OBJECTIVE AND SUBJECTIVE EVALUATION OF THE EFFECTS OF A G-SEAT ON PILOT/SIMULATOR PERFORMANCE DURING A TRACKING TASK

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ABSTRACT AND SUMMARY

A seat cushion to provide acceleration cues for aircraft simulator pilots has been built, performance tested, and evaluated in NASA Langley's Differential Maneuvering Simulator. The four-cell seat, using a thin air cushion with highly responsive pressure control, attempts to reproduce the same events which occur in an aircraft seat under acceleration loading. The pressure controller provides seat cushion responses which are considered adequate for current high-performance aircraft simulations.

An experiment was designed to evaluate the effect of the g-seat on pilot/simulator performance. The statistical analysis of data indicates that the pilot gets information from the seat which allows more precise control of the simulated aircraft. Pilot subjective data support the conclusions of the statistical analysis.

Introduction

In the control of an aircraft, the kinesthetic cues or "seat-of-the-pants" feel provide important information to the pilot concerning the aircraft's dynamic state. Pilots sense such kinesthetic cues as buffet, control forces, and linear and angular accelerations. One of the most important of the acceleration cues is the normal acceleration. Under positive normal acceleration, the pilot is subjected to an increase in weight for each part of the body. This results in such things as the blood pooling in the lower portions of the body and a reduced blood flow to the head which eventually results in tunnel vision and blackout, (Reference 2). The increased body weight also causes increased pressure on the "seat-of-the-pants" as the seat cushion padding becomes fully compressed and no longer conforms to the pilot's buttocks. This causes a greater portion of the pilot's weight to be borne by the area around the tuberosities (the two bones which protrude furthest into the buttocks) and thus a change in the pressure distribution on the buttocks.

There are other acceleration cues such as heaviness in the extremities; however, the "seat-of-the-pants" feel seems to be one of the most noticeable. In view of this, a seat cushion was designed and built to reproduce these pilot sensations in an aircraft simulator. This paper describes the approach to the cushion design, the seat transfer functions, and the design of an experiment to discriminate between pilot performance with and without the seat cues. The statistical analysis of the data and pilot opinions concerning the realism of the seat and its value as a performance aid are presented.

Seat Cushion Design

The objective in building the simulator seat cushion is simply to reproduce as nearly as possible the same events which occur in the aircraft seat. In order to compress the seat padding as if the pilot weighed more, air with pressure control is used as the padding material with a non-compressible surface (wood) underneath the air cushion. The basic design is shown in Figure 1.

The seat is initially biased such that the air conforms to the pilot to support most of his weight as shown in Figure 2. The initial air pressure allows the two main support areas, the tuberosities, to touch the wood surface and thus begin to compress the flesh near these areas. Thus, the bias adjusts the "firmness" of the seat. Then as accelerations increase (positive g) air is removed from the seat giving the effect of compressing the cushion material and causing more of the pilot's weight to be supported by the area around the tuberosities. However, some air is left in the seat to prevent the false cue of the seat falling away from the sides of the legs and buttocks. For negative g, sufficient air is added to seat to remove all contact with the wood and thus uniformly support the body weight, without becoming firm due to too much air.

This manner of seat operation (i.e. reproducing the aircraft seat actions) automatically reproduces other related pilot events as raising or lowering the body which results in changing the eyepoint and the joint (hips and knees) angles.

The full seat design (Reference 1) is shown in Figure 3. The air cushion is made of pliable rubber and has four air cells per seat and back cushion with individual pressure controllers for each of the eight cells. This allows differential control to "tilt" the seat pans for various cues. The air cushions are 2.54 cm (1-inch) thick to minimize "following" as the pilot shifts his weight and to increase response time by lowering the air volume required. The "following" occurs when the pilot moves in such a manner to remove a part of his buttock area from contact with the seat. The constant air pressure would cause the seat cell to "follow" the moving area until the seat reaches the limit of its excursion capability. In this case, the maximum "following" would be 2.54 cm (1-inch) or less.

Pressure Control

The inherent design of the seat requires precise and responsive control of the air pressure in each cell. Therefore, the servo controller utilizes pressure feedback as shown in Figure 4. The design uses large air lines (3/4-inch ID) and locates the pressure transducer at the air cell to get true seat cushion pressures as shown in Figure 5. The air control valve used is a standard aircraft anti-g suit valve with the normal activating slug replaced by a motor which provides the linear actuation of the valve as shown in Figure 6. The aircraft valve was chosen because it provides adequate pressurization time and, more importantly, adequate bleed time without the use of other devices such as booster relays which tend to degrade the pressurization time. The valve has a non-linear relationship between the input displacement and the output pressure, however, the pressure feedback provides linear response.

Seat Cushion Response

In the design of the servo controller, it was considered important for the seat to follow the command with minimum time lag in order to be able to respond to the aircraft dynamics. It was also desired to closely match the seat response with the simulator's visual display response. The design of the seat requires a decrease in air pressure (and, consequently, more of the pilot's buttock area contacting the hard surface) for positive g; therefore, the removal of air from the seat is the most important and most difficult to achieve due to the low-pressure differential. Figure 7 shows a pressurization time (decreasing g) of 45 milliseconds and a bleed time (increasing g) of 60 milliseconds for a 50% step. Both positive and negative steps have settled to within 10% of the final value in 100 milliseconds. Analysis of the step and sinusoidal responses show that the system is essentially a .45 damped, 25 rad/sec, second order system over the range of 0 to 8 Hz. This provides a 35 millisecond time lag from seat command to seat pressure over the seat's full range of operation. The dynamic response data is summarized in Table I.

Drive Signal Development

A complete seat pan was installed in NASA Langley's Differential Maneuvering Simulator (DMS), Figures 8 and 9, which is described in Reference 3. The DMS has a wide F.O.V. visual display where all servos involved in projecting the visual scene are synchronized with a .7 damped, 25 rad/sec, second order transfer functions. The initial step in the development of the complete seat drive signals was to drive the seat pan with normal acceleration. Additional terms for other cues are to be added one at a time. For the normal acceleration drive, the seat cells were subjectively scaled using 6 LRC test pilots and 2 engineers. The scaling (Figure 10) was developed by the test pilots and engineers making comparison flights in the LRC T-38 aircraft. Note that the two forward cells are driven over a smaller pressure range than the two rear cells. This is due to the fact that the pilot's feet, resting on the rudder pedals, do not allow his upper legs to fall as his torso does. Also note (Fig. 10) that no cells are driven to zero differential pressure in order to prevent the false cue of the seat falling away from the pilot's legs and sides of the buttocks. The scaling chosen allows maximum "feel" at +6g and 0g with the 1g neutral position biased (as a function of pilot weight, Figure 11) to allow the pilot's tuberosities to just contact the hard surface as described earlier. This scaling was found to give good pilot sensitivity to small "g" increments while performing tracking tasks as well as providing good overall feel at the maximum "g" levels.

