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**FLIGHT TEST EVALUATION OF A SEPARATE SURFACE ATTITUDE
COMMAND CONTROL SYSTEM ON A BEECH 99 AIRPLANE**

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SUMMARY

A joint NASA/university/industry program was conducted to flight evaluate a potentially low cost separate surface implementation of attitude command in a Beech 99 airplane. Saturation of the separate surfaces was the primary cause of many problems during development. Six experienced professional pilots made simulated instrument flight evaluations in light-to-moderate turbulence. They were favorably impressed with the system, particularly with the elimination of the control force transients that accompanied configuration changes. For ride quality, quantitative data showed that the attitude command control system resulted in all cases of airplane motion being removed from the uncomfortable ride region.

INTRODUCTION

One of the problems associated with general aviation is the large number of accidents due to pilot error. Improvements in airplane handling qualities in the presence of turbulence and a reduction in pilot workload would tend to reduce pilot error and improve flight safety.

Past studies at the Dryden Flight Research Center have shown that an attitude command control system could provide these improvements in general aviation aircraft (refs. 1 to 3). Attitude command is a control concept in which the pilot's control wheel position controls the attitude of the aircraft. This differs from the conventional control system, in which the pilot's control wheel deflection causes a rate of change of attitude; the pilot must neutralize his controls to stop the attitude from changing. When the control wheel position is neutral, the aircraft could be in an infinite number of different attitudes. With attitude command, however, neutral control wheel position results in only one attitude, straight and level; and any control wheel deflection results in a new airplane attitude.

In the meantime, the University of Kansas has been studying the application of separate surfaces for general aviation (refs. 4 to 6). The use of separate surfaces to achieve attitude command appears to be logical in that its cost is low, it meets flight safety requirements, and it is easy to install in existing airplanes. Consequently, a grant was awarded to the University of Kansas to study the feasibility of and designs for attitude command using separate surfaces (ref. 7). Improvements in handling and ride qualities in commuter airline operations would provide an economic advantage, and a Beechcraft Model 99 airplane was chosen because it was representative of commuter airline transports. The University was eventually awarded a contract to design, fabricate, install, and flight test a separate surface system on this airplane. Much of this work is reported in references 8 to 11. The Beech Aircraft Corporation and The Boeing Company, Wichita Division, also participated in the program.

SYMBOLS AND ABBREVIATIONS

F_w	pilot-applied control wheel force, newtons (pounds)
IFR	instrument flight rules
ILS	instrument landing system
K	gain constant
KIAS	knots indicated airspeed
p	roll rate, degrees per second
q	pitch rate, degrees per second
r	yaw rate, degrees per second
rms	root mean square
s	Laplace operator function
TIMS	turbulence-intensity measurement system
t	time, seconds
β	sideslip, degrees
δ	control surface deflection, degrees
θ	pitch attitude, degrees
$\dot{\theta}$	pitch rate, degrees per second

τ	time constant, seconds
φ	roll attitude, degrees
$\dot{\varphi}$	roll rate, degrees per second
ψ	heading attitude, degrees
$\Delta\psi$	increment of heading change, degrees

Subscripts:

a_p	primary aileron (right)
a_s	separate surface aileron (right)
e_p	primary elevator
e_s	separate surface elevator
f	wing flap
H	horizontal stabilizer
r_p	primary rudder
r_s	separate surface rudder

PROGRAM OBJECTIVES

The program objectives were to perform a flight evaluation of the operational characteristics and performance of a potentially low cost separate surface implementation of attitude command on a Beech 99 airplane and to provide the general aviation industry with a first hand evaluation of the control concept by allowing their participation.

SYSTEM DESCRIPTION

Aircraft

Figure 1 is a three-view drawing of the Beech 99 aircraft with separate control surfaces. The aircraft is a twin-engine, turboprop, 17-place commuter airliner. It has a wingspan of 14 meters (46 feet), a length of 13.7 meters (45 feet), and a maximum gross weight of 4716 kilograms (10,400 pounds). It has a maximum cruise of 244 knots at 4877 meters (16,000 feet) and a service ceiling of approximately 8534 meters (28,000 feet). Its approach speed is 96 knots, and it is capable of operating off a 914-meter (3000-foot) runway.

Hardware Implementation

The flight control system modifications consist of electrically interconnected components and include a gyro package, a management and control panel, an operator's console, and electromechanical actuators, which drive small separate control surfaces.

The gyro package consists of a vertical gyro, directional gyro, and three rate gyros; and it is mounted in the proximity of the center of gravity of the airplane.

The management and control panel (fig. 2) contains switches, lights, surface position indicators, and potentiometers; it is installed in the copilot's instrument panel.

The operator's console contains all the electronics for control law computations, gain adjustment, servo amplifiers, ground tests, and power supplies. The unit is installed in the main cabin.

The control actuators are of the electromechanical screw jack type. They require 28 volts dc and produce approximately 181 kilograms (400 pounds) of linear force at a maximum current of approximately 10 amperes. The frequency response of the actuators is approximately 1.5 hertz. They are located in the wings and tail with the separate control surfaces.

Separate Control Surfaces

The separate control surfaces for attitude command are obtained by the dichotomy of the primary control surfaces. In sizing the separate surfaces, consideration was given to static control and the avoidance of saturation. The sizes calculated met the military and civil aircraft performance standards (MIL-F-8785C and FAR Part 23, respectively) for failed hardover conditions. In the roll axis, 39 percent of the total roll control power is provided by the separate surface ailerons; in the pitch axis, 25 percent of the total pitch control power is provided by the separate surface elevators; and in the yaw axis, 27 percent of the total yaw control power is provided by the separate surface rudder.

System Operational Modes

Three modes of system operation are provided: off, slave, and command. A control panel in the copilot's instrument panel allows the pilot to select one of these control modes and the control loops in the command mode.

In the off mode, the separate surfaces are deenergized, and the aircraft flies with approximately two-thirds of its original control power.

In the slave mode, the separate surfaces are electronically slaved to and operate in unison with the primary control surfaces; thus, the basic Beech 99 configuration is restored.

In the command mode, all three axes can be operated individually or in combination; however, all tests were combined-axis tests. The separate surfaces hold the aircraft in the attitude commanded by the position of the pilot's control wheel in the pitch, roll, and yaw axes. Heading is maintained by a combination of roll and yaw heading hold control loops. Yaw-damper-only operation is available in the yaw axis.

The system is designed to operate at the approach and cruise flight conditions.

