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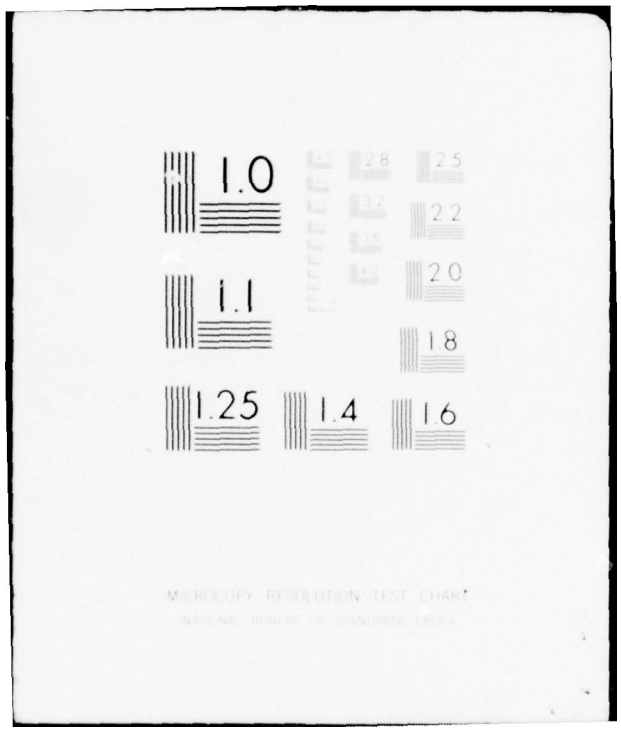
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MANUAL CONTROL IN TARGET TRACKING TASKS AS A FUNCTION OF CONTROL TYPE, TASK LOADING AND VIBRATION

T. G. Drennen
J. G. Curtin
H. D. Warner

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Prepared for:
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T. G. DRENNEN

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An investigation was conducted on the use of fingertip tracking controls which were integrated into an aircraft throttle grip under different levels of task loading and vibration. The experimental variables included two types of control (force and displacement), two levels of task loading (low and high) and four levels of vibration (static, moderate and heavy turbulence and broadband). The low task loading condition required the pilots only to track the displayed targets or to fly the simulated aircraft, while the high task loading condition →

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required simultaneous target tracking and aircraft attitude and airspeed control. The vibration were random vertical accelerations of 0.11 or 0.35 g_{rms} amplitude across the 0.1-20 Hz frequency range. The moderate turbulence condition was 0.11 g_{rms} in magnitude with a vibrational response which peaked at 0.2 Hz. The heavy turbulence condition was similar except it had a 0.35 g_{rms} intensity. The broadband spectra also had a 0.35 g_{rms} intensity but with equal response across the frequency range. In the evaluation 16 pilots performed the target tracking and aircraft control tasks in a motion base simulator. The dependent measures were pitch, roll and airspeed error for the aircraft control tasks and acquisition time and error, overshoots before acquisition, percent time on target and x-y tracking error for the target tracking tasks.

Of the 10 dependent variables, significant differences between the control types were obtained for only two measures; time-on-target and airspeed scores. The force control provided significantly better tracking performance than the displacement control as indicated by the percent time-on-target scores. Significantly lower airspeed errors were found when target tracking with the displacement control rather than the force control. The high task loading condition significantly decreased pilot performance in the target tracking and aircraft control tasks when compared to the low task loading conditions. The high amplitude (0.35 g_{rms}) vibration conditions (heavy turbulence and broadband) significantly impaired pilot performance, but did not interact with task loading or control type. Heavy and broadband vibration did not significantly differ in their effects on pilot performance. These findings suggest that: (1) very low frequency vibration (< 1.0 Hz) can significantly affect performance as a function of intensity level; (2) dissimilar vibration spectra may yield similar effects depending upon vibration intensity and human tolerance to the spectral frequency components; (3) no consistent overall performance differences were found to favor either control type; and (4) vibration did not interact with control type or task loading.

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1.0 SUMMARY

This study was conducted to evaluate fingertip target tracking controls integrated into aircraft throttles using a motion-base simulator. The effects of control type (force and displacement), vibration spectra (static, moderate turbulence, heavy turbulence, broadband) and task loading (low and high) on target tracking and aircraft control performance were assessed.

The force control (Measurement Systems Model 465) was similar to the target tracking control of the F-15 aircraft. The displacement control was a modified Ferranti tracking control to the AV-8A aircraft. The vibration spectra, except for the static condition, were random vertical accelerations of 0.11 or 0.35 g_{rms} amplitude across the 0.1 - 20 Hz frequency range. The moderate turbulence condition was 0.11 g_{rms} in magnitude with a vibrational response which peaked at 0.2 Hz. The heavy turbulence condition was similar to the moderate turbulence except it had a 0.35 g_{rms} intensity. The broadband spectra also had a 0.35 g_{rms} intensity but with equal response across the frequency range. The low task loading condition required the pilots only to track the displayed targets or to fly the simulated aircraft, while the high task loading condition required simultaneous target tracking and aircraft attitude and airspeed control.

Sixteen pilots, 14 of whom were currently rated in fighter aircraft, performed a simulated weapons delivery mission segment which required target tracking and aircraft attitude and airspeed control, depending on the task loading condition. The McDonnell Aircraft Company Motion Base Simulator (MBS) cockpit served as the simulated crew station and motion platform to induce selected vibration spectra through computer control. The subjects were instructed to follow a programmed flight path by maintaining a command attitude. The attitude commands and current conditions were displayed on an attitude director indicator (ADI), and control inputs were made using a conventional flight stick. Airspeed was displayed via an airspeed indicator and controlled through throttle manipulation. The target tracking task required the acquisition and tracking of a target on a separate CRT display employing the integrated tracking control located on the upper forward surface of the throttle quadrant.

One-half of the pilot subjects used the force control, and the other half used the displacement control for target tracking. Each subject was tested twice under each of the eight experimental conditions defined by four levels of vibration and two levels of task loading, for a total of sixteen experimental trials, per pilot, during one session.

The results of this study indicate that the force control provided better time-on-target scores than the displacement control, however, better airspeed scores were obtained when target tracking with displacement control. Therefore, no consistent performance differences were obtained which would suggest the overall preference of one control type. The high task loading condition significantly decreased pilot performance in the target tracking and aircraft control tasks when compared to the low task loading conditions. The high amplitude (0.35 g_{rms}) vibration conditions (heavy turbulence and broadband) significantly impaired pilot performance, but did not interact with task loading or control type. Heavy and broadband vibration did not significantly differ in their effects on pilot performance. These findings suggest that very low frequency vibration (< 1.0 Hz) can significantly affect performance as a function of intensity level.

2.0 INTRODUCTION

The reliable performance of manual control tasks is important to aircraft mission success, but quite often these tasks must be performed under adverse environmental stresses. Of the stresses encountered in such missions, vibration is one of the most common. Aircrew members can be subjected to low frequency vibration caused by the structural response of the aircraft to turbulence in flight. Considerable research has addressed the critical task of aircraft flight control under vibration, although there are additional, secondary control functions which affect the system's overall effectiveness. For example, present attack/fighter aircraft utilize manual target tracking controls to provide information to the navigation/weapons systems about the position of the aircraft, target, or identification point. Despite the high degree of system automation, performance of these manual tracking and acquisition tasks may be required in the event of subsystem failure, when operating in an electronic countermeasures environment, or when employing mission-specific strategies.

Most current aircraft use joystick control which are independent of the flight stick and throttles to provide these manual tracking capabilities. Newer aircraft designs, for example,the F-15 and F-18, make use of small tracking controls integrated into the throttles. These integrated control configurations are more desirable than the independently placed controls because of the periodic time-sharing between these tracking devices and the primary flight controls. Integrated tracking controls are particularly attractive for advanced fighter/attack aircraft due to limited crew size, increasing needs for console space, and anthropometric characteristics such as those associated with the reclined seat design of the high acceleration cockpit. These tracking controls will have additional advanced applications, such as employment for multimode switching devices, electro-optical sensor controls, and aircraft attitude/flightpath controls (Drennen, 1976). Effective utilization of these small, single-digit tracking controls in current and advanced aircraft will be dependent upon the selection of control type and dynamics which provide optimum performance for the appropriate tasks. Therefore, the performance characteristics of these tracking controls and their effects in operational environments need to be more clearly defined.

2.1 Statement of the Problem - While the generalized effects of vibration on manual control performance have been examined in some depth, their influence on tracking controls for attack/fighter aircraft mission situations is limited. The restricting factors are: (a) past studies have not examined the very low frequency, random vibration range, 0.1 to 3 Hz, nor the acceleration levels of 0.1 to over 0.7 g_{rms} typical of the vibratory conditions of attack/fighter aircraft missions; (b) previous investigations have not examined the effects of vibration on the integrated tracking controls; and (c) past studies have not examined vibration effects on operationally relevant, multiple task conditions. Therefore, the effects of vibration on integrated tracking control performance for attack/fighter aircraft under realistic task loading conditions have not been evaluated.

