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EFFECT OF VERTICAL ACTIVE VIBRATION ISOLATION ON TRACKING PERFORMANCE AND ON RIDE QUALITIES

by Frank P. DiMasi, Rush E. Allen, and Peter C. Calcaterra

Prepared by
BARRY WRIGHT CORPORATION
Watertown, Mass. 02172
for Langley Research Center

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16. Abstract

An investigation has been conducted to determine the effect on pilot performance and comfort of an active vibration isolation system for a commercial transport pilot seat. The test setup consisted of: a hydraulic shaker which produced random vertical vibration inputs; the active vibration isolation system; the pilot seat; the pilot control wheel and column; the side-arm controller; and a two-axis compensatory tracking task. The effects of various degrees of pilot isolation on short-term (two-minute) tracking performance and comfort were determined.

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By Frank P. DiMasi, Rush E. Allen, and Peter C. Calcaterra
BARRY, Division of Barry Wright Corporation
Watertown, Mass.

SUMMARY

This report presents the design of a two-axis tracking task and the results of a human factors test program to evaluate the effect vertical vibration isolation has on performance of the task.

Various body isolation configurations consisting of combinations of torso, hand and foot isolation were tested. An active system was used to isolate a subject seated on a standard DC-8 seat from vertical random vibrations typical of those experienced at the cockpit of commercial transports during turbulent flight. A column and wheel (un-isolated from the vibratory motions) and side-arm controller (attached to the isolated seat) were used by the subject for control inputs to a two-axis (pitch and roll) tracking task using a cathode ray tube (CRT) to simulate an aircraft flight director.

Tracking error measurements in roll and pitch were made for fixed base, vibration, isolated seat and simulated total (seat and display) isolation configurations. Combinations of column and wheel, side-arm controller, fixed rudder pedals (un-isolated from the vibratory motions) and footrest (attached to the isolated seat) were used during the tests.

Results from error measurements showed that only minimal changes in control capability occurred from the addition of active seat isolation for the two-minute test period. Subjective response indicated that the seat isolation system provided a dramatic improvement in comfort over that afforded by the standard seat. However, large relative deflections between the subject and displays which occurred for low frequency vibration inputs made it difficult for the subject to analyze and interpret the error in terms of displacement, rate and acceleration. It is postulated that long-time duration testing will show an improvement in tracking ability relative to that of the standard seat as a result of an anticipated decrease in fatigue. Consequently, it is recommended that such a long-time duration test program be conducted to validate this assumption.

Results also showed that the best combination of improved ride comfort and tracking performance can be expected from a system which has the capability of isolating the displays, seat, and controls. It is recommended that a feasibility study be made to determine if such a "total isolation system" is practical to build.

LIST OF SYMBOLS

φ_{WR}	wheel displacement in roll (degrees)
φ_{RHD}	displayed error in roll (degrees)
K_{SF}	subject displacement feedback gain for single integral dynamics (degrees/degree)
V_{SF}	subject feedback voltage (volts)
V_{IR}	roll input voltage (volts)
V_{RE}	roll error voltage (volts)
K_{RHD}	roll horizon display gain (degrees/volt)
K_{WR}	wheel roll gain (volts/degree)
K_{PR}	pilot roll gain per potentiometer turn (volts/volt-turn)
T_{PR}	roll potentiometer setting (turns)
K_{SFD}	subject displacement feedback gain for double integral dynamics (degrees/degree)
K_{SFR}	subject rate feedback gain (degree-second/degree)

SECTION 1: INTRODUCTION

Under a previous development contract, NAS1-8060, an Active Vibration Isolation System (AVIS) prototype was developed to provide maximum protection to pilots from dynamic environments equivalent to that experienced at the cockpit of commercial jet transports during turbulent air penetration. Part of the investigation dealt with an evaluation of the nature of the response of jet transports to severe turbulence. A review of the technical literature on the tolerance and performance characteristics of seated human subjects exposed to whole body sinusoidal and random vibration was also conducted [Ref. 1].

Based on results of that evaluation, it was concluded that vibration isolation was not required in the fore/aft and transverse directions, but better than 70 percent vertical isolation was required between 4 and 5 Hz (fuselage first flexible bending mode resonant frequency) and greater than 85 percent isolation for excitation frequencies between 20 and 50 Hz. In addition, it was undesirable to provide vibration isolation at excitation frequencies less than 1.3 Hz (fundamental wing bending frequency for commercial jet transports) since this would remove the pilot's "seat-of-the-pants" buffeting stall alarm. Thus, based on reducing the levels of acceleration to tolerable levels, it was necessary to devise a combination notch plus broad-band type isolation system which would provide a nominally 2 Hz resonant frequency and the desired isolation characteristics at nominally 4.5 Hz and above 20 Hz. Details of the AVIS design are given in Reference 1.

Results of laboratory tests conducted during the same investigation indicated that:

1. The active vibration isolation system reliably met all design goals including: degree of vibration isolation; control of relative deflection between the pilot and cockpit to ± 1 inch during turbulence penetration, with peak relative deflection of ± 1.5 inches only allowable during severe transients such as buffeting; active repositioning of the seat to its equilibrium position and vibration isolation during sustained acceleration conditions of ± 3 g; and performance independent of variations in pilot weight.

2. The vertical resonant frequency of a conventional jet transport seat cushion is nominally 4 Hz, thus augmenting the primary excitation of the aircraft at a frequency coincidental with human body resonances.

3. Preliminary subjective evaluation tests, demonstrated that the electrohydraulic pilot seat isolation system offers the potential for providing a substantial improvement in subject performance during severe dynamic environments.

It was surmised that this apparent improvement in performance was due primarily to the reduction in dynamic excitation imposed on the subject's torso at 4.5 Hz attained with the active isolation system. However, results also indicated that the vibration which is transmitted directly to the isolated subject's legs via the rudder pedals and that induced in the arms through the controls (where both pedals and controls are coupled directly to the source of vibration), may play a significant role in the overall degradation of subject performance.

Based on these results, an investigation was initiated to: (a) design a task performance experiment incorporating the active vibration isolation system; and (b) conduct cursory tests to evaluate the effect single axis (vertical) vibrations have on a seated subject's ability to perform a two-axis (pitch and roll) compensatory task under various isolation control configurations. This report, therefore, deals with the design of a two-axis compensatory tracking task and with the results of the evaluation tests.

Realization of the many elements which influence human performance dictated a simplification in the number of variables to be considered in the design of the two-axis tracking task. The primary goal was to approximate as much as possible: (1) the physical layout, constraints and mechanisms found in the cabins of typical jet transports; and (2) the human factors relationships involved in a piloting task. However, limitations in the scope of the investigation negated a "total" simulation of the complex dynamics associated with pilot-aircraft interactions during actual flight through turbulence.

A single vertical random vibration input was selected as representative of that experienced at the cockpit of a commercial jet transport flying through moderate turbulence. An electrohydraulic shaker was employed to generate the selected random input. A two-axis (pitch and roll) compensatory task was designed utilizing a cathode ray tube (CRT) to represent an aircraft gyro horizon attitude display. Pitch and roll forcing functions were selected to be representative of the changes in pitch and roll attitude of a commercial transport flying through moderate turbulence. The experimental task requires the test subject to "fly the aircraft level" by introducing control inputs through either a column and wheel or a two-axis side-arm controller to offset the forcing functions and attempt to keep the horizon display at a level attitude. Simplified but representative dynamics are introduced between both the column and wheel and the side-arm controller and the displays to approximate aircraft dynamics [Ref. 2]. Therefore, the control task is closed loop with respect to the tracking task but open loop with respect to the vibration input. That is, the subject's control inputs do not affect the dynamic input and are not required to maintain a stable system.

The variables in the system are: type of control (column and wheel or side-arm controller) and isolation configuration. The vibration isolation configurations included:

(a) no isolation (AVIS off; control using either column and wheel or side-arm controller);

(b) torso isolation only (AVIS on; and control using column and wheel);

(c) torso and feet isolated (AVIS on; control using column and wheel; and isolated footrest);

(d) torso and hands isolated (AVIS on; control using side-arm controller); and

(e) torso, hands and feet isolated(AVIS on; control using side-arm controller and isolated footrest).

In all these conditions, the display was not isolated. A limited number of tests were also conducted under conditions simulating vibration isolation of both the seated subject and the displays.

The effect of each isolation configuration on performance was evaluated in terms of total mean squared error in pitch and roll measured over a two-minute test period. The error signal was generated by comparing the compensated control input signals to the forcing function signals in both pitch and roll. In addition special questionnaires were designed to measure the relative subjective effect each of the various isolation and control configurations have on vision, body motions and ability to track. The length and sequence of test and rest periods were designed to avoid fatigue and allow time for learning effects to be eliminated. A total of 211 two-minute runs were made with one subject, Mr. Robert A. Champine, NASA/LRC test pilot.

Section 2 of this report shows the mechanical and electrical design of the two-axis tracking task. Details of the experimental procedure are discussed in Section 3. Section 4 presents the results of the human factors test program. Conclusions and recommendations are given in Section 5.

SECTION 2: SYSTEM DESCRIPTION

This section describes the design of the two-axis compensatory task developed during the investigation reported on herein, and its use in conjunction with the Active Vibration Isolation System (AVIS) previously developed under NAS1-8060.

The goal of the investigation was to design an experiment for evaluating the effect vertical vibrations have on the performance of a two-axis task by a seated subject under various vibration isolation and control configurations. In establishing specifications for the design of the two-axis task, consideration was given to approximating, whenever possible, conditions associated with a typical piloting task aboard a jet transport cockpit, while maintaining simplicity of design. In addition, man-rating and safety requirements compatible with human factors testing played a primary role in the design of the experiment and test facility.

General Description

Figure 1 identifies the various components of the AVIS and the two-axis task, their location in the area where human factors tests were conducted, and the ancillary equipment used for input and data acquisition. Figure 2 shows a schematic representation of the isolated seat, the controls and displays. Overall views of the test area and controls are shown in Figure 3.

Active Vibration Isolation System (AVIS)

The AVIS is a DC-8 Pilot Seat with modifications to include a hydraulic actuator and servo control to actively reduce the transmitted acceleration from the seat attachment point to the test subject. Figure 4 shows the signal flow diagram for the active vibration isolation system. By means of a multi-loop automatic feedback control system the AVIS can simultaneously provide: (a) broad-band vertical vibration isolation; and (b) a high isolation efficiency notch centered about a frequency corresponding to the first fuselage flexible bending mode of commercial jet transport aircraft. The gains associated with the various feedback loops are controlled from the seat servoamplifier console.

The AVIS control system has two modes of operation: the flight or "on" mode; and the landing/takeoff or "off" mode. In the on mode, the control system can provide broad-band and notch isolation characteristics. In the off mode, the control system is employed in a tight relative position feedback loop such that isolation is only provided by the seat cushion. This latter case is representative of the passive type of vibration protection presently afforded with the existing seats. In addition to the power and mode controls, all the system feedback gains and compensation network time constants are controllable by potentiometers mounted on the front panel of the console. Both the notch frequency and the broad-band isolation characteristics of the AVIS can be varied compatible with system stability requirements.

As part of the modifications to the AVIS prior to its use with the two-axis task, special failsafe circuits were designed to shut down the electro-hydraulic shaker whenever the acceleration levels transmitted to the test subject exceeded preset values. The level of acceleration at which the failsafe circuits were activated are discussed in Section 3.

Two-Axis Compensatory Task Simulator

The two-axis task equipment includes: the simulated cabin floor with either footrests or rudder pedals; the horizon display console; the column and wheel and side-arm controller assemblies; an electronic task director console; a horizon display computer; a dynamic shaker; hydraulic supply; input tape recorder; and output recording devices.

Pitch and roll control inputs to the two-axis tracking task are made by the test subject by means of a simulated jet transport column and wheel. A two-axis antenna control stick was modified to simulate a side-arm controller and positioned forward of the right arm rest of the DC-8 seat, as an alternate means of control. With the AVIS on, the side-arm controller provides a means of decoupling hand control motions from the vibration input motions. These motions are coupled when the column and wheel is used, since the column and wheel is mounted directly to the cabin floor. When the rudder pedals are used, vibrations from the cabin superstructure can reach the subject directly via the legs (Figure 5). The footrest assembly attaches directly to the seat frame (Figure 5). Therefore, with the AVIS on, the subject's feet as well as torso are isolated, hence use of either the column and wheel or side-arm controller, and rudder pedals or footrest allows the following variations in body isolation configurations:

1. Non-isolated hand motion inputs to the column and wheel.
2. Isolated hand motion inputs to the side-arm controller.
3. Non-isolated foot motion inputs when using rudder pedals.
4. Isolated foot motion inputs when using the footrest assembly.

In all the above configurations the subject's torso is isolated from the vibratory input by the AVIS, while the displays are subjected to the full level of vibration transmitted from the shaker.

Two other configurations are possible. One involves the AVIS off and is equivalent to the vibration isolation provided by existing passive seats. The second one involves the AVIS in the off mode and modifying the shaker output in such a manner so that both the seat and displays are subjected to motions equivalent to that provided by the AVIS in the on mode.

Location and Characteristics of Manual Controls

Figure 6 shows the approximate dimensional relationship between the seat, column and wheel, and displays. The column and wheel provides means for varying the following parameters in both pitch and roll: (a) force-deflection gradient; (b) friction damping over the travel of the column and wheel; and (c) viscous damping over the travel of the column and wheel. Figures 7 and 8 show the attainable force gradients of the column and wheel in pitch and roll, respectively.

Task Display, Error Generation, and Test Control

Both column and wheel and side-arm controller are equipped with electrical transducers which generate a signal proportional to angular deflection in pitch and roll. The electrical signals are fed to the Task Director Console shown in Figure 9 as pitch and roll commands. At the Task

Director Console the command signals are compensated according to preselected conditions. The separate compensations for each channel consist of integral ($^1/s$), or double integral ($^1/s^2$) and gain control. The compensation of the command signal provides a means to approximate the effects of aircraft control dynamics. The compensated command signals in pitch and roll are then compared to the random pitch and roll forcing function signals to produce an error signal. The error signal is displayed on the CRT at the Display Console, Figure 10, as a horizon line which the test subject must null out, thus closing the loop on the control task. The horizontal line translates or rotates in proportion to: (a) the compensated pitch and roll deflection signals from either the side-arm controller or column and wheel controller; and (b) a random signal (forcing function) input which is used to simulate the aircraft's pitch and roll orientation. The sum of these two signals (i.e., the pilot's compensated input via controls and the random disturbance input) are displayed on the CRT. Because the test subject's objective is to bring the "horizon" back to its null position, the task is defined to be compensatory. A function block diagram of the compensatory task is shown and discussed in Section 3.

The error signal is therefore manipulated to achieve a measure which is of statistical significance in determining performance. First the error signal is squared. This instantaneous squared signal is then integrated. The integrated squared error signal can be divided manually by the integration time to determine a mean squared error level. This mean squared error level represents the level of error the pilot was operating at for a given test. Comparison of the mean squared error levels for different test configurations gives a quantitative means by which to evaluate the performance effect on pilots.

The Task Director Console is equipped with readout jacks for all important data signals. These readout jacks are intended to interface the signal and recording devices. There are input jacks for the input pitch and roll disturbance signals and the shaker acceleration commmand signal.

Figure 11 shows the Task Director Console, AVIS control console and shaker controls. As previously indicated, provisions for failsafe operation are incorporated in the AVIS and the task electronics. The AVIS has two accelerometers which sense input and output acceleration at the seat. If either accelerometer exceeds a predetermined level the seat and/or shaker servovalve(s) will be nulled, and the actuator(s) will gradually lower to their bottomed positions thus removing the dynamic input. The column and wheel, the side-arm controller and the display console all have switches which can be used to activate the failsafe circuits by the test subject. Switches were provided on the Task Director Console and shaker console for use as emergency shutdown provisions by the test operator.

Figure 12 shows the recording equipment used for data acquisition. A six-channel strip chart recorder was used to record error, error squared and integrated error squared in both pitch and roll. Another tape recorder was used to drive the shaker and generate the pitch and roll forcing function signals on the CRT. All output error signals and the vertical vibration input were recorded on the second tape recorder.

SECTION 3: SELECTION OF PARAMETERS AND EXPERIMENTAL PROCEDURE

This section deals with the selection of vertical vibratory inputs used during the human factors test program; the characteristics of the vibratory motions transmitted to the subject and displays for the various isolation configurations; the calibration of the task and associated error measurement; and the questionnaire developed to evaluate subjective responses.

Vertical Vibratory Input Motions

The purpose of the investigations reported on herein is to evaluate the effect various vibration isolation and control configurations have on task performance. Selection of the random vertical vibration inputs was based on measurements of the vertical accelerations experienced in the pilot cabin of commercial jet transports during flight through turbulence. The overall spectrum of motion transmitted to the pilot is a function of the dynamic response of the aircraft to: (1) atmospheric turbulence; (2) buffeting resulting from unsteady aerodynamics flow conditions; and (3) its internal mechanical components (i.e., engines, compressors, etc.).

Figure 13 illustrates the power spectral densities of the normal (i.e., vertical) vibrations measured at the pilot's cabin of representative jet transports during turbulent flight, for various degrees of turbulence [Ref. 1 and 3]. The composite spectrum of aircraft excitation during turbulent air penetration is primarily a function of the response of its rigid body and flexible bending modes. The excitation of the latter modes can result in large vertical acceleration in the frequency range from 2 to 6 Hz, a range in which the human body is most sensitive to mechanical vibration. The peak at 20 Hz is representative of steady state excitations measured at the pilot's cabin due to internal mechanical components [Ref. 1].

The spectrum of vertical vibration for the tests was selected based on the limitations of the dynamic shaker (stroke, velocity, and force) shown in Figure 14, and on the overall frequency characteristics of typical aircraft response shown in Figure 13. As indicated in Figure 13 the test input levels fall between those levels associated with aircraft's responses to moderate and light turbulence.

Pitch and Roll Angle Input Signals

Figure 15 shows the spectrum of pitch and roll forcing function signals used as inputs to the horizon display. The frequency description of both signals are based on: (a) the measured changes in pitch and roll attitude of an NC-135 tanker due to flight through moderate turbulence [Ref. 4]; and (b) capabilities of the analog computer used to reproduce the spectra. Various gains were used in conjunction with final shaping of the signal levels compatible with the horizontal and vertical scales of the display area of the CRT.

Accelerations Transmitted to Subject During Testing

In order to meet the requirements of the human factors test program reported on herein it was necessary: first, to insure that the vibration levels reaching the subject are not expected to cause distress, pain, impairment of health or injury; and secondly, that the frequency characteristics of the motion reaching the subject be known in order to compare results to those from other experimental investigations.

The AVIS can be operated in two modes. In the off mode the vertical vibratory input motions from the shaker are modified by the dynamic characteristics of the DC-8 seat cushions. Figure 16 indicates the vertical transmissibility between the input and buttocks of a seated subject with the AVIS in the off mode. As shown, the vertical resonant frequency of the seat cushion occurs at approximately 5 Hz thus augmenting the primary excitation of the aircraft at a frequency coincidental with human body resonances.

In the on mode, the AVIS can simultaneously provide: (a) broad-band vertical vibration isolation, and (b) a high isolation frequency notch about a critical frequency. Figure 17 shows the vertical transmissibility between input and output of the AVIS in the on mode. The gains associated with the two active isolation configurations used in testing are shown in Table I. Active isolation configuration 2 results in a higher value of resonant frequency and lower transmissibility at resonance than active isolation configuration 1, while providing a lower degree of isolation above 5 Hz. The significance of the effect this difference in resonance transmissibility has on performance is discussed in the next section.

The overall transmissibility between the buttocks of a seated subject with the AVIS on is shown in Figure 18. Comparison to Figure 17 indicates that the seat cushion does not effect the transmissibility at low frequencies. The only change occurs in the range above 5 Hz.

Figure 19 summarizes the spectrums of acceleration transmitted to the DC-8 seat and to the displays for all body isolation configurations tested during the investigation. Configuration V represents the case where the AVIS is in the off mode; both the seat and displays are subjected to the same level of vibration and the pilot's torso is isolated by the seat cushion only. Configurations I_1 and I_2 represent the two actively isolated configurations. In these cases the seat is subjected to the spectrum indicated by curves I_1 or I_2 while the display experiences the vibration spectrum indicated by curve V. Configurations I_{s1} and I_{s2} are similar to configuration V in that both the seat and displays are subjected to the same vibration levels. However, an analog computer was used to filter the taped vibration input signal such that the output spectrum of the shaker would approximate the frequency characteristics of the "AVIS on" output configuration (i.e., I_1 or I_2 mode). Configurations I_{s1} and I_{s2} represent "simulated total isolation" since they approximate the case where the display, controls and seat would be isolated by an active system having the characteristics of the "AVIS on" mode.

As a means of insuring that the maximum level of acceleration transmitted to the test subject were within safe exposure levels, acceleration limiting circuits were designed capable of sensing over-acceleration and manual failure conditions. Figure 20 shows the envelope of maximum possible acceleration levels based on the maximum shaker capabilities and the automatic acceleration failure circuits set at 1.5g. As can be seen the levels transmitted to the test subject during either the no isolation or isolation tests are below those associated with the one-minute tolerance levels given in Reference 5. In the event that malfunction occurs, the automatic failsafe circuits limit the maximum transmitted accelerations to levels below the envelopes shown.

Task and Error Calibration

Figure 21 shows the function block diagram of the compensatory two-axis task developed during the investigation. The pitch and roll axis parameters and associated dimensions are identified in Table II. The pilot input gains are fixed. For each test configuration the dynamic gains, input gains, and error integrator gains were determined empirically and are dependent on the selected type of pitch or roll dynamics ($1/s$ or $1/s^2$). Table III shows a summary of parameters for converting input angular deflections and input-output voltages to horizon display angular deflections.

The experimental procedure incorporates means to insure that the average level of the error squared voltage neither saturates the integrators under the worst conditions nor is too small under the best conditions. The calibration of the error monitoring integrators is dependent on the difficulty of the performance task. The error monitoring circuits use the error signal which is sent to the horizon display and error recording devices. The average voltage level of this signal may be quite low if the test subject is performing well. Yet when he is performing poorly the voltage level will be ten to fifty times greater. After squaring, the voltage change will be one hundred to twenty five hundred between good and poor performance. In the extreme case if one is to incorporate the whole range, the average level of the error squared voltage will be only four millivolts with a ten-volt voltage limit. Proper selection of gains insured error signals of appropriate levels.