Pitch axis.—A block diagram of the pitch axis is shown in figure 3(a). The pilot controls the primary surface through the mechanical control system and has an electric trim system to position the horizontal stabilizer.

In the slave mode, the primary surface position, through the appropriate slave gain, is used to position the separate surface; thus, the separate surface operates in unison with the primary surface.

In the command mode, when the pilot commands a pitch attitude through the control column, the primary surface position is fed back through the appropriate gain and compared with the actual pitch attitude. The difference between commanded and actual attitudes is filtered and drives the separate surface to reduce the difference to zero by changing the actual attitude of the aircraft. Thus, the attitude of the aircraft becomes proportional to control column displacement.

The separate surface has a streamline position detector which moves the horizontal stabilizer through the autotrim system to keep the separate surface at a near zero position.

Roll axis.—A block diagram of the roll axis is shown in figure 3(b). It functions like the pitch axis except that it is coupled with the yaw axis. In the command and heading hold modes, and when zero bank is commanded, the yaw axis heading is locked. When the pilot applies an aileron wheel force to roll, the yaw axis unlocks to permit aircraft maneuvering.

Yaw axis.—A block diagram of the yaw axis is shown in figure 3(c). In the command, yaw damper, and heading hold modes, heading and heading rate are fed back to the separate surface to keep the aircraft on the heading sensed by the directional gyro. As explained above, the yaw axis automatically unlocks when the pilot maneuvers the aircraft for heading changes and locks when a new heading is established. The pilot can select yaw-damper-only operation, which manually unlocks the yaw axis by opening the heading feedback loop.

INSTRUMENTATION

A pulse code modulation digital data tape instrumentation system was installed in the aircraft to allow the debugging of the system, the optimization of system performance, and the acquisition of quantitative data from the flight test program. Seventy-seven channels at 200 samples per second are available for recording aircraft and system parameters.

A turbulence-intensity measuring system (TIMS) (ref. 12) was installed in the airplane to record the atmospheric gust velocity encountered during flight.

Figure 4 shows the mechanization of the turbulence-intensity measurement system. A pitot-static probe and a differential pressure transducer measure the longitudinal pressure fluctuations in front of the airplane. A bandpass filter attenuates deviations above 20 hertz and below 6 hertz to exclude unwanted high-frequency noise and low-frequency airplane response to turbulence and control inputs. The signal is then integrated in the computer and recorded in the data system. The computer also compensates for variations in the signal due to airplane velocity.

The recorded signal is directly proportional to the shaded area in the turbulence power spectrum in figure 4. The power spectrum shown represents the standard format for quantitative turbulence measurements. This format is the result of extensive turbulence research which showed empirically that the log-log plot of the gust-velocity power spectrum is linear and has a constant and repeatable slope throughout the wavelength range from 3 meters (10 feet) to 3048 meters (10,000 feet). Therefore, changes in turbulence intensity change the magnitude of the spectrum but not its slope. The invariance of the slope is illustrated in the figure by the levels of light-to-moderate and moderate-plus turbulence spectra. Therefore, the shaded area varies directly with the level of turbulence intensity. This area is also directly proportional to the root-mean-squared value of the gust velocity, which is equal to the magnitude of the area under the entire power spectral curve.

DEVELOPMENTAL PROBLEMS

As with most flight programs, problems were encountered with the system during the initial phases of flight. Some of these developmental problems, which may be unique to this system, are discussed below.

Pitch Trim Overshoot

When the pilot commanded a new pitch attitude with a trim input, the aircraft overshoot the commanded attitude and then gradually returned to it. The problem was duplicated on the University of Kansas simulator, and, as shown in figure 5, the separate surface was saturated, allowing the pitch attitude to overshoot. The problem is the result of differences in aircraft responses from separate surface inputs and trim inputs. The pitch trim overshoot was eliminated by adjusting the command gain to the separate control surfaces, as shown in figure 6.

Bank Angle Overshoot

Figure 7 is a time history showing a step input of 5.6° primary aileron for a 12° bank angle, and a resulting 5° bank angle overshoot. Immediately before the bank angle overshoot, the separate surface aileron saturates (it has a 14° limit), and an overshoot ratio of 42 percent results. The forward loop gain is 15.

The overshoot ratio is a function of forward loop gain (fig. 8). Increasing the gain to 60 results in an acceptable overshoot. Increasing the gain requires less primary control surface deflection, and therefore less separate surface authority, for a commanded bank angle; however, the gain is limited by too abrupt control response and excessive control sensitivity.

Heading Hold Operation

The system was originally mechanized to unlock the heading loop when the pilot's control wheel was deflected more than 3° . While this technique was satisfactory for a Piper airplane (ref. 3), it was unsatisfactory for the Beech 99 airplane because of high control system friction and forces. The problem was resolved by replacing the aileron position sensor with a torque-sensitive switch on the control wheel that was activated by a very small wheel force.

Pitch Changes With Configuration Changes

One benefit of the attitude command system is the elimination of pitch changes during aircraft configuration changes. However, the elevator's separate control surfaces saturated during a go-around maneuver, which resulted in the airplane's pitching down. Analysis of the problem indicated that the nose-down pitching moment was generated by flap retraction and that the autotrim rate could not keep up with the changes. It seemed logical to limit the rate of configuration changes to avoid saturation. It was not practical to reduce the flap retraction rate; however, a successful fix resulted from interrupting the flap retraction whenever the autotrim system was operating.

TEST PLAN AND PROCEDURES

Six pilots participated in the qualitative flight evaluation. All were experienced professional pilots. Three were general aviation pilots who were twin-engine, instrument rated, but had no experience in the Beech 99 airplane. The other three were NASA research pilots. All pilots were given a 1-hour familiarization flight in the basic Beech 99 airplane.

The flight test pattern for the qualitative pilot evaluation is shown in figure 9. The vertical-S maneuver is a series of climbing and descending turns. The 90° localizer interception was initiated from the cruise configuration to increase the difficulty of the piloting task. The flights were conducted under simulated instrument flight conditions. Each pilot flew the entire pattern in the slave mode and then immediately repeated the pattern in the command mode. Only two pilots repeated the flights.

The piloting task was evaluated with the Cooper-Harper rating scale (ref. 13). The ratings ranged from 1 to 10, where 1 indicates excellent controllability and 10 indicates that control will be lost during some portion of required operation.

FLIGHT TEST RESULTS

Aircraft Response Characteristics

Roll axis.—The response to an aileron step input in the command mode is shown in figure 10. The separate surface aileron starts in the direction of the primary aileron and opposes it when the desired bank is reached; thus, the bank angle becomes proportional to the pilot's control deflection.

