise trim) had a noticeable effect on impulse requirements. Therefore, to evaluate these effects data were obtained for two trimming tasks: one in which very accurate trim was maintained, and one in which the airplane was allowed to drift through about 5° in roll, pitch, and yaw. The effect of these two control techniques is shown in figure 14. It is seen that the impulse requirements for control within 5° are generally less than half those for precise trimmed flight.

Effect of inertial coupling.- The inertial forces become more dominant factors in establishing the motion of an airplane as dynamic pressure is reduced, until at zero dynamic pressure the equations of motion contain only the inertia and reaction control terms. Thus, the most critical condition for inertial coupling is at zero dynamic pressure; for this condition inertial coupling may occur at low roll rates. For example, with the X-1B airplane a roll rate of 80 degrees per second would produce a pitching acceleration of 2 degrees per second^2 which is about the magnitude of the pitch reaction control. However, there is believed to be little reason for a pilot to demand roll rates of this magnitude at zero dynamic pressure, since it will not be possible to maneuver or change the flight path. For the stabilization task employed in this investigation the roll rates remained low (2 to 3 deg/sec); no inertial coupling effects were evidenced.

Effect of rocket thrust lag characteristics.- Most rockets or jets exhibit a characteristic time lag for full thrust to be developed and a similar thrust decay time at shutdown. These characteristics could be important to the control problem, since for trimmed flight control inputs were predominantly very short duration pulses and the thrust lag time would be an appreciable part of the control input time. Therefore, the effects of thrust lag on control were investigated.

Figure 15 shows the thrust lag characteristics that were simulated on the analog computer. Jet thrust was varied as an exponential function of time both for thrust buildup and cutoff. Buildup times of 0.1 second and 0.25 second for achievement of 67 percent of maximum thrust were used.

No noticeable difference in control was encountered with 0.1 second lag, and it was slightly easier to control with 0.25 second lag. This somewhat unexpected result may be caused by the thrust lag providing smaller control accelerations for short pulse-type control inputs, thus effectively reducing the control effectiveness. As shown in figure 16, the impulse required for the two-minute trim runs decreased slightly as the thrust lag increased to 0.25 second.

Effect of dynamic pressure.- Preliminary studies have indicated that aerodynamic controls will probably be adequate for control at dynamic pressures as low as 10 pounds per square foot. No attempt was made during the present investigation to establish the maximum dynamic pressure region in which reaction controls will be required. Instead, the control characteristics of reaction controls for dynamic pressures up to 20 pounds per square foot were determined. The investigation included tests at Mach numbers of 0.5 and 2.0, using the X-1B aerodynamic derivatives for these Mach numbers. The on-off control configuration with an effectiveness level of 5, 2.5, 2.5 was employed.

The most pronounced effects on control at low dynamic pressure, in contrast to zero dynamic pressure, were caused by the presence of some degree of longitudinal stability and the large dihedral effect. Even though the longitudinal damping was low, the stable oscillation resulted in less pitch control being required. In contrast, because of the dihedral effect considerably more roll control was required to counteract the rolling produced by even small sideslip angles.

Figure 17 shows the variation of reaction control impulse with dynamic pressure up to 20 pounds per square foot for Mach numbers of 0.5 and 2.0. Little difference is evidenced in the impulse level for the zero dynamic pressure condition and the levels for the various low dynamic pressures and Mach number conditions.

To aid in evaluating the control characteristics at low dynamic pressures, a range of the static derivatives C_{m_α}, C_{n_β}, and C_{l_β} was investigated for a dynamic pressure of 5 pounds per square foot. Figure 18 shows the variation of impulse with C_{m_α}. In general, as the longitudinal stability $\left(-C_{m_\alpha}\right)$ increased the impulse decreases, indicating that slightly less control is required. Pilot comments also indicated that it was somewhat easier to maintain trim at the higher values of stability.

The effects of changes in C_{n_β} on the ease of control were not particularly noticeable, except at unstable values of directional stability. Even this condition was described as only slightly more difficult to control than for $C_{n_\beta} = 0$. As C_{n_β} was increased the control task became slightly easier, which resulted in lower thrust-impulse levels as shown in figure 19.

The effects of changes in C_{l_β} on the ease of control were more pronounced than effects from changes in C_{m_α} or C_{n_β}. As C_{l_β} was reduced from the basic X-1B level, control became easier; control at $C_{l_\beta} = 0$ was described as similar to the zero dynamic pressure condition. At the higher levels of C_{l_β} the coupled roll-yaw motions make stabilization much more difficult and constant concentration on the control task is required. Figure 20 shows the increase of thrust impulse required for the more difficult control at higher values of C_{l_β}.

Effects of inertia scaling.- For reaction controls, the thrust-impulse requirements are directly proportional to aircraft moment of inertia and reaction control moment arm and thrust level. Therefore, the impulse data previously presented would be difficult to apply to airplane configurations with mass characteristics different from those of the X-1B airplane. Of interest to other configurations would be the total angular acceleration control (around each axis) required for the two-minute trim runs. This quantity gives a measure of the total control used and should not vary between configurations.

Total angular accelerations for roll, pitch, and yaw are presented in figure 21 for control effectiveness levels of 5, 2.5, 2.5 and 10, 5, 5. It is noted that about an equal amount of pitch and yaw control acceleration is used and that considerably more roll control acceleration is required. The data also show that for a trim control task the total amount of control acceleration increases as control effectiveness is increased.

Mechanical Simulator

Control of the mechanical simulator was characterized by the same type of control inputs as for the analog study; that is, short pulse-type control inputs, as shown in figure 22, a typical time-history run for the simulator. Except for slightly longer control inputs, the time history is very similar to the analog data of figures 8 and 10.

Control effectiveness was evaluated by adjusting jet thrust until satisfactory control effectiveness levels were obtained. Since only a limited range of control effectiveness could be investigated on the simulator, it was not possible to define a satisfactory or unsatisfactory boundary as shown in figure 12 for the analog tests. However, good agreement was obtained between the preferred control effectiveness levels for the mechanical simulator and for the analog studies.

From these studies it was found that during the stabilization task, for which the angular rotation rates remain small, the pilot experiences very little motion stimulus. Therefore, it was not important to the simulation to provide pilot motion in response to control input.

The tests with the simulator indicated problems that were not encountered during the analog investigation. As an example, because of the low value of roll inertia and the high level of thrust in yaw, it was found that a very small misalinement of the yaw jets produced an annoying rolling moment. This indicated that care must be taken in alining the thrust axes of the reaction controls.

Of interest in regard to instrument presentation is the usefulness of the turn and bank indicator to indicate yaw rate. The turn indicator enabled very small yawing motion to be detected and controlled.

CONCLUDING REMARKS

Analog computer and mechanical simulator studies have been made of manually controlled jet reaction controls. These studies have indicated that satisfactory attitude control for an attitude stabilization control task can be maintained with acceleration command jet reaction controls, although constant attention to the control task is required. Control techniques are somewhat different from those used with aerodynamic controls at normal flight speeds. Perfectly trimmed flight is difficult to establish, and continuing overcontrolled motions to some degree are generally encountered.

Because of the ease of overcontrolling with large control powers, much lower control power than that for normal aerodynamic controls was desired. Control levels of 5 or 10 degrees per second^2 of angular acceleration in roll and 2.5 degrees per second^2 of angular acceleration in pitch and yaw were preferred.

No conclusive differences were established between the ease of control with full-on, full-off controls and proportional jet controls.

Reaction control systems with up to 0.25 second in the lag of jet thrust did not have any adverse effect on control.

Moderate values of effective dihedral produced a noticeable increase in the amount of roll control required to maintain trim at dynamic pressures up to 20 pounds per square foot because of the rolling produced by small sideslip angles. Changes in longitudinal or directional stability had only a small effect on the ease of control.

High-Speed Flight Station,
National Advisory Committee for Aeronautics,
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APPENDIX

EQUATIONS OF MOTION

Additional symbols used in the equations of this appendix and not presented in the text are defined as follows:

$A = \frac{\rho V^2 S}{2}$

C_L	lift coefficient, $\frac{\text{Lift}}{\frac{1}{2}\rho V^2 S}$
C_Y	lateral-force coefficient, $\frac{\text{Lateral force}}{\frac{1}{2}\rho V^2 S}$
$C_{L_\alpha}, C_{Y_\beta}$	indicates derivative with respect to subscript
$C_{l_p}, C_{l_r}, C_{n_r}, C_{n_p}$	indicates derivative with respect to $\frac{b}{2V} \times$ subscript
$C_{m_{\dot{\alpha}}}, C_{m_q}$	indicates derivative with respect to $\frac{\bar{c}}{2V} \times$ subscript
g	acceleration due to gravity, ft/sec^2
I_X	moment of inertia of airplane about X-axis, slug-ft^2
I_{XZ}	product of inertia referred to X- and Z-axes, slug-ft^2
I_Y	moment of inertia of airplane about Y-axis, slug-ft^2
I_Z	moment of inertia of airplane about Z-axis, slug-ft^2
l_X	moment arm of roll jet, ft
l_Y	moment arm of pitch jet, ft

l_Z moment arm of yaw jet, ft

m airplane mass, W/g, slugs

$\dot{p}_\delta$ rolling acceleration produced by roll jet, $\frac{l_X}{I_X} T_{X_{\delta_X}} \delta_X$, radians/sec^2

$\dot{q}_\delta$ pitching acceleration produced by pitch jet, $\frac{l_Y}{I_Y} T_{Y_{\delta_Y}} \delta_Y$, radians/sec^2

$\dot{r}_\delta$ yawing acceleration produced by yaw jet, $\frac{l_Z}{I_Z} T_{Z_{\delta_Z}} \delta_Z$, radians/sec^2

T_X roll jet thrust, lb

T_Y pitch jet thrust, lb

T_Z yaw jet thrust, lb

W airplane weight, lb

X,Y,Z body axes of airplane

α_{L_O} angle of attack at zero lift, radians or deg

δ_X roll control stick deflection, deg

δ_Y pitch control stick deflection, deg

δ_Z yaw control stick deflection, deg

The five-degree-of-freedom equations of motion referenced to the body axes are as follows:

$$\dot{p} = \left(\frac{I_Y - I_Z}{I_X}\right)qr + \frac{I_{XZ}}{I_X}\dot{r} + \frac{I_{XZ}}{I_X}pq + \frac{Ab^2}{2VI_X}C_{l_p}p + \frac{Ab^2}{2VI_X}C_{l_r}r + \frac{Ab}{I_X}C_{l_\beta}\beta + \dot{p}_\delta$$

$$\dot{q} = \left(\frac{I_Z - I_X}{I_Y}\right)pr + \frac{I_{XZ}}{I_Y}r^2 - \frac{I_{XZ}}{I_Y}p^2 + \frac{A\bar{c}^2}{2VI_Y}C_{m_q}q + \frac{A\bar{c}^2}{2VI_Y}C_{m_{\dot{\alpha}}}\dot{\alpha} + \frac{A\bar{c}}{I_Y}C_{m_\alpha}\Delta\alpha + \dot{q}_\delta$$

$$\dot{r} = \left(\frac{I_X - I_Y}{I_Z}\right)pq + \frac{I_{XZ}}{I_Z}\dot{p} - \frac{I_{XZ}}{I_Z}qr + \frac{Ab^2}{2VI_Z}C_{n_r}r + \frac{Ab^2}{2VI_Z}C_{n_p}p + \frac{Ab}{I_Z}C_{n_\beta}\beta + \dot{r}_\delta$$

$$\dot{\beta} = \frac{g}{V}m_3 - r + \alpha p + \frac{A}{mV}C_{Y_\beta}\beta$$

$$\dot{\alpha} = q + \frac{g}{V}n_3 - p\beta - \frac{A}{mV}C_{L_\alpha}\alpha + \frac{A}{mV}C_{L_\alpha}\alpha_{L_O}$$

The following equations for the direction cosines l_3, m_3, and n_3 were used:

$$\dot{l}_3 = m_3r - n_3q$$

$$\dot{m}_3 = n_3p - l_3r$$

$$\dot{n}_3 = l_3q - m_3p$$

$$l_3 = -\sin\theta_e$$

$$m_3 = \sin\varphi_e\cos\theta_e$$

$$n_3 = \cos\varphi_e\cos\theta_e$$

where

φ_e, θ_e angles between the body axis and earth gravity axis

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2. Sherman, Windsor L., Faber, Stanley, and Whitten, James B.: Study of Exit Phase of Flight of a Very High Altitude Hypersonic Airplane by Means of a Pilot-Controlled Analog Computer. NACA RM L57K21, 1958.