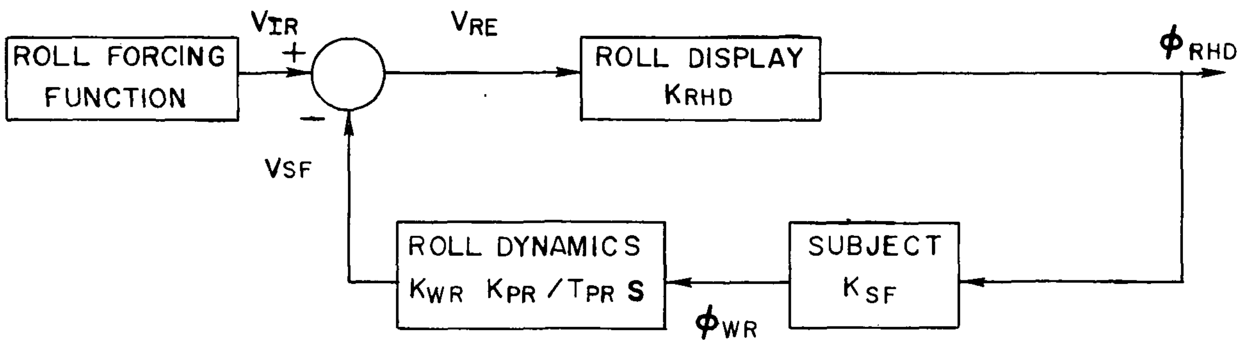
The electronics used for integration are subject to bias offset changes due to temperature instability of nearly one millivolt. This could possibly mean a twenty-five percent error in the integrated error squared signal. The integrator bias or residual drift rate was reduced to insignificant levels by proper scaling and periodic null test procedures.

The integrated squared error was recorded on a strip chart recorder during each test. In all cases the test duration was two minutes. Therefore, the integrated squared error at the end of two minutes represented a figure of merit used to evaluate the relative performance of the subject between different isolation and control configurations.

Significance of Pitch and Roll Dynamics on Work Load

As indicated in Figure 21 two types of pitch and roll dynamics were available; namely, simple integral (1/s) and double integral ($1/s^2$). The following analysis of the roll signal loop can serve to evaluate the effect of both types of dynamics on subject work load.

For the case of simple integral dynamics, the subject chooses to move the controls in the appropriate direction to reduce the displayed angular error at a rate proportional to displacement of the controller from null. Assume that the effect of introducing the subject in the roll signal loop can be represented as follows:



The maximum roll angle that the subject can generate at the wheel $(\varphi_{WR})_{max}$ is 90°, while the maximum roll angle error displayed on the CRT for a typical control situation $(\varphi_{RHD})_{max}$ is approximately 20°. Assuming the subject can maintain a linear displacement gain over the maximum travel of the wheel, the subject displacement feedback gain K_{SF} is given by

$$K_{SF} = \frac{(\varphi_{WR})_{max}}{(\varphi_{RHD})_{max}}$$

$$= \frac{90^{\circ}}{20^{\circ}} = 4.5 \text{ deg/deg} \tag{1}$$

The no-input open loop gain $\frac{V_{SF}}{V_{RE}}$ is given by

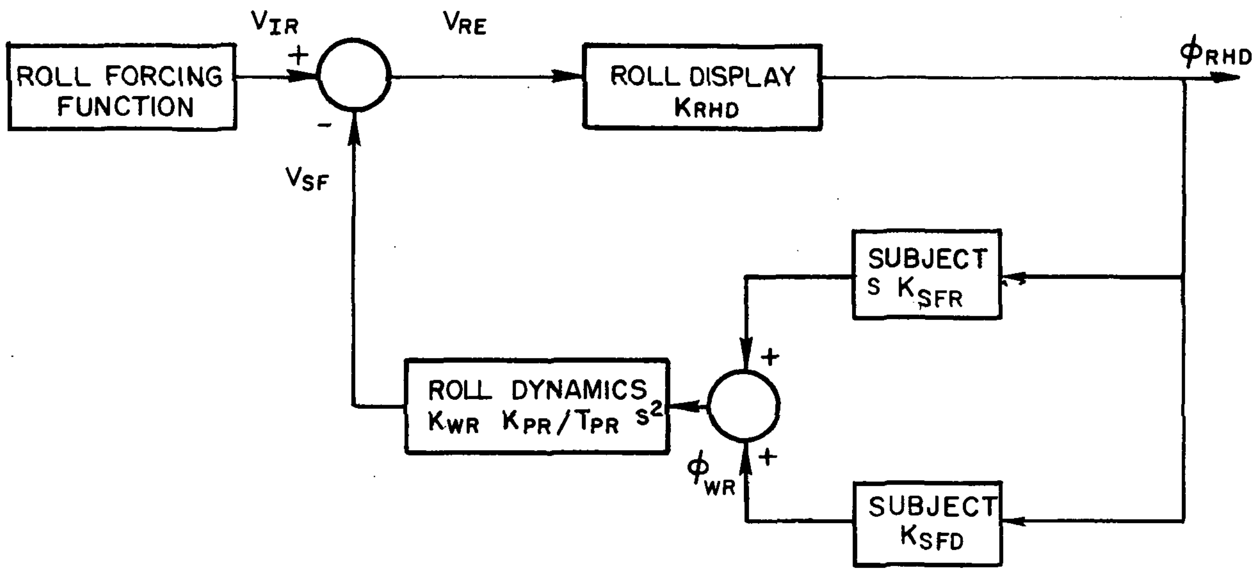
$$\frac{V_{SF}}{V_{RE}} = K_{RHD} \; K_{SF} \; \frac{K_{WR}}{T_{PR}} \; \frac{K_{PR}}{s} \tag{2}$$

Substituting Equation (1) and the values of gains given in Table II in Equation (2) with $T_{PR} = 4$ yields

$$\frac{V_{SF}}{V_{RE}} = \frac{1.2}{s}(4.5) = \frac{5.4}{s} = \frac{2\pi(0.86)}{s} \text{ deg/deg} \tag{3}$$

Equation (3) describes a stable configuration with a bandpass frequency of approximately 1 Hz. Preliminary test results indicated that the relatively high value of bandpass frequency using the simple integral dynamics resulted in an insufficient work load for the subject.

During preliminary tests with double integral dynamics, it was found that the test subject chose to minimize the angular rate of deflection of the displayed signals as the primary goal. After minimizing the angular rate he would attempt to reduce the angular deflections of the horizon line. The closed loop double integral dynamics can be represented as follows:



Since the subject attempts to first minimize the angular rate of deflection, the subject displacement feedback gain for this case, identified as K_{SFD}, will be less than the gain K_{SF} given in Equation (1) for the simple integral dynamics. For the purposes of the double integral analysis assume an order of magnitude reduction in conscious displacement feedback gain; namely

$$K_{SFD} = 0.1\ K_{SF}$$

$$= 0.45 \text{ deg/deg} \qquad (4)$$

Assume that the subject can apply a linear rate gain such that a maximum roll control is applied for a maximum displayed roll signal rate. Let the maximum angular displayed rate be $(\varphi_{RHD})_{max}$ differentiated at the mean frequency of the roll input signal f_R. From Figure 15, $f_R \approx 0.3$ Hz. Therefore, the subject rate feedback gain K_{SFR} is given by

$$K_{SFR} = \frac{(\varphi_{WR})_{max}}{(\varphi_{RHD})_{max}\,(2\pi f_R)}$$

$$= \frac{90°}{20°\,(2\pi \times 0.3)}$$

$$= 2.4 \text{ deg-sec/deg} \qquad (5)$$

The no-input open loop gain $\frac{V_{SF}}{V_{RE}}$ for the double integral dynamics is then given by

$$\frac{V_{SF}}{V_{RE}} = K_{RHD}(K_{SFD} + s\,K_{SFR})\,\frac{K_{WR}}{T_{PR}}\,\frac{K_{PR}}{s^2} \qquad (6)$$

Substituting previously used values of gains and Equations (4) and (5) in Equation (6)

$$\frac{V_{SF}}{V_{RE}} = \frac{1.2}{s^2}\,(0.45 + 2.4s)$$

$$= \frac{0.74}{s}^2 + \frac{2.88}{s}$$

$$= \frac{2\pi(0.119)}{s}^2 + \frac{2\pi(0.46)}{s} \qquad (7)$$

Equation (7) again describes a stable configuration since at the unity gain cross-over frequency near 0.46 Hz, the rate term $(\frac{1}{s})$ dominates the deflection term $(\frac{1}{s})^2$.

If the subject applies only displacement feedback (i.e., does not attempt to minimize the angular rate of deflection of the displayed signals), the task with double integral dynamics will be unstable. In such a case, from Equation (3)

$$\frac{V_{SF}}{V_{RE}} = \frac{1.2}{s^2}(0.45)$$

$$= \frac{5.4}{s^2} = \left[\frac{(2\pi)(0.37)}{s}\right]^2$$

This condition is unstable, with a unity cross-over frequency near 0.37 Hz and a slope of minus two (phase of 180 degrees). The instability arising from improper rate control was noticed when novice subjects attempted to perform the task with double integral dynamics. Within a short time, however, most subjects realized the necessity for rate control.

With double integral dynamics the subject must perform the two mental functions of deflection and rate feedback, and meet the physical requirements to accomplish proper rate feedback. The result is a near ten-fold increase in the subject's work load. In order to detect differences in performance between various test configurations it is desirable that the subject's work load be as high as possible. Therefore, all tests were conducted with double integral dynamics.

Subjective Evaluation

The integrated squared error provided the means to compare quantitatively the effect each isolation configuration and type of control had on the performance of the two-axis task. In addition, it was desired to categorize the subject's own evaluation of the errors and comparison between the various configurations. Figure 22 shows the questionnaire which was developed to qualitatively measure the subject's evaluation of the error and configurations. The test subject was asked to complete one questionnaire after each test.

The pitch and roll error ratings refer to displacements (or rotation) of the horizon line within the ranges shown in the display panel (Figure 10). The remaining questions compared the effects of the particular test to a fixed base condition, and how vision and inadvertent control motions were affected by the isolation or control configuration. It should be emphasized that the questionnaire was not intended as a means of relating the subjective evaluation to any scaled task difficulty rating such as the Cooper Pilot Opinion Rating System for Universal Use. Rather, answers to the questionnaire served as a rough indicator of subjective responses to be compared to the measured values of the average integrated squared error.

SECTION 4: RESULTS OF HUMAN FACTORS TEST PROGRAM

This section describes the sequence and number of tests that were conducted during the investigation and the manner in which average values of error were calculated for each test. The effect various isolation and control configurations have on performance of a two-axis task is evaluated based on a comparison of roll, pitch and total tracking errors for the fixed base, vibration and isolation cases. A summary of subjective responses is presented in terms of the test subject's answers to questions regarding relative comfort and effects on vision and control motion interference between the various configurations.

Sequence of Tests

The final sequence, number and type of tests conducted during the investigation were evolved based on: (a) the number of body isolation configurations to be evaluated; and (b) providing a large enough number of tests to eliminate effects of sequencing due to fatigue and learning. Initially the following parameters were considered:

Manual Control: The subject's control inputs to the tracking task in pitch and roll could be introduced by one of two means: colum and wheel or side-arm controller.

Foot Support: Two methods of foot support were used: fixed rudder pedals and footrest.

Vibration Configuration: The original plan included only three configurations; namely:

Fixed Base (F): this configuration served as the control case (i.e., the basis of comparison) without vertical vibratory motion inputs.

Vibration (V): in this configuration the active vibration isolation system was in the off mode. The vertical motion of the shaker is described by curve V of Figure 19. The only vibration isolation afforded the subject was that provided by the seat cushions.

Isolation (I_1): In this configuration the active vibration isolation system was activated. The same vertical motion of the shaker as in (V) above was used. The vertical motion transmitted to the seat is described by curve I_1 of Figure 19.

Test configurations consisting of one of the types of manual control(column and wheel or side-arm controller) and foot support (rudder pedals or footrest) were set up with the various vibration inputs listed above. Error measurements from these tests allowed a comparison of the effect various combinations of body isolation had on tracking ability.

The scope of the investigation warranted only a limited number of tests with one subject. Therefore, the number and order in which tests were conducted, shown in Table IV, were selected to allow comparison between the various parameters with the minimum number of tests. A run contains an equal number of each body isolation configuration with each of the vibration inputs described above. A battery consists of a particular body isolation configuration with each of the vibration inputs described above.

Run 1 was divided into twelve batteries of six tests each. Within each battery the first and last tests were null tests (N) to check the drift in the integrators and allow for null calibration, if necessary. The second and fifth tests in each battery were identical. Error measurements from these two tests were averaged and considered as one data point. This was done in an effort to reduce the effects of learning and fatigue when comparing tests with and without isolation but with identical control and foot support configurations. In order to keep the total number of tests for each isolation and vibration configuration equal, there were three batteries in each run for a particular isolation configuration.

The duration of each test was two minutes and all tests in a battery were conducted without interruption. Required hardware changes provided normal rest periods between batteries. In order to insure that the time description of the vibratory input motion was identical in all tests, the same two-minute segment of random signal having the spectrum described by curve V in Figure 19 was used.

As will be shown later, error measurements indicated that at the end of Run 1, the subject had not reached a leveling on his learning curve. Therefore, an identical series of tests, identified as Run 2 on Table IV, was conducted. Based on error measurements from tests in Run 2 and on comments by the subject regarding the adverse effect of low frequency motions which caused large relative deflections between the subject and the display during the isolation tests, two additional vibration configurations were included:

Isolation (I_2): This configuration is identical to I_1, except that the vertical motion transmitted to the seat is described by curve I_2 of Figure 18. For this configuration the relative motion problem is reduced.

Simulated Total Isolation (I_{s1}): In configuration I_1 and I_2 there is relative motion between the subject and display since the seat is isolated from the vibratory input but the display is not. In configuration I_{s1}, the vertical motion transmitted to both the seat and display is described by curve I_{s1} of Figure 19.

Simulated Total Isolation (I_{s2}): Similar to I_{s1} except that the motion is described by curve I_{s2} of Figure 19.

The sequence of tests for configuration I_2 is shown as Run 3 on Table IV. As will be discussed later, comparison with earlier tests indicated that the subject's learning curve was leveling off at the end of Run 3 and that no difference was detected in error between footrest and rudder pedals. Therefore, the sequence of tests for Runs 4 and 5, which incorporated configurations I_{s2} and I_{s1}, respectively, did not include repeating tests of the same configuration at the beginning and end of each battery, and used only the footrest. Also, only one null test was conducted at the beginning of each battery.

Error Measurements

The procedure used to calculate the angular error in roll and pitch is described below. Figures 23 through 26 show the records from Run 4, Battery 3 using the column and wheel for controls and the footrest. In each case the roll and pitch error, error squared, and integrated error squared traces are shown, from the start to the end of the two-minute test period. The average gradient of the integrated error squared trace for the test period was drawn in each case. The two-minute average roll and pitch errors were calculated from the average gradients as shown.

Tables V through VIII show the roll, pitch and total two-minute average angular error for all tests.

Discussion of Results

It is recognized that use of only one test subject and the limited number of tests warranted by the scope of the investigation negate placing statistical significance on the results presented herein. Nevertheless, both the quantitative and subjective measurements do provide an initial indication of the relative advantages and disadvantages between the various control and isolation configurations.

Error Measurements: Figure 27 shows the two-minute average roll and pitch errors for the vibration and fixed base configuration using the column and wheel for control. The data indicates the learning curve effect previously mentioned. For both the vibration and fixed base configurations the errors in pitch are lower than in roll. This tendency to concentrate more on controlling pitch rather than roll is to be expected from most pilots. When compared to fixed base, the vibratory motions increase the error by approximately fifty percent with the difference more pronounced in pitch. A comparison between the total roll and pitch error for the vibratory and fixed base configurations using the column and wheel is shown in Figure 28. For Runs 4 and 5 the total error during vibration is approximately fifty percent greater than the fixed base total error.

Figure 29 shows the comparison between vibration and fixed base errors in roll and pitch using the side-arm controller. As in the case of the column and wheel, the data indicates the learning curve effect and lower values of error in pitch. Side-arm controllers have been found to offer improvements for aircraft control [Ref. 6]. However, the side-arm controller used in this investigation did not appear to greatly improve the tracking error when compared to the column and wheel, with the biggest improvement in performance occurring in pitch for the fixed base configuration. This apparent lack of improvement in control with the particular side-arm controller used may be due to the fact that while the column was balanced and both the column and wheel had dampers, the side-arm controller was not balanced and did not have dampers. Therefore, in spite of the arm rest, the hand and wrist did vibrate considerably. Figure 30 shows a comparison between the total roll and pitch error for the vibratory and fixed base configuration using the side-arm controller. The difference between vibration and fixed base error is approximately the same as for the column and wheel.

The effect of the various isolation configurations on tracking error can be evaluated based on the results of Runs 4 and 5. These were the last two runs conducted and the learning effect is no longer a consideration. In addition each battery includes all configurations tested.

Figure 31 shows the measured roll, pitch and total errors using the column and wheel for control. All of the configurations tested are shown; namely, fixed base (F), vibration (V), isolation (I_1 or I_2) and simulated total isolation (I_{s1} or I_{s2}). The error for each active vibration isolation configuration is compared to errors for the fixed base, simulated total isolation and vibration configurations measured during tests of the same battery. Data from Run 5 shows the comparison for errors measured with the AVIS in active isolation configuration 1 (I_1) and errors from corresponding vibration (V), fixed base (F) and simulated total isolation (I_{s1}) test. Data from Run 4 shows a similar comparison for the errors measured with the AVIS in active isolation configuration 2 (I_2).

The tracking errors for the active isolation configurations (I_1 or I_2) are approximately the same as the errors for the corresponding vibration configurations (V). Errors for configuration I_2 (Run 4) are generally equal to or lower than the errors for the corresponding vibration tests, whereas for configuration I_1 (Run 5) the opposite is true.

The tracking errors for the simulated total isolation configurations (I_{s1} and I_{s2}) are lower than those measured for the isolation or vibration configurations and in some cases approach those measured during fixed base tests. In configurations I_{s1} and I_{s2} the display, controls and seat are isolated from the vibratory motions in a manner that approximates the isolation characteristics of the AVIS in active isolation configurations 1 and 2, respectively. In the simulated total isolation configurations, there was no relative motion between the subject and the display except for that arising from the seat cushion dynamics which the subject, an experienced test pilot, was quite accustomed to.

Comparison between curves (a) and (b) for both Runs 4 and 5 (Figure 31) shows the previously mentioned tendency of the subject to concentrate more on pitch rather than roll for all configurations.

Figure 32 shows the measured roll, pitch and total errors using the side-arm controller for control in all configurations tested during Runs 4 and 5. The comments made regarding the comparison between tracking errors for the isolated (I_1 or I_2) and vibration (V) configurations using the column and wheel also apply for the side-arm controller (i.e., they are approximately equal). However, with the side-arm controller a greater improvement in error is afforded by isolation configuration I_2 than I_1, when compared to the error from corresponding vibration tests.

A final comparison between vibration configurations and types of control is shown in Figure 33. Average values of total error for all tests in Runs 4 and 5 are indicated for each condition. In all cases, (a) through (d), the average error for the simulated total isolation configurations, I_{S1} and I_{S2}, is lower than the errors for the vibration configuration V. Errors for isolation configuration I_1, are approximately equal or slightly greater than errors for vibration, with both the column and wheel and side-arm controller. Errors for isolation configuration I_2 are approximately equal or slightly lower than vibration errors with both types of controls.

Subjective Comments: The test subject was asked to answer the questionnaire shown in Figure 22 after each test. A summary of comments regarding comfort and subjective tracking error evaluation between the various conditions follows.

The comparative ride comfort between vibration (V) and isolation (I_1 and I_2) was very dramatic. In addition to the isolation from low frequency motions which eliminated the body resonance, the isolation system also eliminated the jerking motions associated with higher frequencies. When the column and wheel and rudder pedals were used in the isolated configurations (I_1 or I_2) the motions would be transmitted through the hands, wrists and forearms, and also through the feet and lower legs. These vibrations would cause a slight amount of discomfort in the form of muscle tingling and a numb feeling in the hands and feet. When the side-arm controller and footrest were used these effects were totally eliminated.

The isolation characteristics of the AVIS in either configuration (I_1 or I_2) resulted in large relative deflections between the subject and the displays for low frequency vibration inputs. Because of this relative motion it was particularly difficult for the subject to analyze and interpret the error in terms of displacement, rate and acceleration. This phenomenon was due to the interrelation between the apparent error caused by the movement of the display relative to the subject and the actual error presented on the display. Therefore, the improvements in comfort afforded by the seat isolation configurations are not reflected in reduced values of tracking error. The isolation provided by the AVIS in configuration I_2 reduced the relative motions at low frequencies from those experienced in configuration I_1 (see Figure 19). Although this reduction resulted in a more comfortable ride for configuration I_2 compared to I_1, only a minor improvement in error was realized between configurations I_2 and I_1 when comparing the corresponding errors of each isolation configuration. During the simulated total isolation tests (I_{s1} or I_{s2}) the large relative deflections between the subject and display were eliminated. Tests run using this total isolation configuration resulted in the best tracking performance, and according to the subject's comments, the most comfortable ride.

After about a day of testing (25 two-minute tests) there was some general body fatigue which seemed to be located in the lower back muscles and spine. After completing about ten two-minute runs there was considerable eye strain and it was necessary to take about a thirty-minute break. This type of work-rest cycle was typical throughout most of the program.

The task used in the investigation employs control inputs of the rate command with no damping in the display motions. As a result, the subject felt that this type of task caused a full work load requiring continuous concentration and control inputs to keep errors to a minimum.

During the vibration configuration tests, the arms and hands did shake enough to cause inadvertent inputs to both the column and wheel and side-arm controller. These motions or inputs were oscillatory in nature and thus did not cause large tracking errors. However, it was difficult to make small and precise control inputs with the proper timing.

Although the side-arm controller did not have the best of feel characteristics, it was preferred over the wheel and column. The comparison between rudder pedals and the isolated footrest was only an improvement in comfort.