Pitch axis.—The response to an elevator step input in the command mode is shown in figure 11. Again, the separate surface elevator produces a change in attitude proportional to the pilot's control deflection.

The control force transients in the slave mode during configuration changes are shown in table I. The elevator wheel forces required to trim are high, and can rise as high as 311 newtons (70 pounds) during a go-around maneuver. Depending on the duration of the transient forces, pilots generally oppose the forces rather than trim. These transient forces, and the accompanying pitch changes, are eliminated in the command mode. The flap interrupt modification about doubles the normal flap retraction time, and figure 12 shows a hands-off vehicle response during a configuration change.

Yaw axis.—The most significant change that occurred in the yaw axis with the command mode is the yaw damping effect. Figure 13 shows the response of the aircraft to a rudder doublet in the slave mode. Dutch roll damping is low. Figure 14 is the aircraft response in command mode to a rudder doublet. Dutch roll damping is improved.

Pilot Evaluations

This flight test program is oriented towards the generation of pilot opinions concerning the handling and ride qualities of the modified Beech 99 airplane. The flight profile reflects this philosophy. The maneuvers are designed to task the pilot to enable him to evaluate the changes in aircraft dynamics, although the profile does not depart from being a realistic IFR mission. Therefore, the pilots' comments and the Cooper-Harper pilot ratings constitute the most important results of the flight tests.

After the pilots performed the mission in the slave and command modes, they were debriefed. The following discussion gives the pilots' consensus of opinion concerning the handling qualities of the test airplane.

The pilots were favorably impressed with the elimination of the control force transients that accompanied configuration changes. They seemed to like the pitch stabilization provided by the attitude command system; however, some pilots tended to resist adapting to the system. Comments characterizing this discussion are presented in table II.

Holding aileron force during turns was annoying. Most pilots stated that they did not like using the aircraft's manual trim. Some pilots thought that a wheel-mounted electric trim might be acceptable. One pilot said he felt that it was unsafe to trim to some bank angles.

The workload was greatly reduced by the command mode, especially for precision maneuvers like localizer and glidepath tracking. The improvement was even more pronounced in turbulence.

Most pilots agreed that with the attitude command system on, the ride qualities and turbulence response of the aircraft were substantially improved. Comments regarding ride qualities are presented in table III.

Pilot Ratings

The nonresearch pilots had not used the Cooper-Harper rating scale before. Perhaps as a consequence of this, their ratings did not indicate much improvement when the attitude command system was on; however, their unrecorded comments and enthusiasm after flying with the system indicated that the airplane flew better than they had expected, and that they were pleased with the operation of the system.

The pilot ratings generated from the flight profile as a function of turbulence are presented in figure 15. The TIMS output in rms volts is correlated with the pilot assessment of the turbulence level in the slave mode. In the command mode, the pilot rating shows an improvement of at least 0.5 over the airplane in the slave mode. The mean improvement in pilot rating is between 1.25 and 1.50.

The instrument approach is the most demanding of all the piloting tasks. A measure of pilot workload for this task is shown in terms of aileron activity in figure 16. There is substantially less aileron activity in the command mode. Figure 17 shows the standard deviation in heading versus turbulence. Although the figure shows no significant improvement in performance, the pilots felt that their performance was improved.

Ride Qualities

The precision heading task is typical of enroute flight of commuter airliners. Atmospheric turbulence during these evaluations was light to moderate. The vertical and transverse accelerations of the aircraft are shown in figure 18. The solid symbols represent the averages of six flights. In terms of percentages, the data show an 18.5-percent reduction in vertical acceleration and a 32.2-percent reduction in transverse acceleration when the system is in the command mode.

The effects of attitude command on passenger comfort are also apparent in figure 18. Boundaries of passenger comfort were extracted from studies of passenger ride quality determined from commercial airline flights in which a Beech 99 airplane was one of several aircraft used (ref. 14). Passenger comfort responses in light-to-moderate turbulence are generally borderline to uncomfortable when the

airplane is in the slave mode. In all cases, putting the airplane in the command mode removes it from the uncomfortable region.

CONCLUDING REMARKS

Flight testing the Beech 99 airplane demonstrated that the use of separate surface controls is practical for general aviation and that the use of small separate surfaces is effective in controlling the response of the airplane. Because the separate surfaces were small, they were easily saturated; but the saturation problems could always be resolved. Improvements in the handling qualities and the ride qualities of the Beech 99 aircraft were demonstrated in flight tests.

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TABLE I. - CONTROL FORCE TRANSIENTS
 [120 KIAS, clean configuration, 1524 meter (5000-foot) altitude,
 slave mode]

Configuration change	Elevator wheel force required to maintain attitude, N (lb) (push)
Gear down	33 (7.5)
Flaps down	222 (50.0)
Half to full power	80 (18.0)

TABLE II. - HANDLING QUALITIES COMMENTS

<p>Pitch attitude command:</p> <p>I liked the decoupling effect of being able to control the glide slope and the rate of descent with the pilot trim and the speed with power.</p> <p>Glide slope was more positive with the system on.</p> <p>Pitch attitude command is probably the biggest improvement that I see in that the attitude tends to be locked in.</p> <p>Not much change in the pitch axis except for the gear and flap transients.</p> <p>Missed approach much easier, aircraft well controlled.</p> <p>When the go-around was executed, I was forced to establish a climb attitude. The basic aircraft would naturally pitch up with acceleration.</p>
<p>Roll attitude command:</p> <p>The workload is much lower, especially in the roll axis; I felt much more confident of my ability to perform the mission.</p> <p>The localizer was easier to maintain.</p>
<p>Heading hold:</p> <p>The basic aircraft wallows around. It is difficult to hold heading. The aileron forces are high. When you turn your system on, it relieves the pilot workload, particularly when maintaining heading in turbulence. If turbulence knocks you off [the heading], the system brings you back to it.</p> <p>Initially I was fighting the heading hold system; I wasn't turning loose and letting it settle down. I found out later if I flew almost hands off, heading hold was pretty good.</p>

**TABLE III.—RIDE QUALITY COMMENTS WITH
ATTITUDE COMMAND SYSTEM ON**

**In all the axes, as soon as you turn the attitude
command on it seems as if the turbulence decreases
by half.**

The ride is much smoother.

The airplane seems as if it is on a rail or track.