2.2 Literature Review - The effects of vibration on manual tracking performance have been investigated by a variety of researchers. The acceleration (g) and frequency (Hz) characteristics employed in these studies using sinusoidal and random z-axis vibration are illustrated in Figures 2-1 and 2-2. The acceleration values are described by the root-mean-square (rms) values in g's.

From these studies, it can be generally concluded that continuous exposure to vibration degrades operator performance. This impairment is related to both the frequency and acceleration components of the vibration environment. In terms of acceleration load factors (g's), there is generally a linear relationship between g force and control proficiency; that is, as acceleration level increases, performance efficiency deteriorates. As for the frequency component, the effects of vibration are generally limited to the lower frequency range, below 30 Hz, because above this level, any vibratory energy transmitted to the body is likely to be absorbed at the point of body contact with the oscillating surface, and therefore, will have little effect on the rest of the body. Within the 1-30 Hz envelope, the operator is most susceptible to vibration frequencies of 3-5 Hz due to the transmissibility and resonant characteristics of the body. These effects are graphically described in Figure 2-3. This graph from Brumaghim (1974) describes the frequency-intensity characteristics of performance decrement threshold for short-term (less than 4 minutes) vertical vibration exposure. The solid line curve is derived from MIL-STD-1472A; the dashed line is from the proposed MIL-F-9490D limitations. It is readily apparent that the main difference in these two curves is the inclusion of the 0.3-1.0 Hz region by MIL-F-9490D.

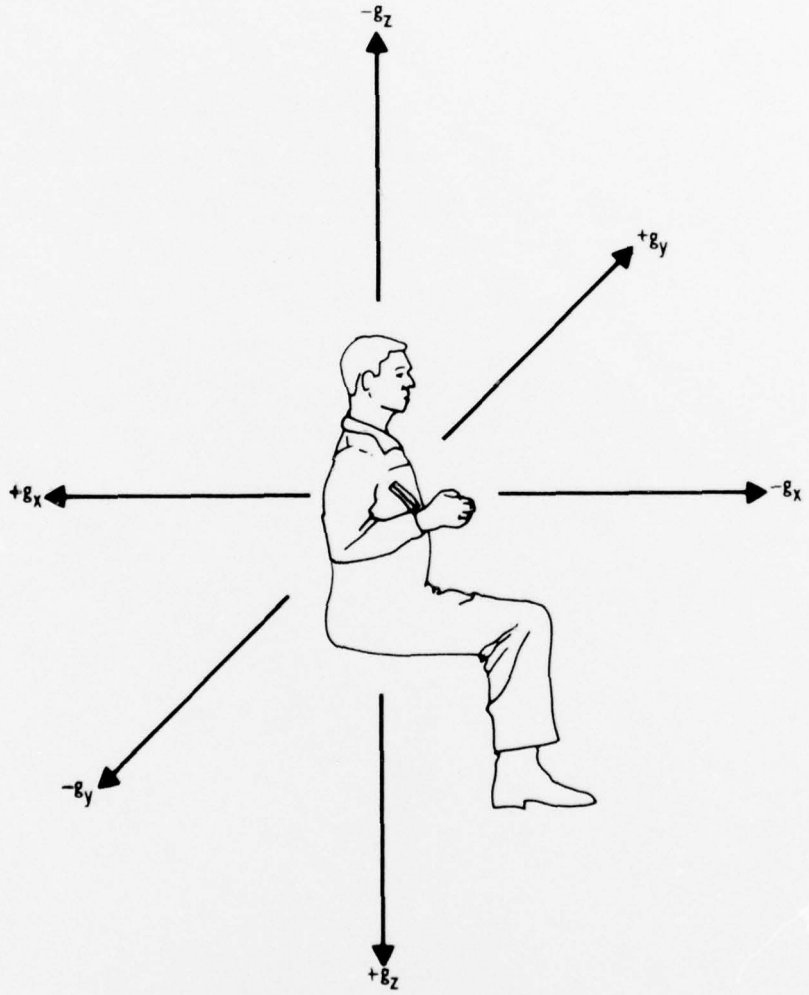


FIGURE 2-1 VIBRATION AXES

CONSTANT ACCELERATIONS-SINUSOIDAL (Z AXIS)

1 WEISZ, GODDARD & ALLEN (1965)
2 SHURMER & SILVERTHORN (1967)
3 BUCKOUT (1964)
4 PIRANIAN (1975)
5 SHOENBERGER & WILBURN (1973)
6 SHOENBERGER (1970)
7 CATTERSON, HOOVER & ASHE (1962)
8 HARRIS & SHOENBERGER (1966)
9 ALLEN, JEX & MAGDALENO (1973)
10 HORNICK (1962)
11 PARKS (1961)

RANDOM ACCELERATION-SINUSOIDAL (Z AXIS)