SECTION 5: CONCLUSIONS AND RECOMMENDATIONS

Conclusions made based on subjective comfort evaluation and objective measurements of tracking errors employing an active vibration isolation system for a commercial transport pilot seat are:

1. The active seat system providing broadband vertical vibration isolation and a high isolation efficiency notch centered about the critical input (fuselage bending) frequency of 4.2 Hz can provide dramatic improvement in comfort over that afforded by a standard pilot seat.

2. The short term (two-minute) tracking accuracy attained with the active seat isolation configurations I_1 and I_2 is approximately equal to that measured with the standard aircraft seat. The subject's comments indicated that large relative deflections between the subject and display occurred for low frequency vibration inputs for the seat isolation configurations. Because of this relative motion it was particularly difficult for the subject to analyze and interpret the error in terms of displacement, rate, and acceleration. This phenomenon was due to the interrelation between the apparent error caused by the movement of the display relative to the subject, and the actual error presented on the display.

3. As expected, the best combination of comfort and improved tracking performance (in some instances approaching that for fixed base tests) was obtained by isolating both the seat and displays to the levels provided by the active seat isolation system.

Recommendations

While the results of this investigation show that the best combination of improved comfort and tracking performance can be expected from an active system which has the capability of isolating the displays, seat and controls, this system would be much more complicated and expensive when compared to the active seat isolation system alone. It is recommended that a feasibility study be made on the problems involved with the design and implementation of such a "total" active isolation package.

Also, while the results of this investigation showed no significant change in the subject's control capabilities for the active seat isolation configurations based on the two-minute test period, it is expected that an improvement would be realized for long-time duration testing. It is postulated that long-time duration tracking ability with active isolation of the seat only will improve relative to that of the standard seat as a result of an anticipated decrease in fatigue. This would be particularly significant considering the severe dynamic environments associated with helicopter, LAHS or ASW missions.

Long-time duration testing was beyond the scope of the investigation reported on herein. Therefore, it is recommended that such a test program be conducted to validate this assumption. If results indicate that an improvement in ride quality and tracking performance can be realized, it is recommended that an actively isolated pilot seat be tested in actual flight conditions.

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LEGEND OF ABBREVIATIONS USED IN TABLES I THROUGH VIII

C&W	column and wheel
SAC	side-arm controller
F. R.	footrest
R. P.	rudder pedals
N	null test
F	fixed base test
V	vibration test; AVIS in off mode
I_1	vibration test; AVIS in on mode, Configuration 1
I_2	vibration test; AVIS in on mode, Configuration 2
I_{s1}	simulated isolation of seat and display; AVIS in off mode
I_{s2}	simulated isolation of seat and display; AVIS in off mode

TABLE I

AVIS FLIGHT MODE POTENTIOMETER GAINS

PARAMETER	GAIN	
	Configuration 1	Configuration 2
Acceleration	5.0	5.0
Notch Flow	1.0	3.5
Wide-Band Flow	2.6	2.6
Position	10.0	10.0
Velocity	2.75	5.0
Notch Network	1.0	1.0
Acceleration Time Constant	10.0	10.0
Velocity Time Constant	5.0	5.0
Notch Frequency Time Constant	3.55	3.55

TABLE II

PITCH AND ROLL PARAMETERS

Description		Dimension	Description		Dimension
INPUTS			INPUTS		
Roll Voltage	V_{IR}	± 1.4 Vpeak	Pitch Voltage	V_{IP}	± 1.4 V peak
Wheel Roll Angle	φ_{WR}	$\pm 90^\circ$	Column Pitch Angle	θ_{CP}	$\pm 12^\circ$
SAC Roll Angle	φ_{SR}	$\pm 42.5^\circ$	SAC Pitch Angle	θ_{SP}	$\pm 30^\circ$
GAINS			GAINS		
Roll Input	K_{IR}	0.59 V/V-T	Pitch Input	K_{IP}	0.46 V/V-T
Wheel Roll	K_{WR}	0.1 V/°	Column Pitch	K_{CP}	0.86 V/°
SAC Roll	K_{SR}	0.2 V/°	SAC Pitch	K_{SP}	0.4 V/°
Pilot Roll	K_{PR}	0.48 V-T/V-S	Pilot Pitch	K_{PP}	0.39 V-T/V-S
Roll Squared	K_{RS}	5.4 V/V	Pitch Squared	K_{PS}	3.1 V/V
Roll Int. Squared	K_{RIS}	0.092 V/V-T	Pitch Int. Squared	K_{PIS}	0.088 V/V-S
TIME CONSTANTS			TIME CONSTANTS		
First R.I.S.	$1/\tau_{R1}$	1.0 V/V-S	First P.I.S.	$1/\tau_{P1}$	1.66 V/V-S
Second R.I.S.	$1/\tau_{R2}$	0.13 V/V-S	Second P.I.S.	$1/\tau_{P2}$	0.27 V/V-S
OUTPUTS			OUTPUTS		
Roll Integral Meter	K_{RIM}	8.3 μA/V	Pitch Integral Meter	K_{PIM}	8.3 μA/V
Pilot Roll Meter	K_{RM1}	5.5 μA/V	Pilot Pitch Meter	K_{PM1}	4.5 μA/V
Error Roll Meter	K_{RM2}	5.5 μA/V	Error Pitch Meter	K_{PM2}	4.5 μA/V
Roll Horizon Display	K_{RHD}	100° /V	Pitch Horizon Display	K_{PHD}	2.7 in./V

LEGEND
- V: Volts
- S: Seconds
- T: Turns
- μA: Microamp
- R.I.S.: Roll Integral Squared
- P.I.S.: Pitch Integral Squared

TABLE III

SCALING OF HORIZON DISPLAY ANGULAR DEFLECTIONS AND ERROR MEASUREMENTS

INPUT/OUTPUT	DIMENSION	ROLL AXIS	PITCH AXIS*
Vibration Input	deg/volt	$\varphi_{RHD}/V_{IR} = 14.7$	$\theta_{PHD}/V_{IP} = 15.8$
C&W	deg/sec^2-deg	$\ddot{\varphi}_{RHD}/\varphi_{WR} = 1.2$	$\ddot{\theta}_{PHD}/\theta_{CP} = 11.5$
SAC	deg/sec^2-deg	$\ddot{\varphi}_{RHD}/\varphi_{SR} = 4.8$	$\ddot{\theta}_{PHD}/\theta_{SP} = 10.7$
Error	deg/volt	$\varphi_{RHD}/V_{RE} = 100$	$\theta_{PHD}/V_{PE} = 69$
Error Squared	deg^2/mv	$\varphi^2_{RHD}/V_{RES} = 1.86$	$\theta^2_{PHD}/V_{PES} = 2.8$
Integrated Error Squared Gradient	deg^2-sec/mv	$\varphi^2_{RHD}/\dot{V}_{IRES} = 1.86$	$\theta^2_{PHD}/\dot{V}_{IPES} = 1.72$
Two Minute Average Error Squared	deg^2/mv	$(\varphi^2_{RHD})_{AVE}/V_{IRES} = 0.0155$	$(\theta^2_{PHD})_{AVE}/V_{IPES} = 0.0143$
Two Minute Average Error	deg/$\sqrt{mv}$	$(\varphi_{RHD})_{AVE}\ \sqrt{V_{IRES}} = 0.124$	$(\theta_{PHD})_{AVE}/\sqrt{V_{IPES}} = 0.119$
Strip Chart Average Error	deg/$\sqrt{div}$	$(\varphi_{RHD})_{AVE}/\sqrt{V_{IRES}} = 1.97$	$(\theta_{PHD})_{AVE}/\sqrt{V_{IPES}} = 1.89$

*Pitch Angular Conversion Factor: 25.5 deg/in. based on 4.5 in. diameter CRT

<u>LEGEND</u>

V_{RES}	roll error squared
V_{IRES}	integral roll error squared
V_{PES}	pitch error squared
V_{IPES}	integral pitch error squared

TABLE IV

IDENTIFICATION OF TESTS

Run	Battery	Test	Control	Feet	Configuration	Run	Battery	Test	Control	Feet	Configuration
1	1	1	C&W	FR.	N	1	7	37	SAC	FR.	N
		2			F			38			F
		3			I_1			39			I_1
		4			V			40			V
		5			F			41			F
		6			N			42			N
	2	7	SAC	R.P.	N		8	43	SAC	R.P.	N
		8			V			44			I_1
		9			I_1			45			V
		10			F			46			F
		11			V			47			I_1
		12			N			48			N
	3	13	C&W	R.P.	N		9	49	C&W	FR.	N
		14			I_1			50			V
		15			V			51			I_1
		16			F			52			F
		17			I_1			53			V
		18			N			54			N
	4	19	SAC	FR.	N		10	55	SAC	FR.	N
		20			V			56			I_1
		21			I_1			57			V
		22			F			58			F
		23			V			59			I_1
		24			N			60			N
	5	25	C&W	R.P.	N		11	61	C&W	R.P.	N
		26			F			62			V
		27			I_1			63			I_1
		28			V			64			F
		29			F			65			V
		30			N			66			N
	6	31	C&W	FR.	N		12	67	SAC	R.P.	N
		32			I_1			68			F
		33			V			69			I_1
		34			F			70			V
		35			I_1			71			F
		36			N			72			N

TABLE IV (Continued)

IDENTIFICATION OF TESTS

Run	Battery	Test	Control	Feet	Configuration	Run	Battery	Test	Control	Feet	Configuration
2	1	73	C&W	FR	N	2	7	109	SAC	FR.	N
		74			F			110			F
		75			I_1			111			V
		76			V			112			I_1
		77			F			113			F
		78			N			114			N
	2	79	SAC	R.P.	N		8	115	SAC	R.P.	N
		80			V			116			I_1
		81			F			117			F
		82			I_1			118			V
		83			V			119			I_1
		84			N			120			N
	3	85	C&W	R.P.	N		9	121	C&W	FR.	N
		86			I_1			122			V
		87			F			123			F
		88			V			124			I_1
		89			I_1			125			V
		90			N			126			N
	4	91	SAC	FR.	N		10	127	SAC	FR.	N
		92			V			128			I_1
		93			F			129			F
		94			I_1			130			V
		95			V			131			I_1
		96			N			132			N
	5	97	C&W	R.P.	N		11	133	C&W	R.P.	N
		98			F			134			V
		99			V			135			F
		100			I_1			136			I_1
		101			F			137			V
		102			N			138			N
	6	103	C&W	FR.	N		12	139	SAC	R.P.	N
		104			I_1			140			F
		105			F			141			V
		106			V			142			I_1
		107			I_1			143			F
		108			N			144			N

TABLE IV (Continued)

IDENTIFICATION OF TESTS

Run	Battery	Test	Control	Feet	Configuration	Run	Battery	Test	Control	Feet	Configuration
3	1	145	C&W	FR.	N	3	7	181	SAC	FR.	N
		146			F			182			F
		147			I_2			183			I_2
		148			V			184			V
		149			F			185			F
		150			N			186			N
	2	151	SAC	R.P.	N		8	187	SAC	R.P.	N
		152			V			188			I_2
		153			I_2			189			V
		154			F			190			F
		155			V			191			I_2
		156			N			192			N
	3	157	C&W	R.P.	N		9	193	C&W	FR.	N
		158			I_2			194			V
		159			V			195			I_2
		160			F			196			F
		161			I_2			197			V
		162			N			198			N
	4	163	SAC	FR.	N		10	199	SAC	FR.	N
		164			V			200			I_2
		165			I_2			201			V
		166			F			202			F
		167			V			203			I_2
		168			N			204			N
	5	169	C&W	R.P.	N		11	205	C&W	R.P.	N
		170			F			206			V
		171			I_2			207			I_2
		172			V			208			F
		173			F			209			V
		174			N			210			N
	6	175	C&W	FR.	N		12	211	SAC	R.P.	N
		176			I_2			212			F
		177			V			213			I_2
		178			F			214			V
		179			I_2			215			F
		180			N			216			N

TABLE IV (Continued)

IDENTIFICATION OF TESTS

Run	Battery	Test	Control	Feet	Configuration	Run	Battery	Test	Control	Feet	Configuration
4	1	217	C&W	R.P.	N	4	5	237	C&W	FR.	N
		218			F			238			I_2
		219			I_{s2}			239			V
		220			V			240			I_{s2}
		221			I_2			241			F
	2	222	SAC	FR.	N		6	242	SAC	FR.	N
		223			V			243			I_{s2}
		224			I_2			244			F
		225			F			245			I_2
		226			I_{s2}			246			V
	3	227	C&W	FR.	N		7	247	C&W	FR.	N
		228			I_{s2}			248			I_2
		229			V			249			F
		230			F			250			V
		231			I_2			251			I_{s2}
	4	232	SAC	FR.	N		8	252	SAC	FR.	N
		233			V			253			I_{s2}
		234			F			254			I_2
		235			I_2			255			F
		236			I_{s2}			256			V

TABLE IV (Continued)

IDENTIFICATION OF TESTS

Run	Battery	Test	Control	Feet	Configuration	Run	Battery	Test	Control	Feet	Configuration
5	1	257	C&W	FR.	N	5	5	277	C&W	FR.	N
		258			F			278			I_1
		259			I_{s1}			279			V
		260			V			280			I_{s2}
		261			I_1			281			F
	2	262	SAC	FR.	N		6	282	SAC	FR.	N
		263			V			283			I_{s1}
		264			I_1			284			F
		265			F			285			I_1
		266			I_{s1}			286			V
	3	267	C&W	FR.	N		7	287	C&W	FR.	N
		268			I_{s1}			288			I_2
		269			V			289			F
		270			F			290			V
		271			I_1			291			I_{s2}
	4	272	SAC	FR.	N		8	292	SAC	FR.	N
		273			V			293			I_{s1}
		274			F			294			V
		275			I_1			295			F
		276			I_{s1}			296			I_1

TABLE V

TWO-MINUTE AVERAGE ANGULAR ERROR WITH C&W AND AVIS IN ISOLATION CONFIGURATION 1

RUN	BATTERY	FEET SUPPORT	TEST CONFIGURATION											
			FIXED BASE(F)			VIBRATION (V)			ISOLATED SEAT(I_1)			SIMULATED ISOLATION (I_{S1})		
			Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ
1	1	Footrest	5.5	3.9	9.4	5.9	5.2	11.1	5.6	4.8	10.4	--	--	--
	3	Rudder Pedals	5.6	4.2	9.8	5.3	4.8	10.1	5.9	5.4	11.3	--	--	--
	5	Rudder Pedals	4.3	3.5	7.8	4.0	4.0	8.0	5.0	4.8	9.8	--	--	--
	6	Footrest	3.3	2.5	5.8	4.8	4.5	9.3	5.1	4.3	9.4	--	--	--
	9	Footrest	4.5	3.9	8.4	4.4	6.3	10.7	5.7	5.1	10.8	--	--	--
	11	Rudder Pedals	3.3	3.5	6.8	4.4	3.8	8.2	4.8	4.7	9.5	--	--	--
2	1	Footrest	4.1	3.0	7.1	4.5	4.3	8.8	5.3	4.4	9.7	--	--	--
	3	Rudder Pedals	4.0	3.2	7.2	4.8	4.7	9.5	5.8	4.7	10.5	--	--	--
	5	Rudder Pedals	3.8	2.6	6.4	4.3	3.8	8.1	4.8	3.8	8.6	--	--	--
	6	Footrest	3.8	2.9	6.7	4.8	3.4	8.2	4.9	3.9	8.8	--	--	--
	9	Footrest	3.8	2.7	6.5	4.1	3.4	7.5	4.0	3.6	7.6	--	--	--
	11	Rudder Pedals	3.3	2.4	6.7	4.1	3.4	7.5	4.7	3.6	8.3	--	--	--
5	1	Footrest	2.9	1.7	4.6	3.5	2.5	6.0	3.5	2.7	6.2	3.0	1.9	4.9
	3	Footrest	2.5	1.8	4.3	3.3	2.3	5.6	3.3	2.6	5.9	3.1	2.1	5.2
	5	Footrest	3.1	2.0	5.1	3.4	2.6	6.0	3.3	2.8	6.1	2.8	2.1	4.9
	7	Footrest	2.9	1.7	4.6	3.4	2.6	6.0	3.4	2.6	6.0	3.1	1.8	4.9
AVERAGE:		RUN 5 only	2.9	1.8	4.7	3.4	2.5	5.9	3.4	2.7	5.1	3.0	2.0	5.0

ALL VALUES IN DEGREES

TABLE VI

TWO-MINUTE AVERAGE ANGULAR ERROR WITH C&W AND AVIS IN ISOLATION CONFIGURATION 2

RUN	BATTERY	FEET SUPPORT	TEST CONFIGURATION											
			FIXED BASE (F)			VIBRATION (V)			ISOLATED SEAT (I_2)			SIMULATED ISOLATION (I_{S2})		
			Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ
3	1	Footrest	3.5	2.1	5.6	3.9	3.2	7.1	3.8	2.7	6.5	--	--	--
	3	Rudder Pedals	3.8	2.7	6.5	--	3.5	--	3.9	3.4	7.3	--	--	--
	5	Rudder Pedals	3.4	2.6	6.0	4.1	3.6	7.7	4.0	3.6	7.6	--	--	--
	6	Footrest	3.3	2.6	5.9	3.9	3.6	7.5	3.9	3.3	7.2	--	--	--
	9	Footrest	3.5	2.7	6.2	3.7	3.5	7.2	3.9	3.2	7.1	--	--	--
	11	Rudder Pedals	2.9	2.2	5.1	3.8	3.3	7.1	3.5	2.9	6.4	--	--	--
4	1	Footrest	2.9	2.0	4.9	3.4	2.9	6.3	3.5	2.8	6.3	3.0	2.4	5.4
	3	Footrest	2.8	1.9	4.7	3.6	2.8	6.4	3.9	2.9	6.8	3.4	2.6	6.0
	5	Footrest	2.9	1.6	4.5	3.8	2.8	6.6	3.3	2.6	5.9	3.1	2.1	5.2
	7	Footrest	2.4	1.7	4.1	3.4	2.7	6.1	3.4	2.5	5.0	3.2	2.1	5.3
AVERAGE: RUN 4 only:			2.8	1.8	4.6	3.5	2.8	6.3	3.5	2.7	6.2	3.2	2.3	5.5

ALL VALUES IN DEGREES

TABLE VII

TWO-MINUTE AVERAGE ANGULAR ERROR WITH SAC AND AVIS IN ISOLATION CONFIGURATION 1

RUN	BATTERY	FEET SUPPORT	TEST CONFIGURATION											
			FIXED BASE (F)			VIBRATION (V)			ISOLATED SEAT (I_1)			SIMULATED ISOLATION (I_{S1})		
			Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ
1	2	Rudder Pedals	5.0	3.6	8.6	6.4	5.0	11.4	6.4	5.5	11.9	--	--	--
	4	Footrest	5.0	4.2	9.2	4.8	4.7	9.5	6.1	6.0	12.1	--	--	--
	7	Footrest	5.2	3.2	8.4	4.7	3.6	8.3	6.0	5.4	11.4	--	--	--
	8	Rudder Pedals	4.2	2.7	6.9	4.1	3.4	7.5	4.5	4.2	8.7	--	--	--
	10	Footrest	2.9	2.4	5.3	4.1	3.6	7.7	4.7	4.0	8.7	--	--	--
	12	Rudder Pedals	4.0	3.1	7.1	4.5	3.8	8.3	4.6	4.2	8.8	--	--	--
2	2	Rudder Pedals	4.1	2.8	6.9	4.8	3.9	8.6	5.0	5.0	10.0	--	--	--
	4	Footrest	4.1	2.8	6.9	4.5	4.2	8.7	3.4	3.8	7.2	--	--	--
	7	Footrest	3.8	2.7	6.5	5.0	5.2	10.2	4.7	4.7	9.3	--	--	--
	8	Rudder Pedals	4.1	2.7	6.8	4.1	3.7	7.8	4.5	4.1	8.6	--	--	--
	10	Footrest	3.5	1.7	5.2	4.0	3.6	7.6	4.9	3.8	8.7	--	--	--
	12	Rudder Pedals	2.9	1.3	4.2	3.5	3.2	6.7	3.8	3.4	7.2	--	--	--
5	2	Footrest	2.5	1.3	3.8	3.0	2.2	5.2	3.2	2.7	5.9	2.6	1.9	4.5
	4	Footrest	2.8	1.5	4.3	2.9	2.1	5.0	3.8	2.6	6.4	2.7	1.8	4.5
	6	Footrest	2.9	1.3	4.2	3.6	2.2	5.8	3.5	2.8	6.3	3.3	1.9	5.2
	8	Footrest	3.1	1.2	4.3	3.2	2.7	5.9	4.1	2.6	6.7	3.1	1.7	4.8
AVERAGE:	RUN 5 only		2.8	1.3	4.1	3.2	2.3	5.5	3.7	2.7	6.4	2.9	1.8	4.8

ALL VALUES IN DEGREES

TABLE VIII

TWO-MINUTE AVERAGE ANGULAR ERROR WITH SAC AND AVIS IN ISOLATION CONFIGURATION 2

RUN	BATTERY	FEET SUPPORT	TEST CONFIGURATION											
			FIXED BASE (F)			VIBRATION (V)			ISOLATED SEAT (I_2)			SIMULATED ISOLATION (I_{S2})		
			Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ	Roll	Pitch	Σ
3	2	Rudder Pedals	3.3	2.2	5.6	3.9	3.0	6.9	4.1	3.0	7.1	--	--	--
	4	Footrest	3.6	2.2	5.8	3.5	2.8	6.3	3.5	2.9	6.4	--	--	--
	7	Footrest	3.1	1.8	4.9	3.6	2.6	6.2	3.6	2.9	6.5	--	--	--
	8	Rudder Pedals	3.4	1.9	5.3	3.6	2.8	6.4	3.8	3.0	6.8	--	--	--
	10	Footrest	2.9	1.9	4.8	3.5	3.1	6.6	3.8	3.1	6.9	--	--	--
	12	Rudder Pedals	3.1	1.9	5.0	3.8	3.0	6.8	3.4	2.6	6.0	--	--	--
4	2	Footrest	3.5	1.8	5.3	3.6	2.9	6.5	3.6	3.1	6.7	3.0	2.7	5.7
	4	Footrest	3.1	1.6	4.7	3.4	2.8	6.2	3.5	2.9	6.4	2.9	2.0	4.9
	6	Footrest	3.0	1.2	4.2	3.4	2.4	5.8	2.9	2.2	5.1	3.2	1.8	5.0
	8	Footrest	2.9	1.3	4.2	3.4	2.3	5.7	3.6	2.6	6.2	3.1	1.9	5.0
AVERAGE: RUN 4 only			3.1	1.5	4.6	3.5	2.6	6.1	3.4	2.7	6.1	3.1	2.1	5.1