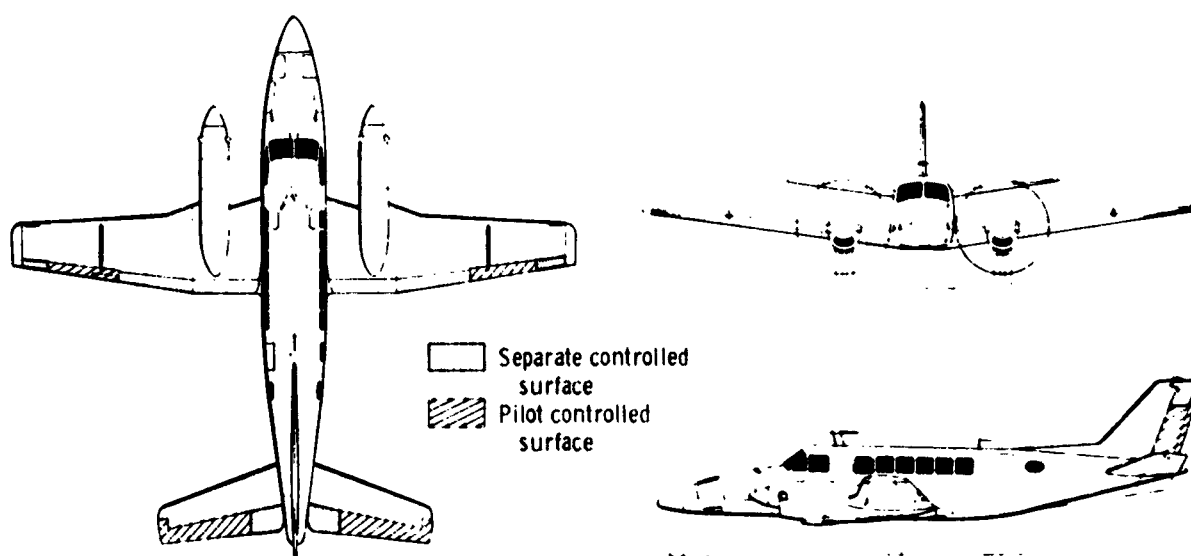


Figure 1.—Beech 99 airplane with separate surface controls.

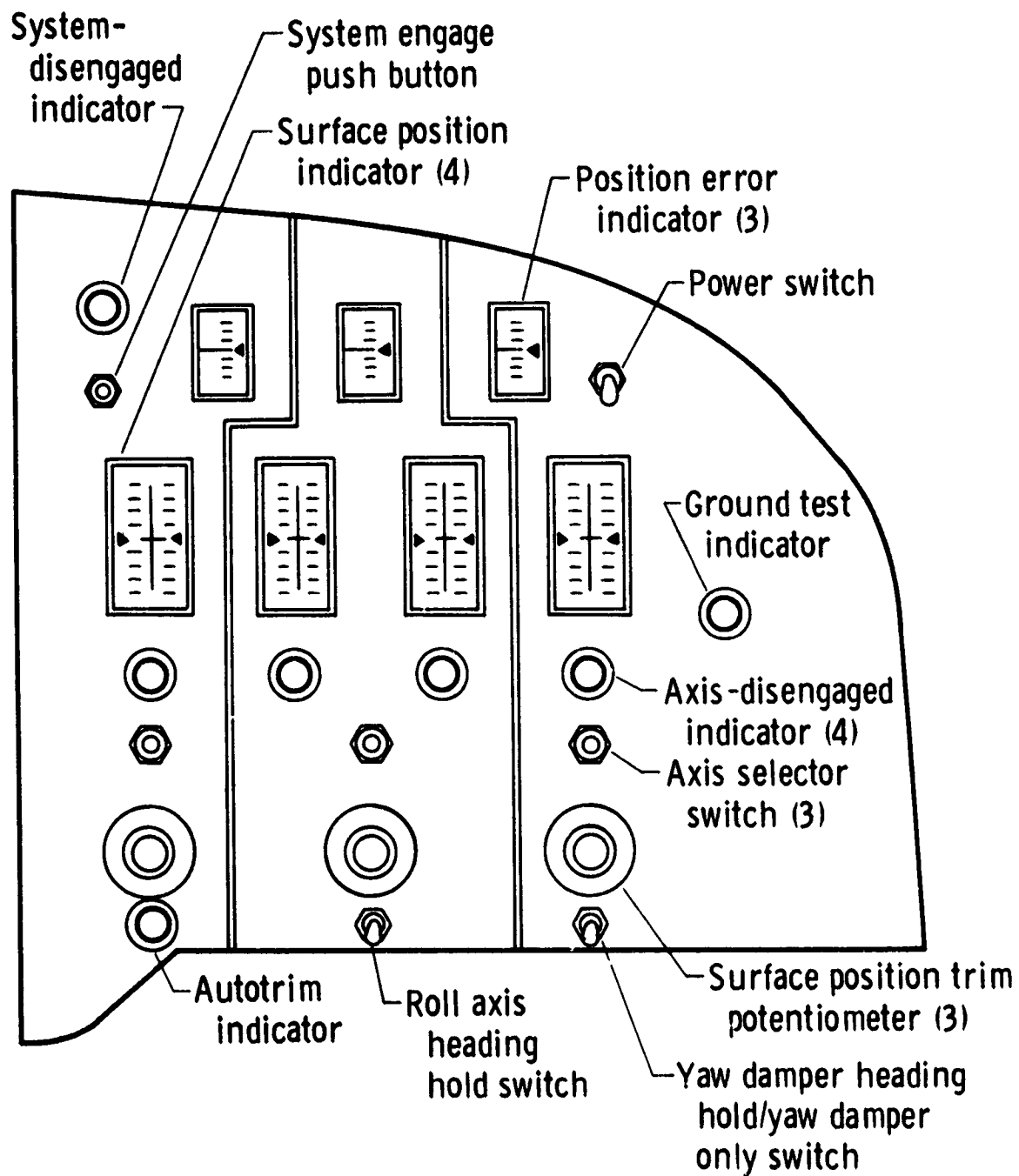
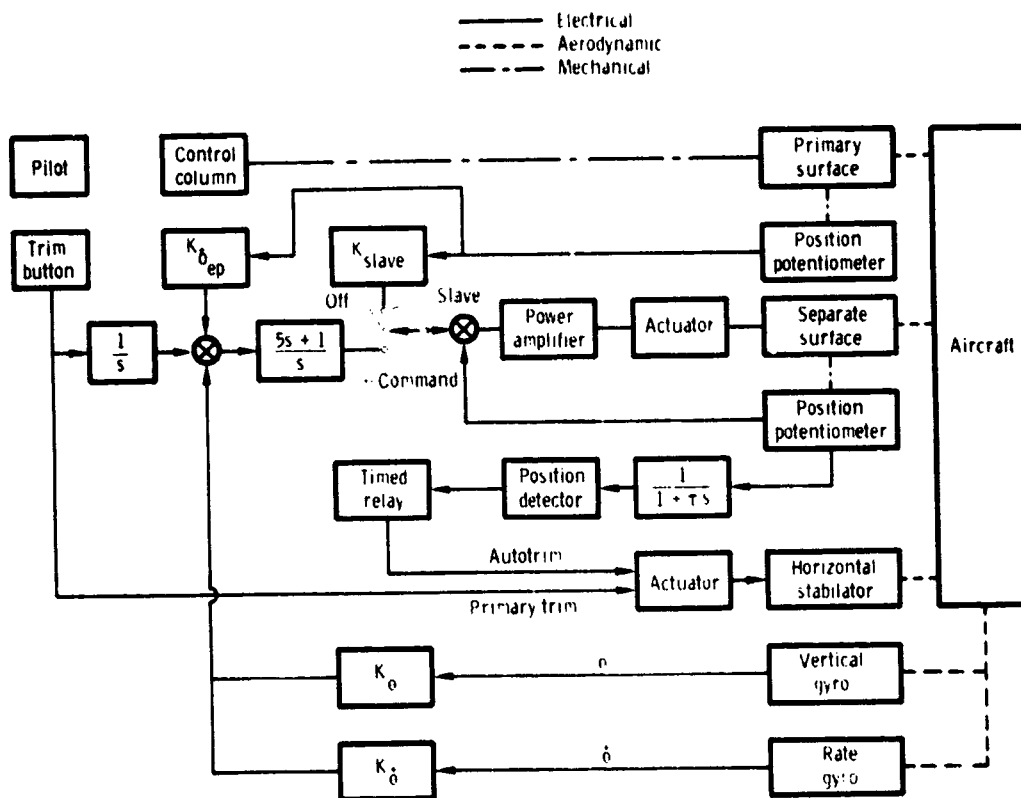