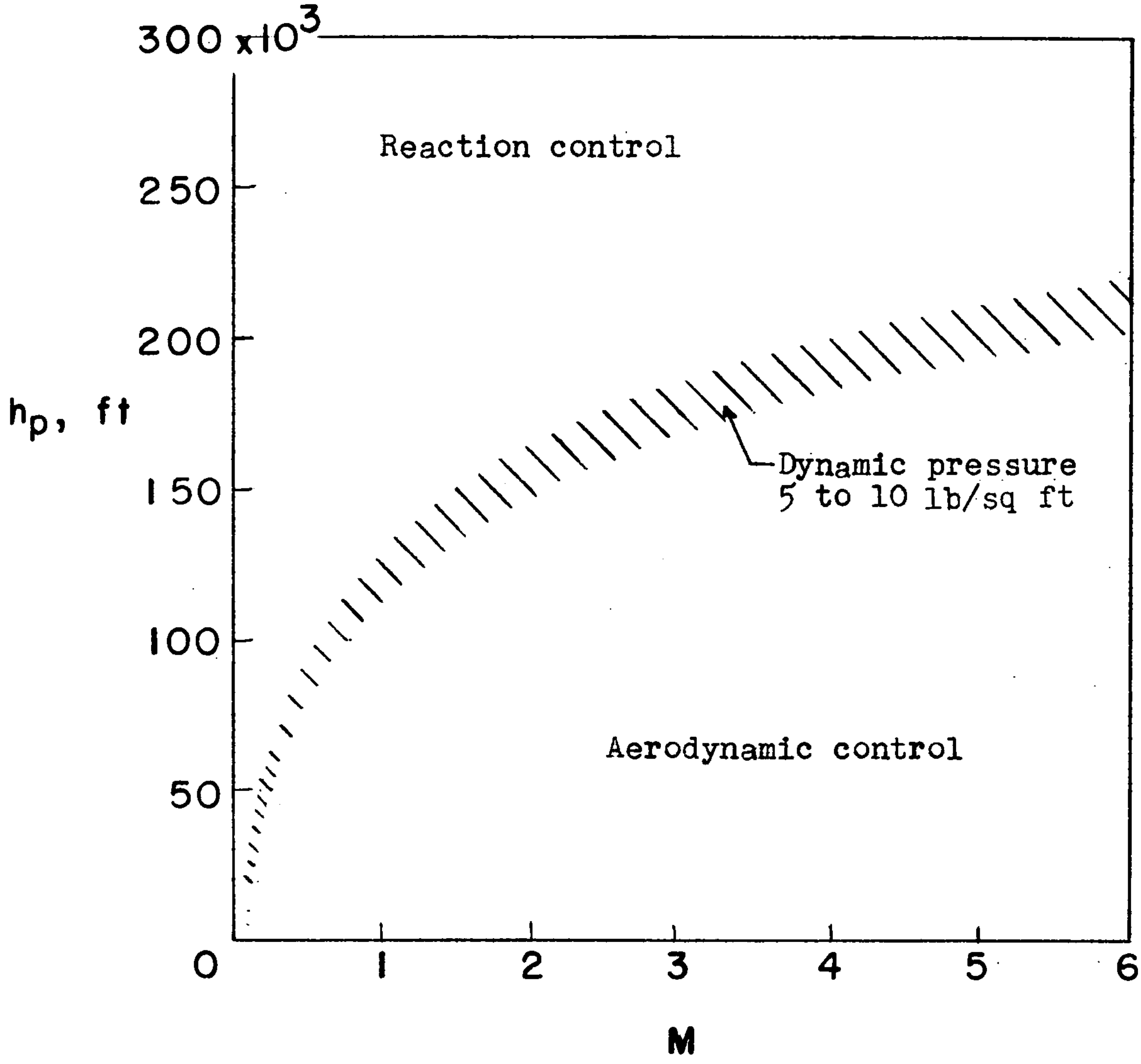
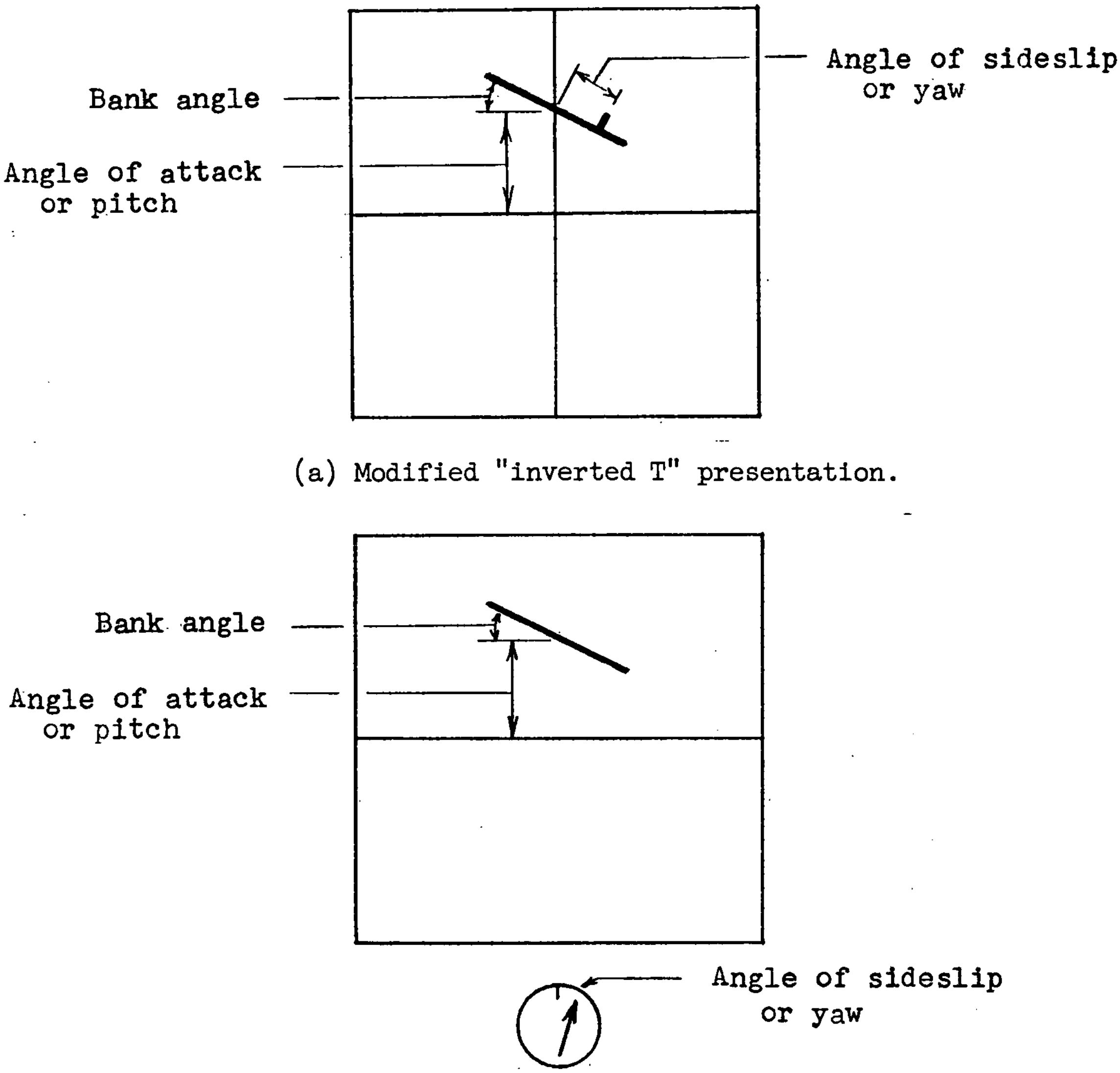


Figure 1.- Aerodynamic and reaction control regions.



(a) Modified "inverted T" presentation.

(b) Standard presentation.

Figure 2.- Sketches of pilot presentation.