Initial Performance Tests

Following the scaling of the normal acceleration drive term, an experiment was defined to determine the effect of the g-seat (driven by normal acceleration only) on the simulator pilot's performance. The experiment consisted of a tracking task with the pilot's tracking reference (a standard reticle pattern) driven by a square wave. The studies were conducted in the DMS using an F-14 simulation as the test aircraft. The pilot's task required tracking a maneuver (at a constant range of 1500 ft) flown by one of the test pilots and stored on permanent files for computer playback. This provided a repeatable task for evaluation of the pilot's performance with and without the g-seat. The target maneuver consisted of a 3g wind up-turn at a constant airspeed of 325 knots. The pilot's tracking reference (reticle) was driven during each run from 10° lead to 5° lag and vice-versa every 10 seconds. This caused the pilot to reacquire the target every 10 seconds (Figure 12) increasing and decreasing "g" from the 3g nominal point. The reticle was equipped with a standard range analog bar scaled for 1500 feet at the 6 o'clock tab. This provided range information to aid the pilot in maintaining a 1500 foot range to the target throughout the run. For data analysis purposes, the tracking task is broken down into four basic parts as shown in figure 12. These parts are: (1) transitioning from -10^o (lead) reticle setting to $+5^o$ (lag) reticle setting (+T), (2) tracking at $+5^o$ reticle setting (+S), (3) transitioning from $+5^o$ reticle setting to -10^o reticle setting (-T), and (4) tracking at -10^o reticle setting (-S). The pilot is considered to have transitioned when the vertical tracking error (TKE) reaches 80% of the required value (-10^o or $+5^o$). Each data run lasts approximately 70 seconds. At the beginning of a run there is a 10 second period for the pursuit craft to stabilize. The 70 second data runs alternate seat-on, seat-off conditions and the runs are grouped into sessions. One session consists of 10 sixty-second runs, five with seat-on and five with seat-off.

Statistical Performance and Analyses Measures

During each data run, eleven system states are recorded every 1/16-second. Variables recorded (raw data) are vertical tracking error (TKE), lateral tracking error (TKL), total tracking error (TKC), normal acceleration (NZ), pitch rate (THEO), roll rate (PDT), range to target (RT), reticle command (REI), stick deflection for pitch (DE), stick deflection for roll (DA), rudder deflection (DR), reticle switching time (SWT) and time (T). This raw data is then transformed to performance measures.

In order to create the performance measures, four measurement calculations are used. They are the arithmetic mean, root mean square, maximum, and minimum. These calculations are applied to the four basic parts of the reticle switch cycle and the eleven system states. Performance measures such as mean normal acceleration during a positive transition from -10^o to $+5^o$ (MNZ+T), mean normal acceleration during a negative transition from $+5^o$ to -10^o (MNZ-T) and mean normal acceleration during a positive tracking (MNZ+S) are available from the program. Also, the positive transition times (TS+) and the negative transition times (TS-) are used as performance measures. Altogether ninety performance measures were created and analyzed to determine whether the g-seat affected pilot performance.

In order to analyze the performance measures, two statistical tests were used. They were the student's t-test for paired and unpaired data and the variance ratio test. In addition to these tests, other pertinent statistical parameters computed included: mean values for seat-on and seat-off conditions, variances for seat-on and seat-off conditions, total variances, and correlation matrices.

Presentation of the Results

Two sets of pilots were used in this study. The first set contained two Langley test pilots with many hours in fighters and in simulators. These two test pilots were used to scale the g-seat and as a result were very experienced with the g-seat and the simulator. The second set contained five NASA test pilots with varying degrees of time in fighter aircraft and little famialiarity with the DMS and g-seat. The first set of pilots flew 7 sessions per pilot for data. The first two of which were not used to ensure that the pilots were far along learning curves. The second set of pilots flew 4 sessions per pilot for data. The first two of which were not used as before. None of the 5 pilots in this group had flown the task before the study began A large sample of pilots (4 or more) with about 7 sessions of the experiment would have been the ideal situation, but due to the limited number of Langley test pilots and their busy work schedule, this was not possible. Hence, two samples were used; a small sample, set one, with many sessions, and a larger sample, set two, with fewer sessions. The pilots in both sets used a wide variety of approaches to tracking the target. This variation can be seen by looking at the average transition times for each pilot shown in Table 2. Some pilots used a near maximum aircraft pitch rate to transition which resulted in large overshoots/undershoots and larger oscillations about the desired tracking, while others transitioned much slower to ensure much smaller overshoots/undershoots and better steady-state tracking. Thus, the pilot samples cover a large range of approaches to the task.

Table 3 presents a summary of the analysis for the 2-pilot set and Table 4 presents a summary of the analysis for the 5-pilot set. Contained in the table are the results of the variance ratio test for seat-on variances versus seat-off variances and the two-sided students-t test on paired data. The probabilities listed are those of the event, "the difference between seat-on and seat-off is not due to chance." One minus any of the probabilities will give an α-level at which the test result is considered significant. Only probabilities greater than or equal to .9 are listed. A computer subroutine was used to calculate the probabilities from an f-distribution and a t-distribution. Round-off and truncation error results in some probabilities being given as 1.000. The arrows beside the probabilities indicate whether the measures tested were lower (↓) or higher (↑) for the seat-on condition. It is considered important that over 90% of the significant measures for both pilot sets combined have lower variances for the seat-on condition. This would indicate that the pilot gets information from the seat which allows more precise control of his aircraft, thereby lowering the variance of some performance measures.

The pilots were each required to fill out a questionnaire (fig. 14) concerning the realism of the seat and any effect they thought the g-seat had on their performance. The comments given by each pilot indicated that they thought that they handled the airplane more gently with the seat on. This appears to be verified by the results of statistical tests on the longitudinal measures which show lower mean values for aircraft parameters (pitch rate, normal acceleration, longitudinal stick position) and generally higher means for the longitudinal performance measures (vertical tracking error and transition time). The pilot's comments also indicated that the aircraft appeared to be "easier to control" or "better damped" in roll with the seat on. This can be seen in the data which shows a large number of significant measures in the variances and means for the lateral-directional measures; even though the task was essentially vertical tracking. The lateral problem seems to come from the pilots making lateral corrections to track the target aircraft and consequentially being "out of plane" with the target when transitioning. The seat appears to be providing (through the normal acceleration drive signal) information which makes it easier to make the lateral corrections, i.e., sensing the out of plane accelerations more rapidly. Other pilot comments indicated good to excellent realism for the normal acceleration cues. None of the pilots considered that the seat had any noticeable time lag.

Conclusions

Objective (statistical test results) and subjective (pilot comments) evaluations of the effect of the g-seat on pilot performance during a tracking task indicates that the g-seat does affect the performance of the man/machine system. The g-seat gives information that allows more precise control of the aircraft. This is shown by significant differences in the variances of many response measures for seat-on versus seat-off conditions and over 90% of the response measures that do show a significant difference have a lower variance for the seat-on condition. This is further supported by pilot comments. A surprise result was the positive effect the g-seat had on lateral control problems. Again the objective and subjective evaluations supported each other. Pilot comment said that the aircraft appeared to be easier to control or better damped in roll with the seat-on. Again, significant differences in the means and variances of lateral response measures implied that the g-seat supplied information that aided lateral control of the simulated F-14 aircraft. Analysis of the data from this experiment is continuing. Tests to determine the pilot describing functions for the seat-on and seat-off conditions are planned. The seat and back drive equations are being modified to drive the g-seat system as a function of normal acceleration, roll acceleration, directional, and longitudinal accelerations.