Figure 2.- Management and control panel.



(a) Pitch axis.

Figure 3.- Mechanization of attitude command control system.

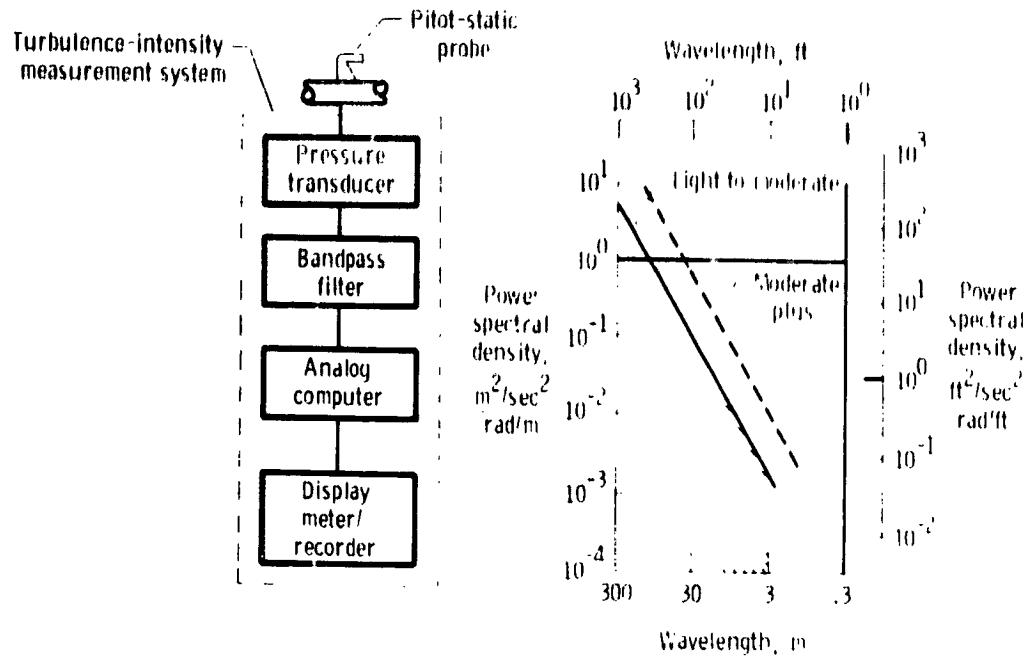


Figure 4.- Turbulence-intensity measurement system.

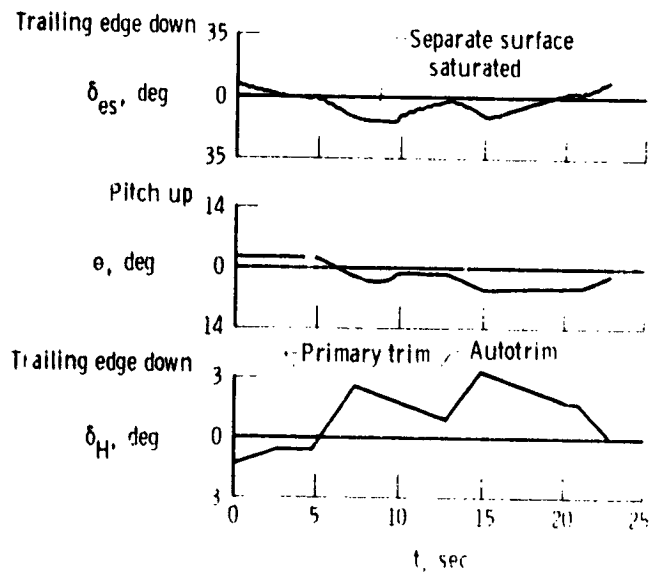


Figure 5.- Simulator pitch axis response due to pilot trim input with $K_{ep} = 10$. (Pitch angle overshoot induced by δ_{es} saturation.)