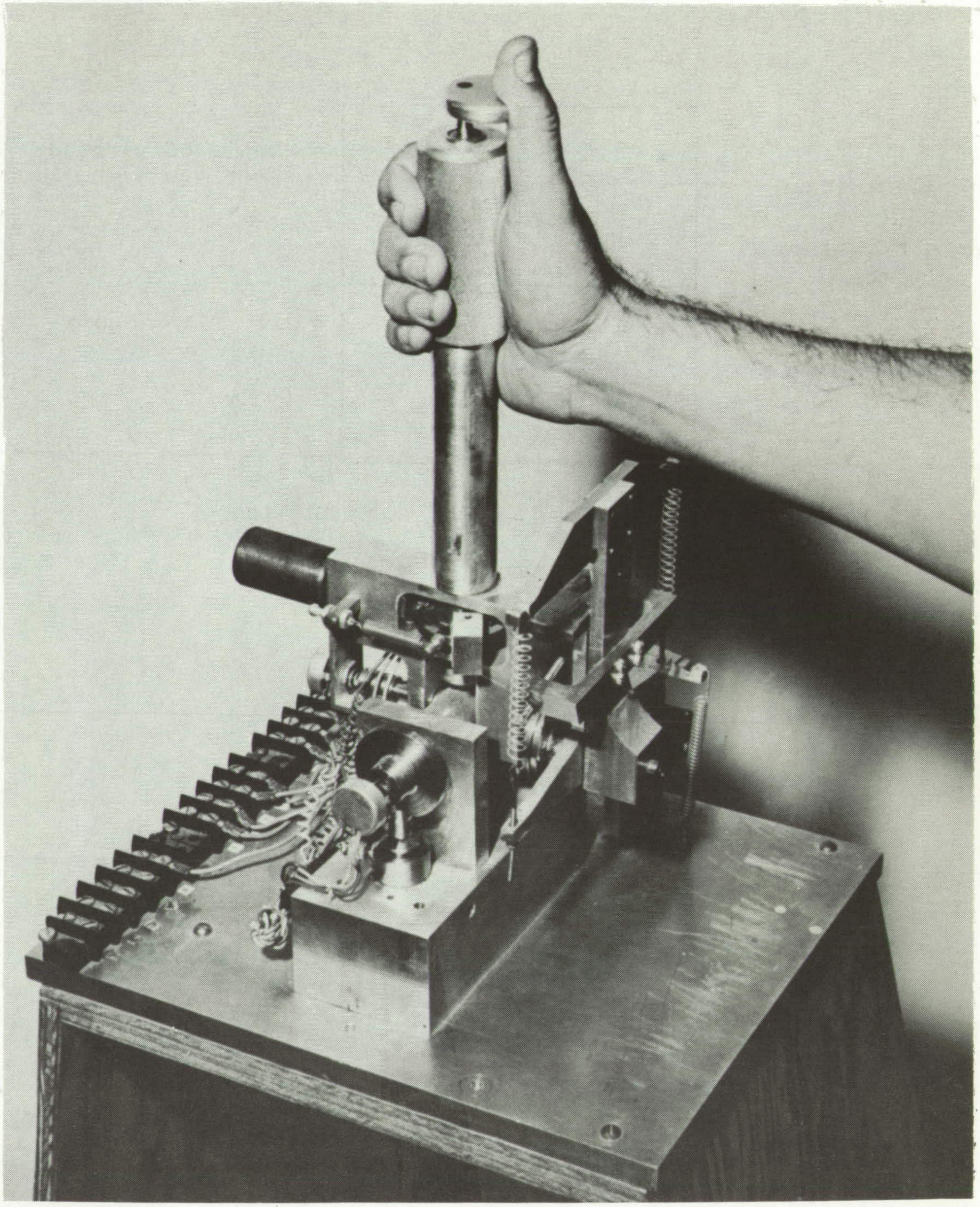


Figure 3.- Photograph of three-axis control stick. E-2633

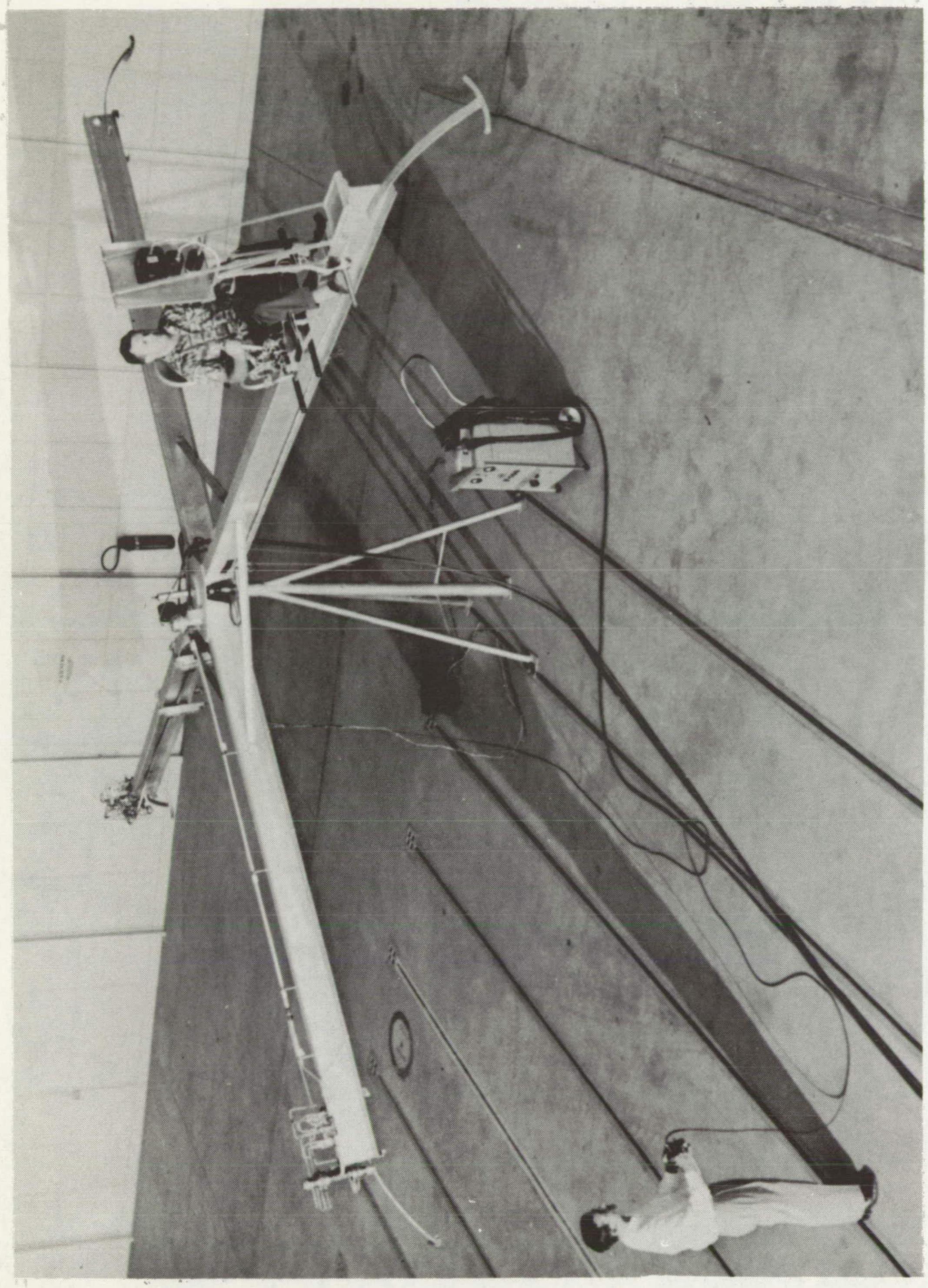
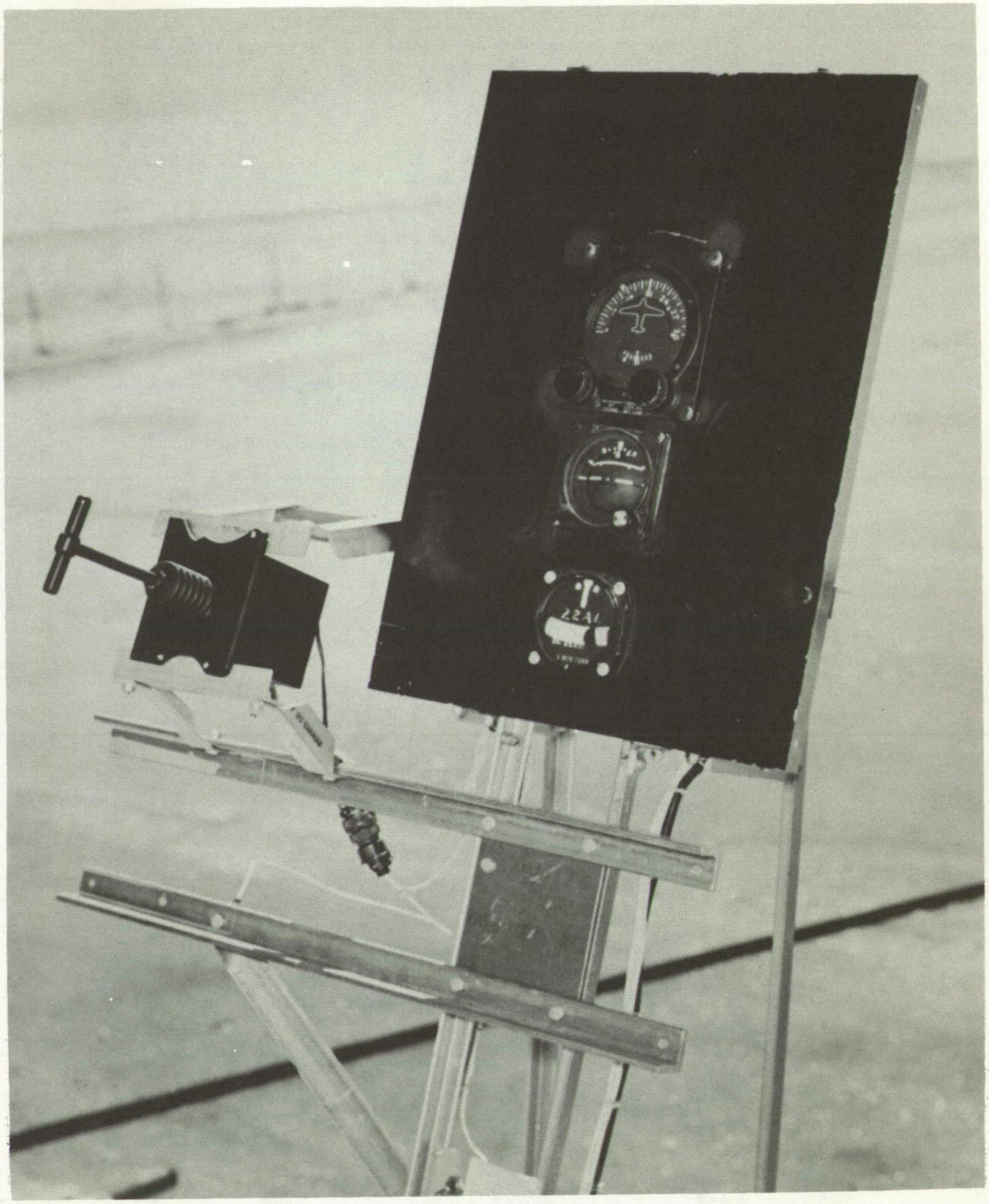


Figure 4.- Photograph of mechanical simulator. E-2306



E-2906

Figure 5.- Photograph showing instrument panel and control stick.

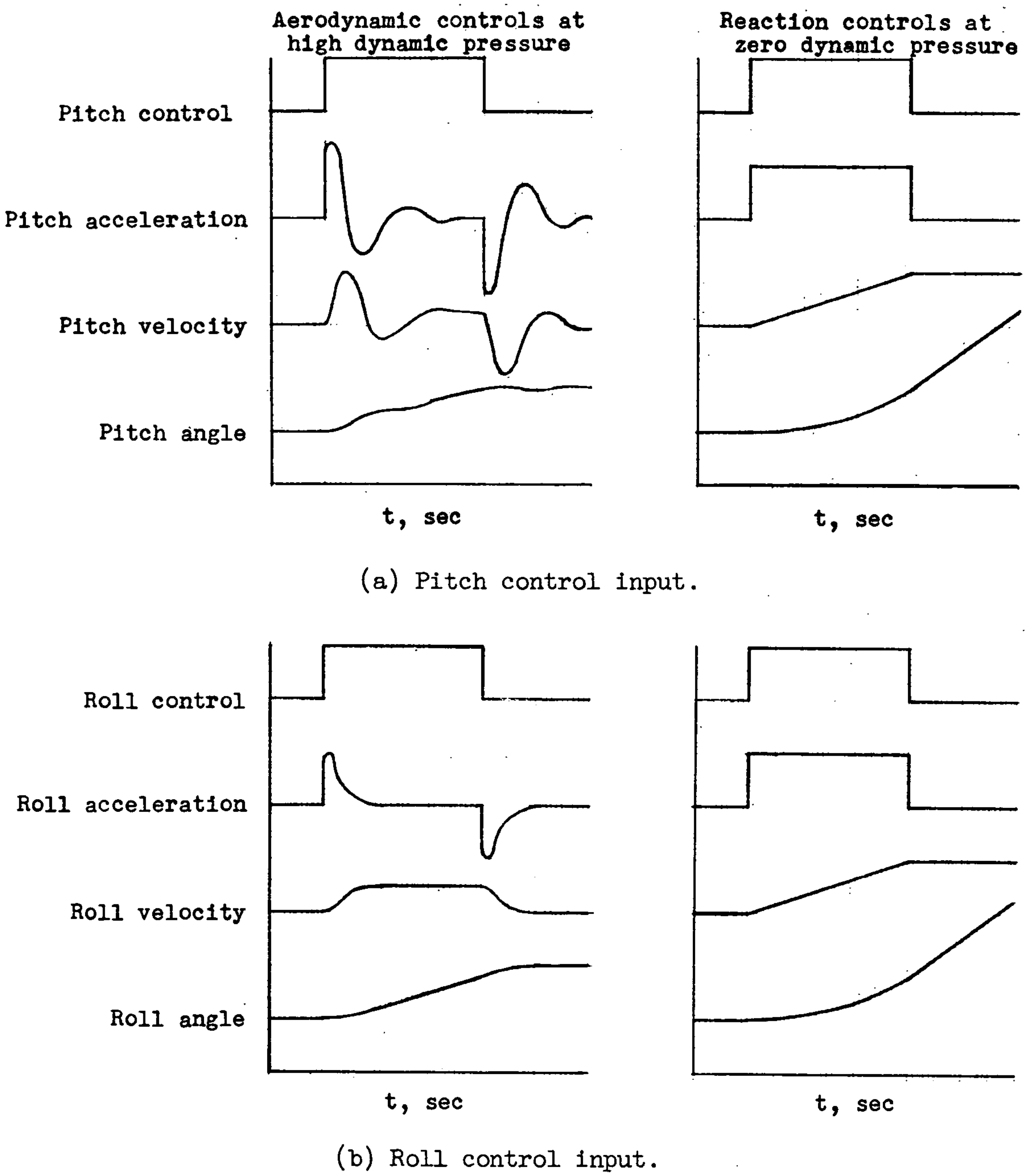


Figure 6.- Comparison of airplane motions resulting from aerodynamic and reaction controls.