1. Ashworth, B. R.: A Seat Cushion to Provide Realistic Acceleration Cues for Aircraft Simulators. NASA TM X-73954, 1976.

2. Singer, S. F.: PROGRESS IN THE ASTRONAUTICAL SCIENCES. Interscience Publishers, Inc., c.1962.

3. Ashworth, B. R.; and Kahlbaum, William M., Jr.: DESCRIPTION AND PERFORMANCE OF THE LANGLEY DIFFERENTIAL MANEUVERING SIMULATOR. NASA TN D-7304, 1973.

TABLE 1. SEAT CUSHION DYNAMIC RESPONSE CHARACTERISTICS

Command	Maximum Time Lag
50% Step	65 milliseconds
Full Amplitude Sinusoidal Response	35 milliseconds Constant over (0 - 8 hz)

TABLE 2.- PILOT TRANSITION TIMES

		Average Transition Time seconds		
PILOT				
(1A)	TS+		3.77	
	TS-		4.26	
(2A)	TS+		4.03	
	TS-		5.09	
(1B)	TS+		3.50	
	TS-		3.13	
(2B)	TS+		3.47	
	TS-		3.61	
(3B)	TS+		2.95	
	TS-		2.96	

TABLE 2. Concluded.

PILOT		Average Transition Time seconds	
(4B)	TS+	1.97	
	TS-	1.94	
(5B)	TS+	2.41	
	TS-	2.18	

TABLE 3(a). SIGNIFICANT VARIANCES FOR THE TWO-PILOT SAMPLE

↓ - Variance less seat-on
↑ - Variance more seat-on

Measures		Probability
TS+		.962 ↓
TS-		-
+T	Longitudinal	
MTK +T		.949 ↓
-T	Longitudinal	
MDE -T		.975 ↓
MTD -T		.995 ↓
MNZ-T		.976 ↓
TD MIN-T		.999 ↓
NZ MIN-T		1.000 ↓
+S	Longitudinal	
MDE +S		.955 ↓
TD MAX +S		.943 ↓
NZ MIN +S		.943 ↓
-S	Longitudinal	
TD MAX -S		.929 ↓
+T	Lateral	
MPDT +T		.926 ↓
PDT MIN +T		1.000 ↓
PDT MAX +T		1.000 ↓
-T	Lateral	
MDR -T		.995 ↓
MTKL -T		.932 ↓
MPDT -T		.991 ↓
PDT MAX -T		.968 ↓
+S	Lateral	
MDA +S		.993 ↓
MPDT +S		.996 ↓
PDT MAX +S		.993 ↓

TABLE 3(a). Continued.

↓ - Variance less seat-on
↑ - Variance more seat-on

Measures		Probability
-S	Lateral	
MDA -S		.956 ↓
PDT MIN-S		.998 ↑

TABLE 3(b). SIGNIFICANT MEANS FOR THE TWO-PILOT SAMPLE

↓ - Mean less seat-on
↑ - Mean more seat-on

Measures		Probability
TS+		-
TS-		.972 ↑
-T	Longitudinal	
MDE -T		.998 ↓
MTD -T		.958 ↓
TD MAX -T		.918 ↓
-S	Longitudinal	
MTK -S		.970 ↓
NZ MAX -S		.993 ↓
TD MIN -S		.991 ↑
NZ MIN -S		.997 ↑
+T	Lateral	
PDT MIN +T		.980 ↓
PDT MAX +T		.987 ↓
-T	Lateral	
MDR -T		.958 ↓
+S	Lateral	
PDT MAX +S		.992 ↓
-S	Lateral	
MTKL -S		.985 ↓
PDT MAX -S		.965 ↓

TABLE 4(a). SIGNIFICANT VARIANCES FOR THE 5-PILOT SAMPLE

5 PILOTS MIXED — ↓ - Variance less seat-on; ↑ - Variance more seat-on

Measures		Probability
TS+		-
TS-		.918 ↓
+T	Longitudinal	
MTK +T		.921 ↓
+S	Longitudinal	
MDE +S		.971 ↓
-S	Longitudinal	
MTK -S		.972 ↑
+T	Lateral	
MDA +T		.971 ↓
PDT MAX +T		.929 ↓
-T	Lateral	
MDA -T		.960 ↓
PDT MIN -T		.965 ↑
+S	Lateral	
PDT MIN +S		.987 ↓
-S	Lateral	
MTKL -S		.993 ↑
PDT MAX -S		.968 ↓
PDT MIN -S		.967 ↓

TABLE 4(b). SIGNIFICANT MEANS FOR THE 5-PILOT SAMPLE

5 PILOTS MIXED — ↓ - Mean less seat-on; ↑ - Mean more seat-on

Measures		Means 0-60 sec Prob.
-T	Longitudinal	
TD MAX -T		.973 ↑
+T	L Lateral	
MDR +T		.930 ↑
-T	Lateral	
MDA -T		.963 ↓
-S	Lateral	
MDR -S		.930 ↑
MPDT -S		.970 ↑

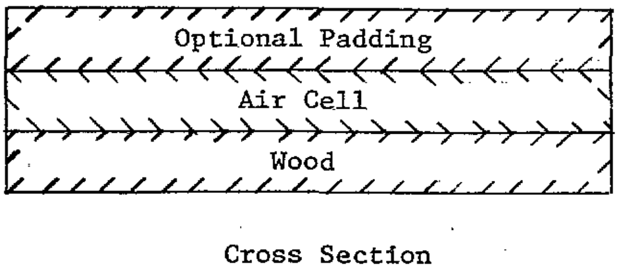
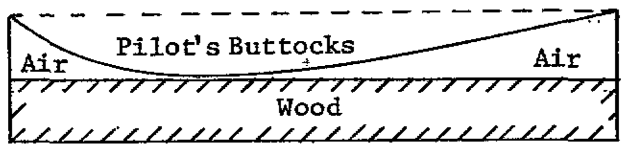
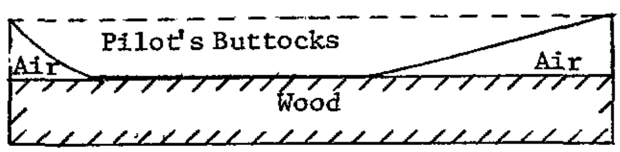