12 WEISZ, GODDARD & ALLEN (1965)
13 WEISZ, ALLEN & GODDARD (1966)
14 PARKS (1961)

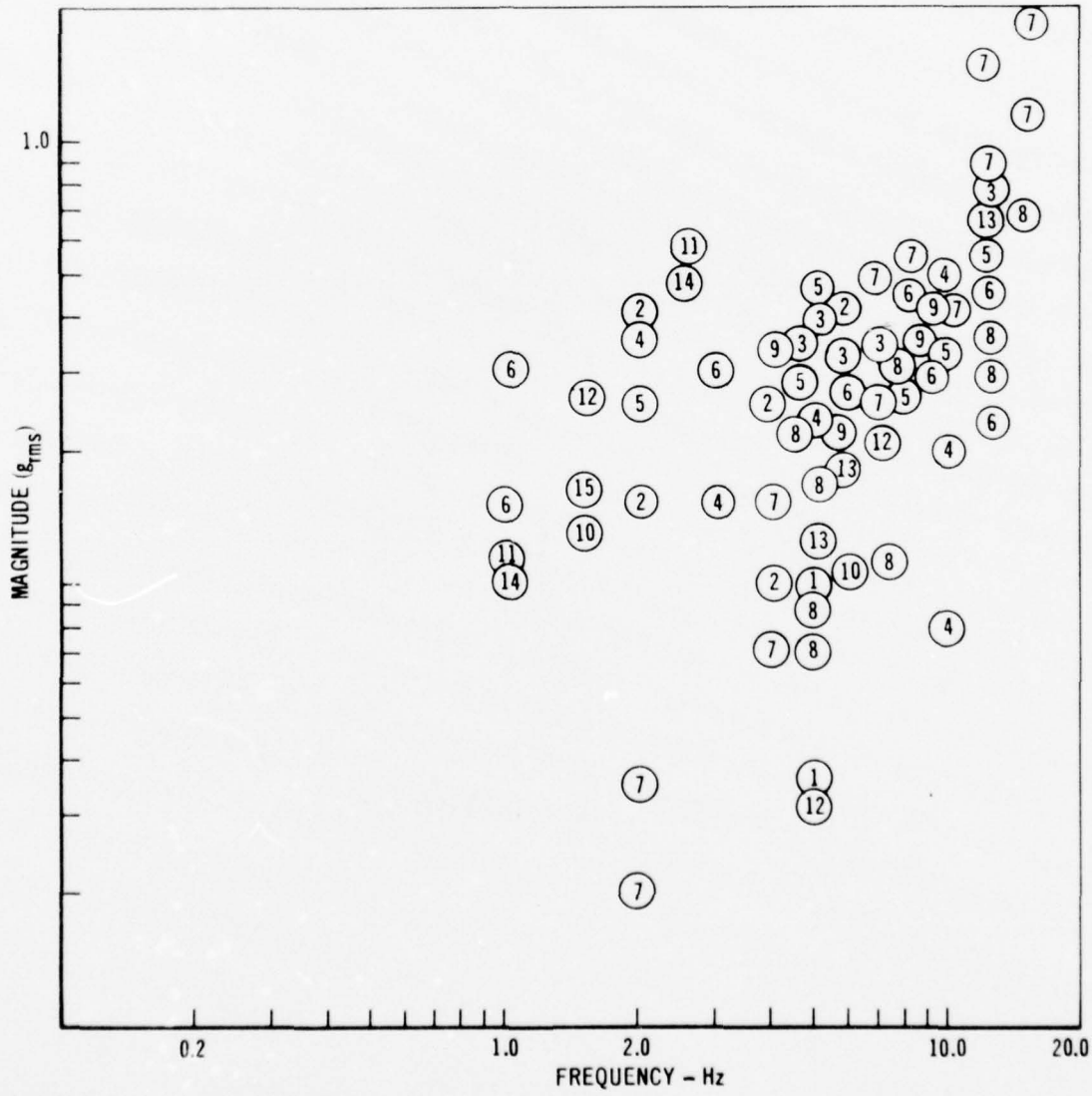


FIGURE 2–2 SINUSOIDAL VERTICAL VIBRATION STUDIES

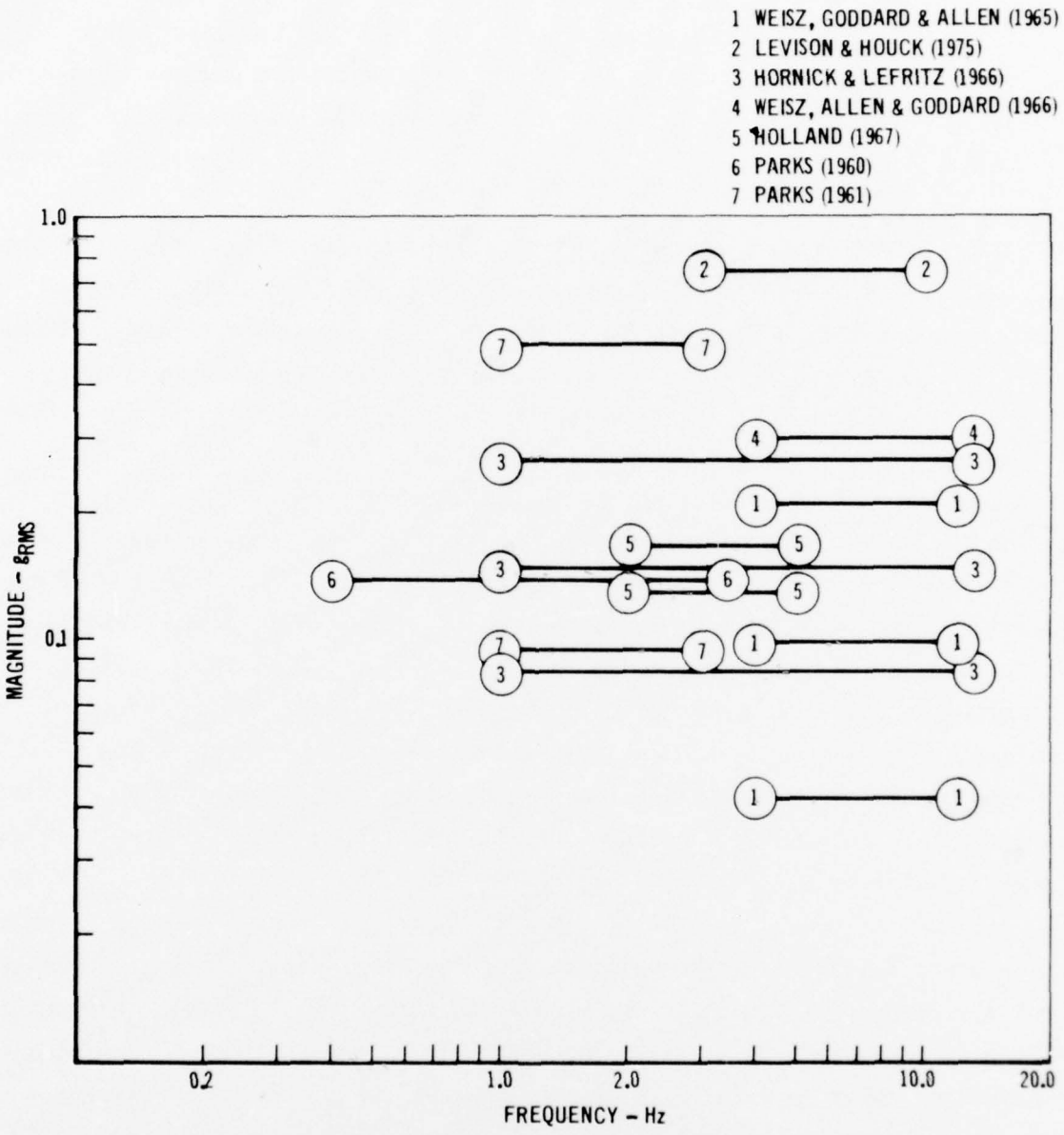


FIGURE 2-3 RANDOM VERTICAL VIBRATION STUDIES

It is this frequency range that predominates the random, vertical vibration characteristic of in-flight turbulence for fighter/attack aircraft. As shown in the power spectral density (PSD) curve for in-flight vibration spectra in Figure 2-4, the largest vibration components are in this very low frequency range. [The PSD curve indicates the power at the discrete frequencies for a given bandwidth while the rms value indicates the total energy across the frequency band (Hornick, 1967, Meeder, 1964)].

The MIL-F-9490D curve suggests this very low frequency range may be as critical as the 3-5 Hz region since in both areas relatively low intensity values can induce performance decrements. This proposed limitations curve, however, was derived from a similar curve developed by Rustenburg (1971) which extrapolated the function into the 0.3-1.0 Hz region due to the paucity of performance effects data available for this frequency range. These data are not available because of the difficulties experienced in generating this type of vibration with any appreciable intensity (Rustenburg 1971; Jex and Allen, 1974). Such vibrational spectra require a motion system which can provide fast, large amplitude crew station movement beyond the capability of most simulators. While performance data are quite limited, some research has been conducted to determine subjective estimates of discomfort and motion sickness for very low frequency vibration. Typically in these evaluations, sinusoidal motion was used. An excellent review of these activities along with proposed human exposure limits are found in McCauley and Kennedy (1976). This paper also points out the need to determine the effects of such motion on tracking and other psychomotor tasks.

The direction of vibration has been found to be an important factor (Figure 2-5). Lateral vibration (g_y) generally has been found to be less tolerable than vertical vibration (g_z) (Rustenberg, 1971). Threshold differences between g_y and g_z vibration have been reported with a factor of $\sqrt{2}$, and subject comfort limits for g_y and g_z vary by a factor of 1.4 to 2.0 in intensity. Rustenburg also has indicated that tracking performance tolerance limits for g_y and g_z vibration differ by a factor of about 2.4.