ALL VALUES IN DEGREES

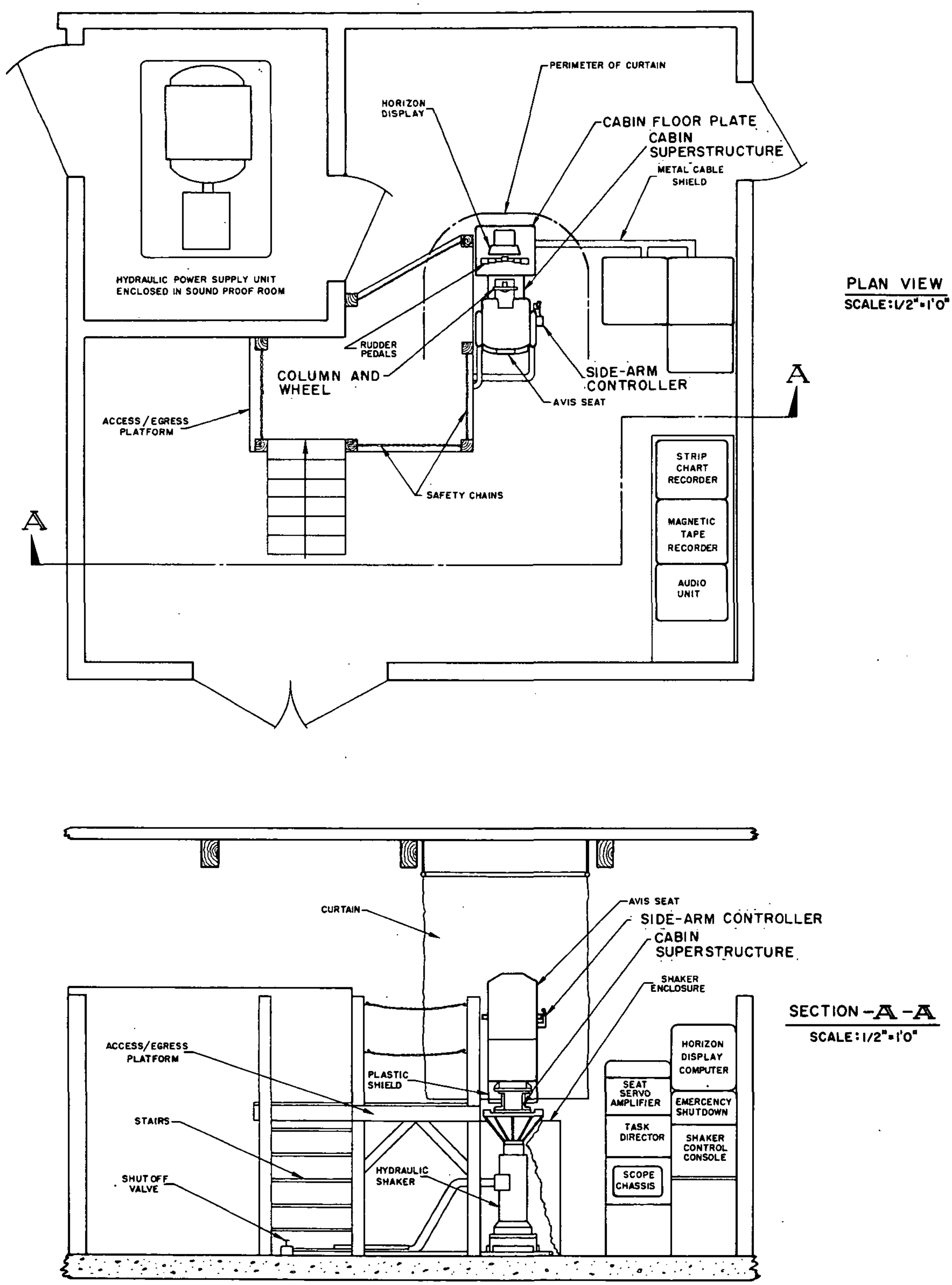


Figure 1. - Layout of Human Factors Test Area and Equipment

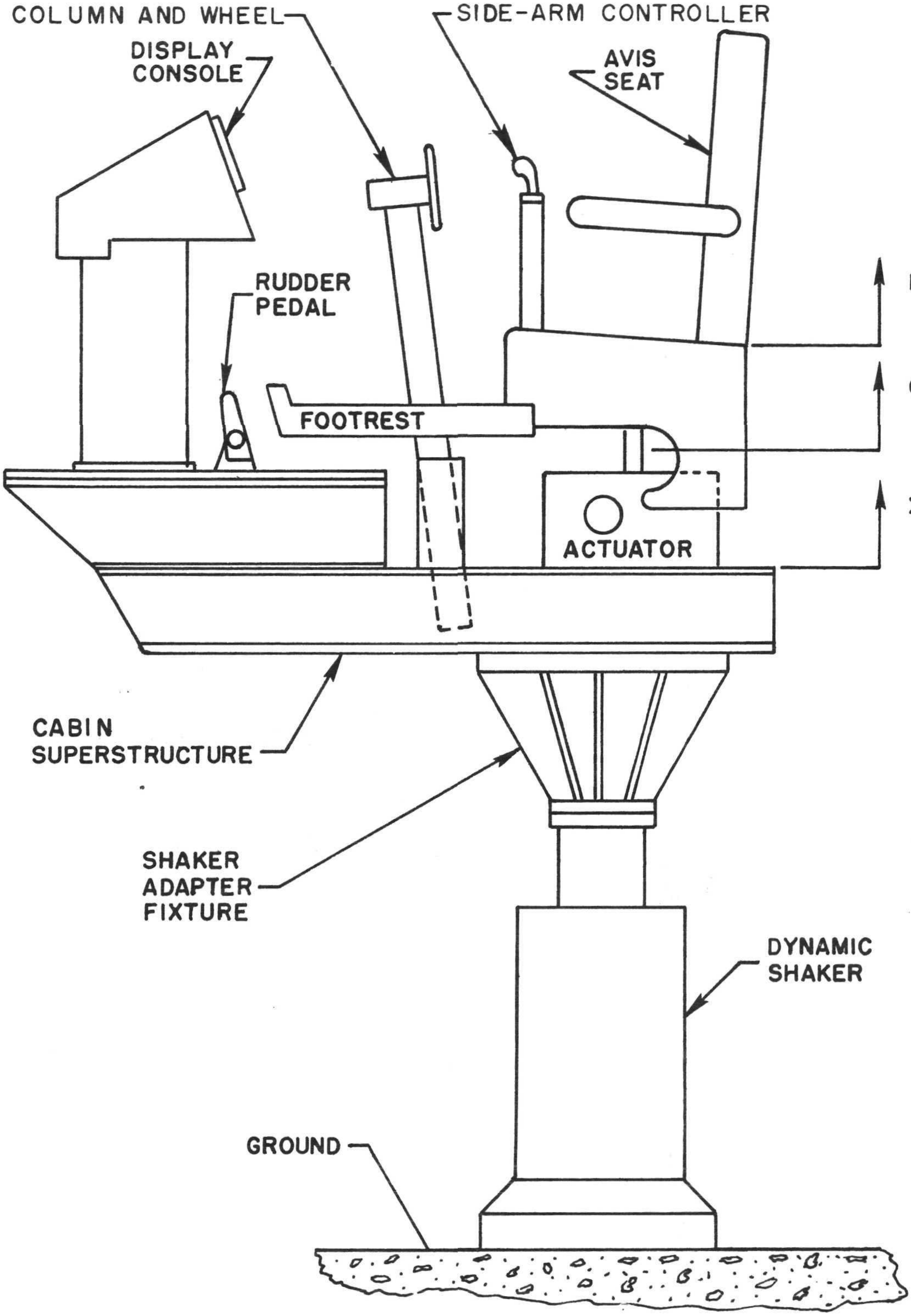


Figure 2. - Schematic Representation of Isolated Seat, Controls and Display

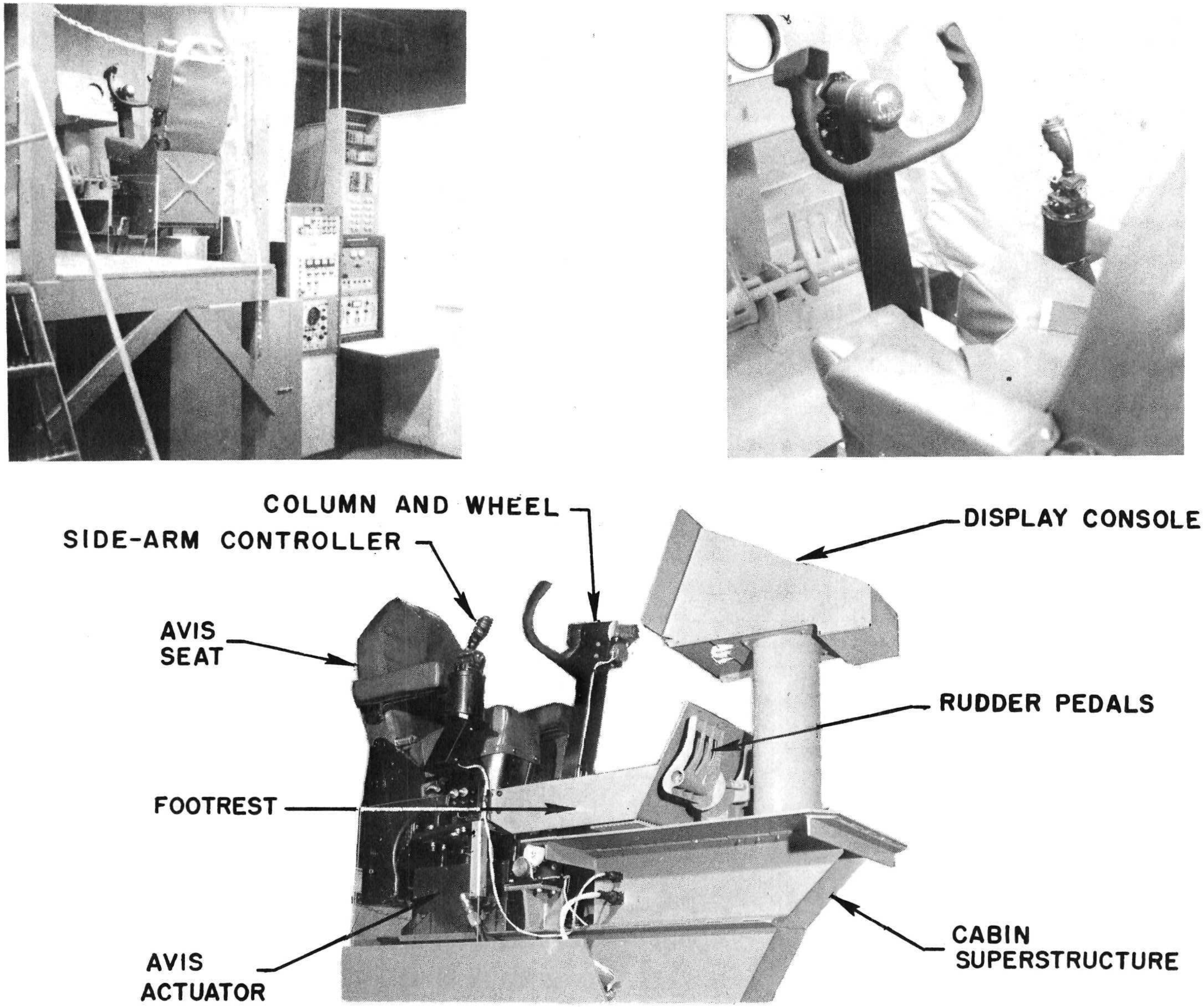


Figure 3. - Overall View of Test Area, Column and Wheel and Side Arm Controller

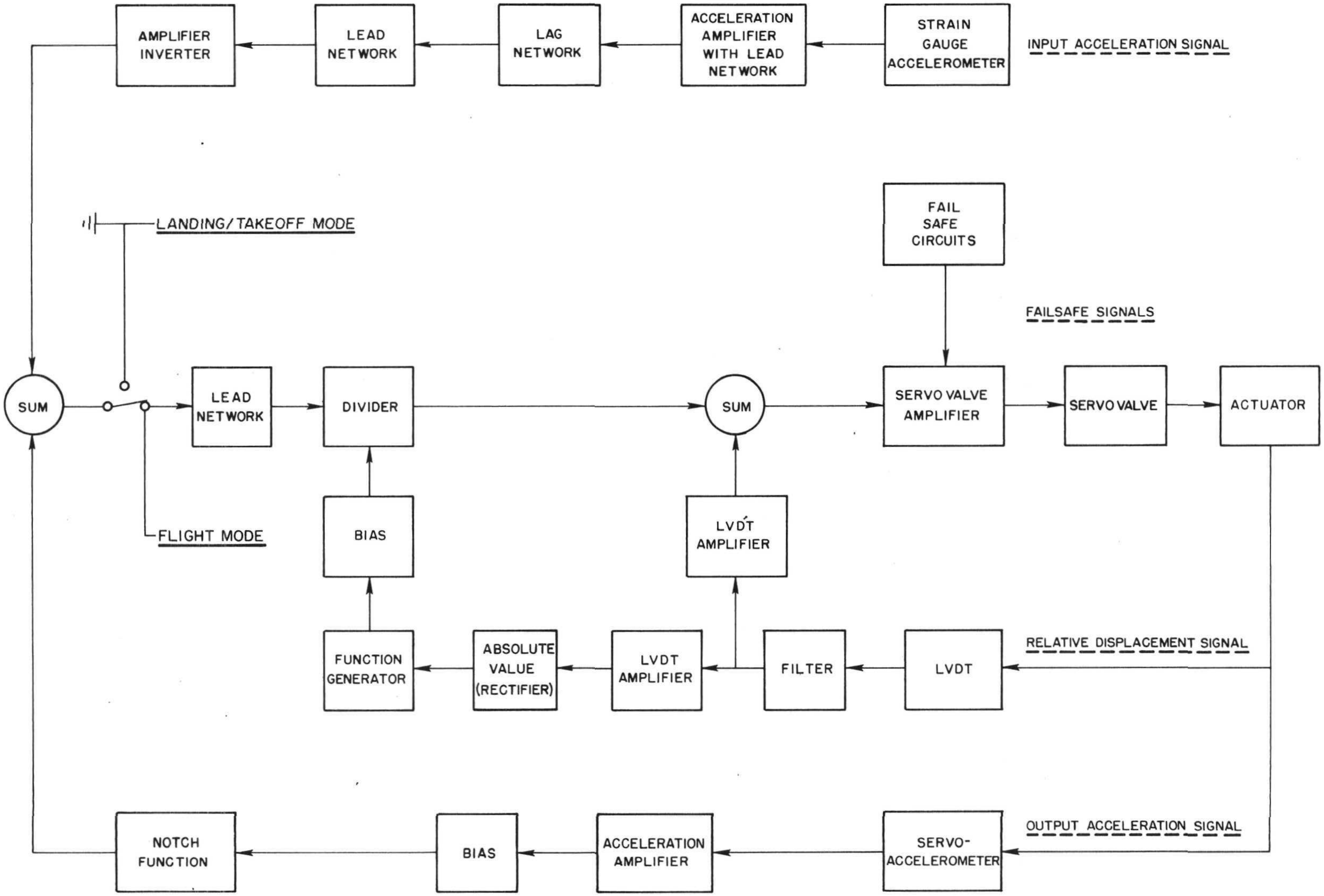
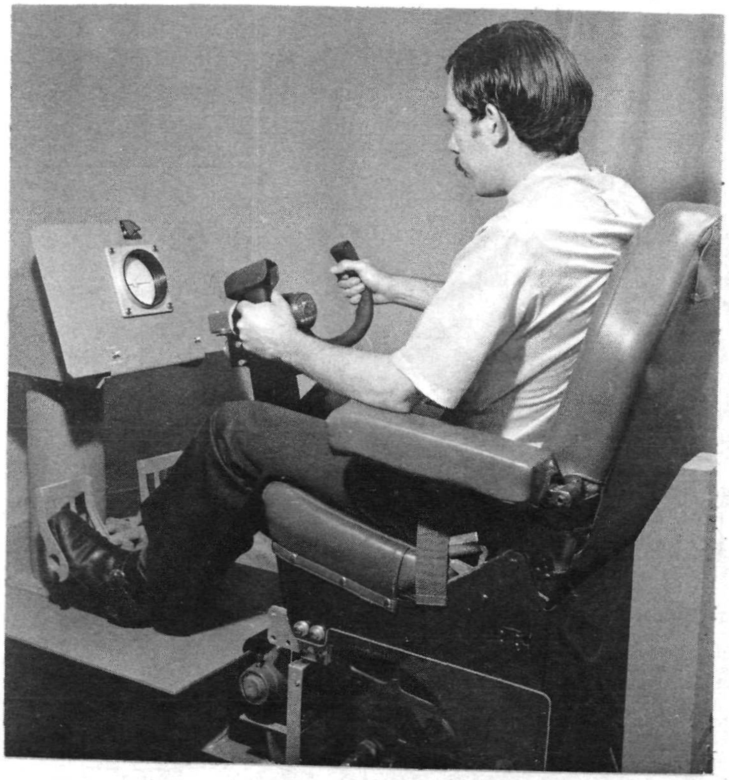