Figure 1. Basic Seat Concept for One Cell



(a) Neutral - 1g Bias



(b) Positive g

Figure 2. Seat Operation

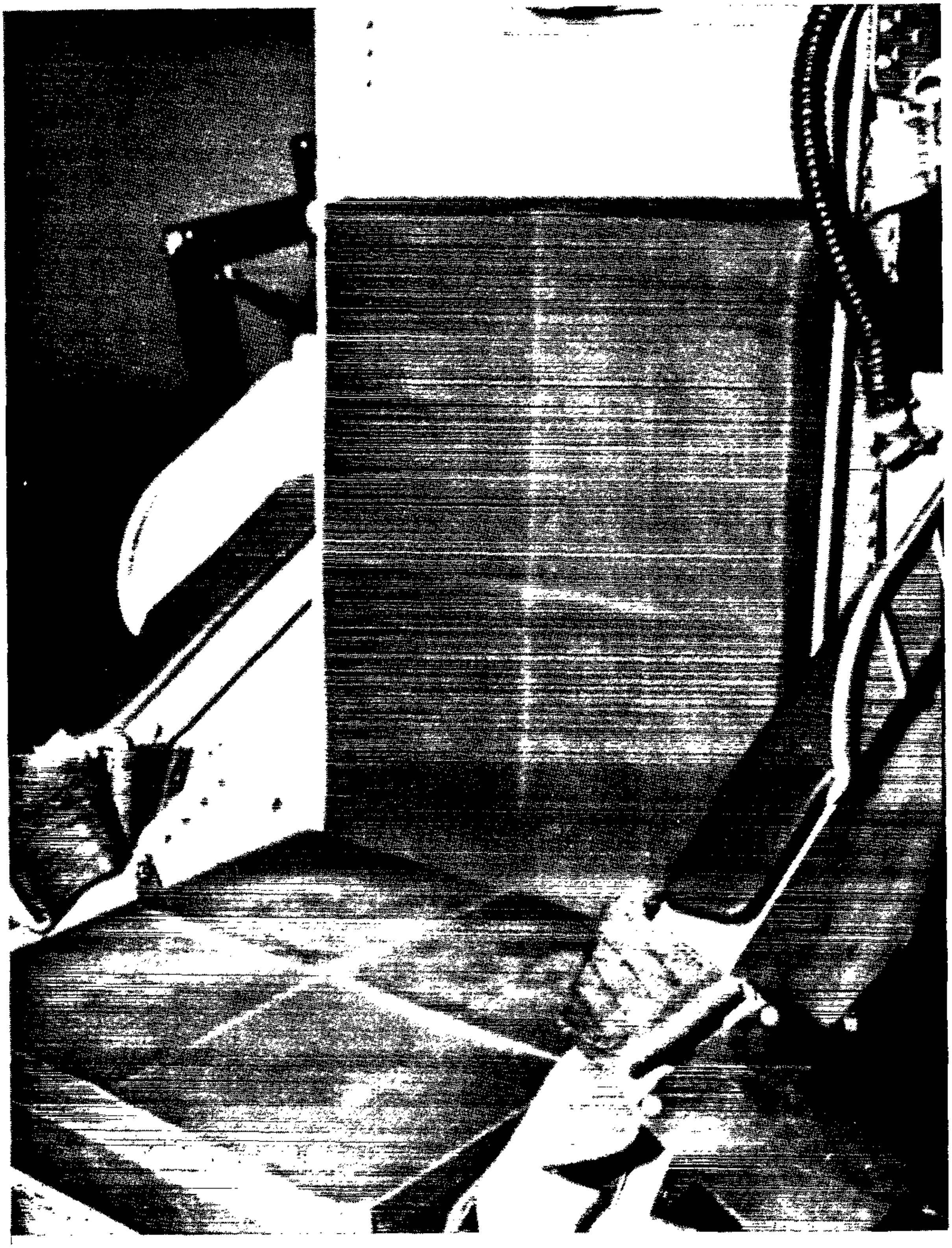


Figure 3. Seat and Back Cushions
(Four Cells Each)