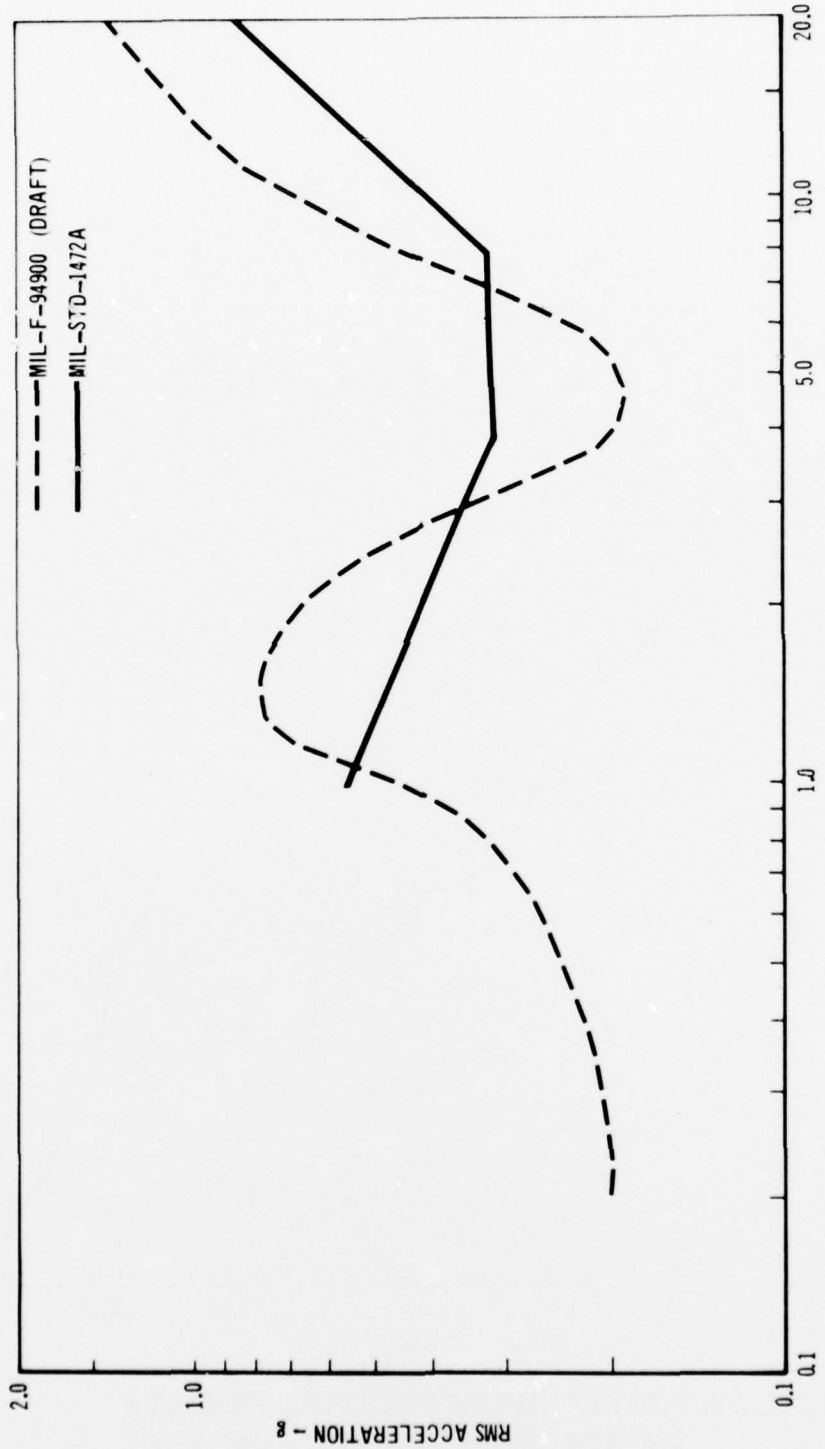


FIGURE 2-4 PERFORMANCE DECREMENT THRESHOLD CURVES FOR Gz
SHORT TERM VIBRATION (ADAPTED FROM BRAMAGHIM, 1974)

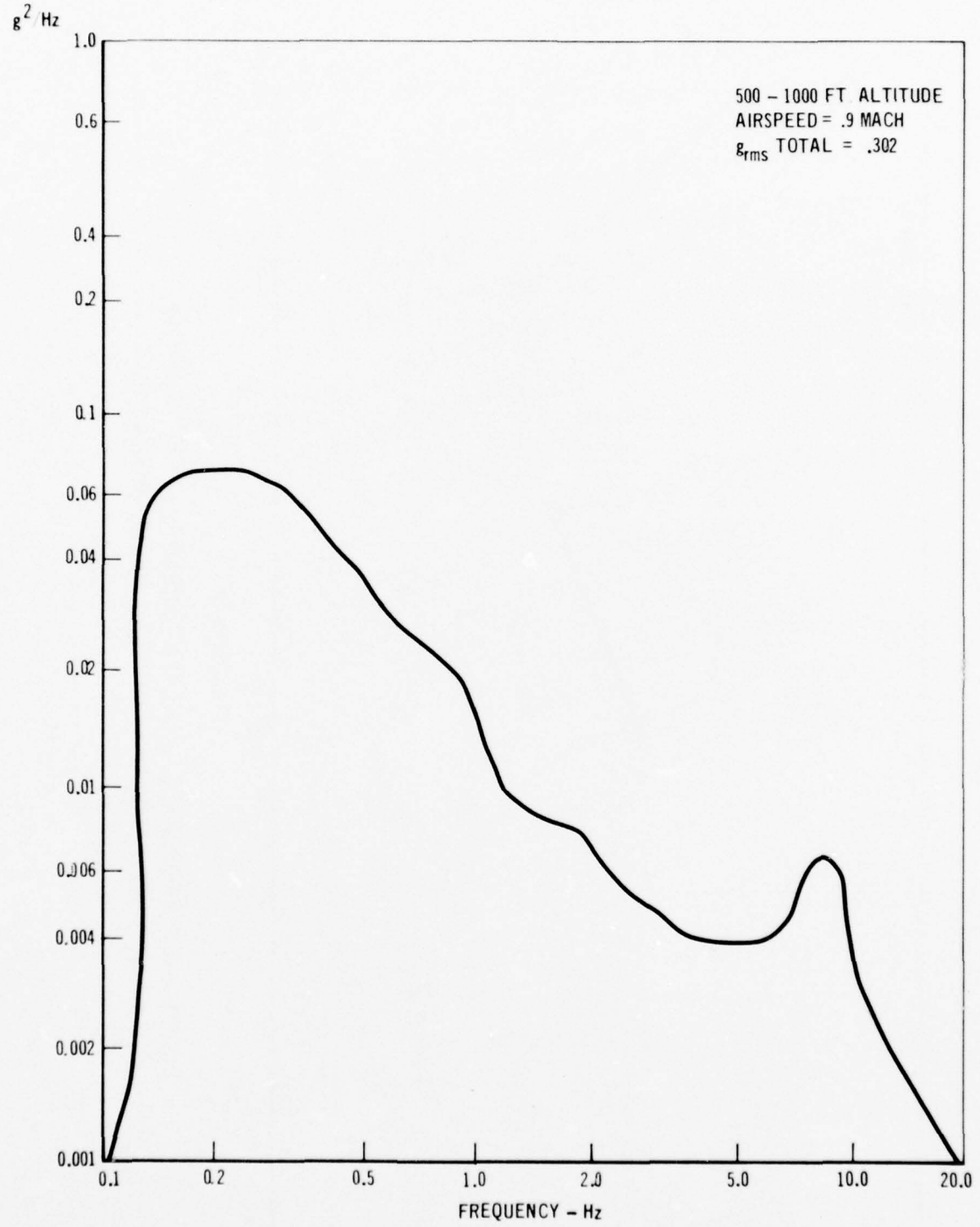


FIGURE 2–5 FIGHTER AIRCRAFT VERTICAL VIBRATION SPECTRA (ADAPTED FROM SCHERZ, 1973)

While humans are apparently more sensitive to g_y than g_z vibration, lateral motion may not be as critical as vertical motion in the manipulation of integrated tracking controls because of the relatively lower g_y intensity levels during mission segments when these controls are typically utilized. The lateral gust sensitivities of fighter/attack aircraft are generally much smaller than the vertical gust intensities for other than low altitude missions (< 2500 ft.). The lateral accelerations would be four to five times less than the vertical accelerations due to turbulence. For example, a current fighter aircraft flying at 10,000 feet at 0.9 Mach has vertical and lateral gust sensitivities of about 0.0213 and 0.0046 g_{rms}/ft/sec. With expected rms gust intensities of 5 ft/sec for clear air turbulence at 10,000 ft, the resultant vibration levels would be 0.11 and 0.02 g_{rms} (Chalk et al, 1969). While lateral vibration does not seem to be as critical as vertical vibration in this situation, it is still an important and influential factor when combined with the effect of vertical vibration (Rustenburg, 1971).

One design consideration suggested as a means of reducing biomechanical interference under conditions of vibration is to use a force control device in favor of a displacement control (Frost, 1972). Presumably, a force control is less susceptible to inadvertent control inputs because it provides resistance to the vibratory energy transmitted through the controlling body member. There are other factors favoring the force control, such as reduced size and weight, higher reliability due to no moving parts, and typically lower cost (Fox, 1968; Mehr, 1972). Therefore, in the event of equivalent operator performance with force and displacement controls, force controls would be preferred. Past research has not consistantly supported the contention of force control superiority. Conflicting results have been reported throughout the literature under static, vibration, and flight test conditions as indicated in Table 2-1 through 2-3. The differences in these studies may be due to the wide variation in the experimental conditions, e.g., control characteristics, control dynamics, vibration spectra, tracking task, and subject training (Poulton, 1974).

Few of these studies examined small, integrated tracking controls, or other controls of a comparable design and function, for example, where the control has up-down, left-right movement instead of the typical fore-aft, left-right movement. Previous studies of force and displacement integrated tracking controls have been limited to fixed-base simulator investigations and generally have found no