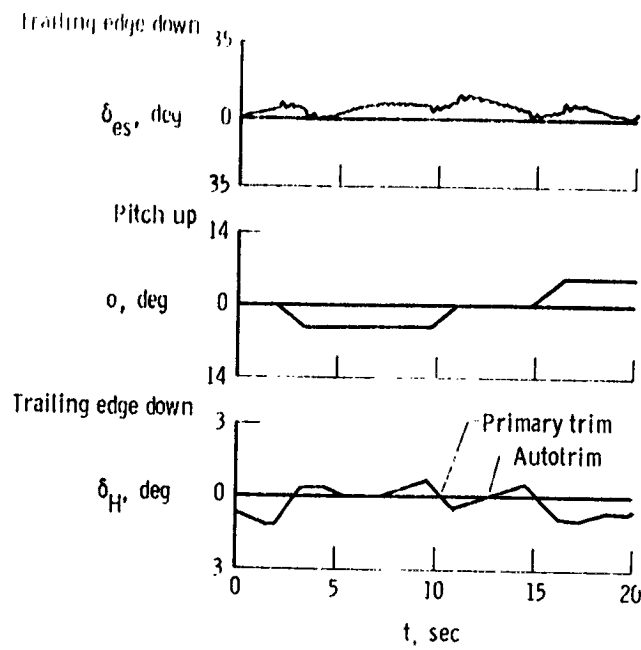


Figure 6.- Simulator pitch axis response due to pilot trim input with $K_{\delta_{ep}} = 20$.

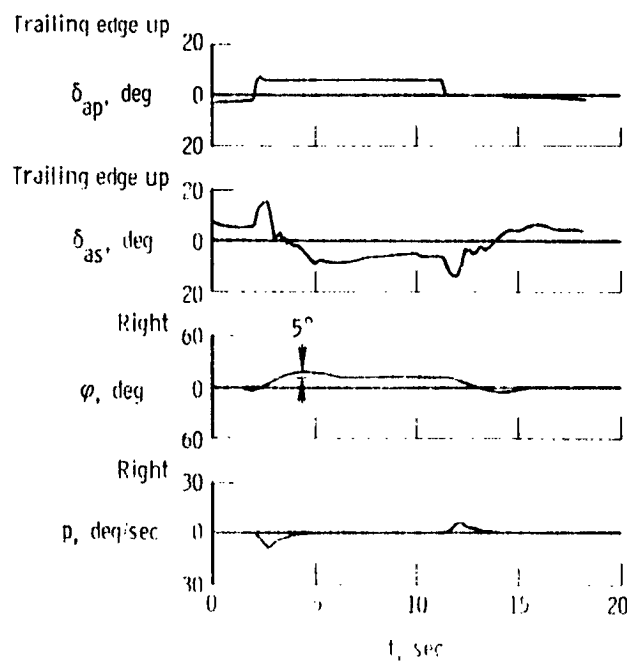


Figure 7.- Time history of bank angle overshoot. Gear and flaps down; airspeed = 110 knots; $K_{\delta_{dp}} = 15$.

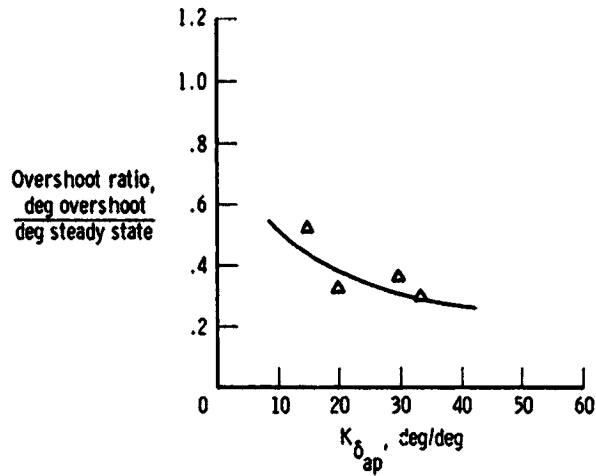


Figure 8.- Effect of $K_{\delta_{ap}}$ on overshoot ratio. Flight data.

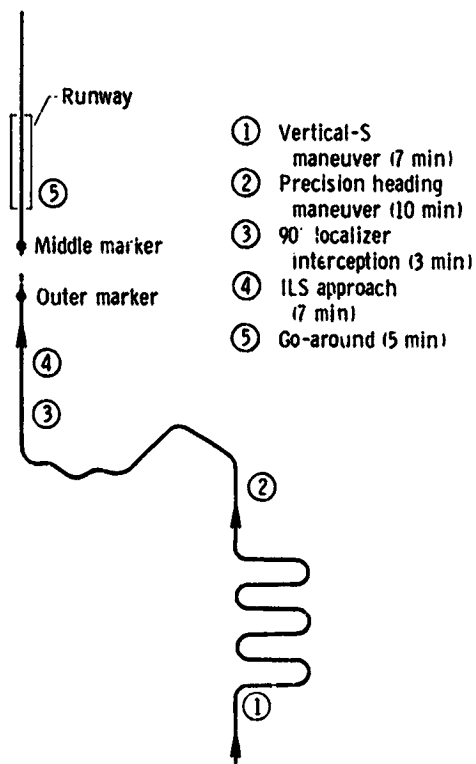


Figure 9.- Qualitative flight profile.

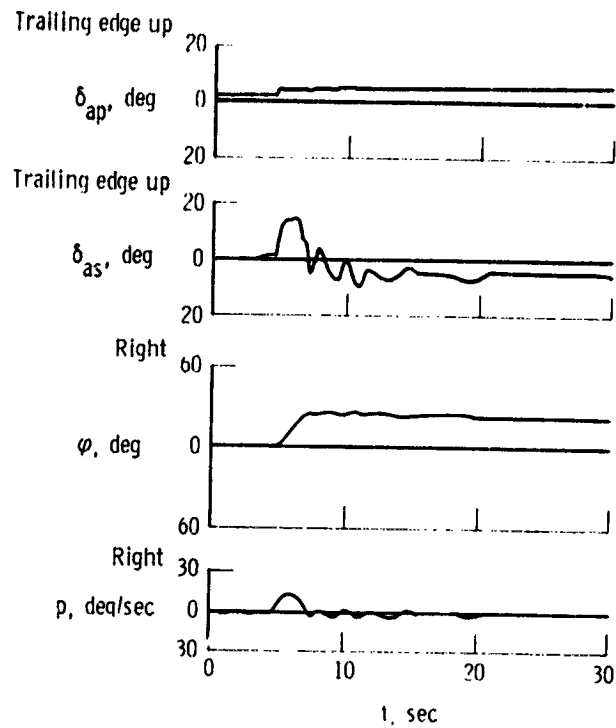


Figure 10.- Aileron step response.
 Command mode.