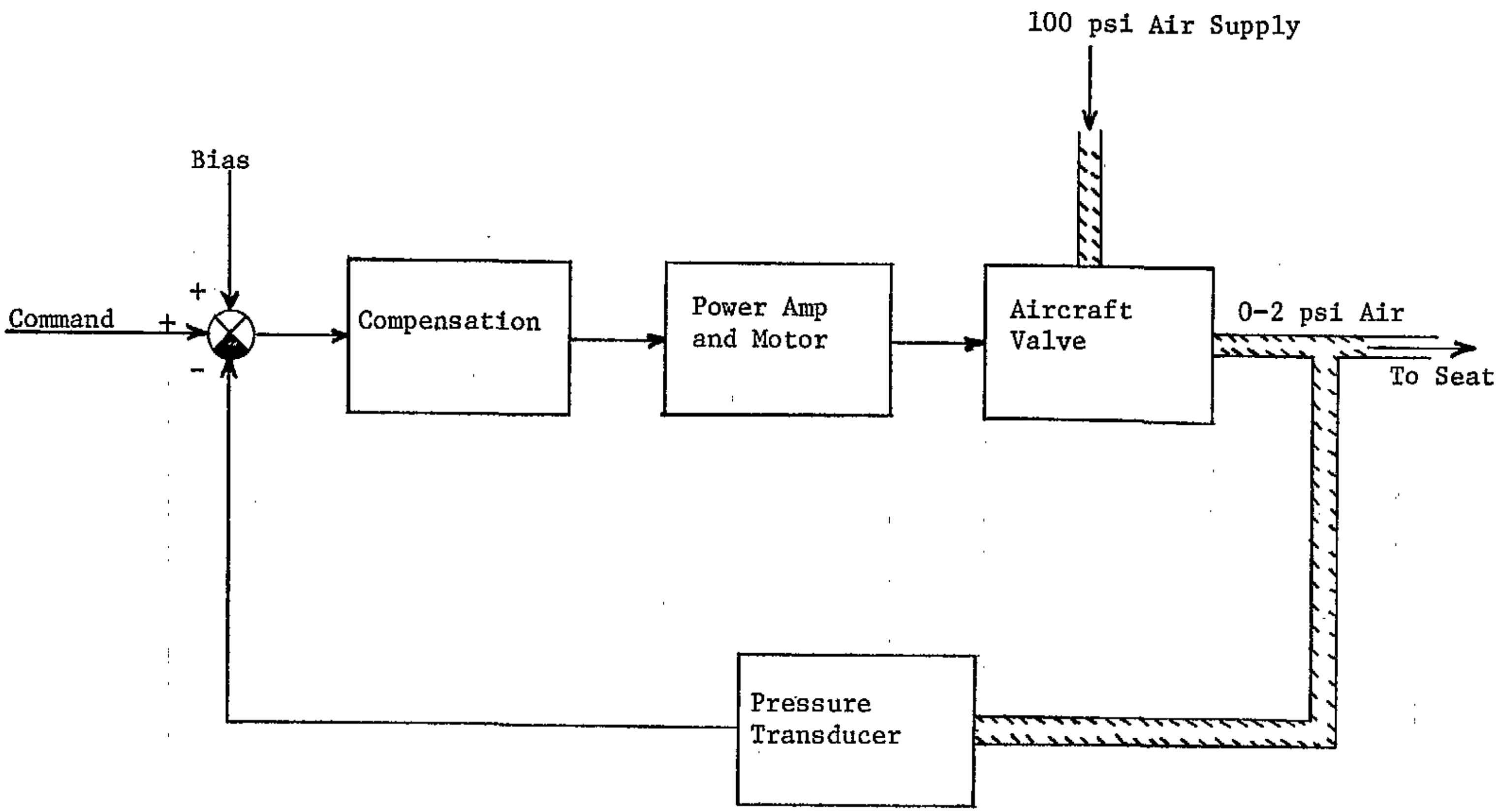


Figure 4. Servo Controller for One Seat Compartment

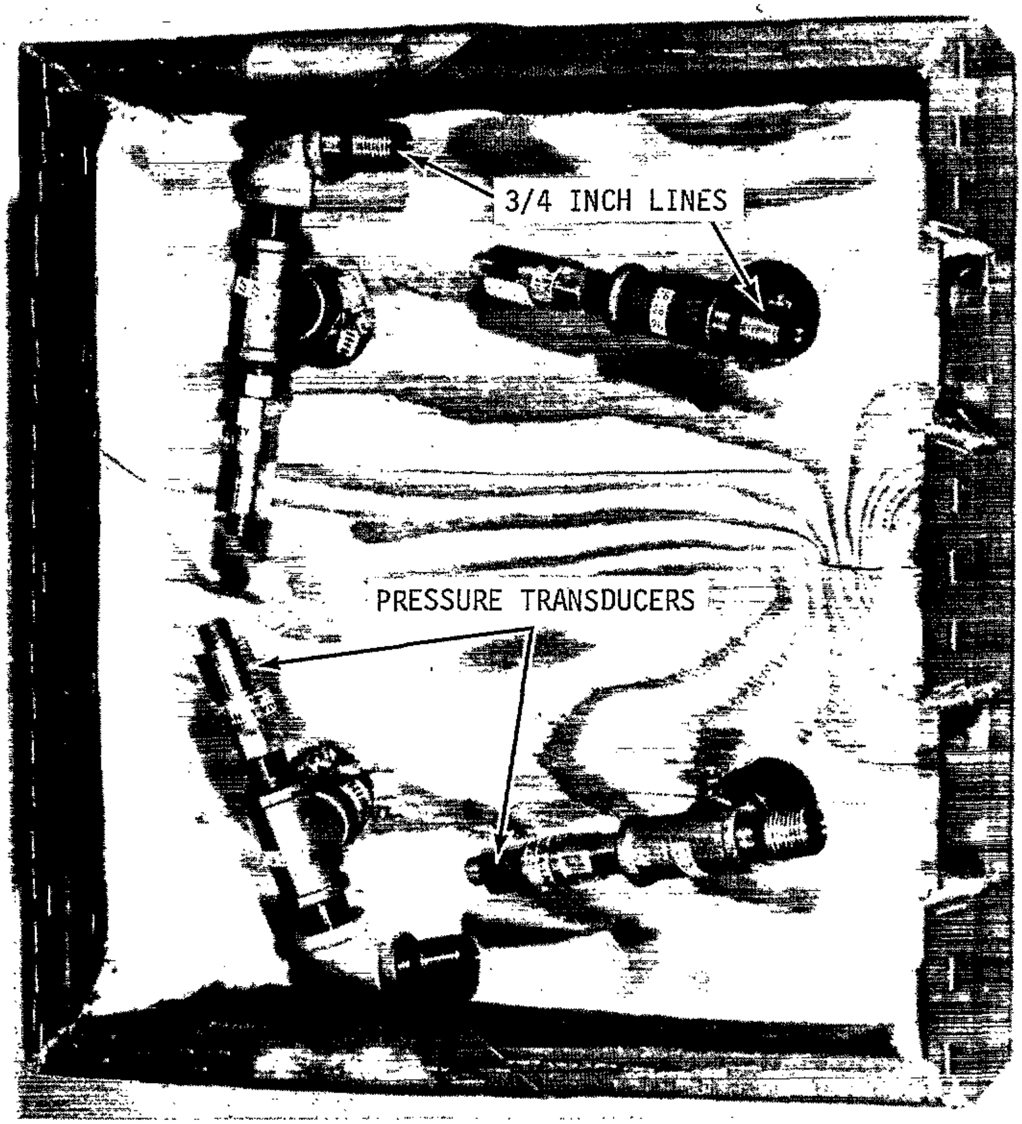


Figure 5. Seat Cushion Bottom View

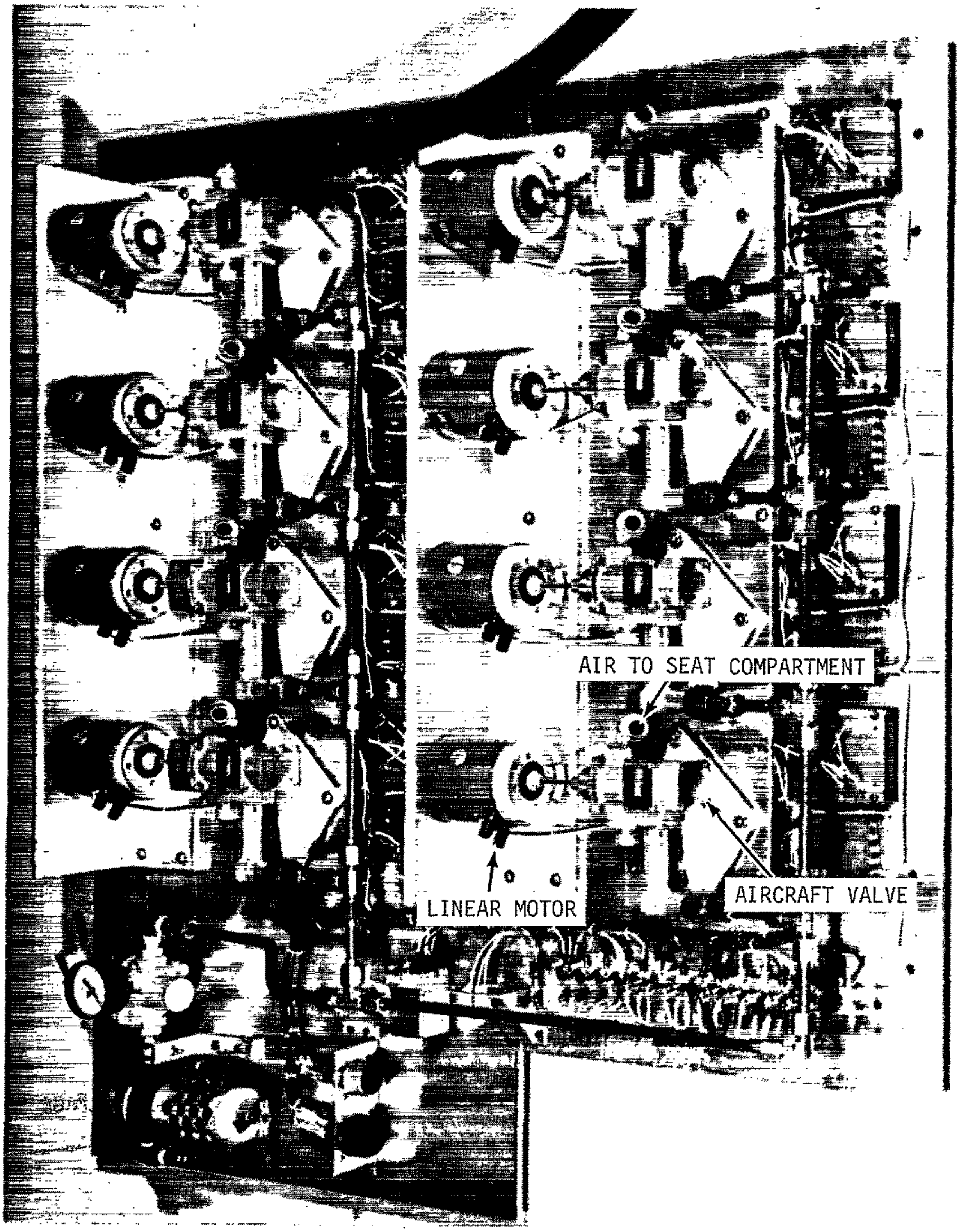