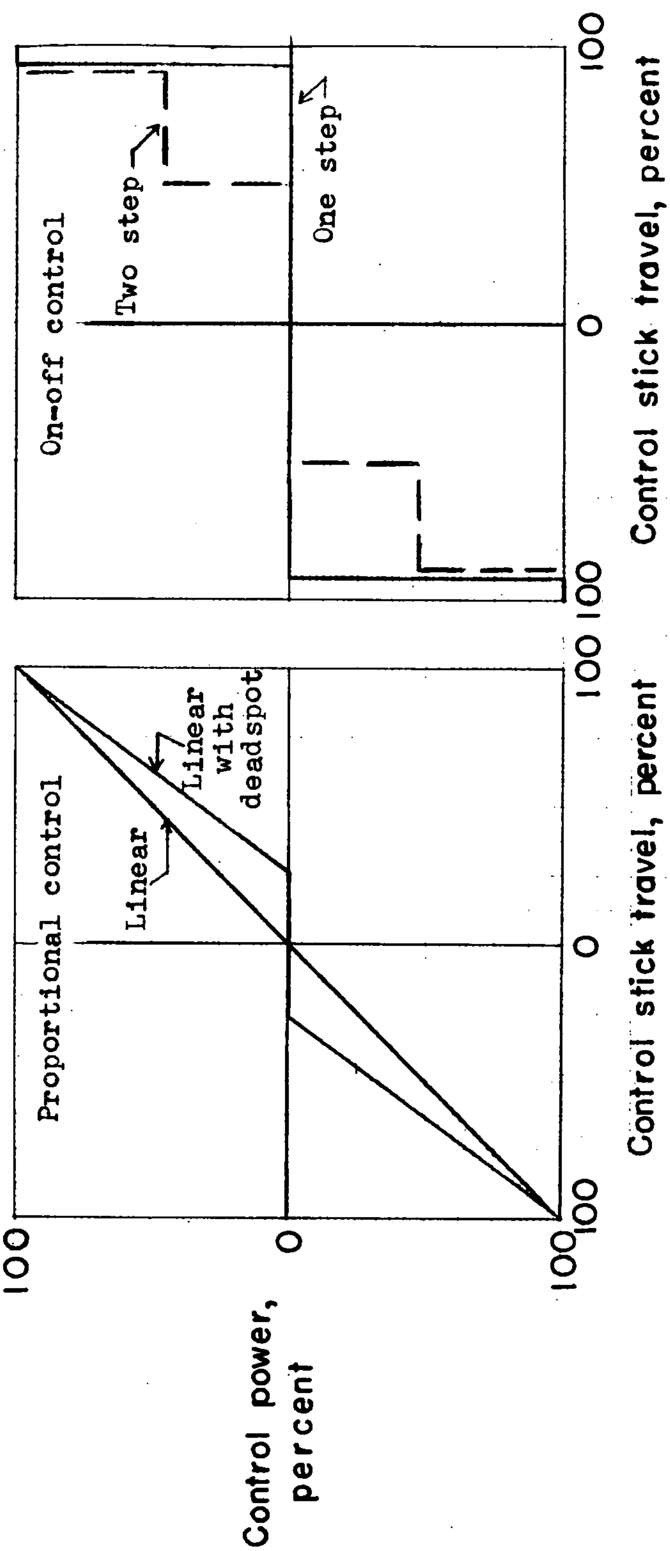
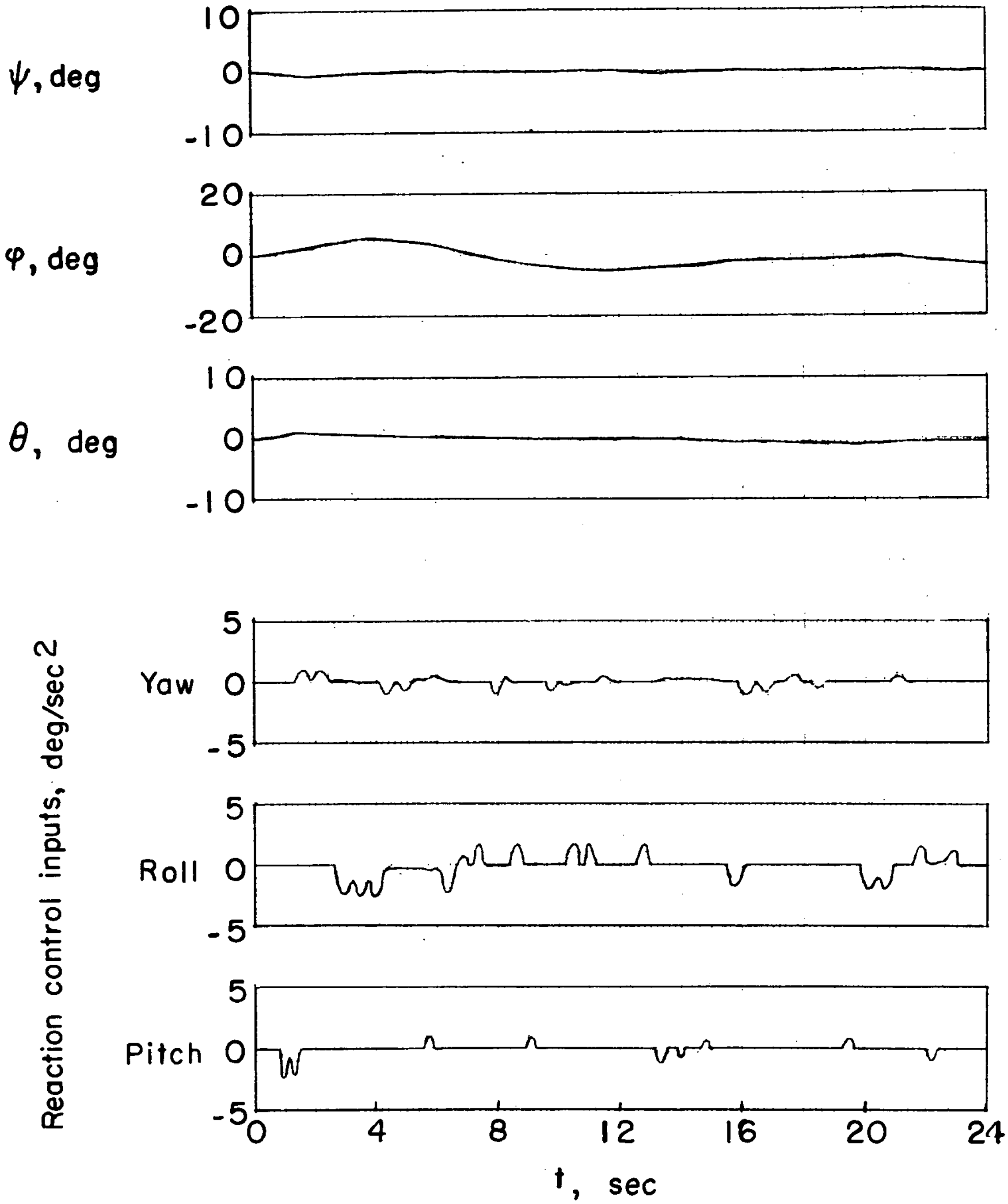
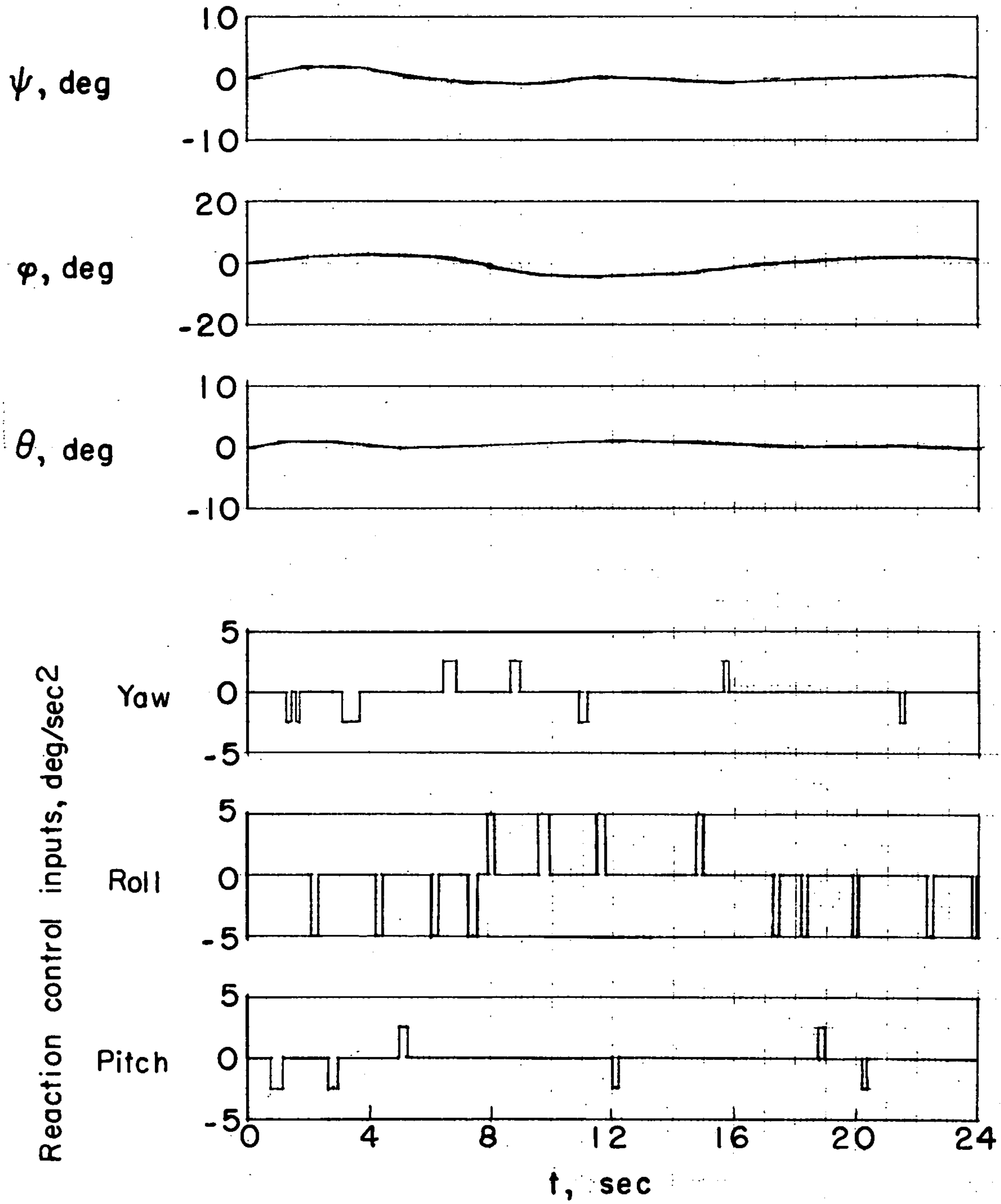


Figure 7.- Control configurations.



(a) Proportional control.