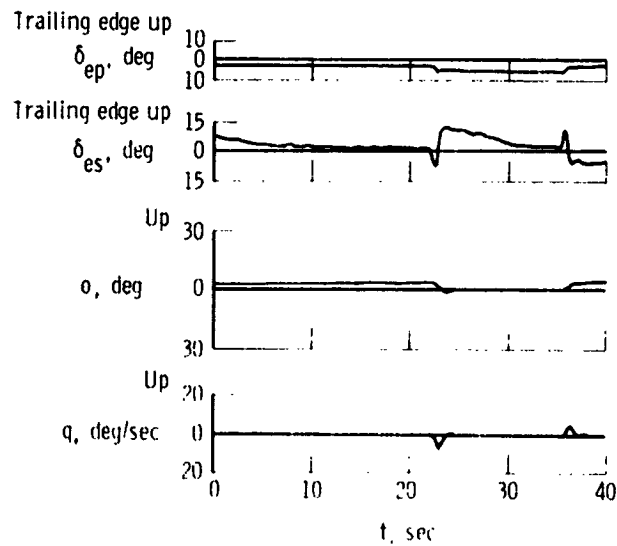


Figure 11.- Elevator step response.
 Command mode.

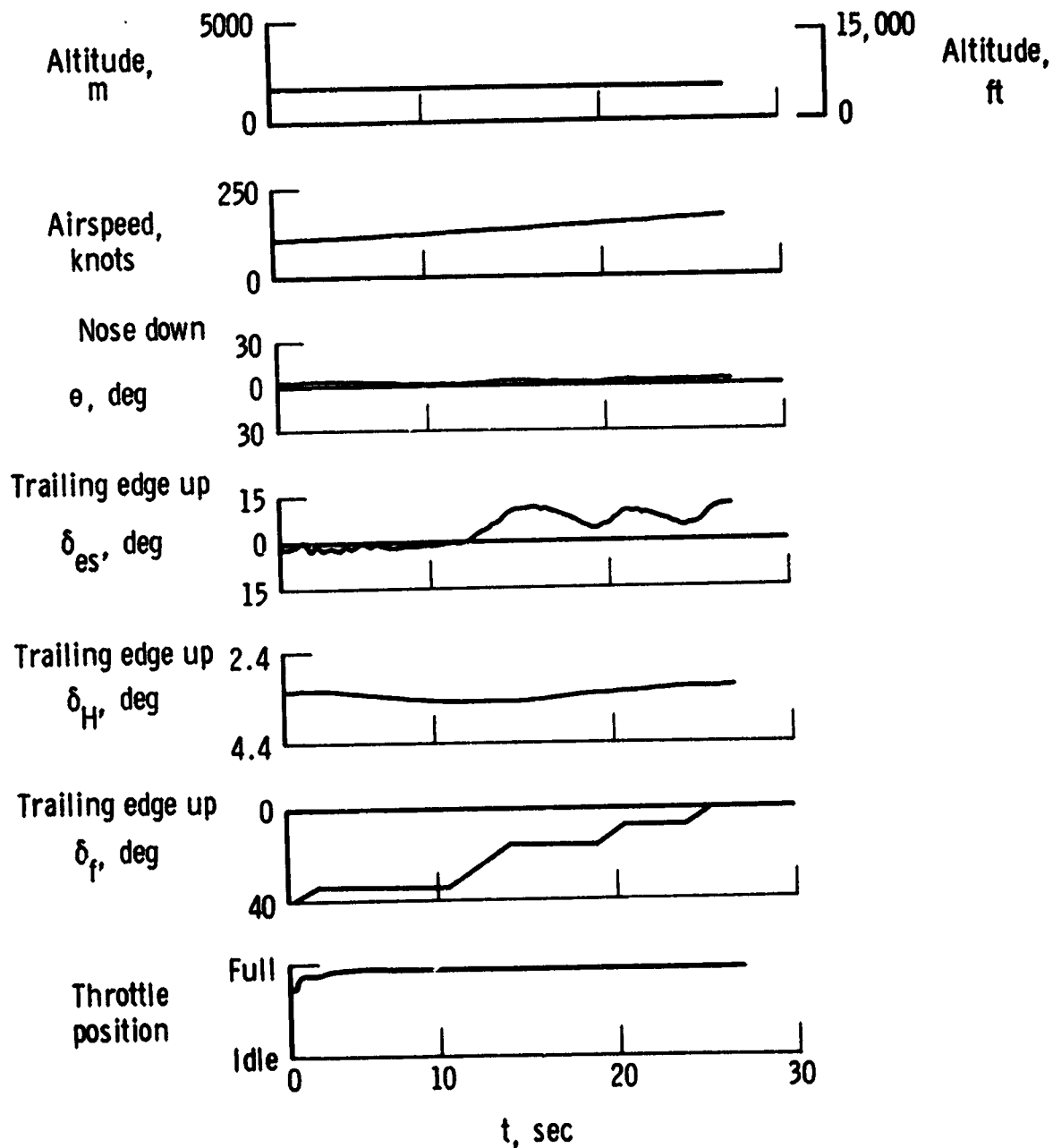


Figure 12.- Aircraft response to configuration changes. Hands off, $K_{\theta} = 20$,
 $K_{\delta} = 4$, $K_{\delta_{ep}} = 24$.

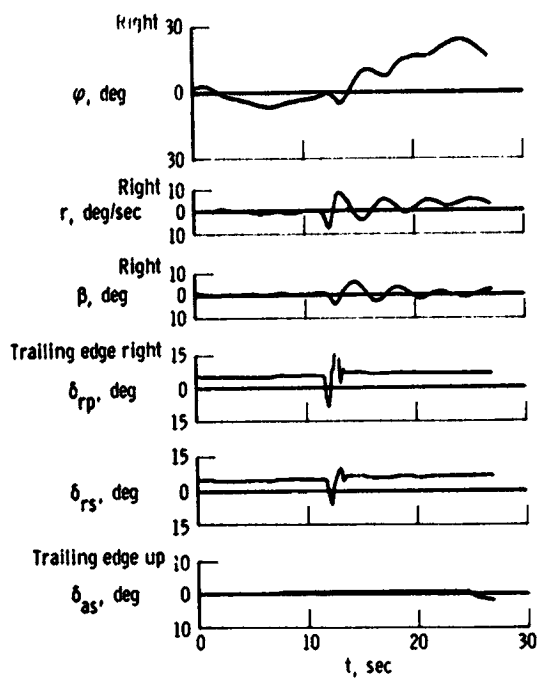


Figure 13.- Aircraft response to rudder doublet in slave mode.