Figure 6. G-Seat Pressure Controllers

Figure 7 a.- Negative g Response

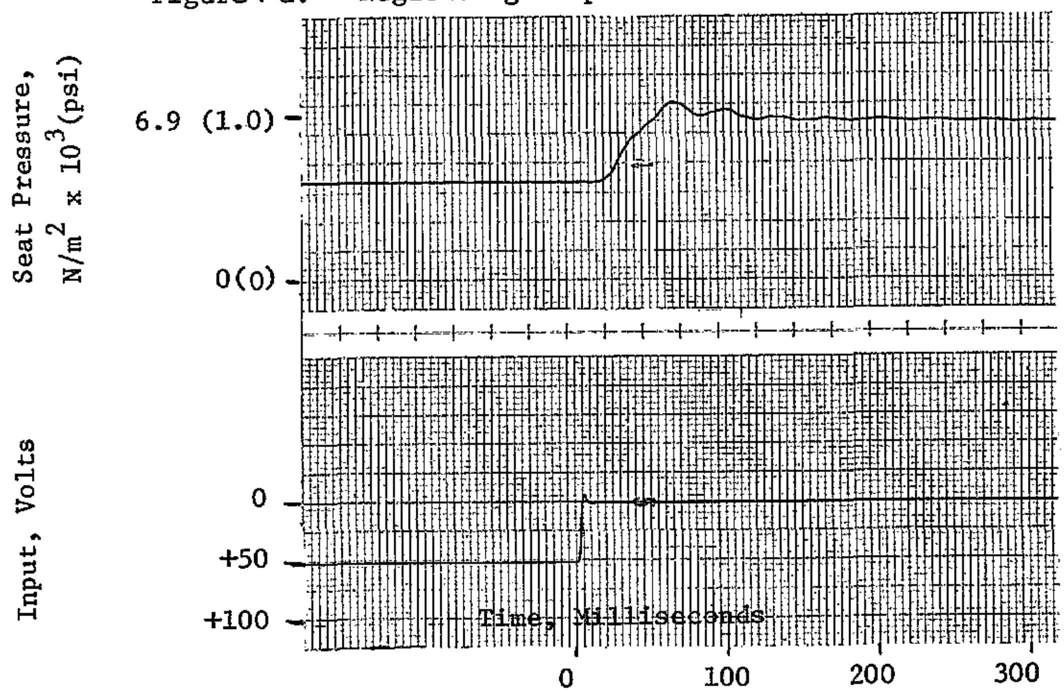


Figure 7 b.- Positive g Response

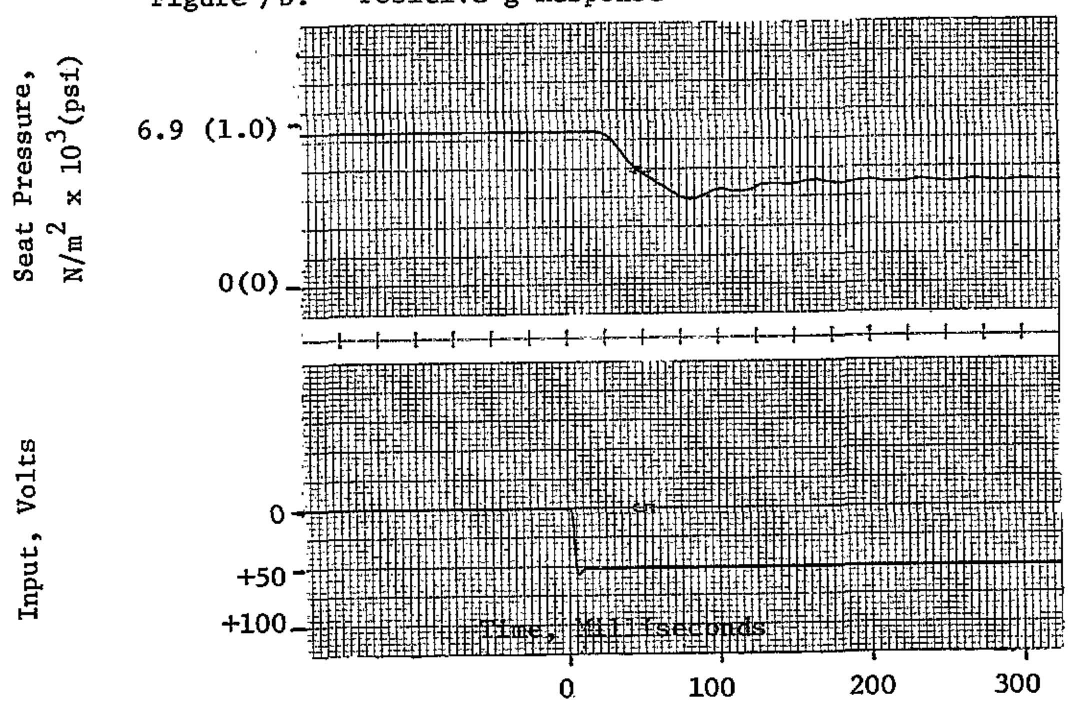


Figure 7. G-Seat Step Response for 50% Step Input (1 cell)