Figure 8.- Time histories of stabilized trim runs with proportional and on-off reaction controls of equal effectiveness. Dynamic pressure = 0.



(b) On-off control.

Figure 8.- Concluded.

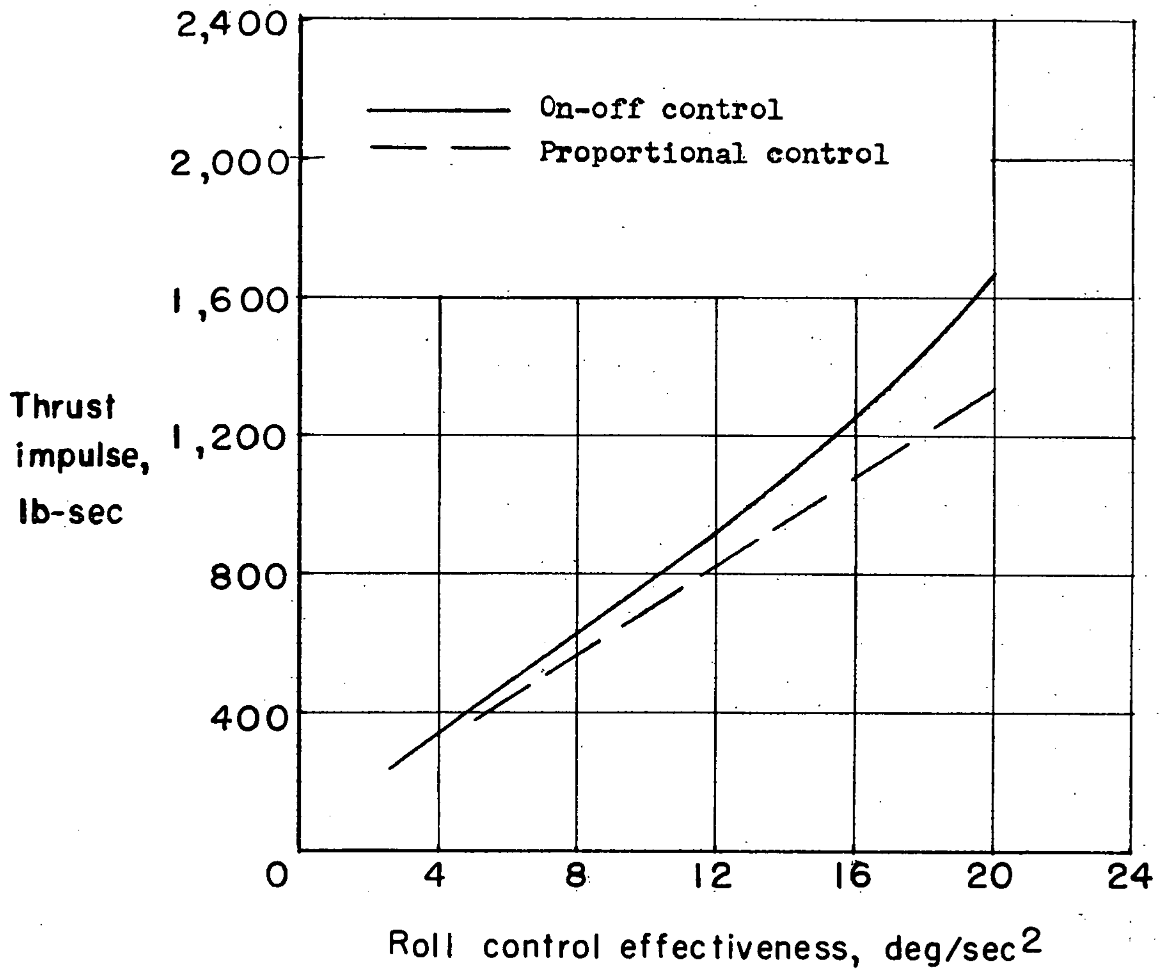
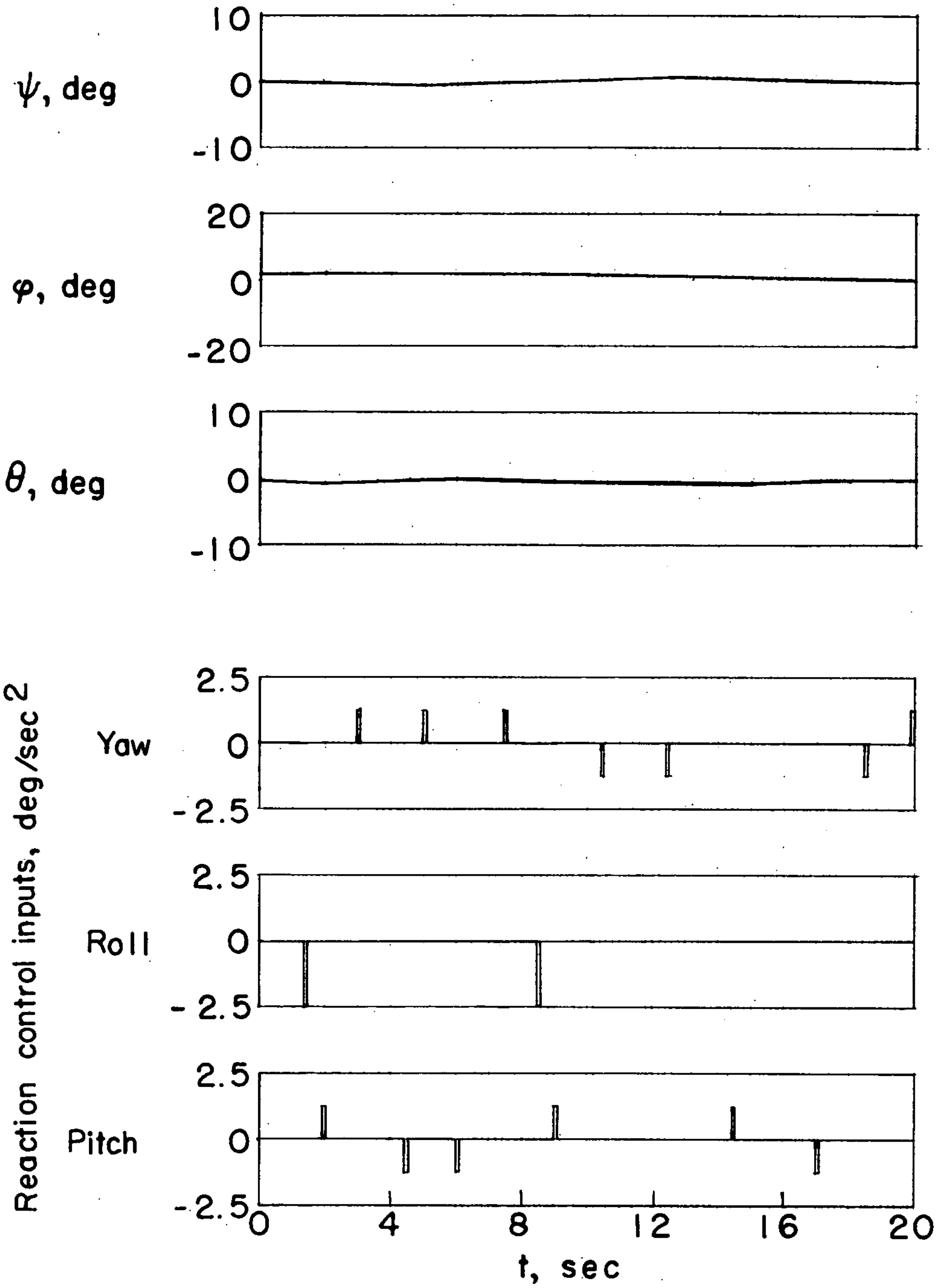
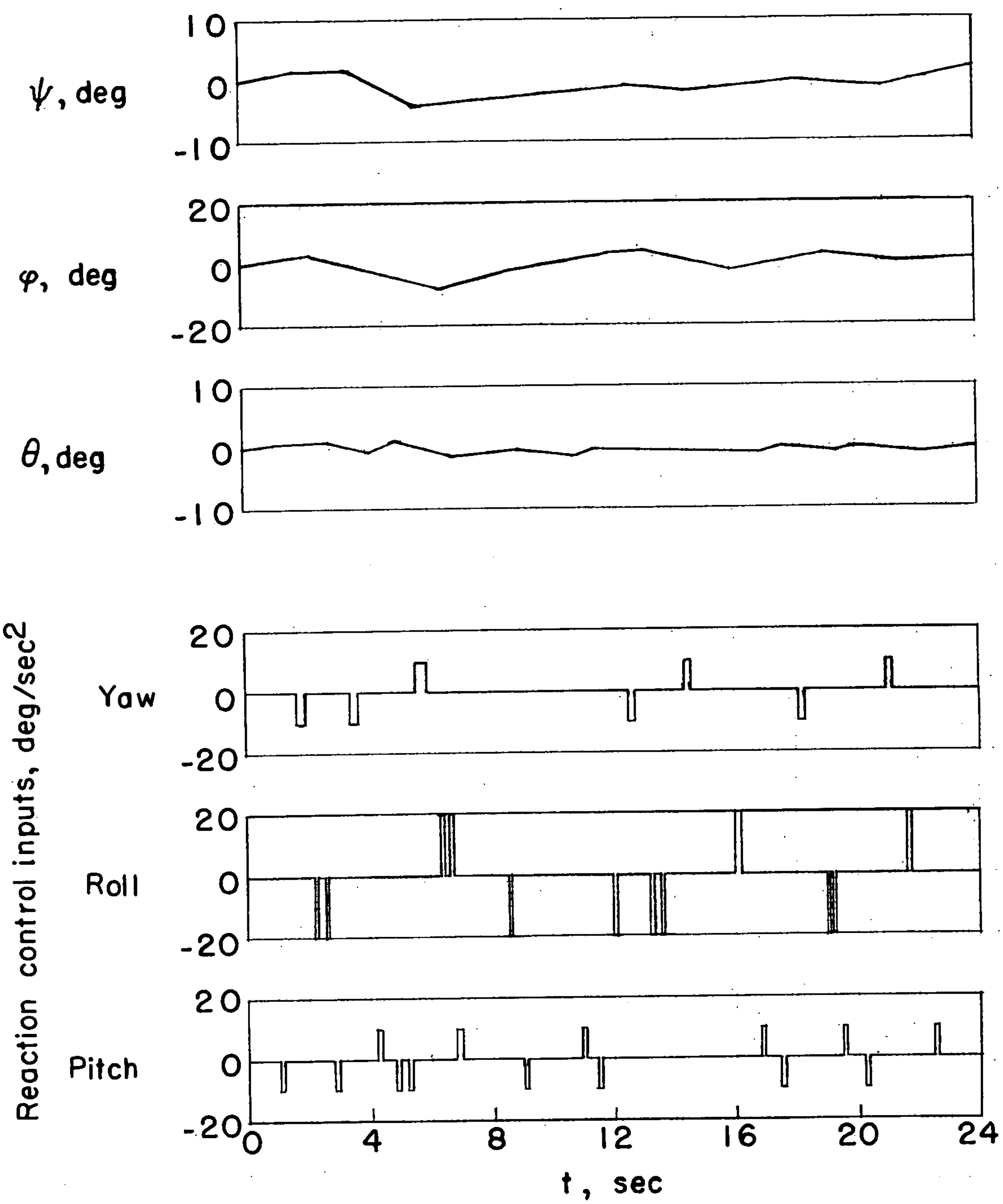


Figure 9.- Comparison of impulse requirements for two-minute stabilized trim runs. R = 2; dynamic pressure = 0.



(a) Control effectiveness levels of 2.5, 1.25, 1.25.

Figure 10.- Time histories of stabilized trim runs showing effect of control effectiveness. On-off control; dynamic pressure = 0.



(b) Control effectiveness levels of 20, 10, 10.