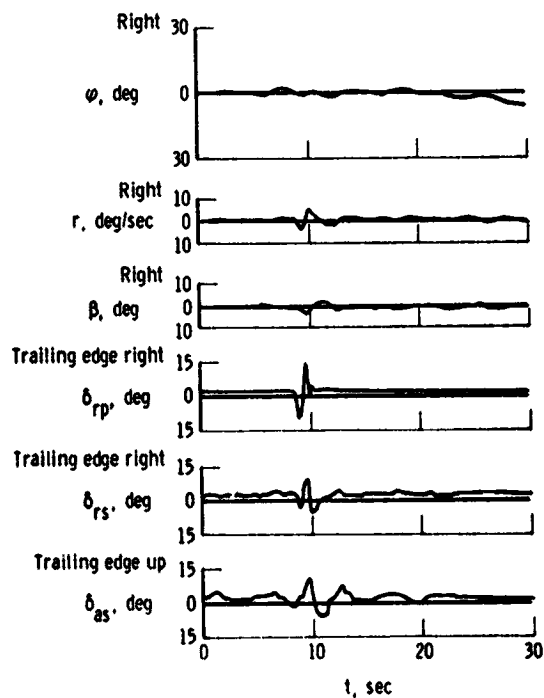


Figure 14.- Aircraft response to rudder doublet in command mode.

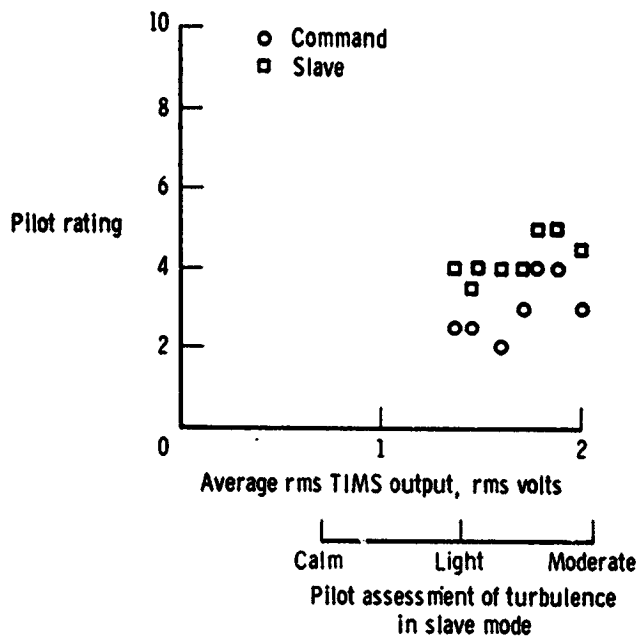


Figure 15.- Pilot ratings versus turbulence for tasks 3, 4, 5.

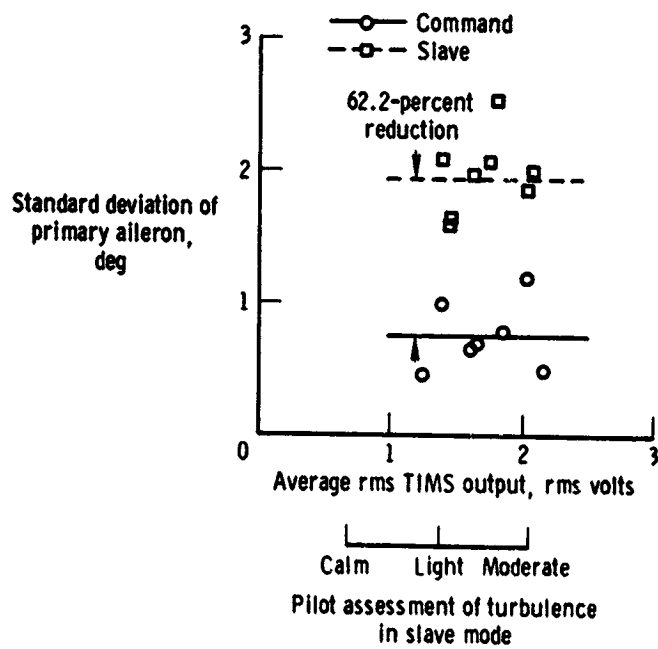


Figure 16.- Standard deviation of primary aileron versus turbulence. Task 4.

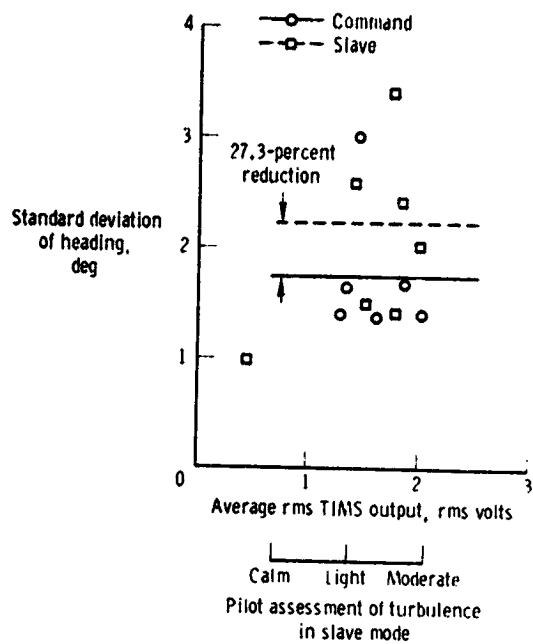


Figure 17.- Standard deviation of heading versus turbulence. Task 2.

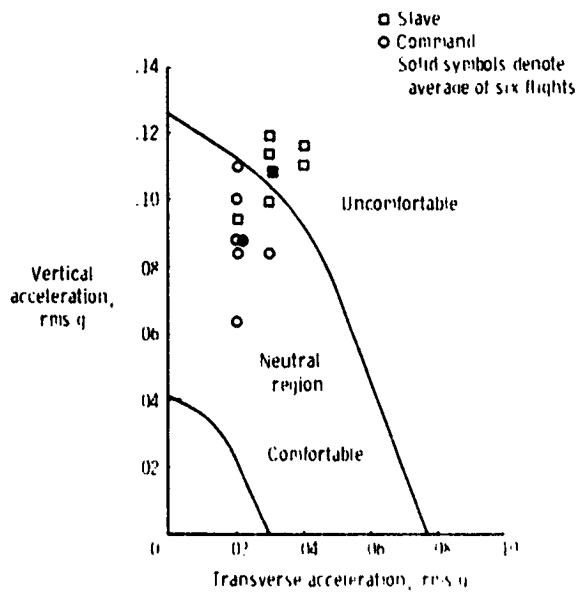


Figure 18.- Passenger comfort response contours.