Figure 4. - Signal Flow Diagram for Active Vibration Isolation System



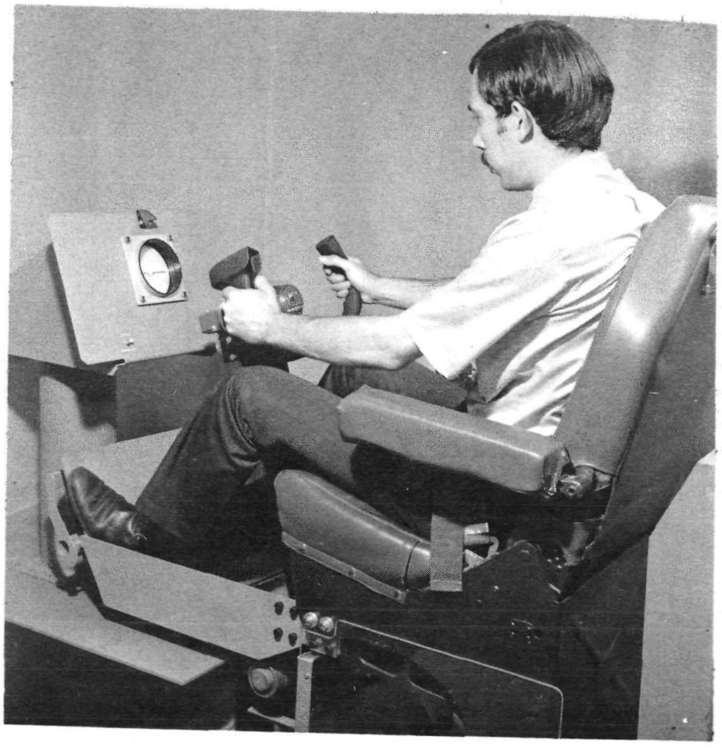


Figure 5. - Test Subject Using Rudder Pedals and Footrest

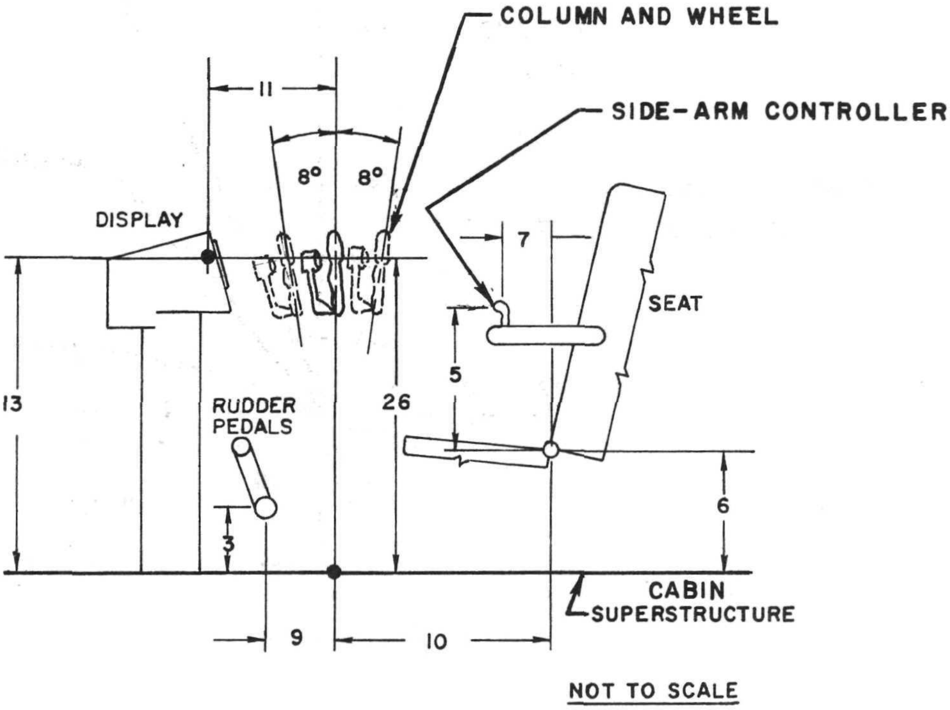


Figure 6. - Location of Seat, Column and Wheel, Side-Arm Controller and Displays

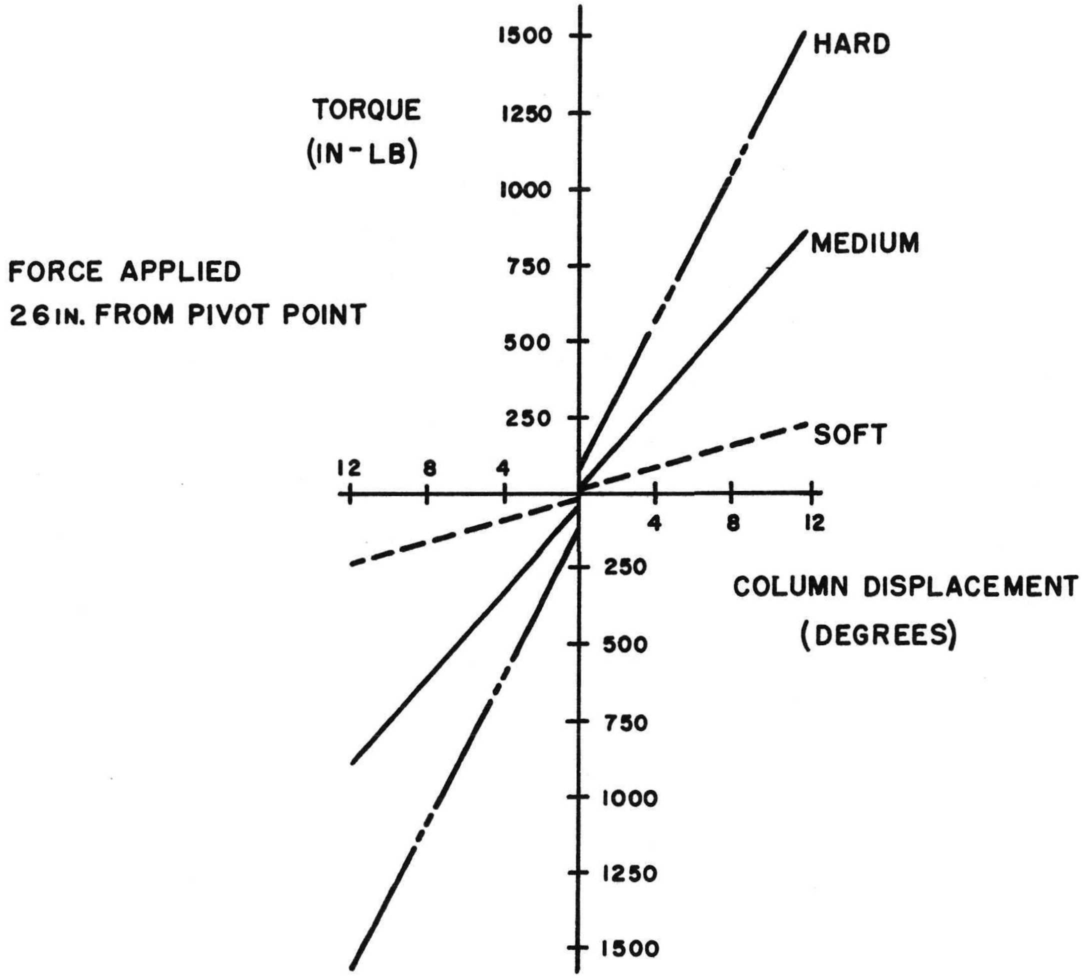


Figure 7. - Column Force Gradient in Pitch

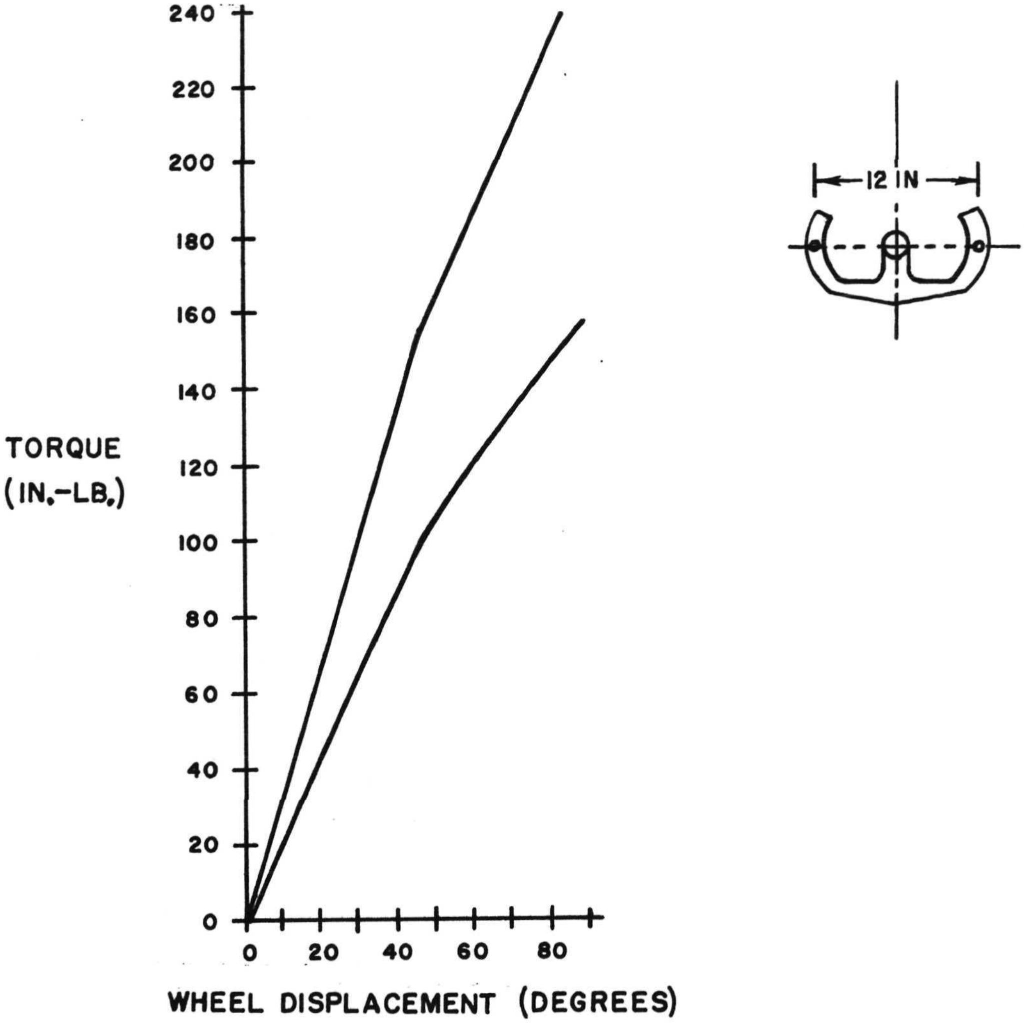


Figure 8. - Wheel Force Gradient in Roll

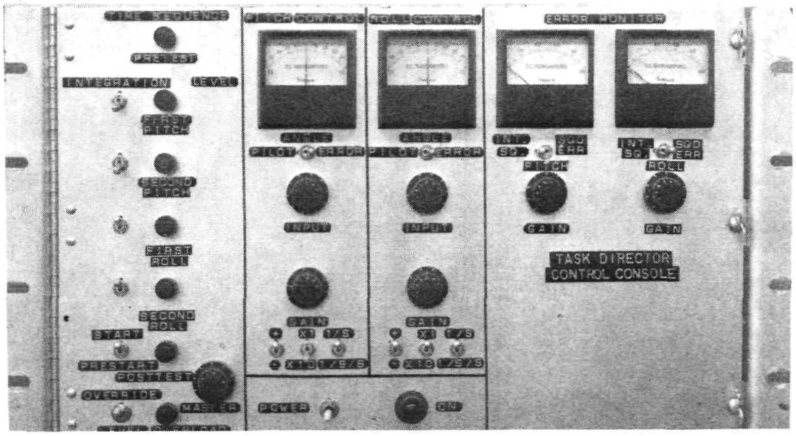
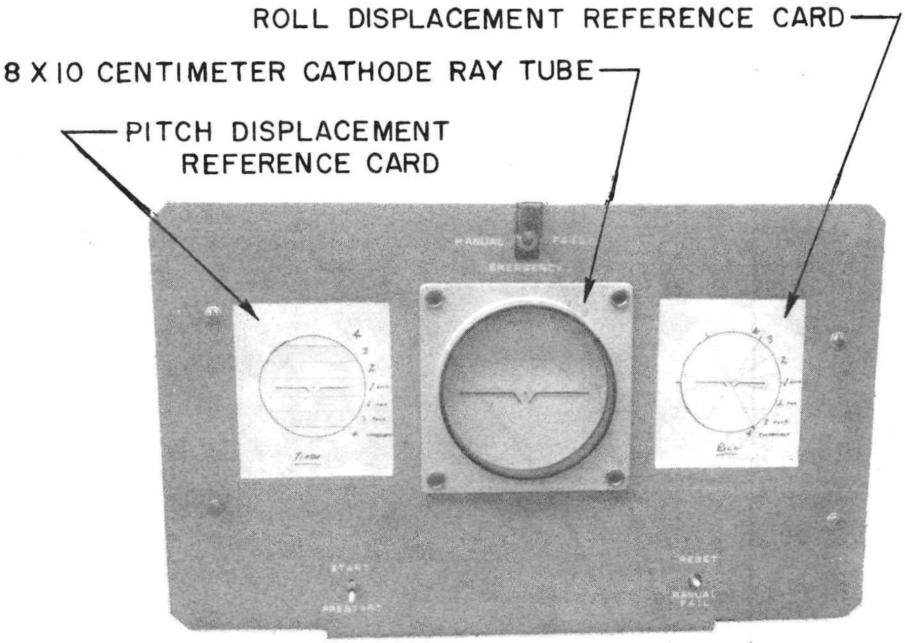
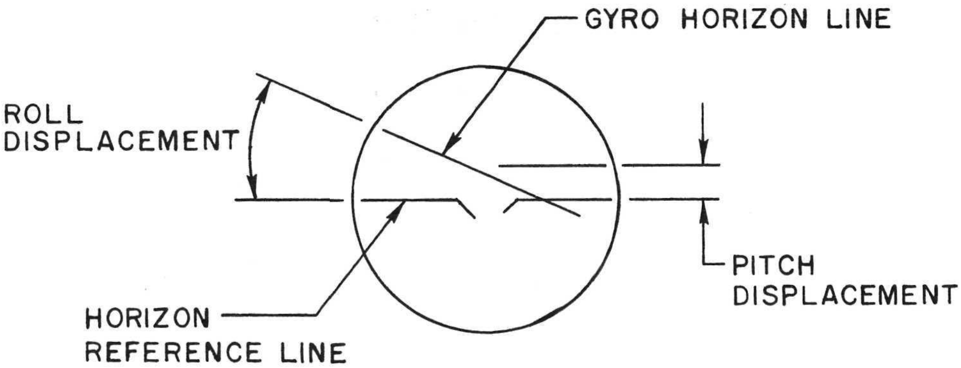


Figure 9. - Task Director Console



(a) PHOTOGRAPH OF PANEL



(b) SCHEMATIC SHOWING DETAILS OF DISPLAY

Figure 10. - Horizon Display and Panel

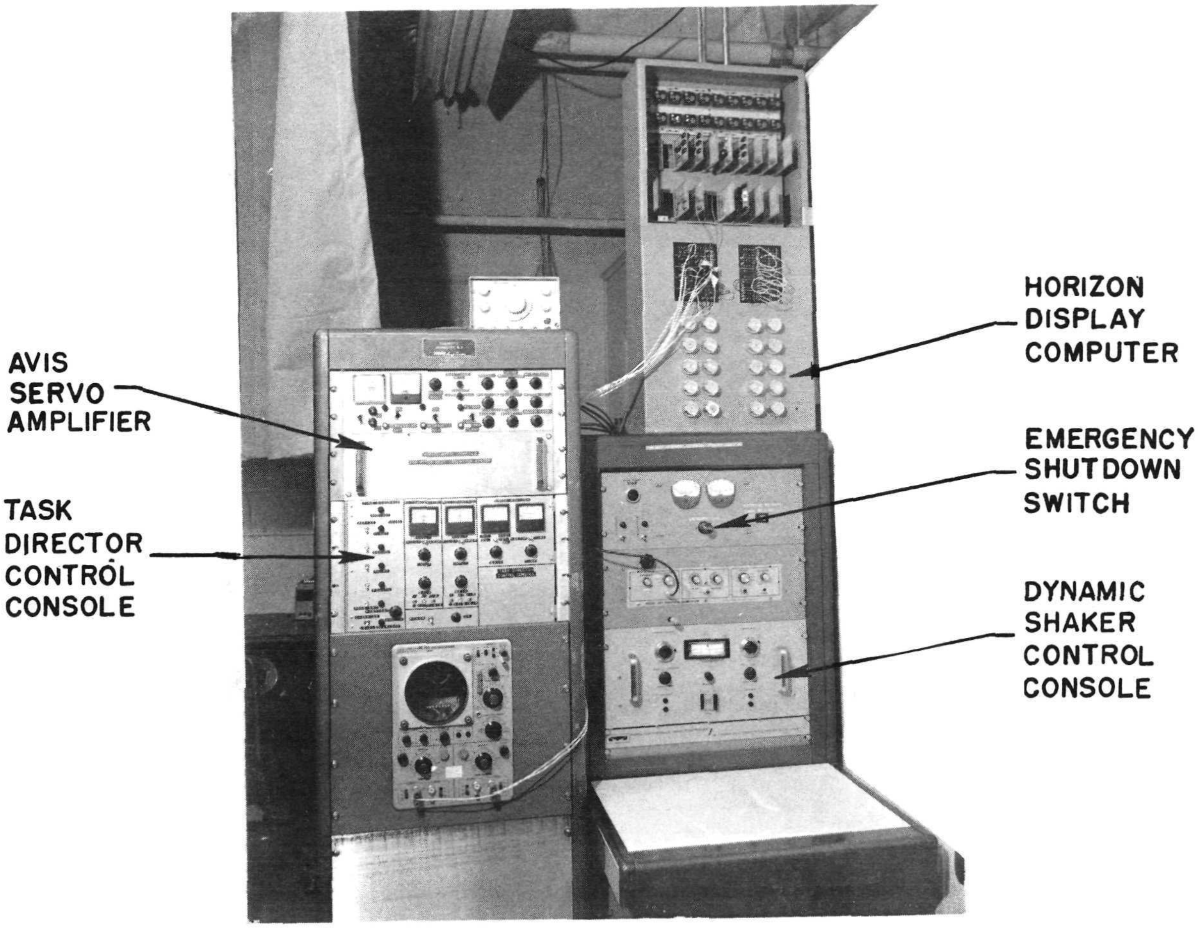


Figure 11. - Horizon Display Computer and Controls for AVIS, Two-Axis Task and Dynamic Shaker

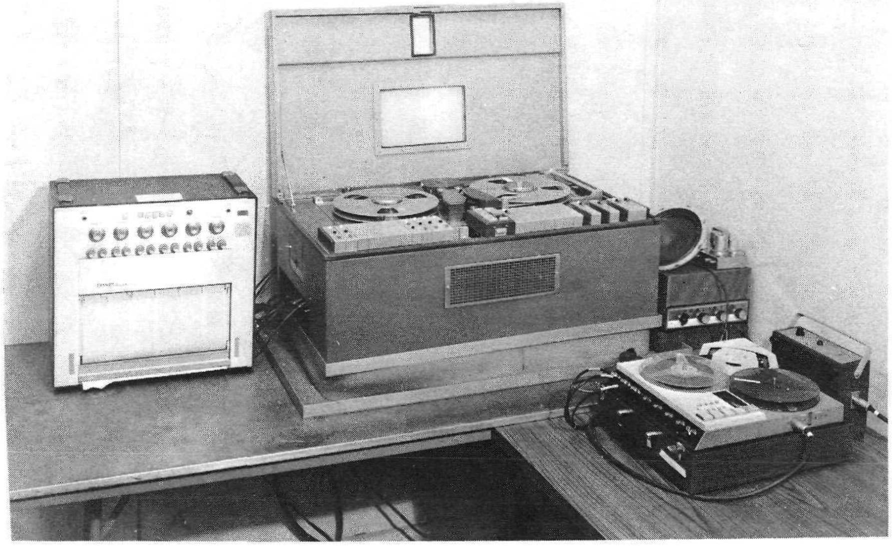


Figure 12. - Recording Equipment

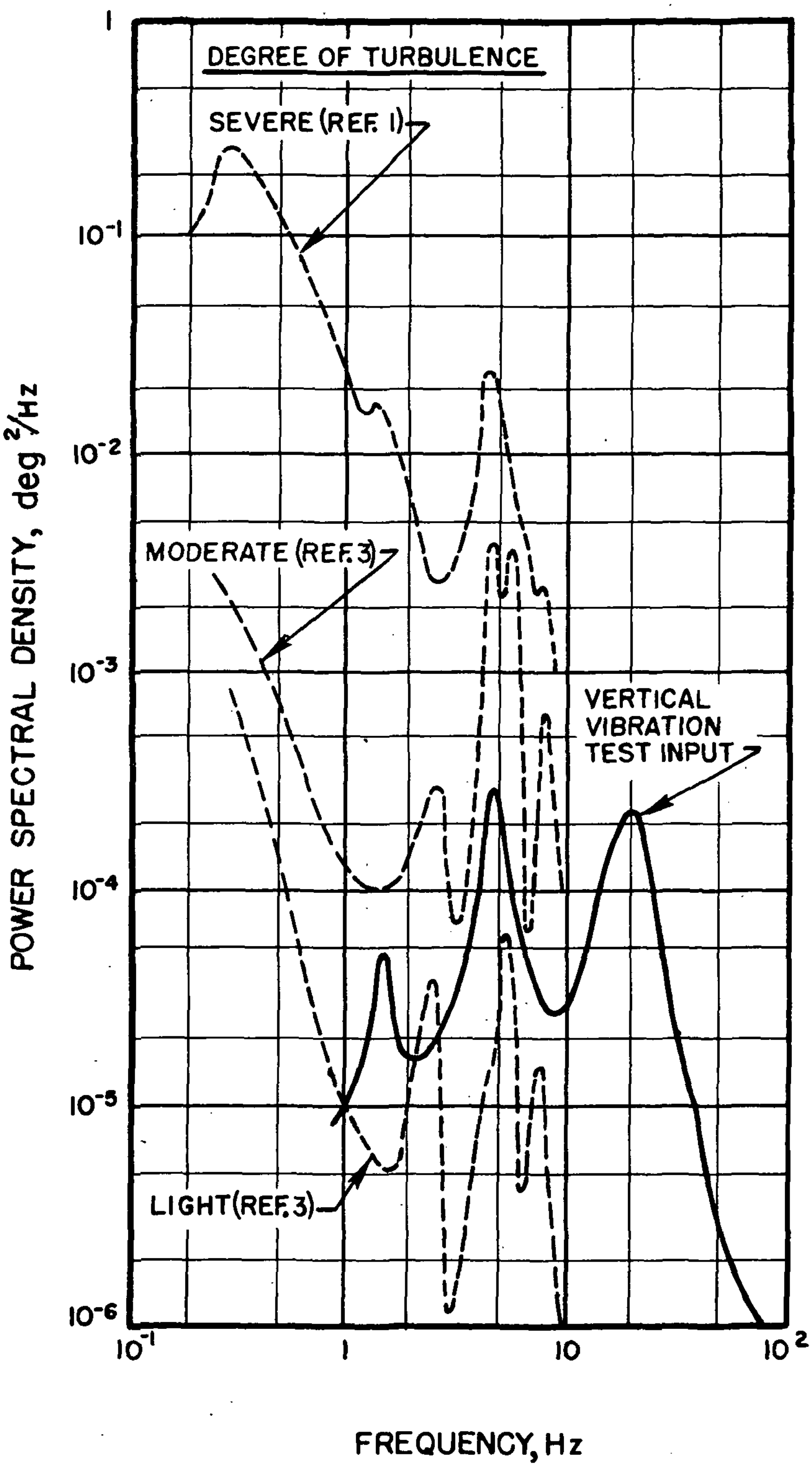


Figure 13. - Spectral Density of Vertical Vibration Test Input and Vertical Vibrations Expected at Pilot's Cabin During Turbulent Flight