Figure 10.- Concluded.

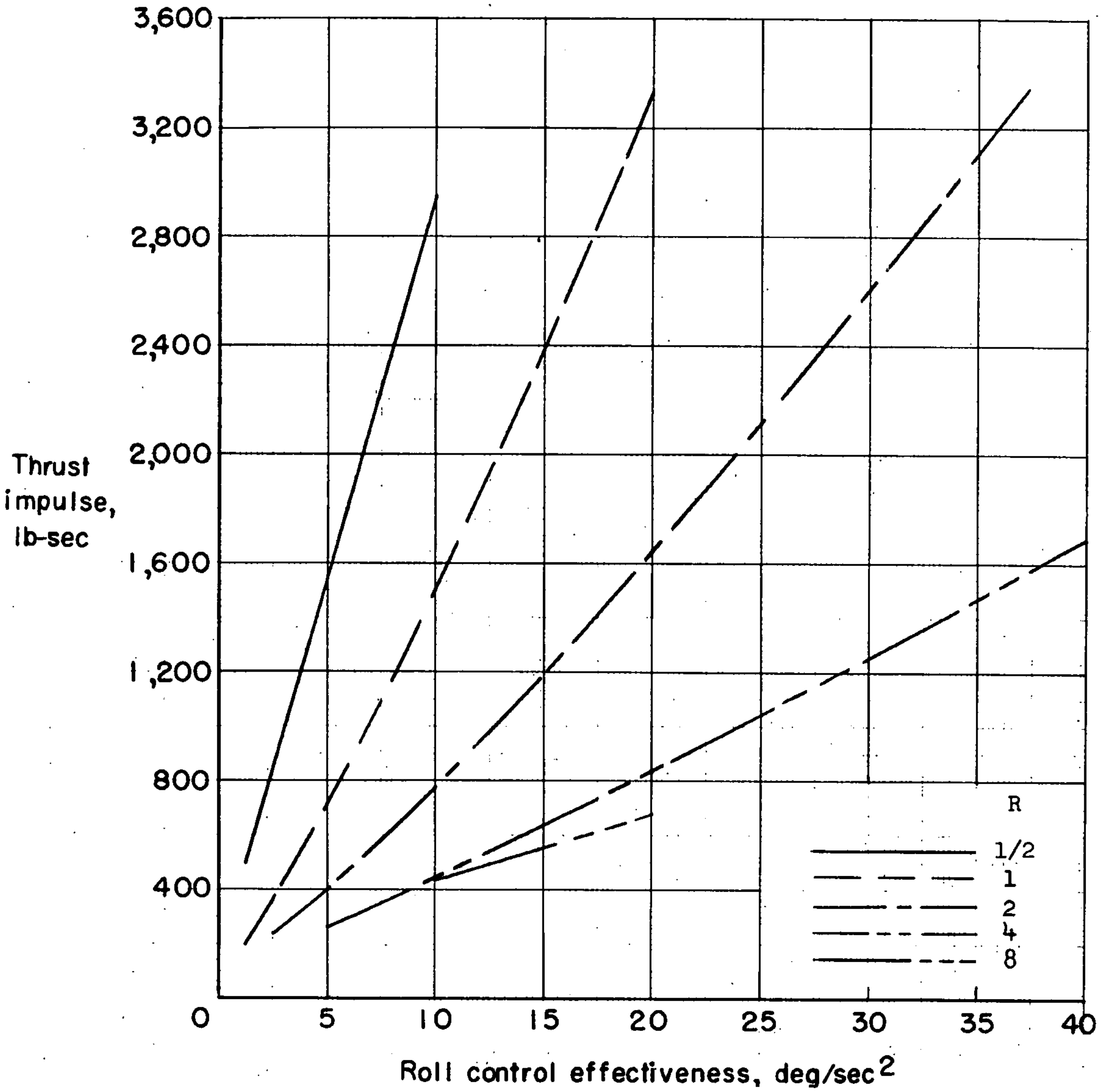


Figure 11.- Variation of impulse with control effectiveness and control ratio for two-minute trim runs. Dynamic pressure = 0; on-off control.

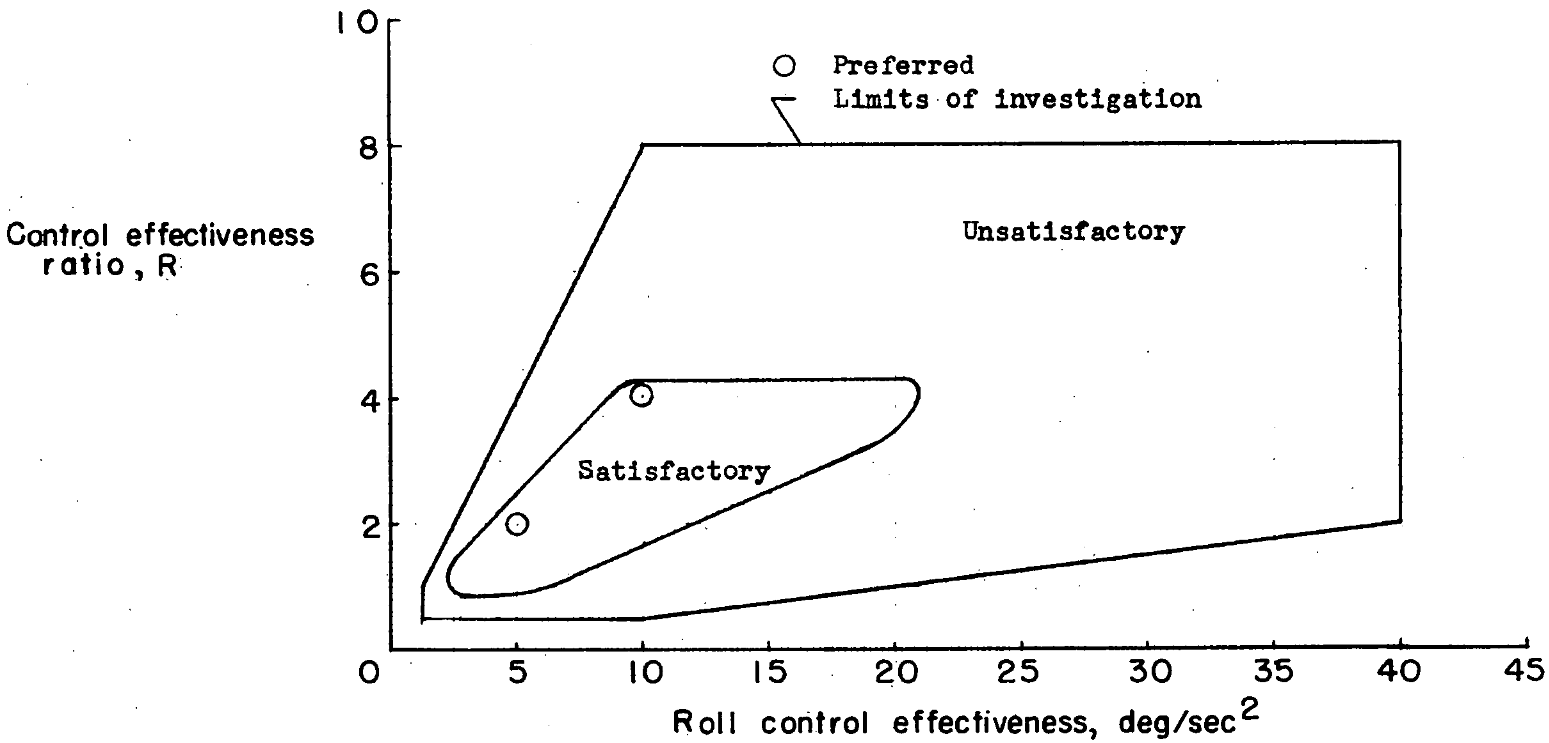


Figure 12.- Satisfactory control effectiveness levels as determined from pilot opinions. Dynamic pressure = 0; on-off control.

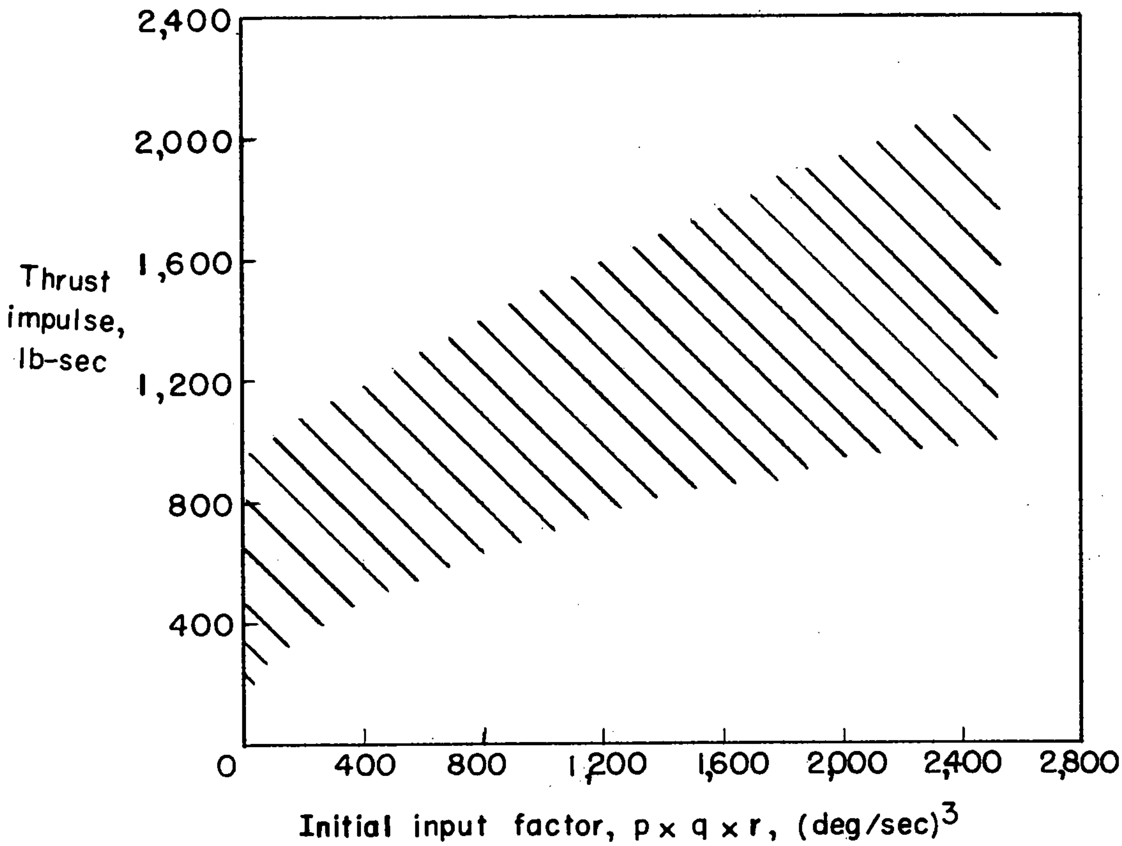


Figure 13.- Thrust impulse required for control of disturbances. Dynamic pressure = 0; on-off control.