TABLE 2-1 FORCE/DISPLACEMENT CONTROLS STUDIES - STATIC

SOURCE	CONTROL TYPES	TRACKING TASK	RESULTS
Gibbs, 1951	o Free moving finger Joystick o "Force" finger Joystick (strong spring loading)	2 axis compensatory tracking with rate control dynamics.	"Force" control was better for discrete and continuous movement with faster learning.
Gibbs & Baker, 1957	o Free moving finger Joystick o Force finger Joystick (strong springloading)	2 axis compensatory tracking with rate control dynamics with various gains.	"Force" control yielded best tracking performance under all conditions.
Weiss, 1954	o Aircraft flight stick - 0-30 lbs force - 0-30° displacement	Single axis, "blind positioning" task.	Displacement cues more important than pressure cues.
Weiss, 1955	o Aircraft flight stick - 0-30 lbs force - 0.6° displacement	Single axis "blind positioning" task.	Pressure variation had no effect.
Bahrick, Bennett & Fitts (1955)	o Single axis (horizontal) joystick. - Variable torque	One axis, horizontal positioning task.	Positioning errors were lowest for the high torque condition.
Bahrick, Fitts & Schneider, 1955	Center joystick with variable mass, damping and spring loading.	Reproduction of circular and triangular motions.	Increased mass and damping improved accuracy and uniform velocity of movements.
Faber, 1955	Wheel type aircraft flight yoke with variable force-displacement gradients.	One axis compensatory tracking with heavily damped aircraft dynamics.	Tracking accuracy increased as displacement decreased to almost zero. Improved tracking also was found as force decreased.
Briggs, Fitts & Bahrick, 1957	Aircraft flight stick with variable spring-loading and gains.	2 axis compensatory tracking with aircraft control dynamics.	Force and displacement cues interact with tracking performance with displacement cues slightly more important. As $\frac{\Delta F}{F \Delta D}$ increases for a given displacement, positioning accuracy increases.
Faber, 1958	Wheel type aircraft flight stick with variable force displacement gradients.	One axis compensatory tracking with lightly and heavily damped (fighter and transport aircraft dynamics.	For a lightly damped aircraft, moderate forces and displacements are desirable. For a heavily damped aircraft, low stick displacements (nearly non-moving) and low force gradients are desired. Viscous damping and friction were undesirable.
North and Lomnicki, 1961	o Lightly spring-loaded hand joystick o Force hand joystick	One axis compensatory tracking with rate control dynamics and 10 gains.	Force control yielded better tracking performance.
Notterman & Page, 1962	o Pure force and displacement joysticks with electronically variable mass, spring and damping. o Displacement joystick with mechanically variable mass, spring and damping.	One axis compensatory tracking.	"Pure" force control yielded superior overall performance but force plus displacement control was best when controls were "mathematically equilavent."
Abbott, 1962	o Wheel type aircraft flight stick with variable force gradients.	One axis (pitch or lateral) sine wave tracking (pursuit) with position control dynamics.	As target frequency increased, tracking error increased for the "heavier" controls.
Knoop, 1964	o Viscous damped joystick o Force joystick	Two axis compensatory tracking.	Force control is superior in: speed of response, cross-coupling, linearity, resistance to vibration and minimum energy.
Burke & Gibbs, 1965	o Free moving displacement joystick o "Pressure" joystick with variable force/displacement ratios.	One axis (internal) pursuit tracking with position control dynamics.	o No differences in force/displacement ratios. o Pressure joystick (spring-loaded) yielded better tracking scores than the free moving joystick.

TABLE 2-1 FORCE/DISPLACEMENT CONTROLS STUDIES - STATIC (Continued)

SOURCE	CONTROL TYPES	TRACKING TASK	RESULTS
Fox, 1968	o Track ball o Finger force joystick o Thumb force control	Two axis target designation (pursuit) with position control dynamics.	No performance differences between controls.
Ziegler & Chernikoff, 1968	o Spring-loaded joystick o Force joystick o On-off "bang bang" control	One axis, compensatory tracking with "jerk" (third order) control dynamics.	Tracking errors were lowest for the force control and highest for the on-off control
Herzog, 1970	o Joystick with electrically variable spring constant, mass, damping and displacement characteristics	One axis compensatory tracking with various control dynamics.	Tracking performance was best when both force and displacement cues
Cole, 1970	o Side and center mounted spring-loaded aircraft flight stick o Side and center mounted force control	Two axis, compensatory tracking task with aircraft control dynamics.	Force control configuration was superior in performance and pilot ratings. Little differences were found between placements for force control. Side displacement control was worst.
Faubert, 1971	o Displacement hand joystick o Thumb force control	Two axis, compensatory tracking with variable rate dynamics (simulated weapons delivery).	Force control yielded best tracking error.
Mehr & Mehr, 1972	o Displacement finger joystick o Spring-loaded finger joystick o Thumb force control o Finger force control o Track ball	Two axis positioning task (pursuit) with position control dynamics for non-spring-loaded joystick and track ball and rate control dynamics for the others.	With optimized dynamics, the acquisition time performance order was (from best to worst) - Trackball, finger force control, thumb force control, spring-loaded joystick then the displacement joystick.
Curtin, Emery & Drennen, 1973*	o Throttle-integrated fingertip force control o Throttle integrated, finger tip on-off control o Force finger control independently mounted o Spring-loaded finger joystick independently mounted	Two axis pursuit tracking with rate control dynamics, aircraft attitude and airspeed control also were required.	The integrated placement was best with little differences between force and displacement controls.
McGuinness, Drennen & Curtin, 1974*	o Throttle integrated, fingertip force control o Throttle integrated fingertip spring-loaded control	Two axis pursuit tracking with rate control dynamics. Aircraft attitude control was also required.	Force control with "step" output appeared to be best combination, but no overall differences between force and displacement controls.
Warner, Drennen & Curtin, 1976*	o Throttle integrated, fingertip force control o Throttle integrated fingertip spring-loaded control	Two axis pursuit tracking with rate control dynamics, aircraft attitude and airspeed control also were required.	No performance differences between control types. A modified technique to calculate off-axis movement for nonlinear control-display function, was found to be better than a conventional technique.

* See Section 7.0 - Program Overview

TABLE 2-2 - FORCE/DISPLACEMENT CONTROLS STUDIES - VIBRATION

SOURCE	CONTROL TYPES	TRACKING TASK	VIBRATION CHARACTERISTICS	RESULTS
Weisz, Allen & Goddard, (1966)	o Free moving side joystick o Viscous damped side joystick o Force side joystick	2 axis, compensatory tracking with position control dynamics.	o 5 Hz random amplitude Z axis (.248 g_{rms}) o Random frequency (4-12 Hz)(.248g_{rms}) o Static	Force control yielded best tracking under static and vibration conditions. Viscous damped joystick slightly better than free moving joystick.
Rosenberg & Segal (1966)	o Rolling ball control o Spring-loaded side joystick o Force side joystick	Simulated helicopter weapons delivery. o 2 axis, compensatory o Stabilized and unstabilized sight o Position control dynamics with lead-lag network	o Static o Sine gz 5-120 Hz o .15 g_{rms}	The force control generally was superior to the other controls. The spring-loaded joystick was better than the force control only when both used pure position control dynamics and under low frequency vibration.
Shurmer (1967) (U)	o Spring-loaded side joystick o Force side joystick	2 axis, compensatory trading with rate control dynamics	o Static o Random gz	Force control better for static condition but no differences in vibration environment.
Shurmer & Silverthorn (1967)	o Spring loaded side joystick o Force side joystick	2 axis compensatory tracking with position control dynamics.	o Sine gz & gy o 2 Hz (.176&.353 g_{rms}) o 4 Hz (.127&.254 g_{rms}) o Roll - sine 2&4 Hz (.25-3° peak)	The displacement control gave superior performance under all conditions.
Price, 1970	o Leg mounted finger displacement joystick (spring-loaded) o Thumb force control on hand-held grip.	2 axis compensatory tracking with rate control dynamics and lead-lag characteristics.	o Static o Random Gz o Simulated light plane response to .5 to 3 ft/sec gusts.	The force control yielded superior performance under gust conditions when lead-lag dynamics were used.
Allen, Jex & Magdaleno (1973)	o Lightly spring-loaded control A/C joystick o Force center A/C joystick	One axis (pitch or roll) compensatory tracking with rate and aircraft control dynamics.	o Static o Separate sine - gx - gy - gz 1.3-10 Hz (.282 g_{rms})	The force control generally showed the most high-frequency vibration feed through and the displacement control had the most low-frequency vibration feed through. Tracking errors for the force control were lower than the displacement control.
Magdaleno, Allen & Sex (1974)	o Lightly spring-loaded center A/C joystick o Force center A/C joystick	One axis (pitch) compensatory tracking with aircraft control dynamics.	o Static o Sine gz o 2,3.3,5,7&10 Hz o .28 g_{rms}	The force control tracking errors better than displacement control. Tracking errors for force control increased only at the higher frequencies (7-10 Hz) and the displacement control scores increased over all frequencies.
Levison & Houck (1975)	o Center & side spring-loaded A/C joystick with 3 spring gradients. o Center & side force A/C joystick with 3 "stiffnesses" (gains)	Single axis (pitch) compensatory task with aircraft control dynamics	o Static o Sum of sines gz o 2,3,5,7&10 Hz o .26 g_{rms}	Force control error scores were slightly better than for displacement control. The force control was more affected by vibration. Greater percentage increase in tracking error from static condition and increased control activity than the displacement control. Stick location differences were not significant.
Lewis & Griffith (1976)	o Side joystick with three stiffnesses	Two axis compensatory task.	o Static o Sum of sines gz o 3,5&8 Hz o .044, .088 & .176 g_{rms}	Tracking error scores and "channel capacity" values were better for the "stiffer" controls as vibration increased.