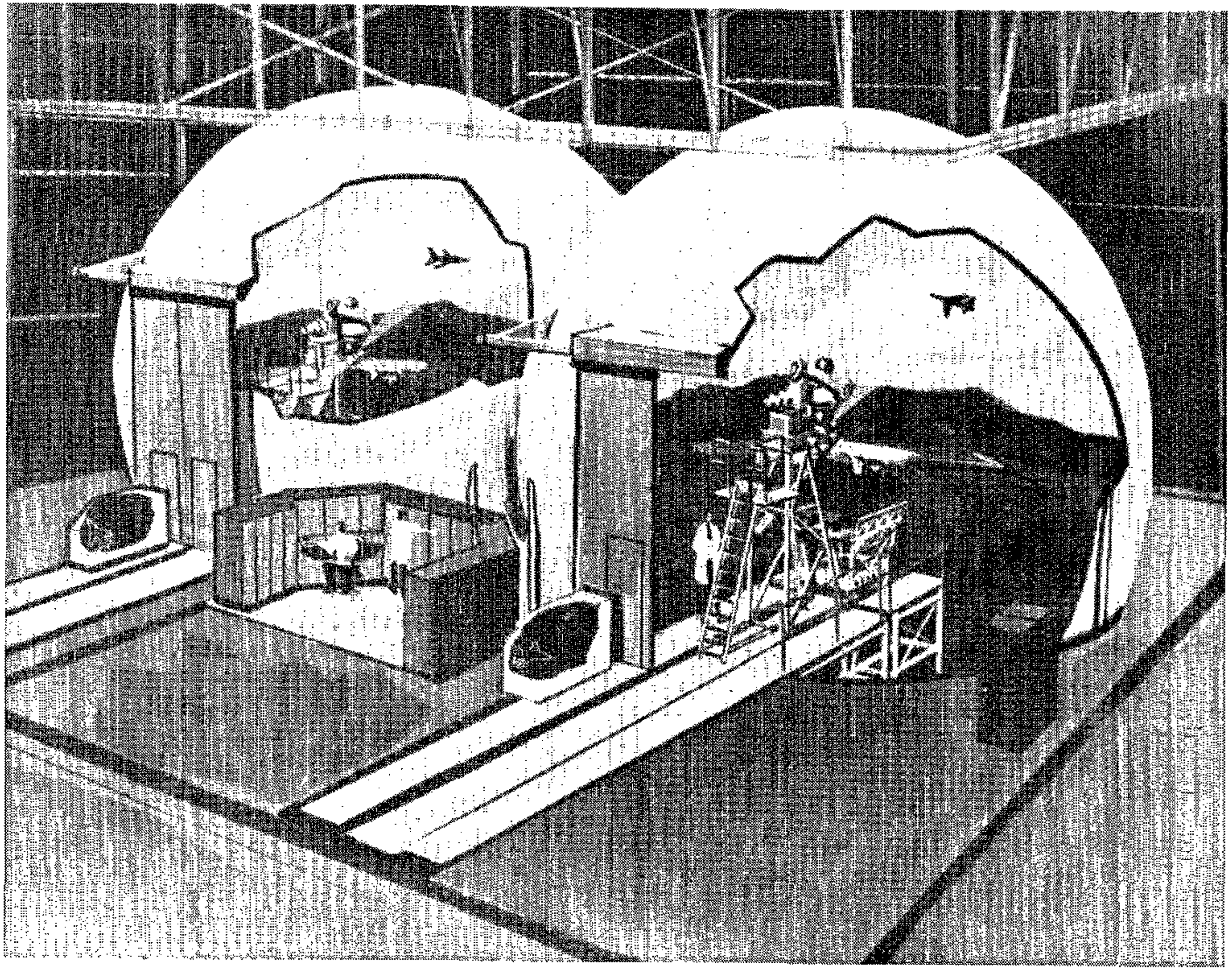


Figure 8. DMS Facility

Figure 9. DMS Pilot's View

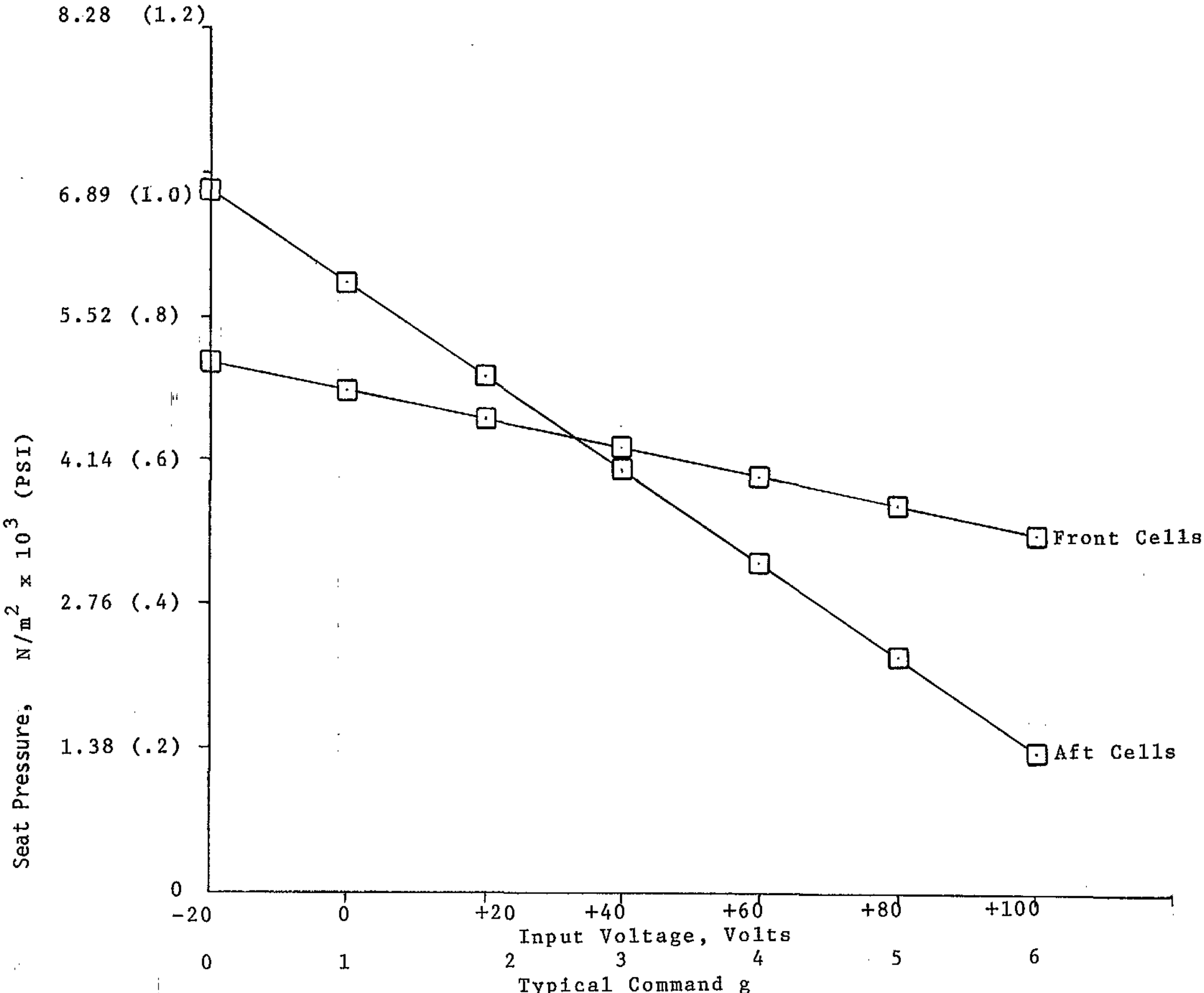


Figure 10. G-Seat Scaling for 160-Pound Pilot

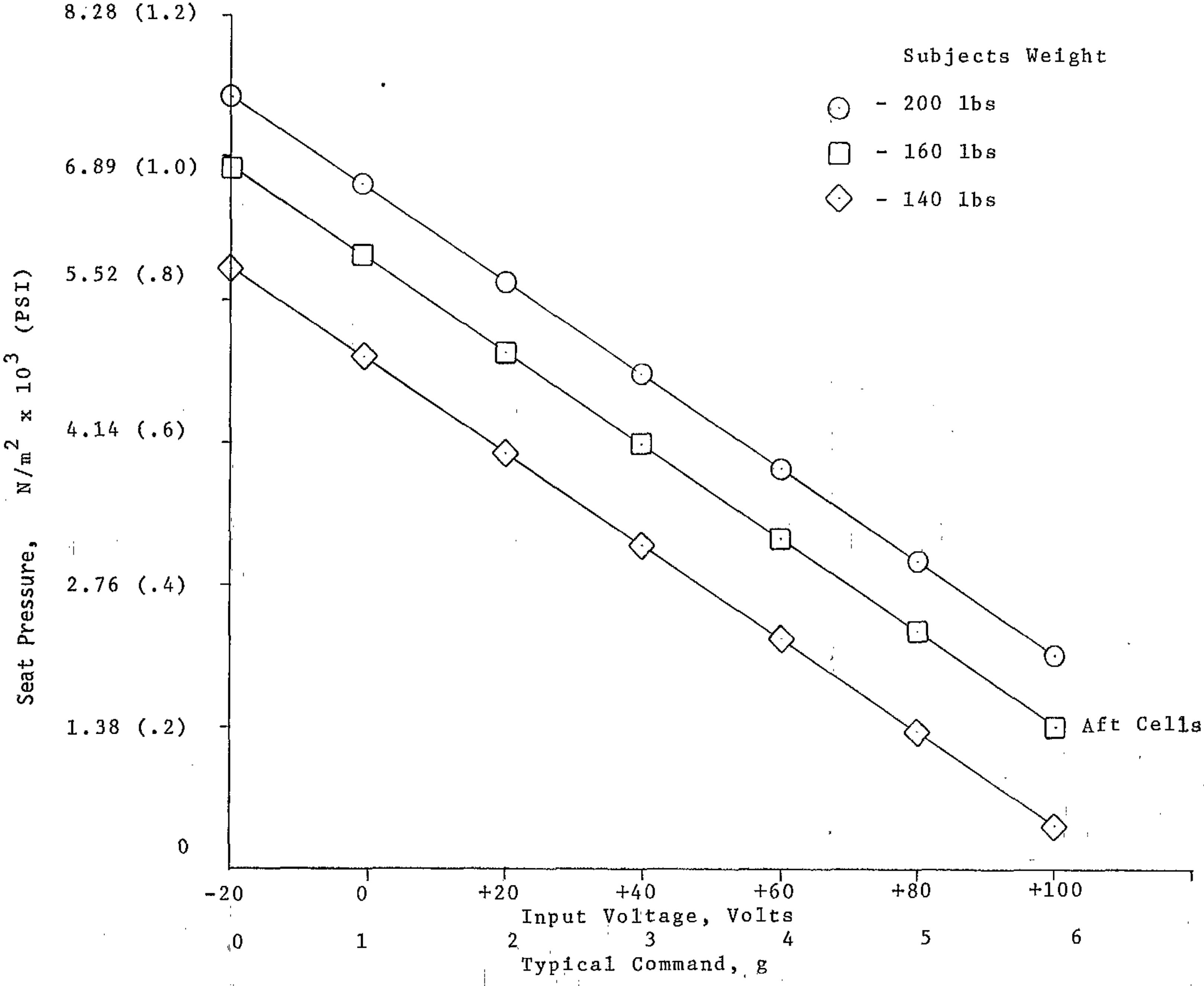


Figure 11. G-Seat Scaling as a Function of Pilot Weight

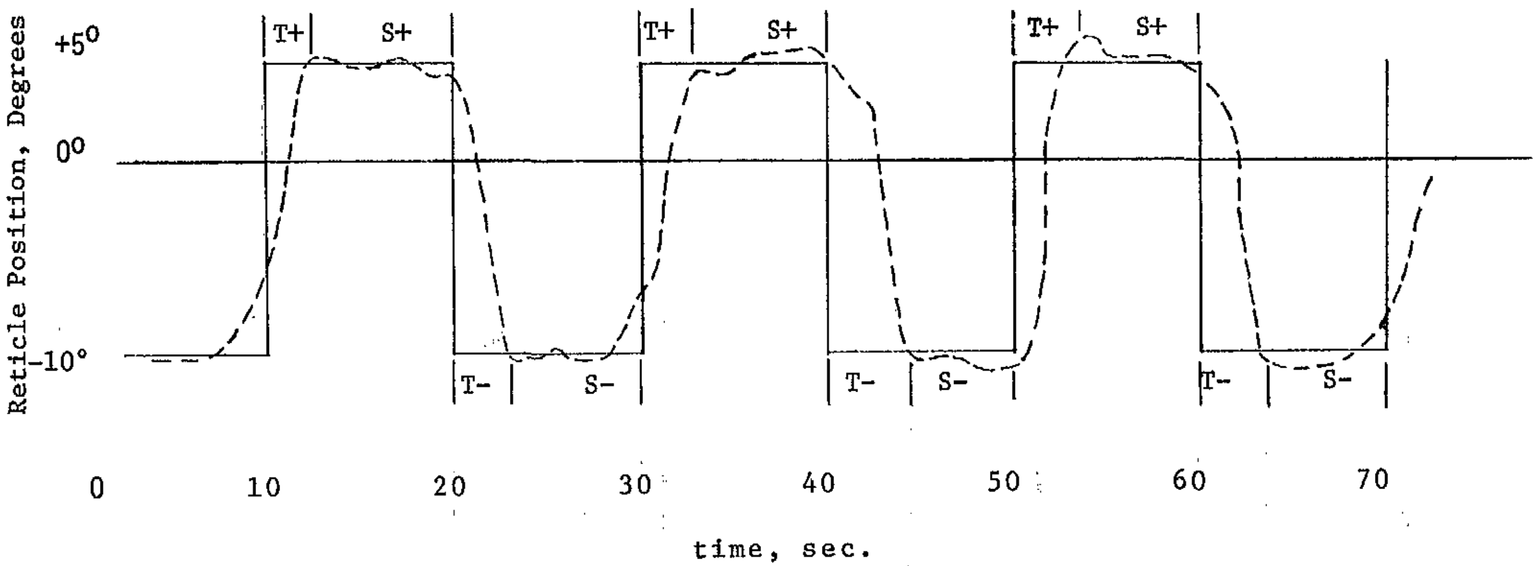


Figure 12. Structure of One Computer Run

Please note the realism of the seat on the scale below:

	Excellent	Good	Fair	Poor	Unacceptable
Realism - Overall					
Positive G					
Increasing +G					
Decreasing +G					
Negative G					
Increasing -G					
Decreasing -G					

Does the presence of the seat have any effect on your:

1) Overall Tracking performance? YES ____ NO ____
   a. over shoot YES ____ NO ____
   b. time to stabilize YES ____ NO ____
2) Control inputs? YES ____ NO ____
3) Maximum A/C rates? YES ____ NO ____

Is there any noticeable time lag in the seat response to your inputs?

YES ____ NO ____

Additional Comments:

Figure 13. Pilot Questionnaire

ABOUT THE AUTHORS

MR. BILLY R. ASHWORTH is a Project Engineer in NASA's Simulator Development Section. He has worked on the differential maneuvering simulator and the general aviation aircraft simulator. He has also worked on kinesthetic cues for simulators developing control laoding systems and g-cueing systems for which he holds a U.S. patent. He is presently working on a g-seat system and investigating digital time-delay effects on pilot/simulator systems. He holds a B.S.E.E. degree from Tennessee Technological Institute, an M.S.E.E. degree from University of Virginia, and is working on a doctor of science in computer science at George Washington University.

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