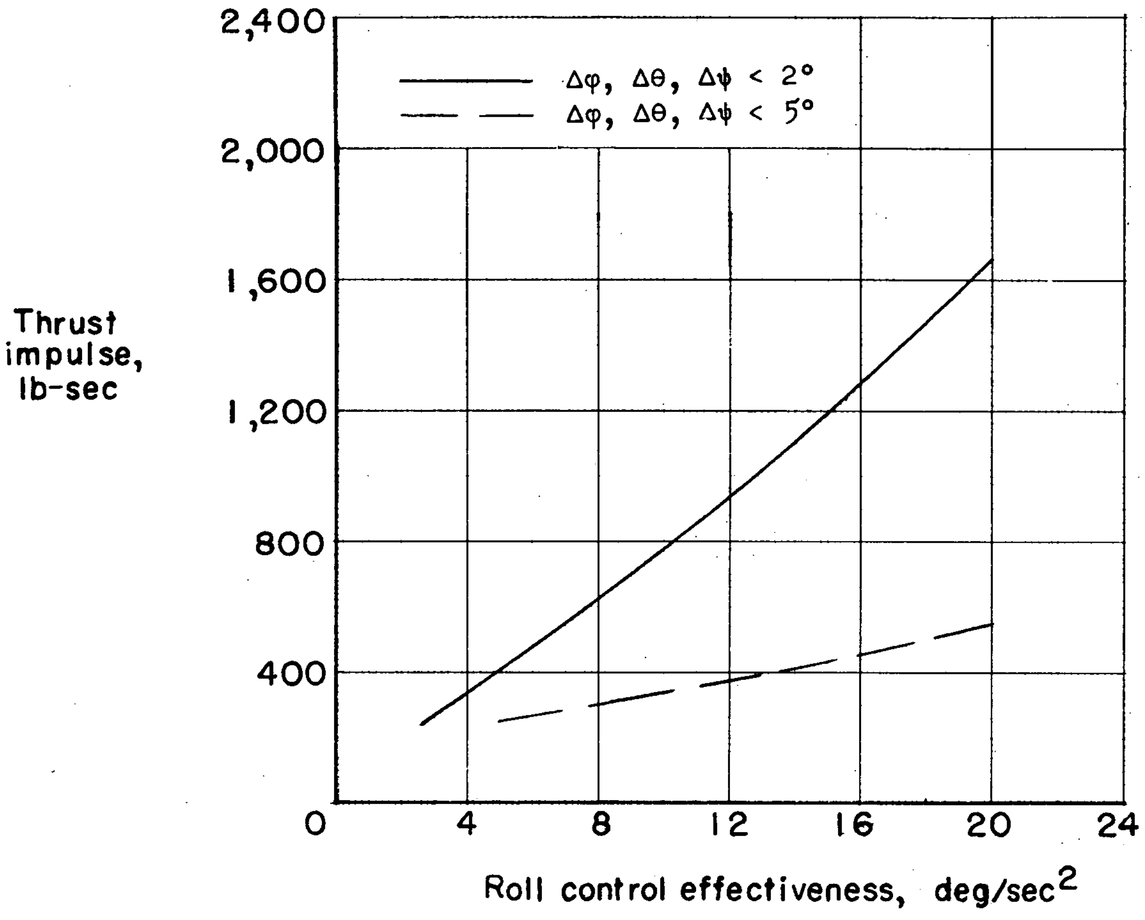


Figure 14.- Effect of control task on thrust impulse for two-minute trim runs. Dynamic pressure = 0; on-off control; R = 2.

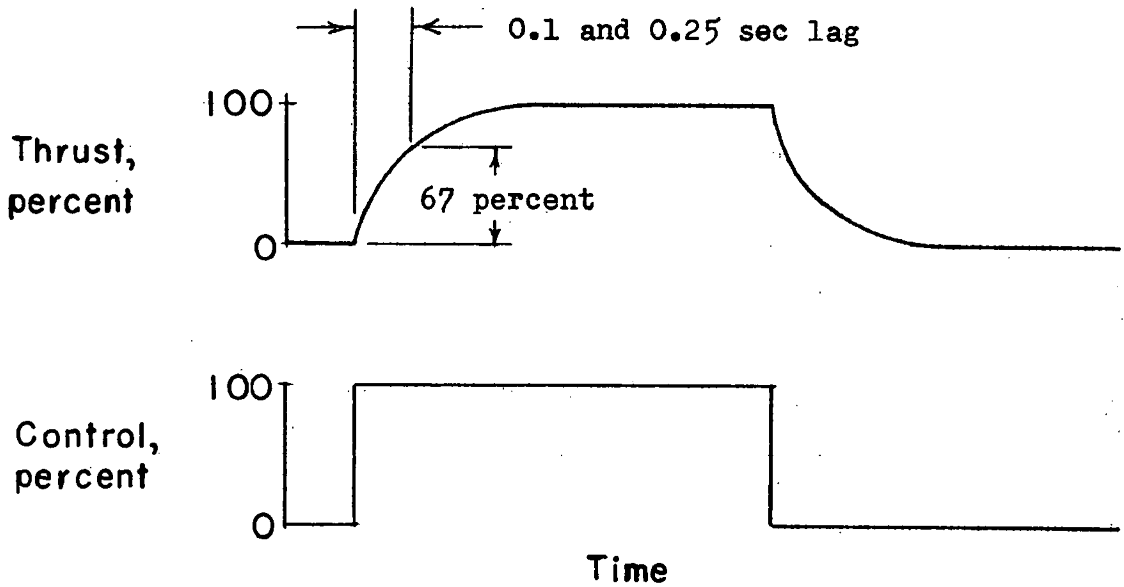


Figure 15.- Simulated thrust lag.

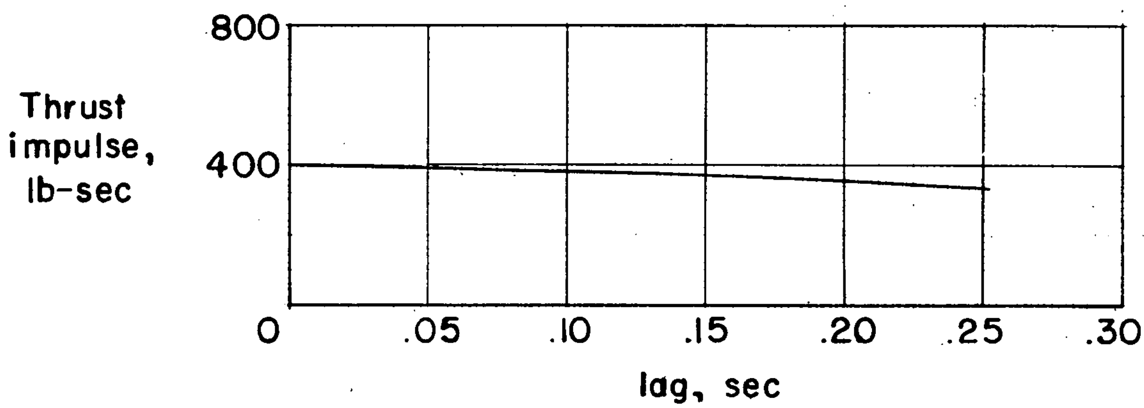


Figure 16.- Effect of lag on thrust impulse for two-minute trim runs. Dynamic pressure = 0; control effectiveness levels of 5, 2.5, 2.5.

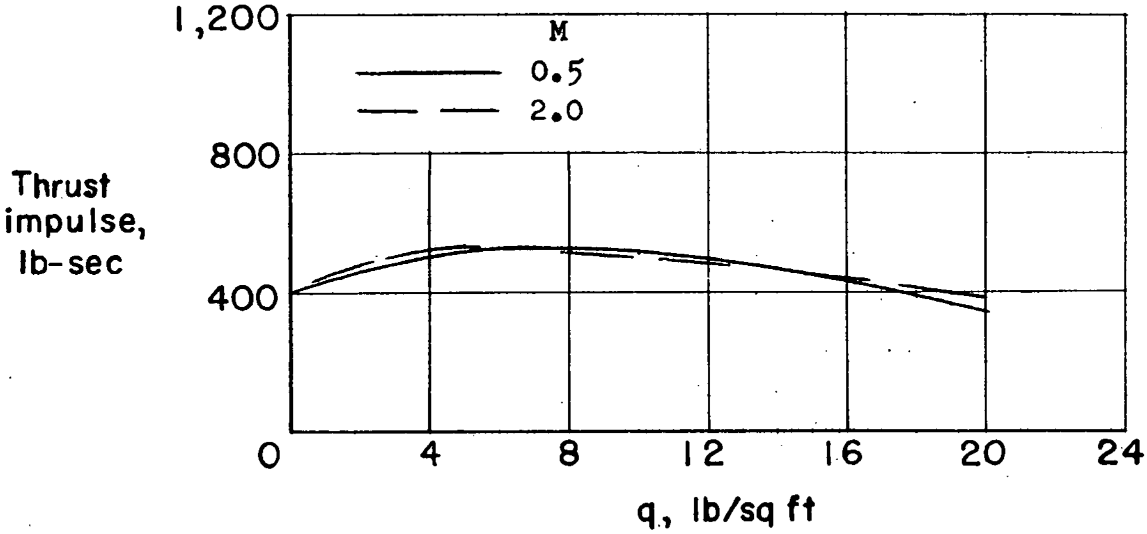


Figure 17.- Effect of dynamic pressure on thrust-impulse requirements for two-minute trim runs. On-off control; control effectiveness levels of 5, 2.5, 2.5.

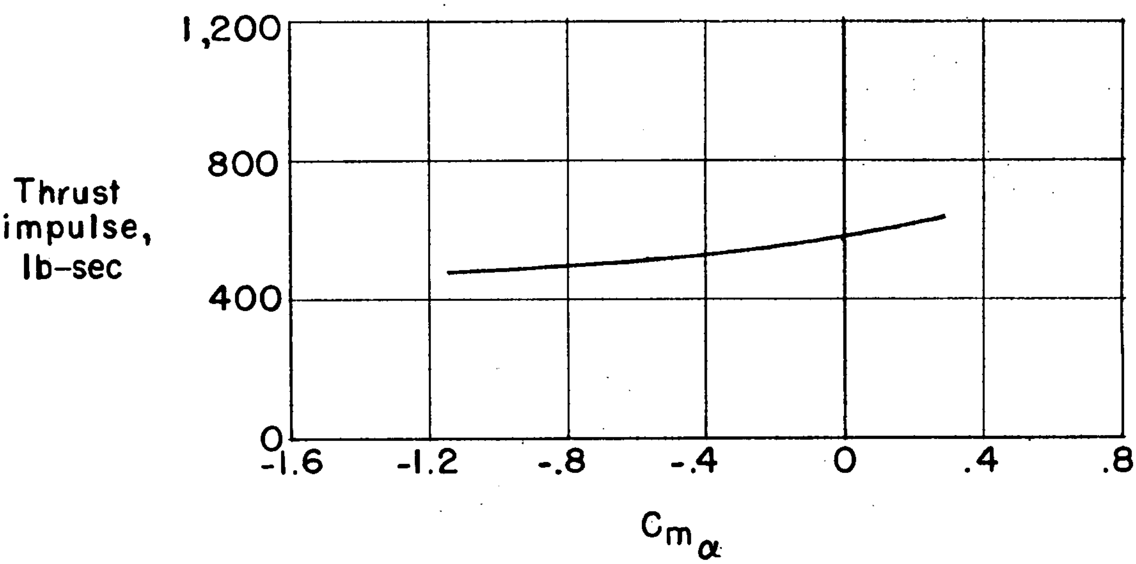


Figure 18.- Effect of C_{m_α} on thrust-impulse requirements for two-minute trim runs. On-off control; control effectiveness levels of 5, 2.5, 2.5; dynamic pressure = 5 lb/sq ft; M = 0.5.