TABLE 2-3 - FORCE/DISPLACEMENT CONTROLS STUDIES - CENTRIFUGE & FLIGHT TEST

SOURCE	CONTROL TYPES	TRACKING TASK	RESULTS
Russell & Alford, 1959	o Conventional aircraft flight stick o Force center mounted aircraft flight stick	In-flight evaluation with pullup, roll, stall approach, landing, and rough air flying maneuvers.	The pilots opinions considered the force control unsuitable. The lack of displacement was not felt to be objectionable, but some displacement was desirable.
Graves, Bailey & Mellon, 1962	o Spring-loaded side hand control o Force side hand control	o Fixed base cockpit study o Centrifuge study* o Flight test study - JF-101A aircraft	The force control was preferred during the ground simulator studies but the displacement control was preferred during the flight tests.
*Chambers, 1961	o 2 3 axis hand displacement controls o A 2 axis hand displacement control o 2 axis finger displacement control o 2 axis hand force control o 2 axis finger force control Foot pedals for yaw control with Z axis controls	3 axis compensatory tracking with X-15 aircraft dynamics under various constant g conditions	Finger operated controls yielded superior performance. No direct comparisons were made between displacement and force controls, however, performance with force controls was not significantly affected by g environment.
Corey, 1977	o Isometric sidestick control o Base pivot displacement side stick control o Palm pivot displacement side stick control o Palm/base pivot displacement side stick control o Palm pivot side stick control internal feel	Flight test in variable stability NT-33 with simulated F-15 dynamics. The flight test maneuvers included: o Takeoff and landings o Air-to-air tracking o Constant g turns o Max rate rolls o Straight & level flight o ILS approaches	Based mainly on subjective ratings, the controls were rated from best to worst: o Base pivot side stick with non-linear lateral feel o Base pivot side stick o Palm pivot side stick o Palm base pivot side stick o Isometric side stick

significant performance differences between control types (Curtin, Emery and Drennen, 1973; McGuinness, Drennen and Curtin, 1974; and Warner, Drennen and Curtin, 1976). A detailed review of these studies is provided in Section 7.0 - PROGRAM OVERVIEW. These earlier, integrated control studies illustrate the utility of multitask conditions. Most vibration/control studies have examined performance on a single task, usually compensatory tracking, while operational situations require multitask performance of the attack/fighter pilot. Not only does the multitask performance better represent realistic task loading conditions, but it also provides improved discrimination between performance effects for varying control characteristics (Warner, et al, 1976).

It is readily apparent that the following issues have not been satisfactorily resolved in previous investigations:

- o What type of integrated tracking control is best suited for an operational, multitask application?
- o What are the effects of very low frequency, random vibration on tracking control performance for high as well as low task load conditions?

2.3 Purpose and Scope - The purpose of this study was to determine the effects of Z-axis, random vibration on integrated tracking performance and its interactions with the effects of control type and task loading. The scope of this study included the following characteristics:

Independent Variables:

- o Type of control (force and displacement)
- o Type of g_z spectra (static, moderate and heavy turbulence and broadband)
- o Task loading (low and high workload).

Dependent Variables:

- o Flight control task performance
  - Pitch error
  - Roll error
  - Airspeed error

- Target tracking task performance
  - Acquisition error and time
  - Times on target
  - X and Y tracking error
  - Overshoots.

3.0 EXPERIMENTAL METHOD

3.1 Subjects - Sixteen pilots participated in the study. Each had a minimum of 1000 hours of flying experience, most of which were in fighter aircraft. The group was comprised of seven McDonnell Douglas Corporation (MDC) test pilots, five Air National Guard pilots, two pilots from the Air Force Plant Representative Office at the MDC St. Louis facility, and two MDC commercial jet pilots. All subjects held at least a current FAA Class II flight physical rating with the average flight experience of the subject group being 3900 hours.

3.2 Apparatus - The experimental apparatus consisted of the McDonnell Douglas Aircraft Company (MCAIR) motion base simulator (MBS) (Figure 3-1). The cockpit is mounted on the end of a 20-foot movable boom which has two rotational degrees of freedom, and the cockpit has three rotational motions obtained by rotating the boom about hydraulically actuated gimbals permitting two translational degrees-of-freedom. Acceleration, deceleration, oscillation, and buffet characteristics of an aircraft may be translated into one or more of these degrees of freedom. The MBS met all related safety standards. It was subject to continual safety/calibration checks and to daily preflight checkouts prior to pilot occupancy. The man-rated capabilities of the MBS are described in Table 3-1.

The open-loop vibration of the crew station together with the control/display interface and data collection were controlled by a CDC 6600 computer and related hardware. The software for the control/display interface was similar to the system used in the static, part-task simulation system in previous investigations (Section 7.0, PROGRAM OVERVIEW).

The functional displays for the simulated crew station (Figure 3-2) were a TV monitor, which displayed an attitude director indicator (ADI) (Model No. ARU-11A) used as the source of aircraft attitude and command information (Figure 3-3), an airspeed indicator (Figure 3-4), and a Textronix 604 oscilloscope to provide simulated weapons delivery information in the form of target and cursor symbology (Figure 3-5). An additional indicator light for signaling the beginning and end of trial and appearance of a new target was located below the target tracking CRT.

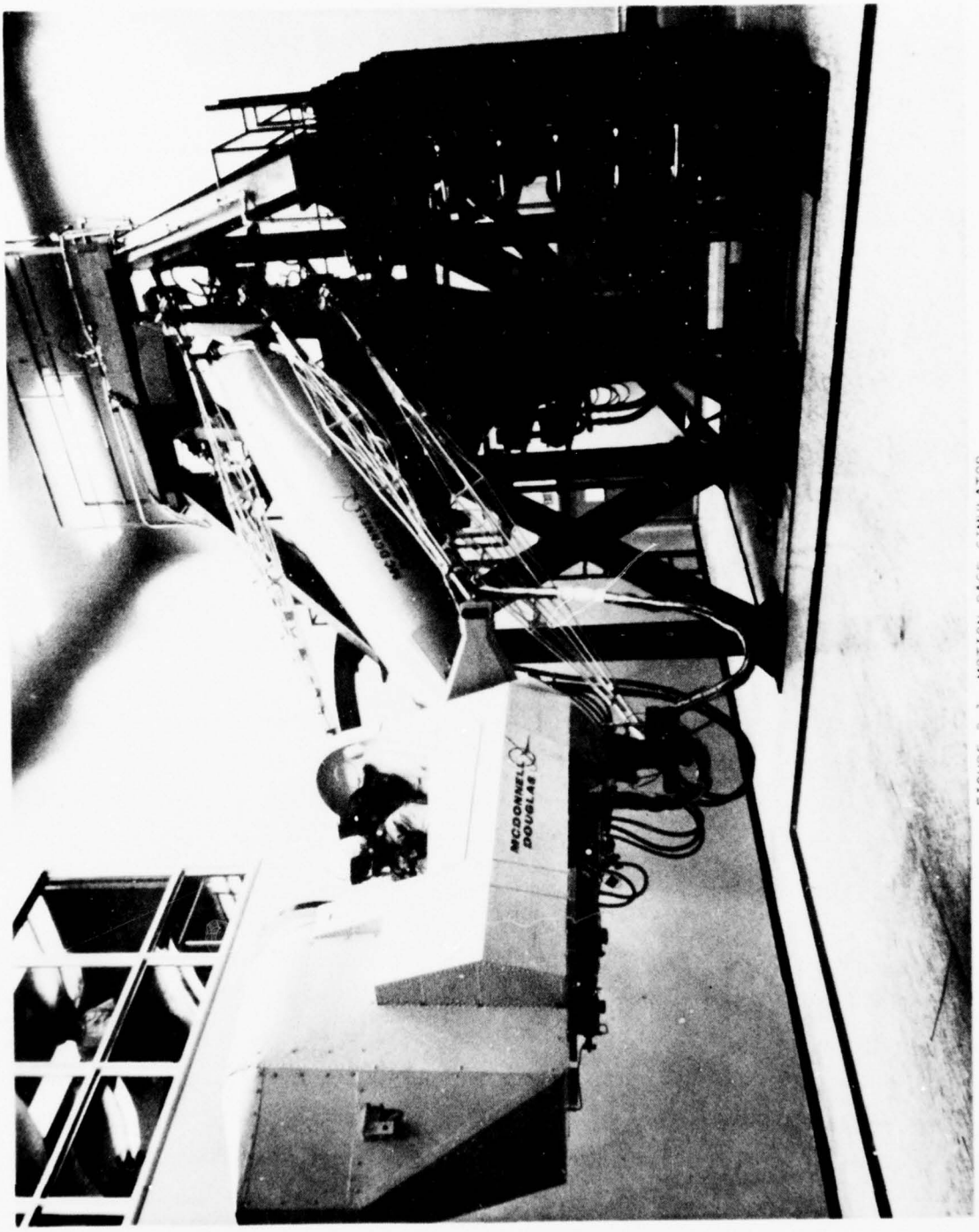


FIGURE 3-1 MOTION BASE SIMULATOR

TABLE 3-1 MAN-RATED MBS CAPABILITIES

AXIS	DISPLACEMENT	VELOCITY	ACCELERATION
Vertical	±8 ft	±8 ft/sec	+3, -1 G
Lateral	±4 ft	±6.5 ft/sec	±1 G
Roll	30°	105°/sec	300°/sec^2
Pitch	30°	30°/sec	300°/sec^2
Yaw	30°	30°/sec	240°/sec^2