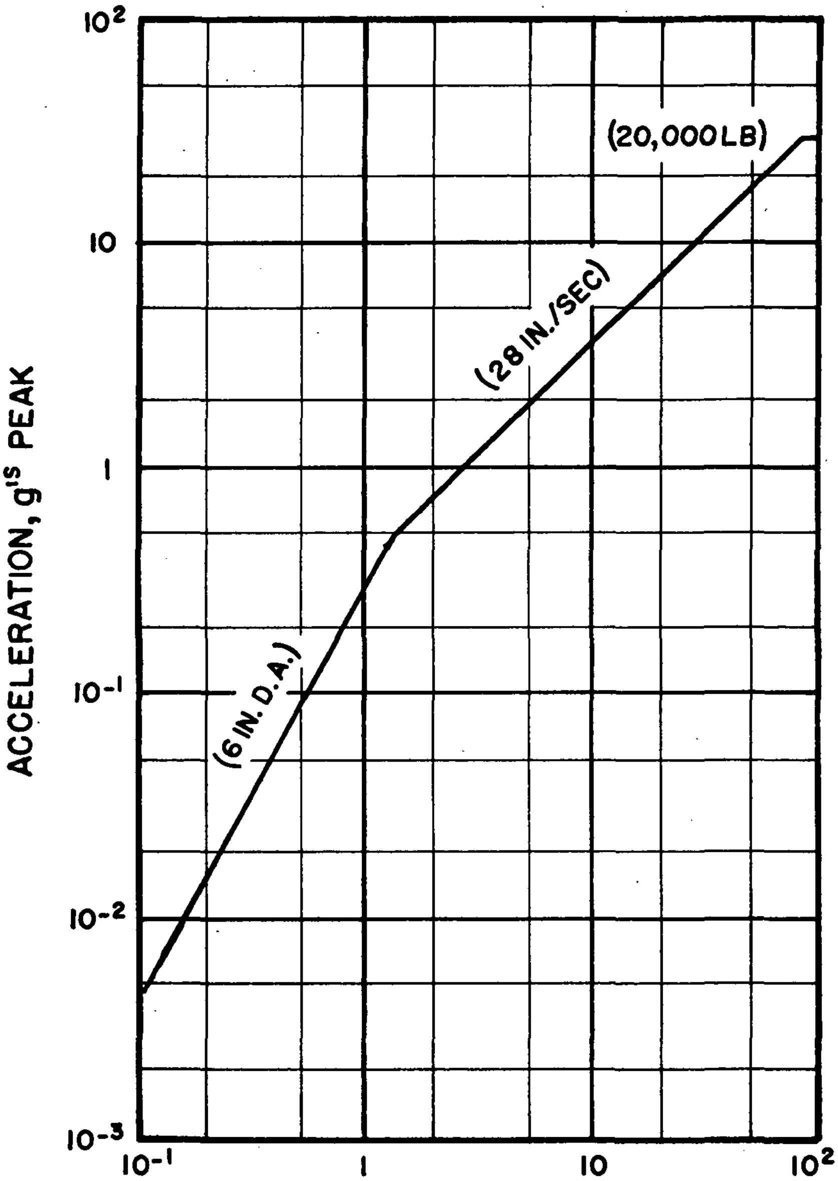


Figure 14. - Envelope of Dynamic Shaker Capabilities

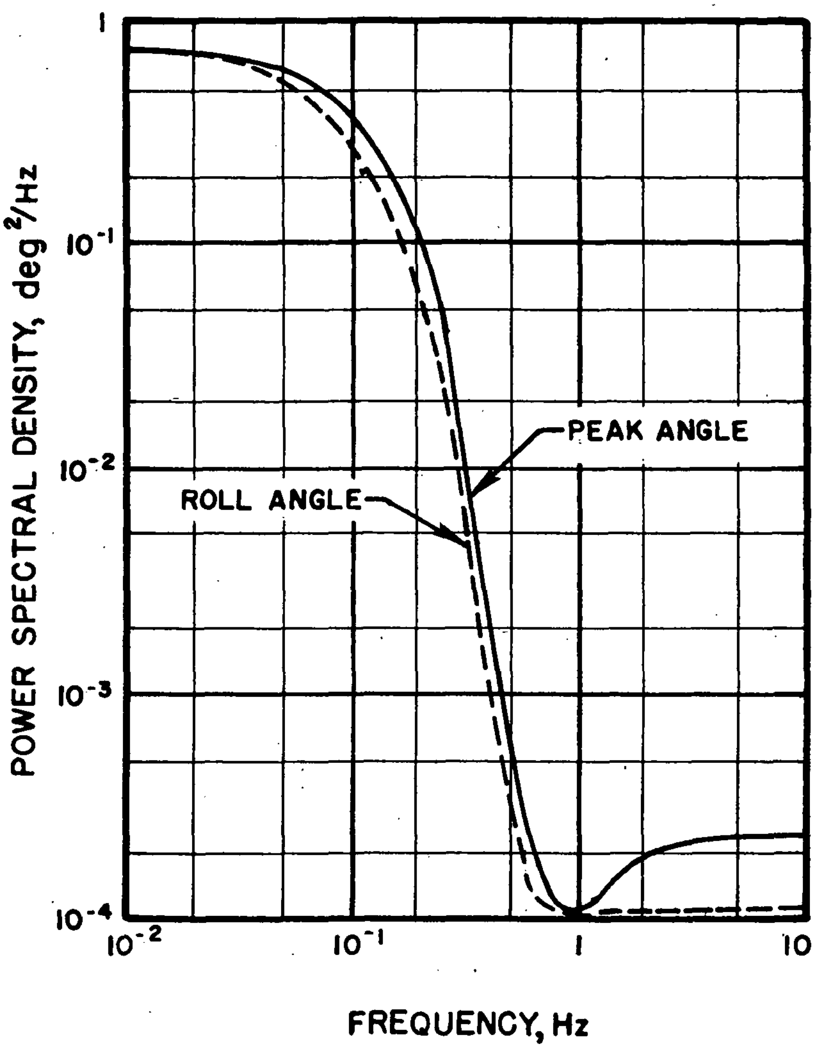


Figure 15. - Power Spectral Density of Pitch and Roll Angle Signals Used as Inputs to the Horizon Display

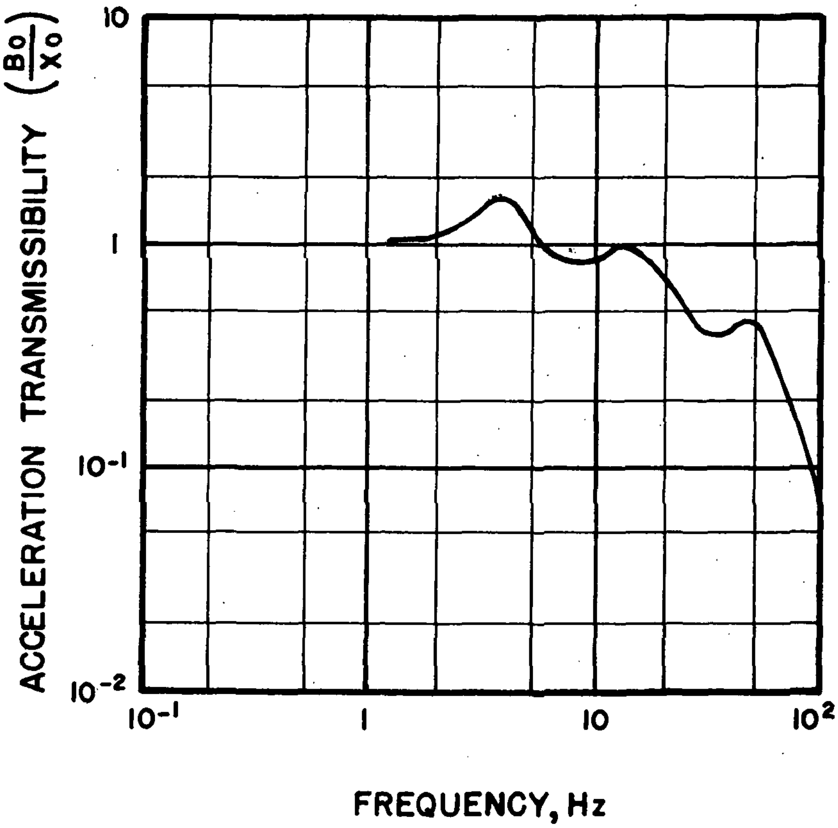


Figure 16. - Vertical Transmissibility Between Input and Buttocks with AVIS in Off Mode

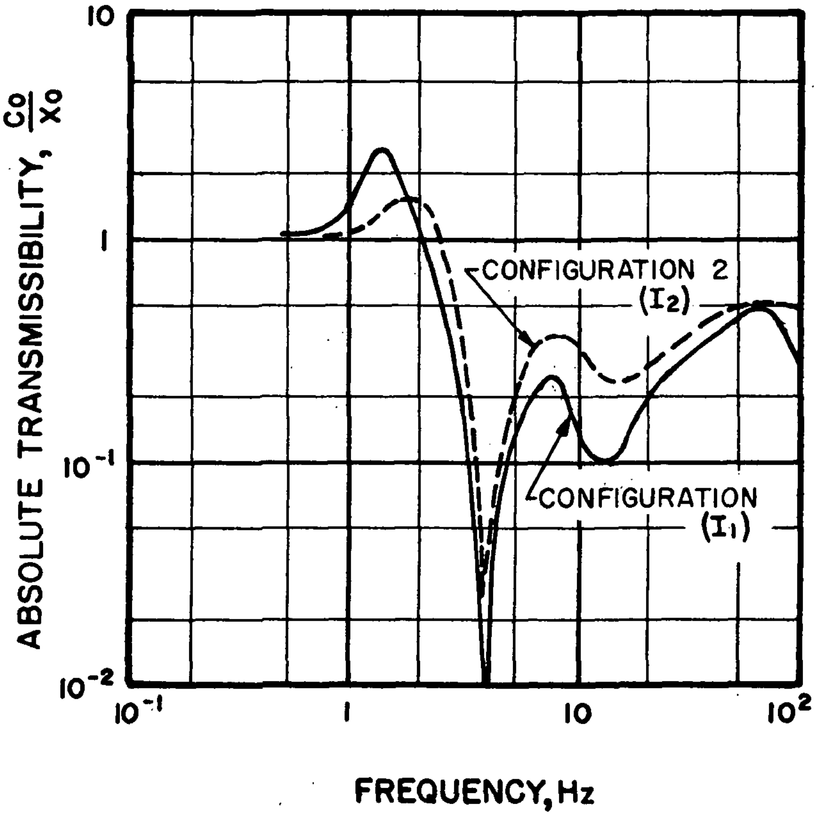


Figure 17. - Vertical Transmissibility Between Input and Output at Actuator with AVIS in On Mode

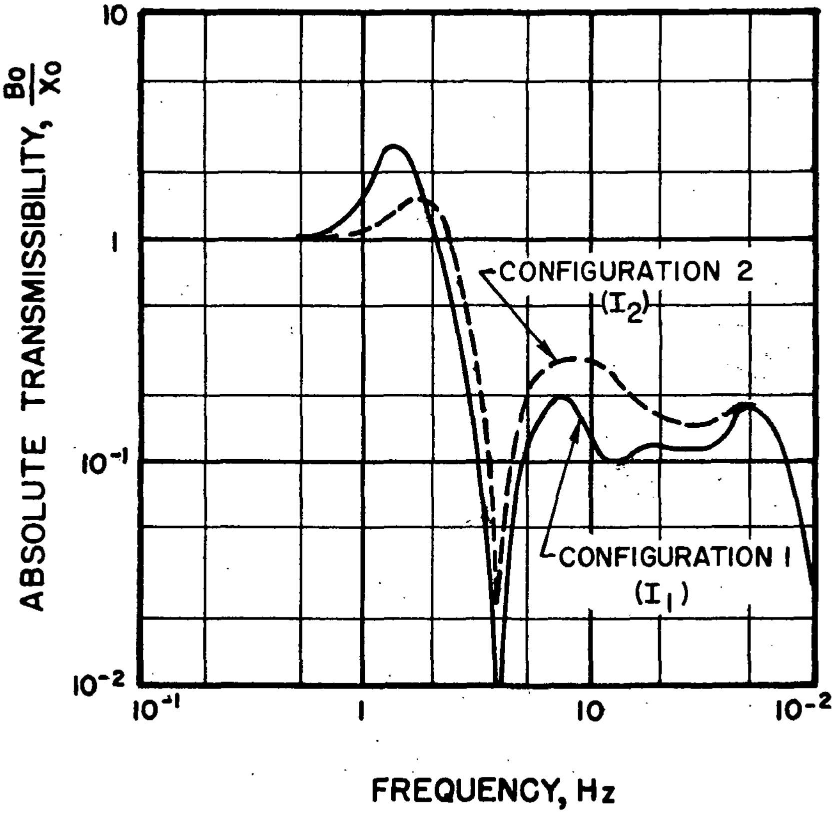
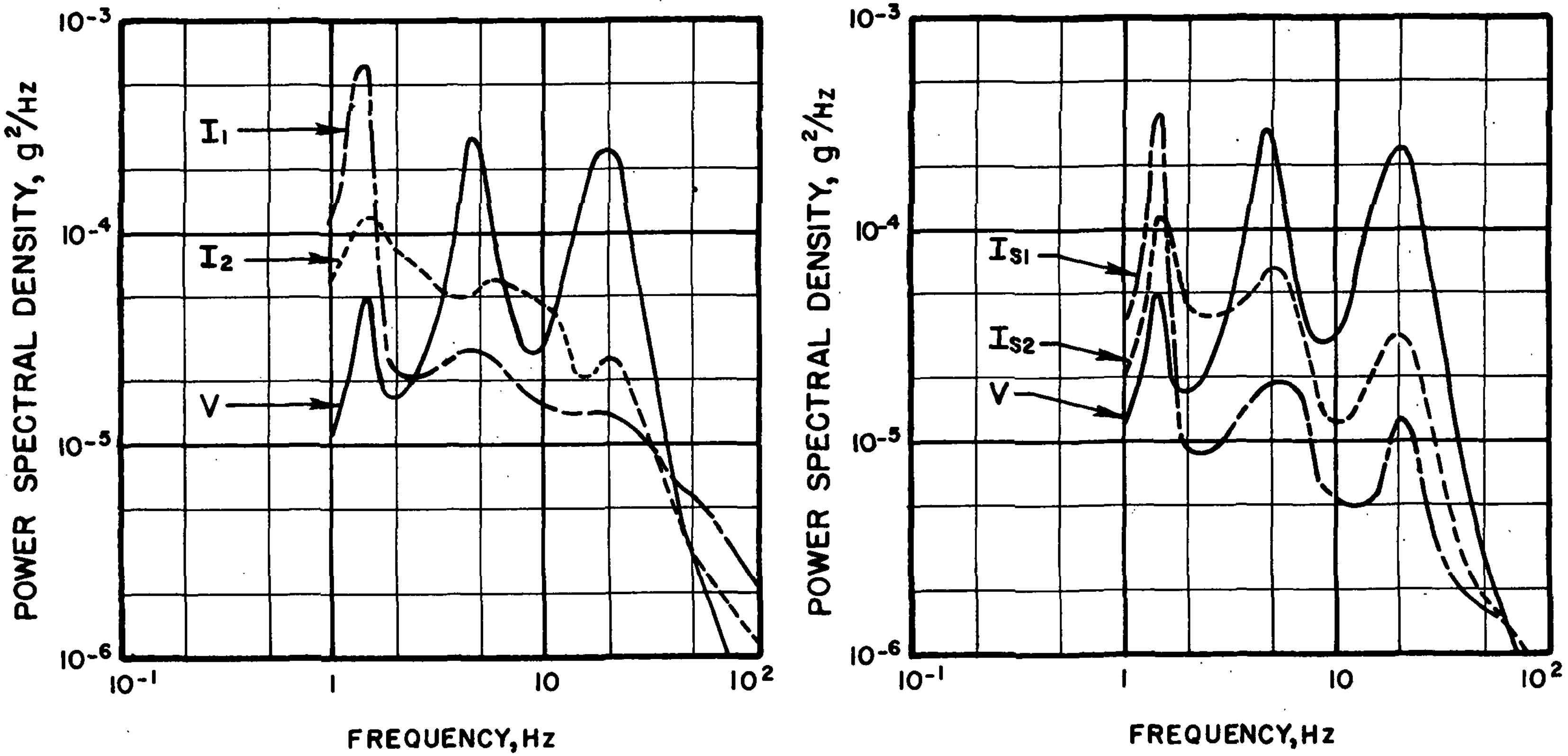
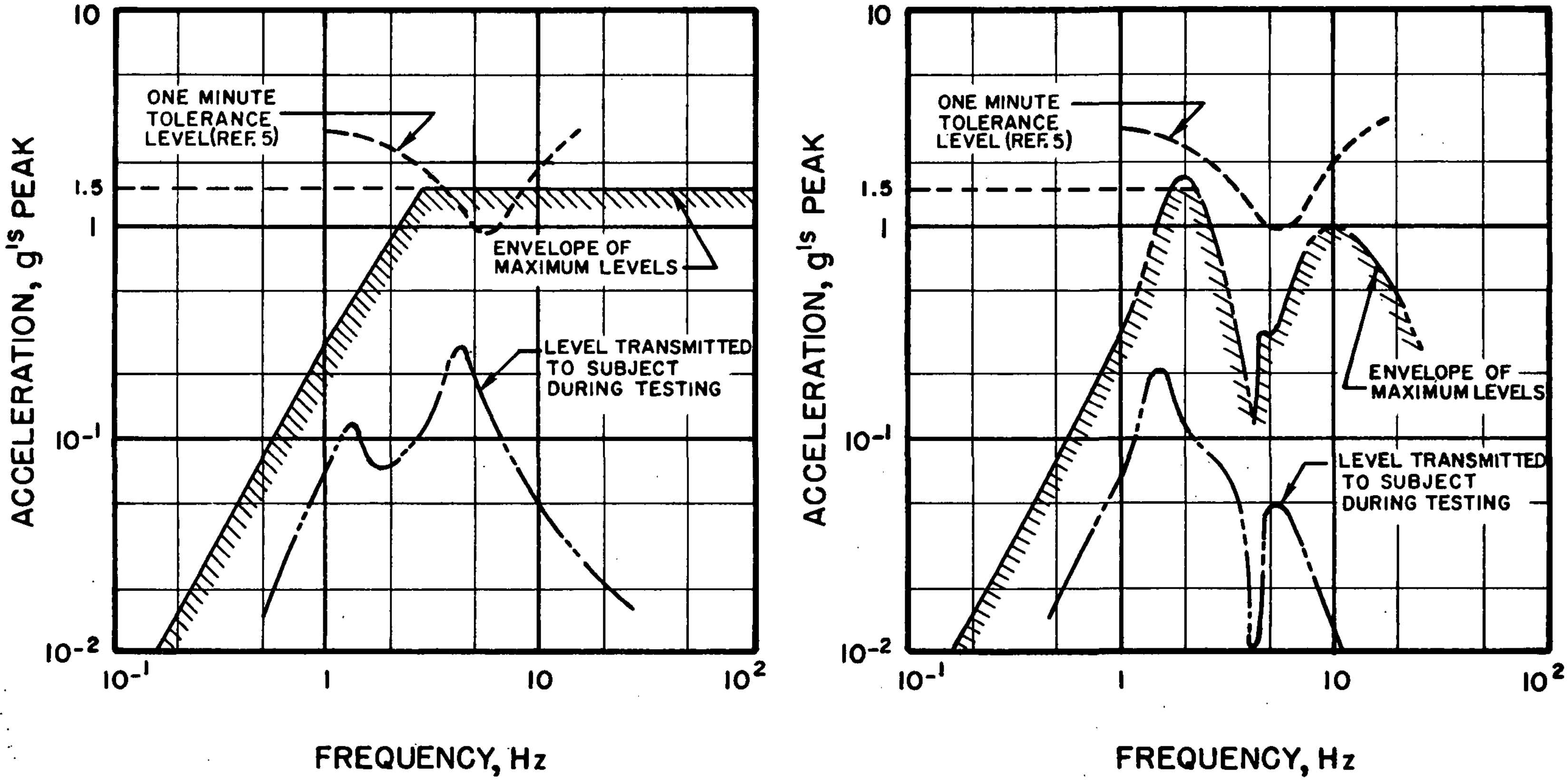


Figure 18. - Vertical Transmissibility Between Input and Buttocks with AVIS in on Mode



CONFIGURATION	AVIS	ACCELERATION LEVEL TRANSMITTED TO SEAT	ACCELERATION LEVEL TRANSMITTED TO DISPLAY
V	OFF	V	V
I_1	ON	I_1	V
I_2	ON	I_2	V
I_{S1}	OFF	I_{S1}	I_{S1}
I_{S2}	OFF	I_{S2}	I_{S2}

Figure 19. - Spectral Density of Accelerations Transmitted to Seat and Display for Various Test Configurations



a) NO ISOLATION CONFIGURATION (V)

b) ISOLATION CONFIGURATION $(I_1), (I_2), (I_{S1}), (I_{S2})$

Figure 20. - Comparison of One-Minute Acceleration Tolerance Levels, Level Transmitted to Subject During Testing, and Maximum Levels Generated by the Shaker with Acceleration Limiting Circuits Actuated

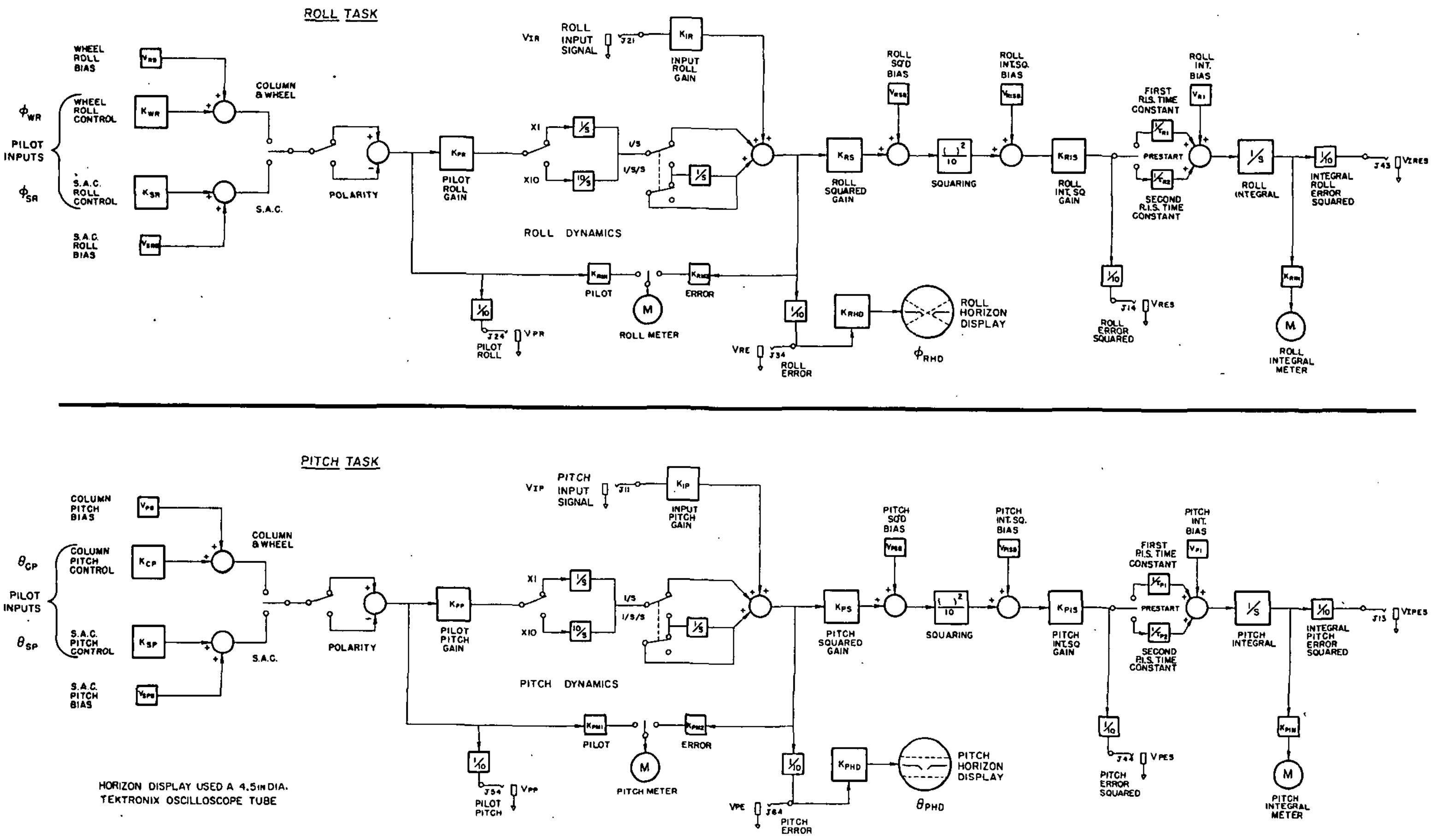


Figure 21. - Function Block Diagram of Two-Axis Task

PILOTS QUALITATIVE QUESTIONNAIRE

Test No.______ Subject__________________ Date______________ Time______________

CONFIGURATION - TASK SETUP

☐ Wheel/Column
☐ Side-Arm Controller
☐ Normal Rudder Pedals
☐ Isolated Footrests

$\frac{1}{s^2}$ ☐ Pitch ☐ Roll

$\frac{1}{s}$ ☐ Pitch ☐ Roll

Simulated Isolation Condition

1☐ 2☐

			CONFIGURATION				
				High		Simulated	
			None	No Isol	Isolated	Isolation	
			(F)	(V)	(I)	(I_s)	
ERROR RATING	PITCH	1 Good					
		2 Fair					
		3 Poor					
		4 Impossible					
	ROLL	1 Good					
		2 Fair					
		3 Poor					
		4 Impossible					
EFFECT OF VIBRATION ON ERROR COMPARED WITH FIXED BASE (INCREASE OF ERROR COMPARED TO FIXED BASE)		None					
		Minor					
		Moderate					
		Excessive					
DO BODY MOTIONS INDUCE INADVERTENT TRACKING INPUTS		None					
		Minor					
		Moderate					
		Excessive					
EFFECT OF VIBRATION ON VISION		None					
		Minor					
		Moderate					
		Excessive					