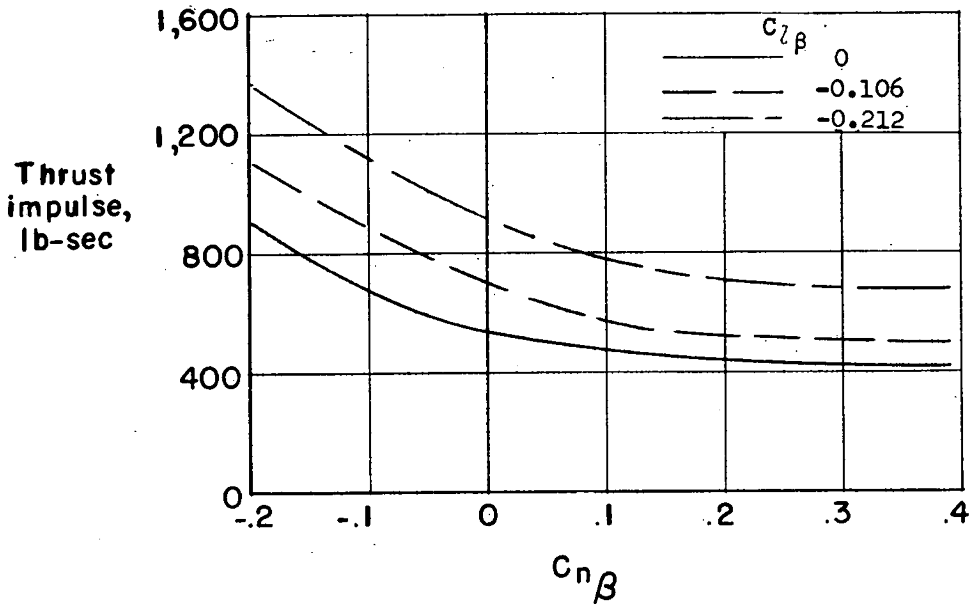


Figure 19.- Effect of C_{n_β} on thrust-impulse requirements for two-minute trim runs. On-off control; control effectiveness levels of 5, 2.5, 2.5; dynamic pressure = 5 lb/sq ft; M = 0.5.

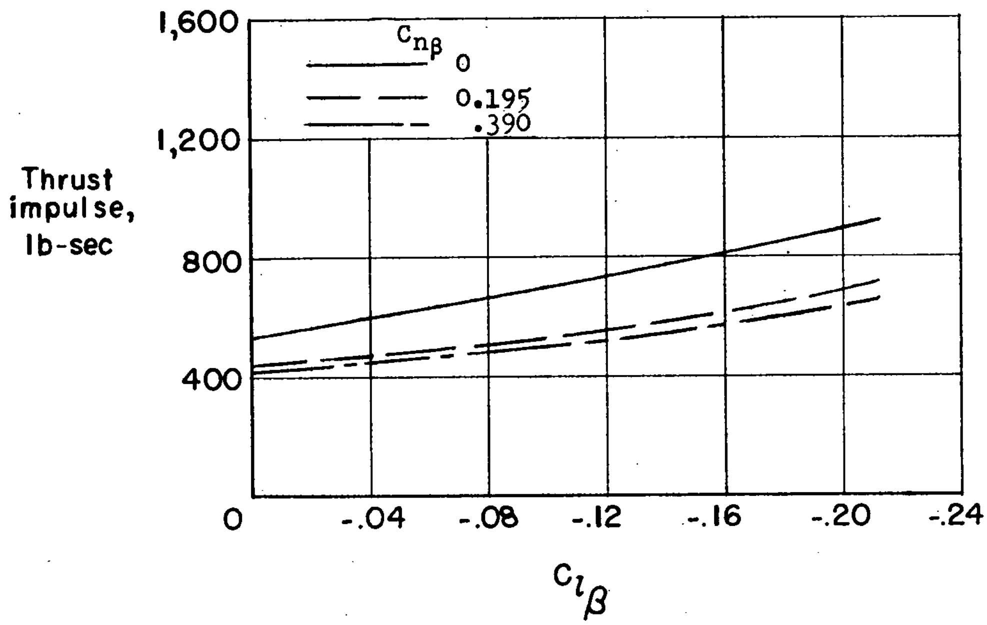


Figure 20.- Effect of C_{l_β} on thrust-impulse requirements for two-minute trim runs. On-off control; control effectiveness levels of 5, 2.5, 2.5; dynamic pressure = 5 lb/sq ft; M = 0.5.

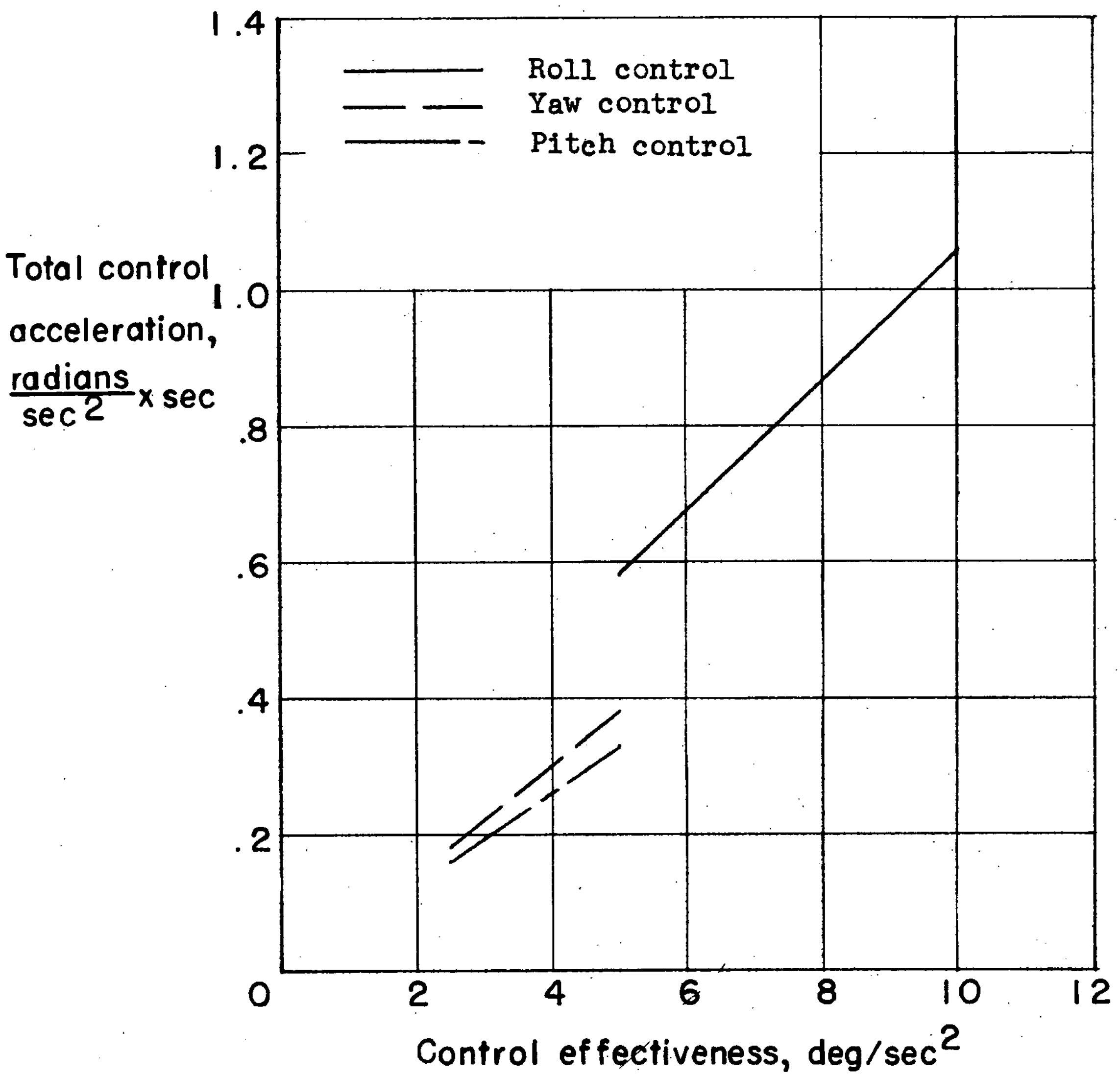


Figure 21.- Total control acceleration required for roll, pitch, and yaw control during two-minute trim runs. On-off control; R = 2; dynamic pressure = 0.

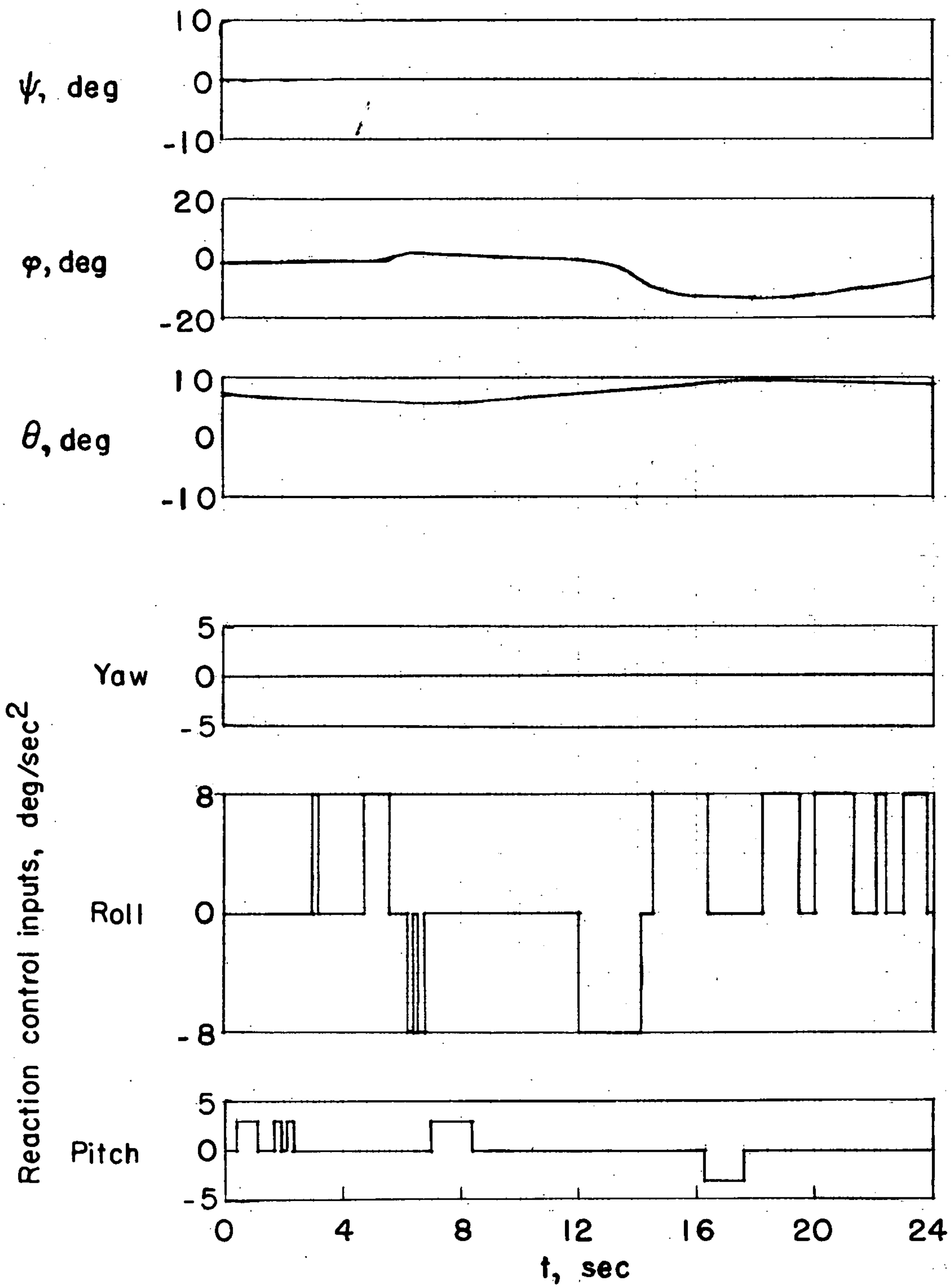


Figure 22.- Time history showing control of mechanical simulator. On-off control; control effectiveness levels of 8, 3, 3.