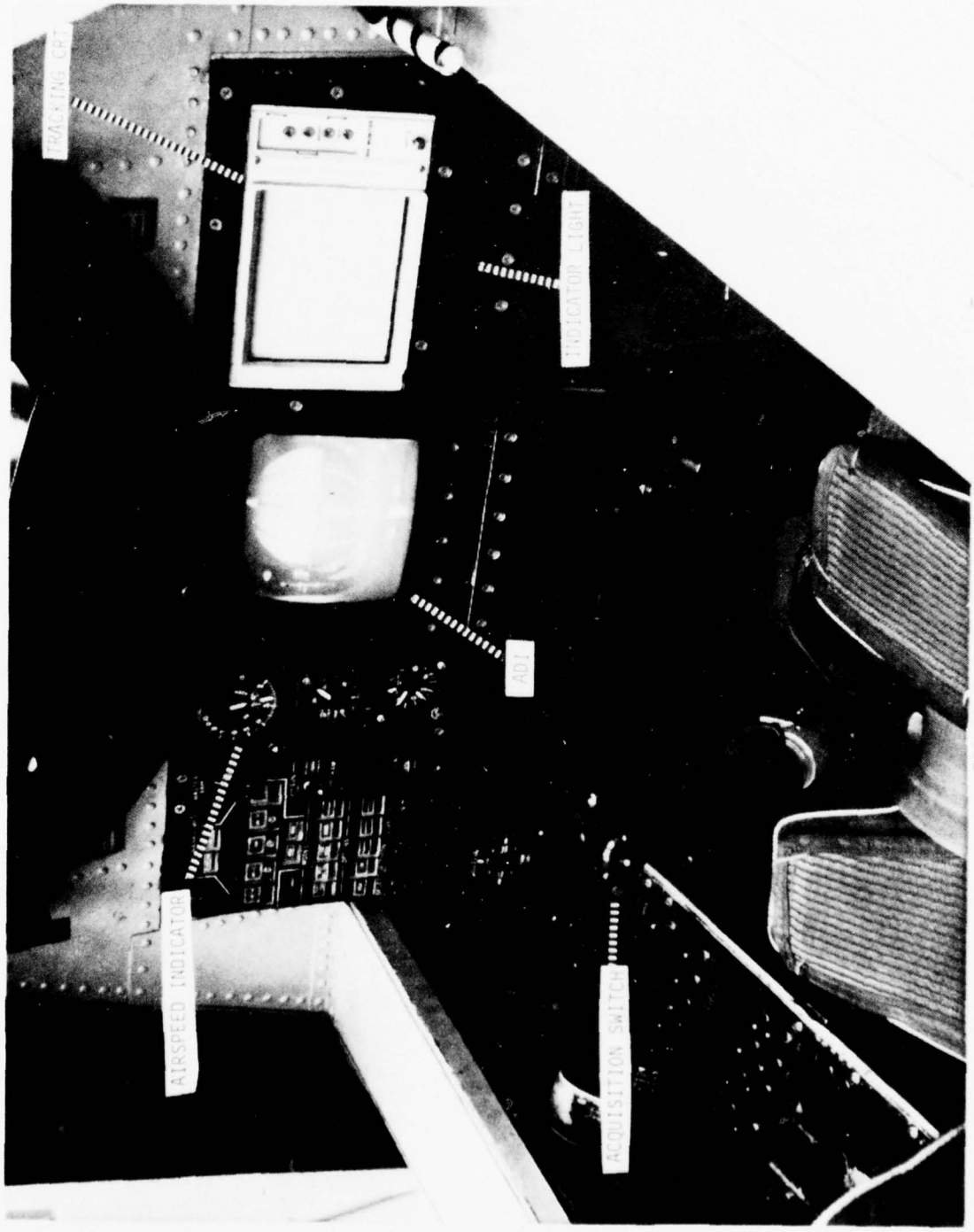


FIGURE 3-2 M&S CREW STATION

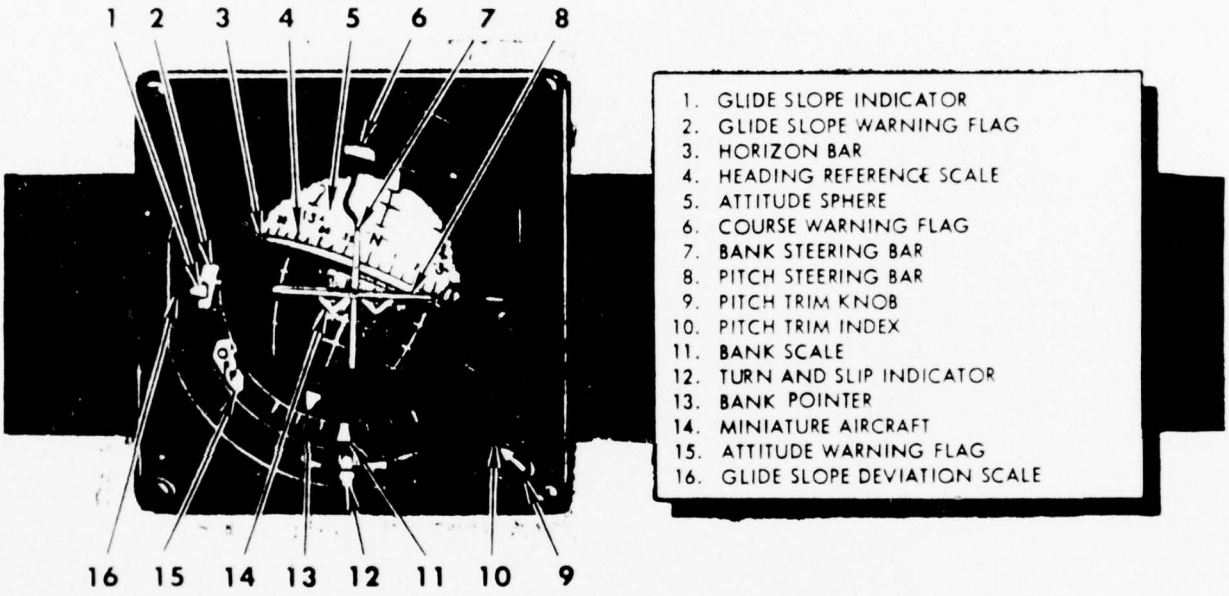


FIGURE 3-3 ATTITUDE DIRECTOR INDICATOR (ADI)