Figure 22: Questionnaire for Subjective Evaluations of Error and Effects of Test Configuration on Tracking Inputs and Vision

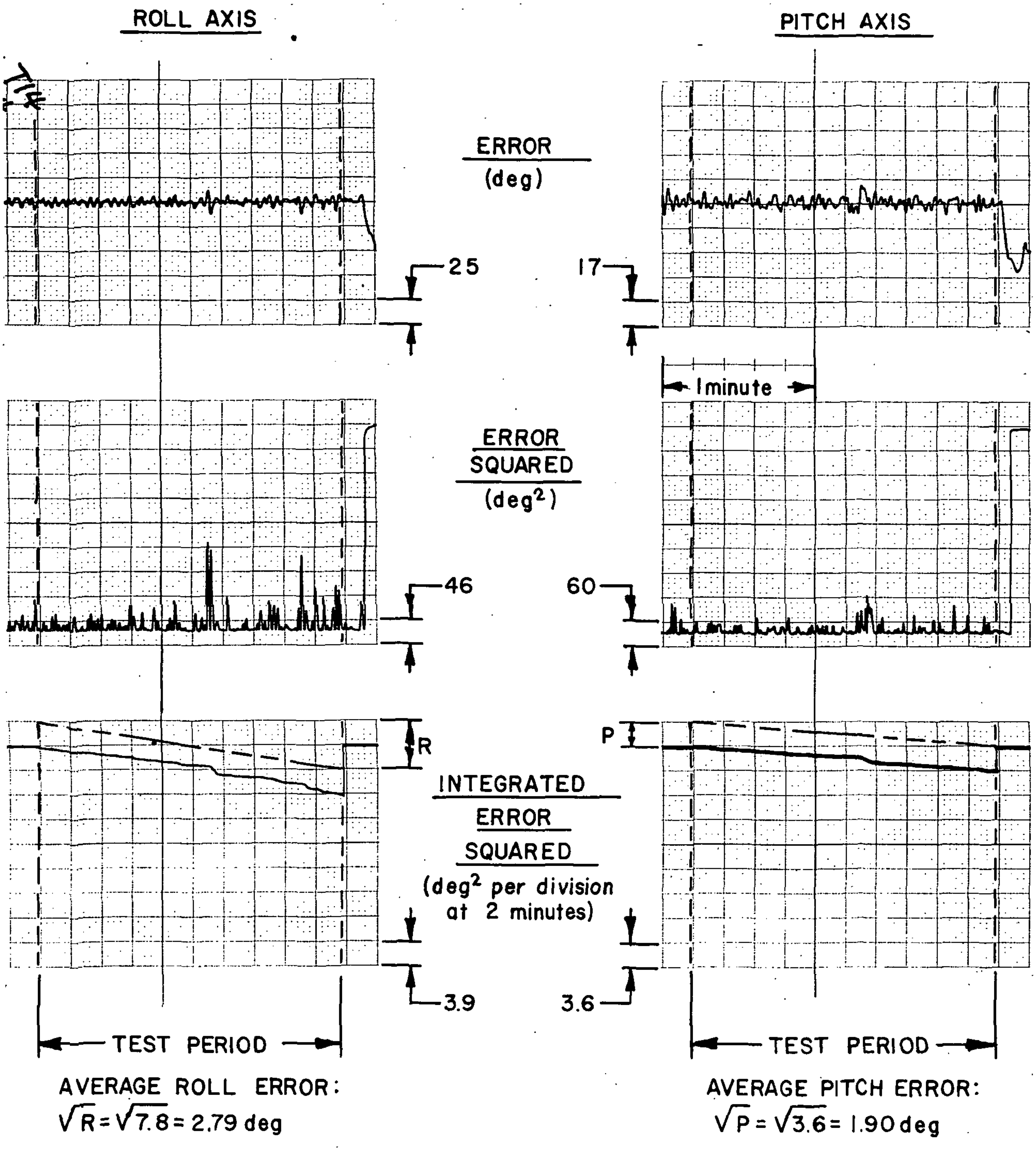


Figure 23. - Roll and Pitch Error, Error Squared, and Integrated Error Squared for: Column and Wheel, Fixed Base and Footrest. (Run 4, Battery 3, Configuration F)

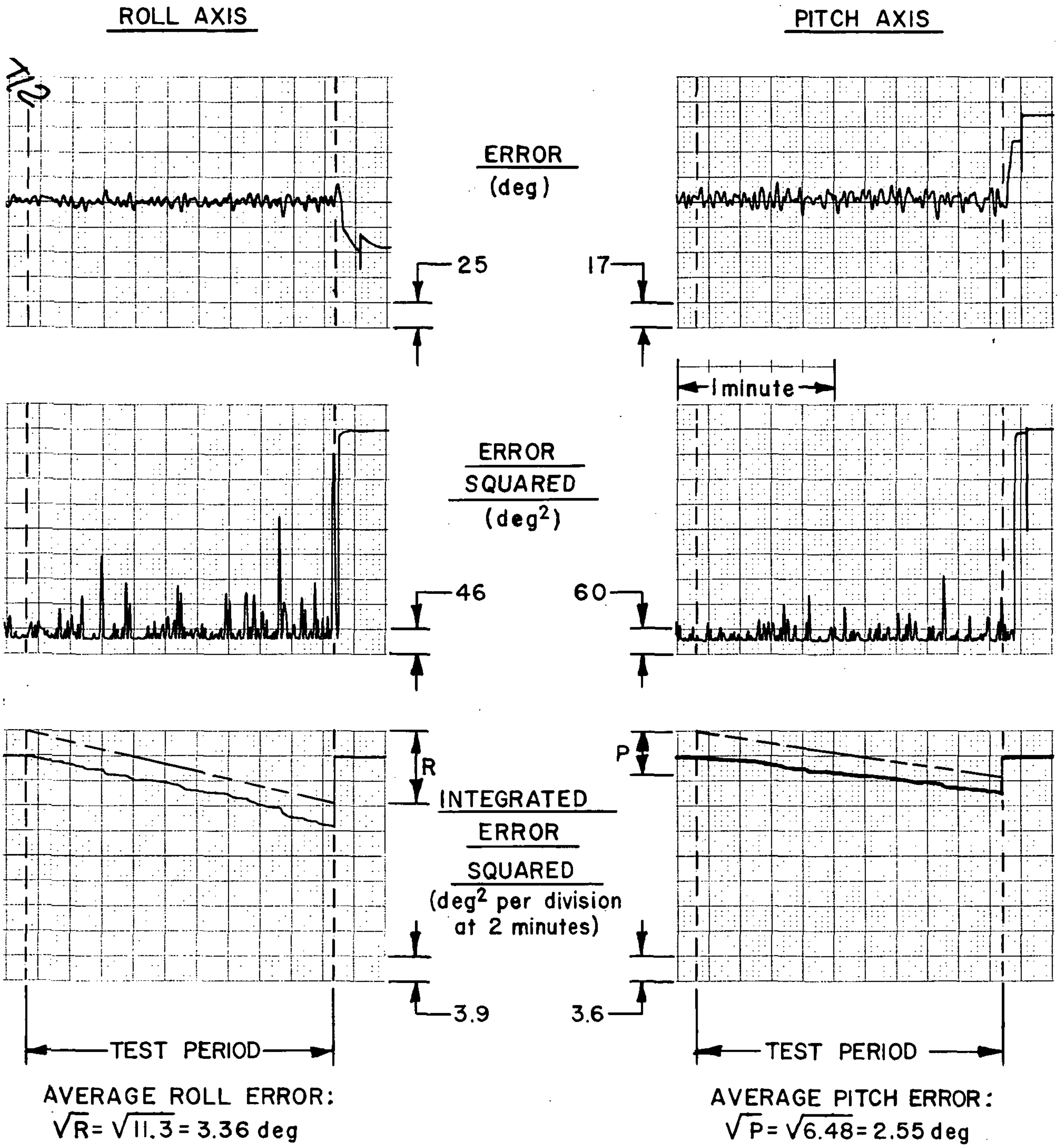


Figure 24. - Roll and Pitch Error, Error Squared and Integrated Error Squared for: Column and Wheel, Simulated Seat and Display Isolation, and Footrest. (Run 4, Battery 3, Configuration I_{S2})

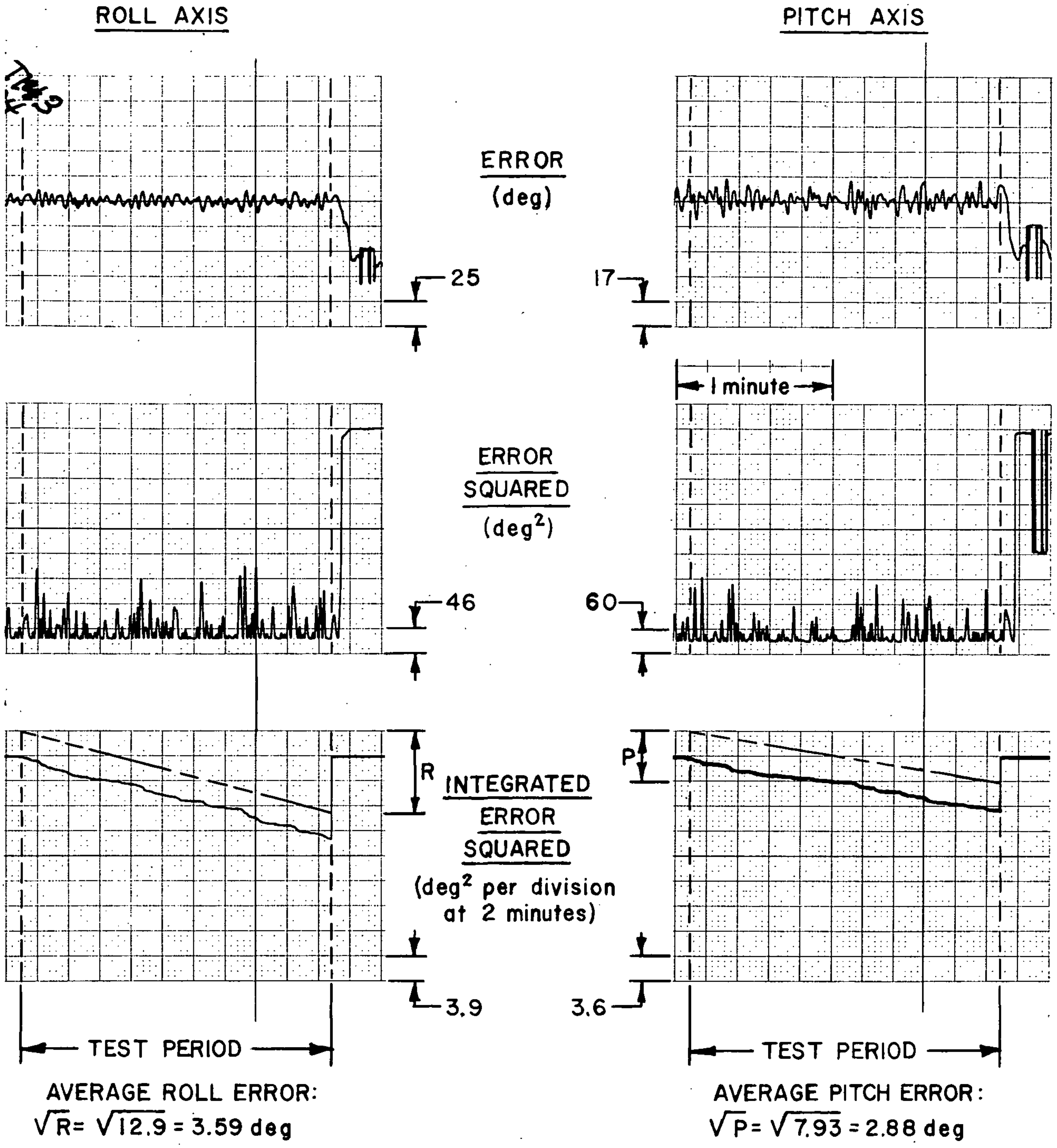


Figure 25. - Roll and Pitch Error, Error Squared and Integrated Error Squared for: Column and Wheel, No Vibration Isolation and Footrest (Run 4, Battery 3, Configuration V)

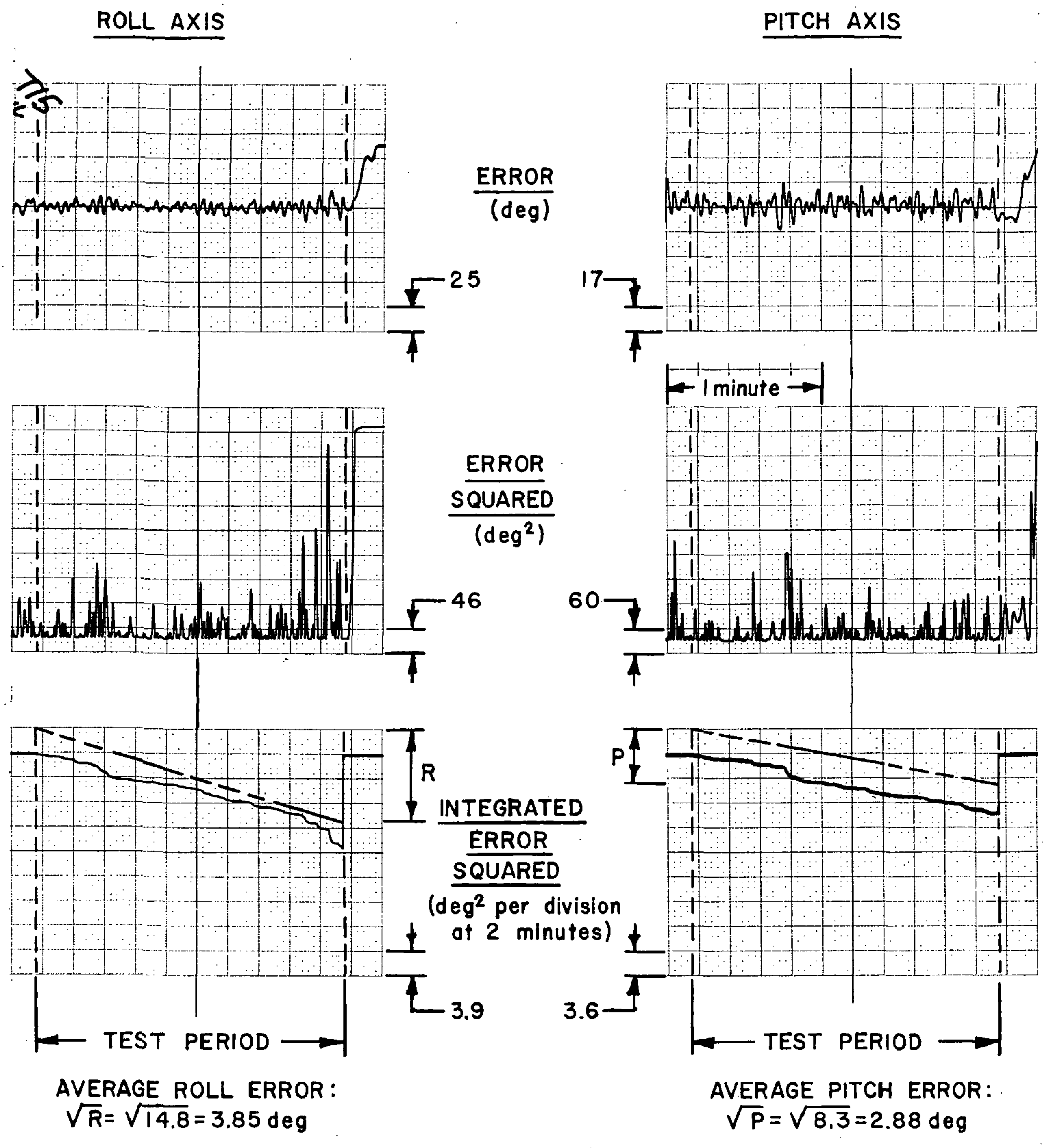


Figure 26. - Roll and Pitch Error, Error Squared and Integrated Error Squared for: Column and Wheel, Isolated Seat (AVIS On, Isolation Configuration 2) and Footrest (Run 4, Battery 3, Configuration I$_B$)

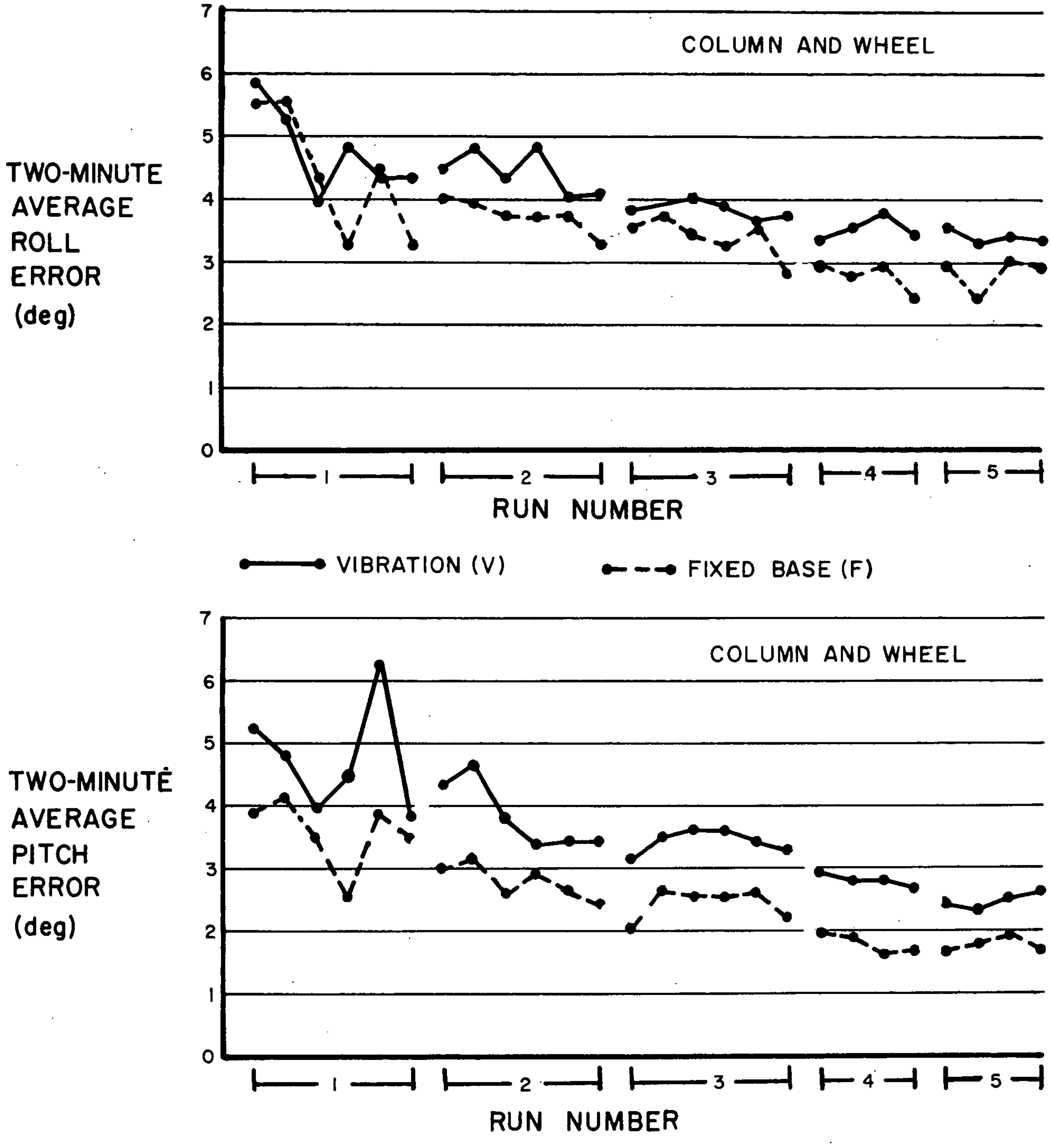


Figure 27. - Two-Minute Average Roll and Pitch Errors for Vibration and Fixed Base Configurations Using Column and Wheel for Control

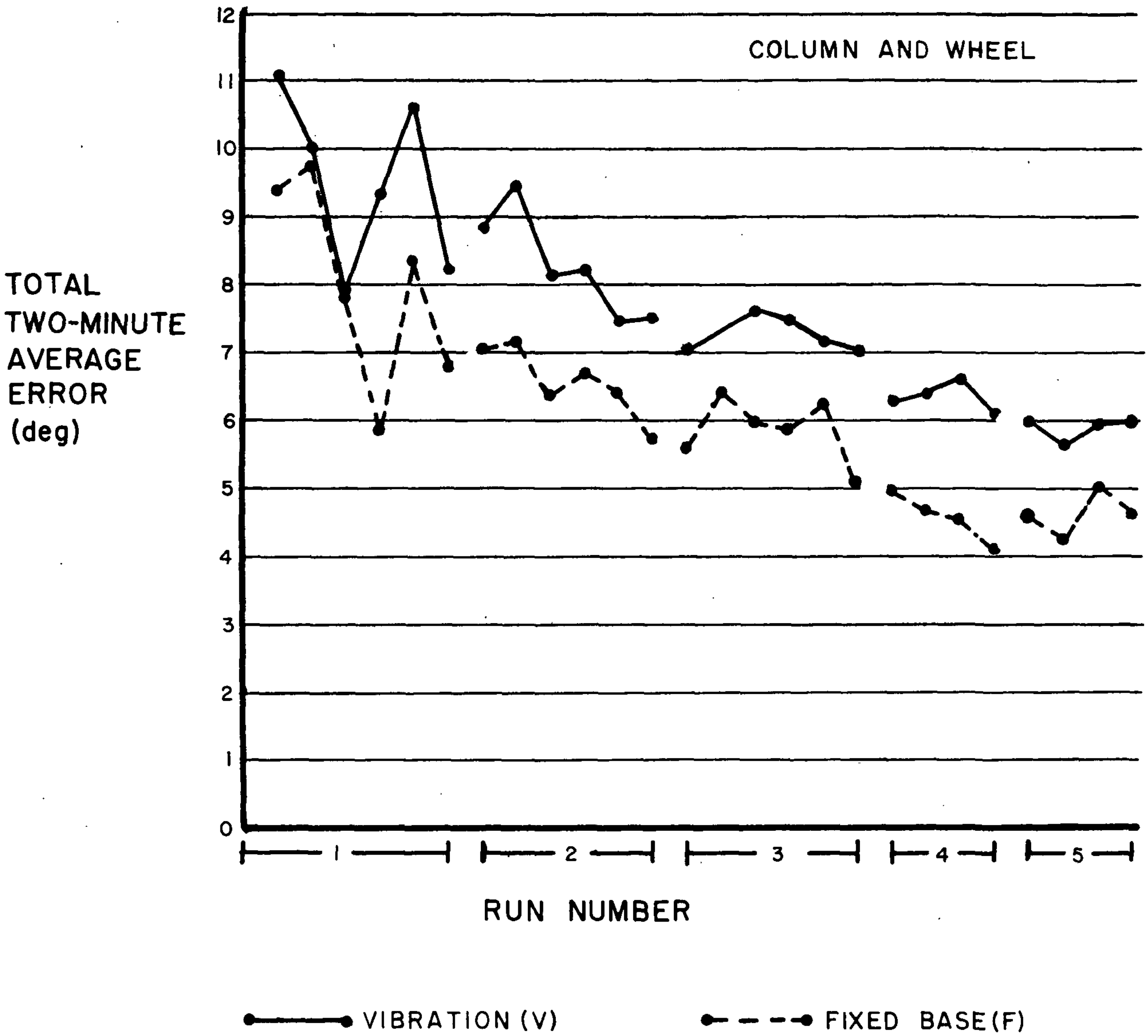


Figure 28. - Total Two-Minute Average Error for Vibration and Fixed Base Configurations Using Column and Wheel for Control

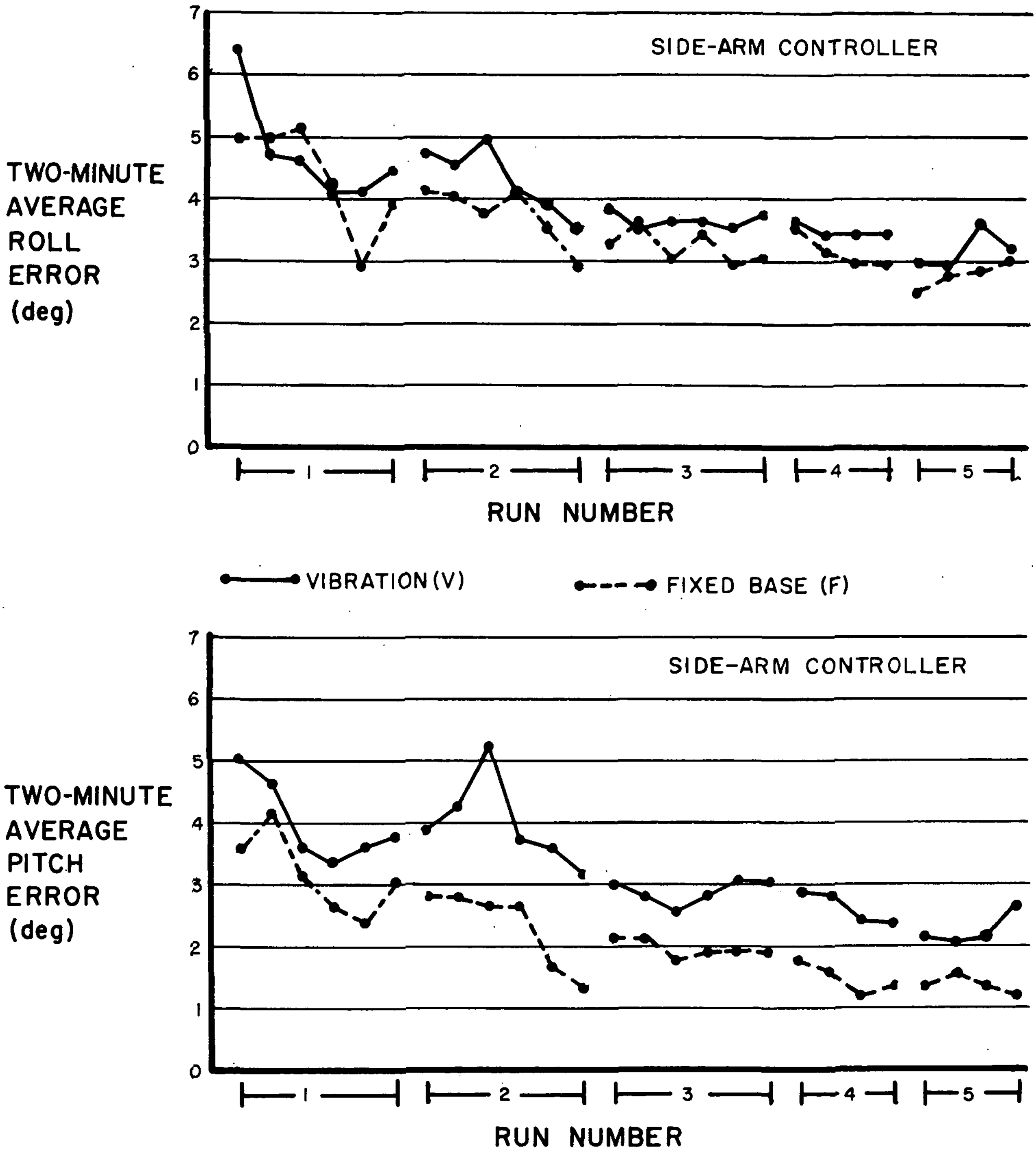


Figure 29. - Two-Minute Average Roll and Pitch Errors for Vibration and Fixed Base Configurations Using Side-Arm Controller for Control

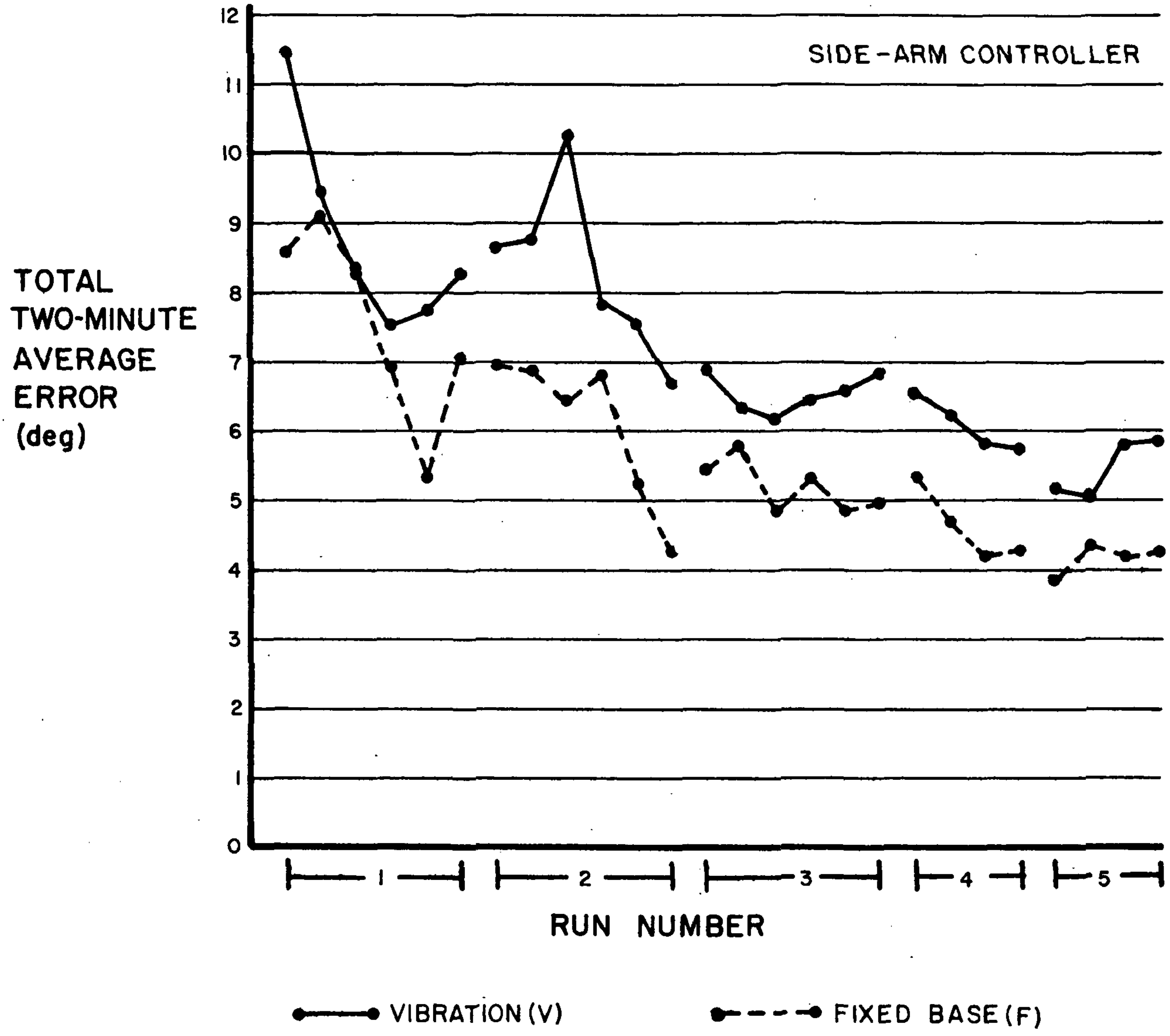


Figure 30. - Total Two-Minute Average Error for Vibrations and Fixed Base Configurations Using Side-Arm Controller for Control

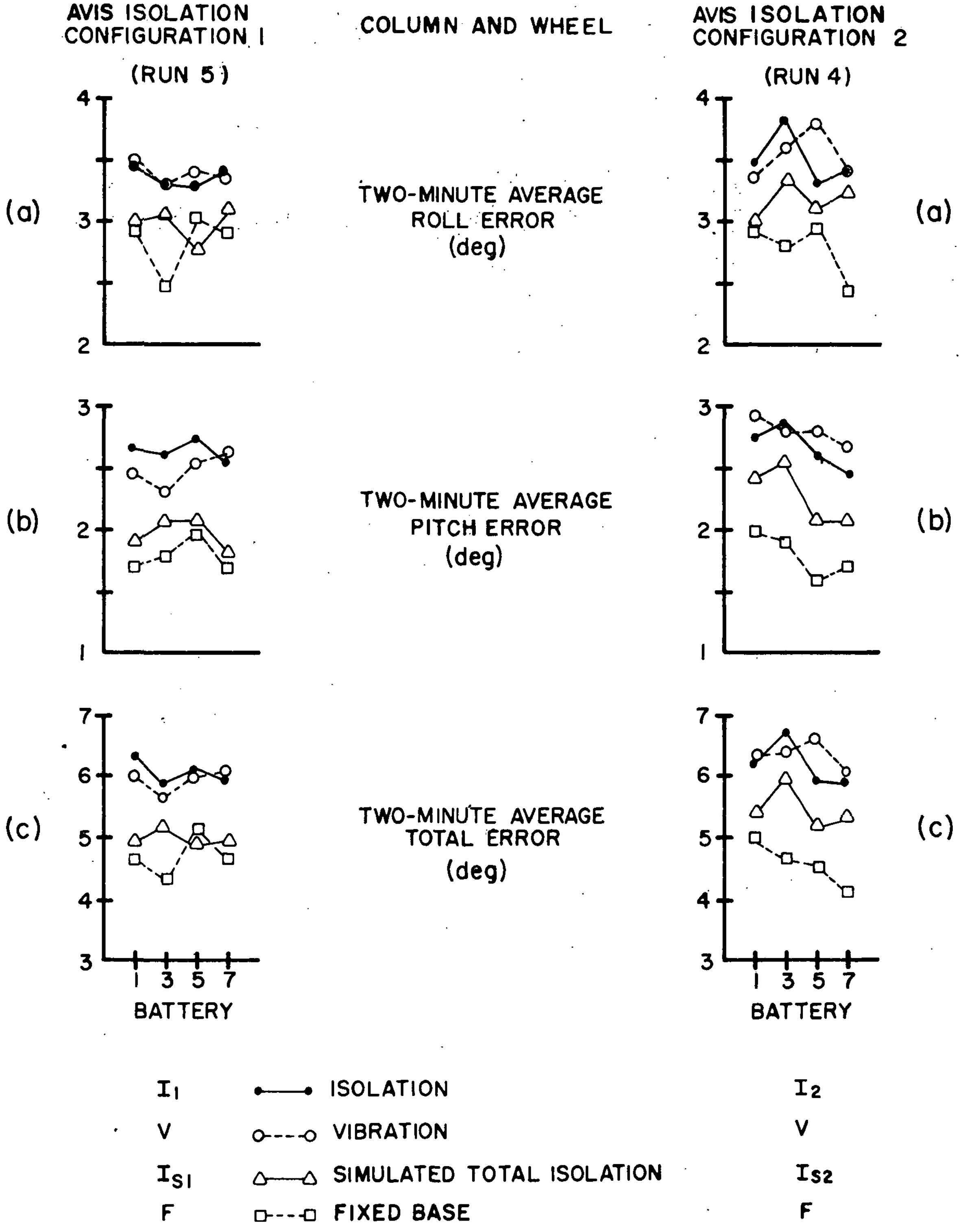


Figure 31. - Comparison of Average Errors for Various Isolation Configurations Using Column and Wheel for Control

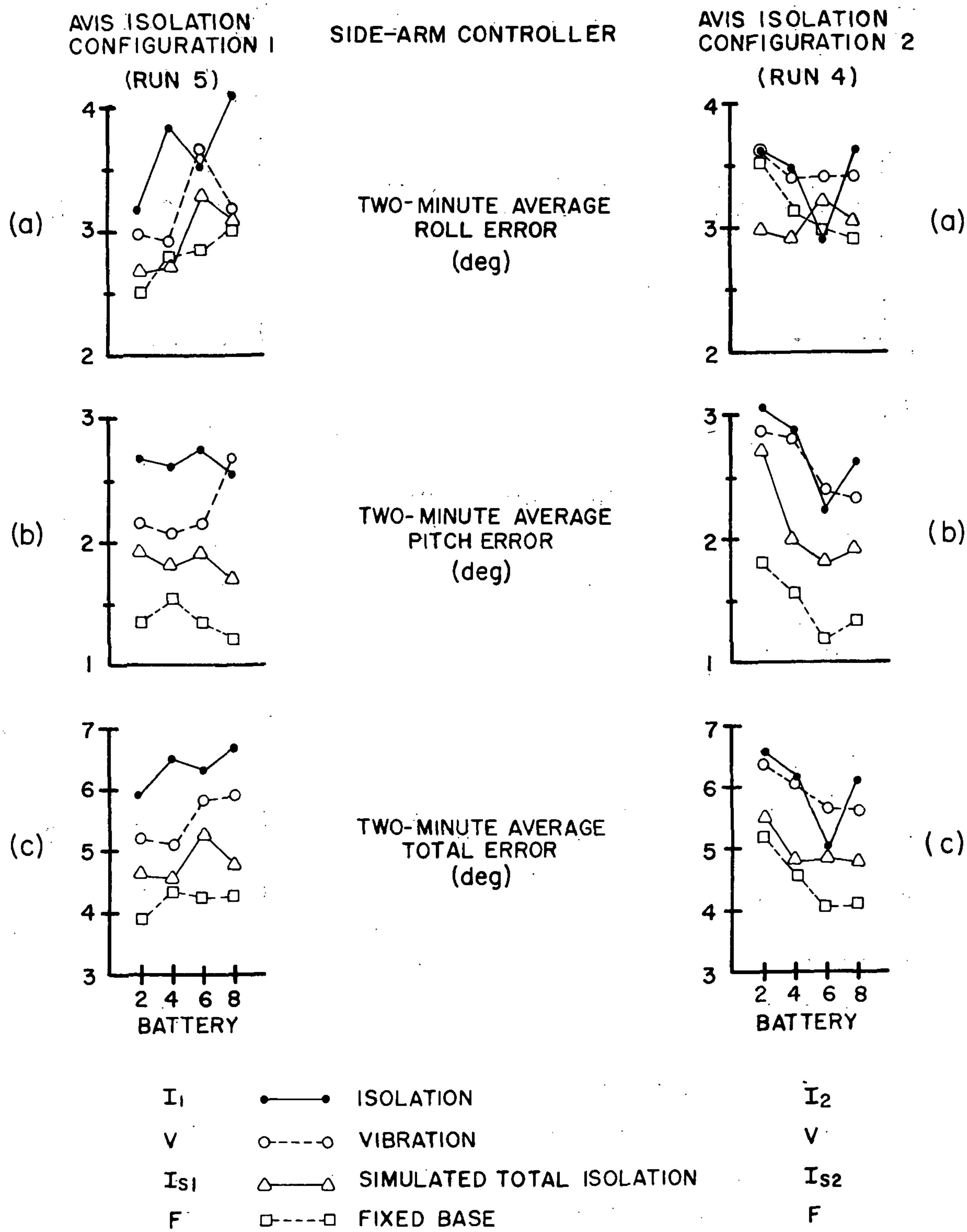


Figure 32. - Comparison of Average Errors for Various Isolation Configurations Using Side-Arm Controller for Controls

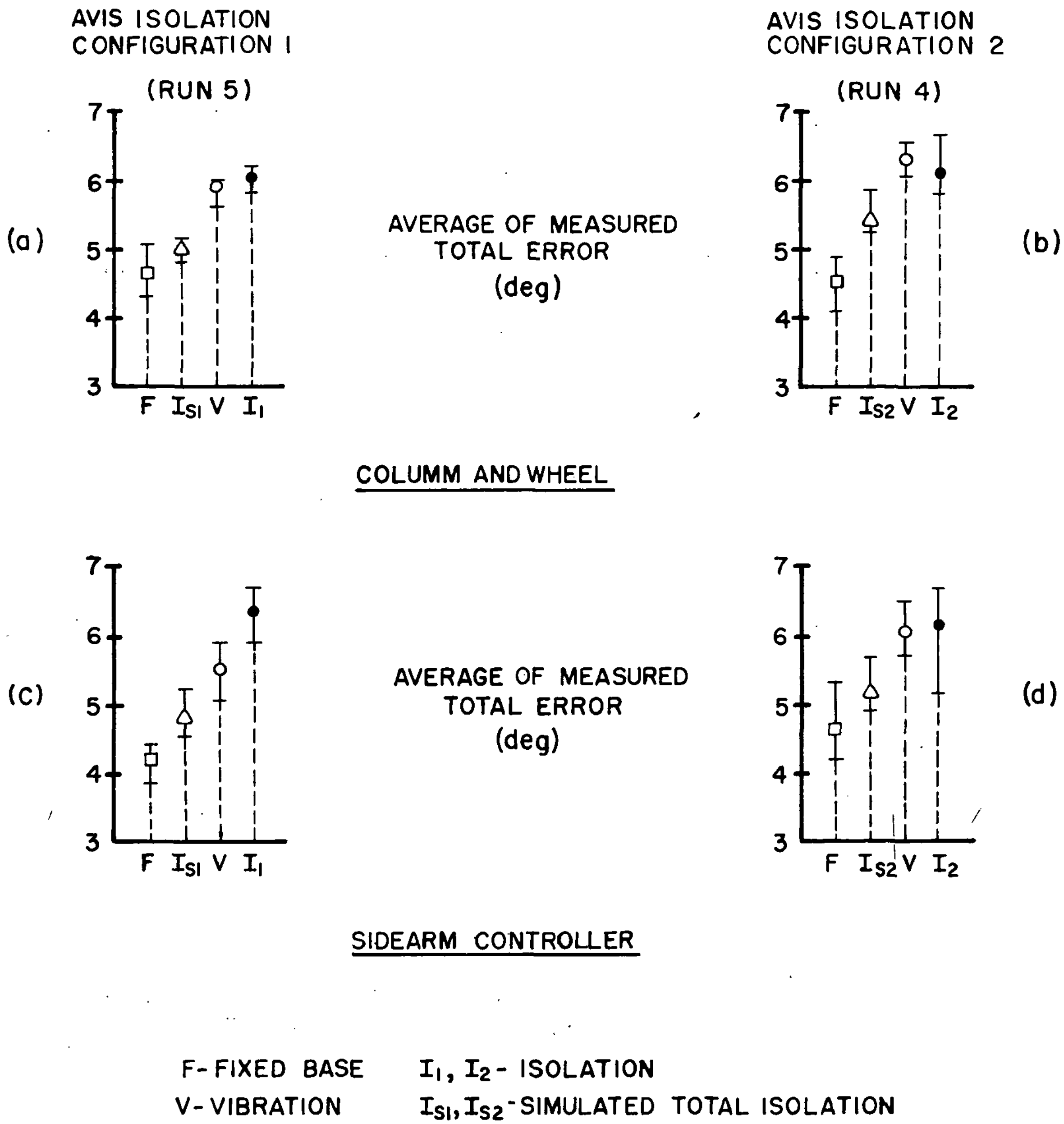


Figure 33.- Comparison Between Averages of Total Error for Various Configurations with Column and Wheel and Side-Arm Controller

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