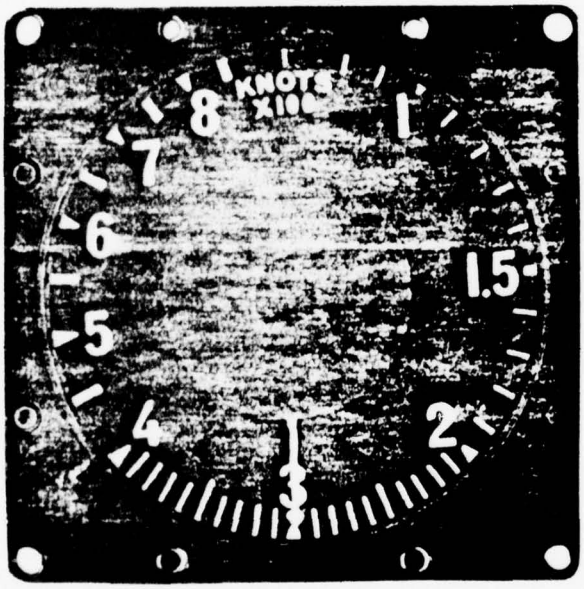
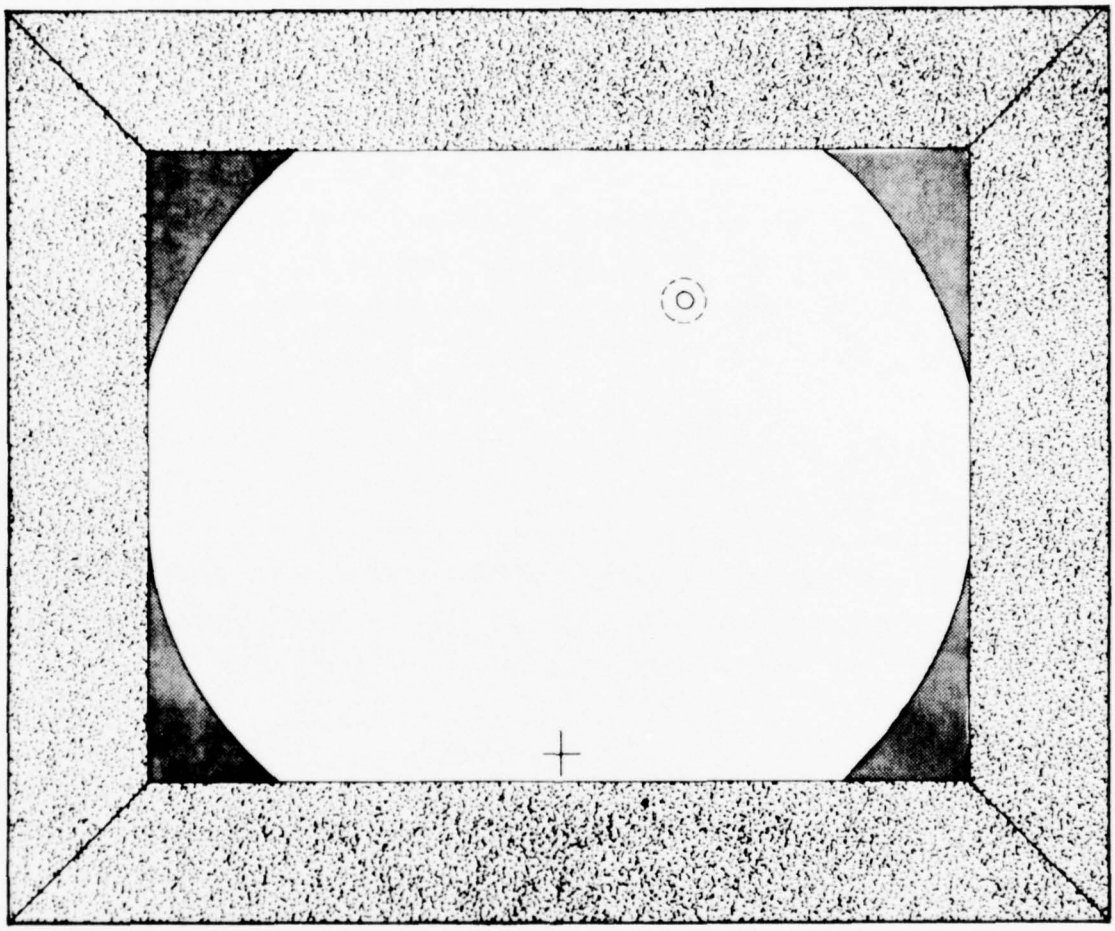


FIGURE 3-4 AIRSPEED INDICATOR



+ = CURSOR 0.187 INCH x 0.187 INCH

○ = TARGET 0.094 INCH DIA.

◌ = TARGET "WINDOW" 0.25 INCH DIA
(FOR ILLUSTRATION ONLY – NOT DISPLAYED TO SC)

FIGURE 3-5 SIMULATED TARGET AND CURSOR SYMBOLOGY

The functional controls were a flight control stick, configured with representative stick forces for aircraft attitude control, an acquisition switch on the flight stick, throttles for airspeed control, and finger operated tracking controls integrated into the throttle quadrant for the performance of the target acquisition and tracking tasks. The simulated aircraft dynamics were representative of attack aircraft class and were similar to the dynamics used with the static, part-task simulator for the previous studies (Ref. Section 7.0).

An F-111A aircrew seat and restraint system was used in the MBS (Figure 3-6). During all experimental sessions, the restraint harness was locked, and the subjects wore protective helmets. The helmets contained a head set and microphones for the MBS intercom system.

The test operator directed the experimental session, controlled the presentation of the experimental conditions, and monitored the pilot's performance from the MBS control room. The MBS control room contained a computer control teletype terminal through which the experimental conditions were selected, the MBS control panel which provided direct control of the MBS motion system, and strip chart recorders and repeater instruments to monitor pilot performance.

3.3 Experimental Variables - Three experimental variables were examined in this investigation. These variables, and the levels of each, are described in the following subsections.

3.3.1 Control Types - Two finger-operated target tracking control devices were tested, a force control and a displacement control. The force control was a Measurement Systems Model 465. The displacement control was a modified Ferranti miniature spring-loaded joystick adapted from an AV-8A Harrier hand control. The controls were integrated into separate throttles as shown in Figure 3-7. The control inputs required for control breakout, as well as the maximum effective control inputs, are identified for the two controls in Table 3-2. The controls, input characteristics, and throttles were the same as those employed in two previous investigations (McGuinness, et al, 1974; Warner, et al, 1976)

FIGURE 3-6 MBS SEAT/RESTRAINT SYSTEM

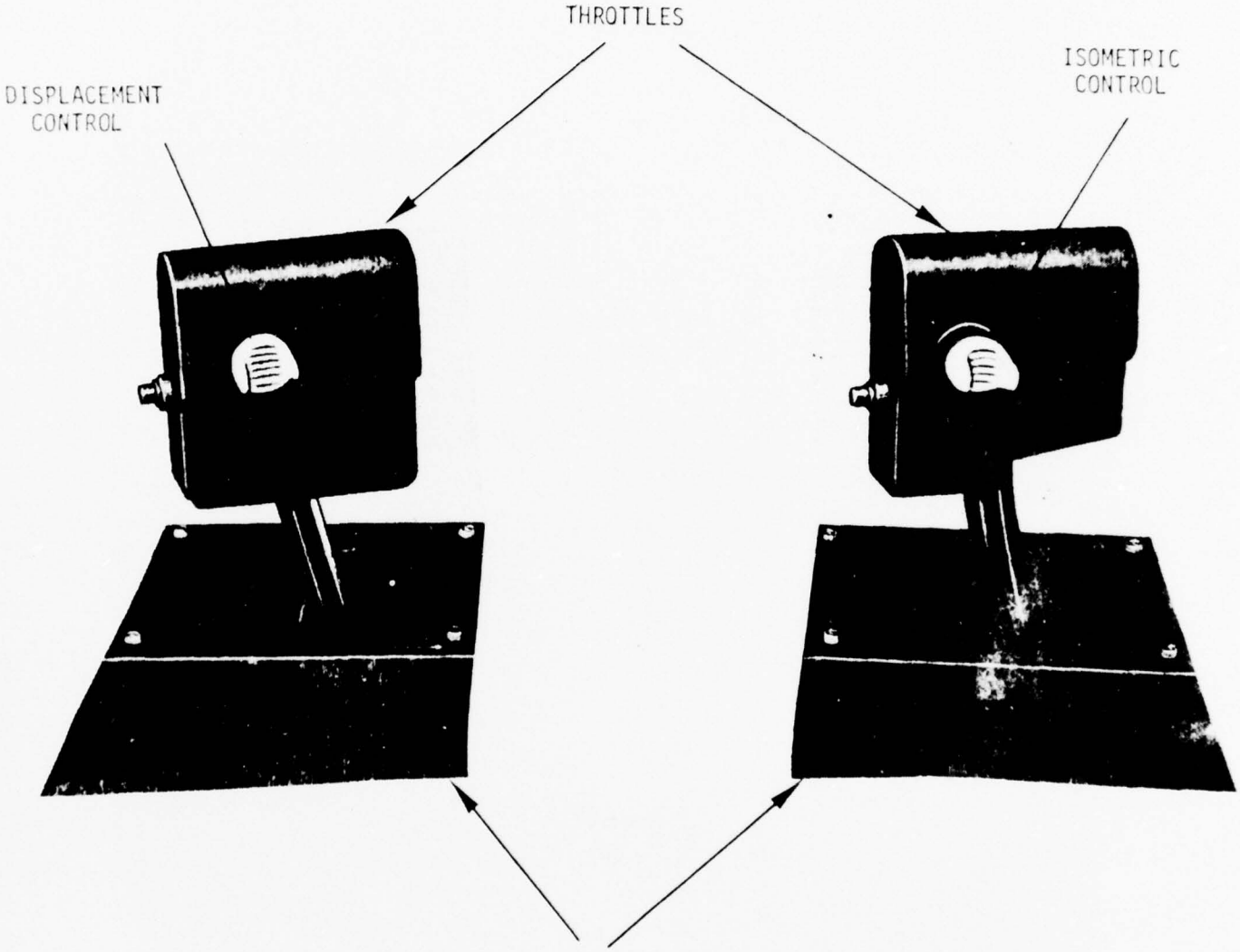


FIGURE 3-7 INTEGRATED TRACKING CONTROLS

TABLE 3-2. CONTROL INPUT CHARACTERISTICS

Control Type	Control Breakout	Maximum Effective Control Input
Force	3.5 oz.	48 oz. (0.08" Displacement)
Displacement	(Approximately 1 oz.)	(Approximately 2.5 oz. Force)

Control inputs determined the X-Y position of the cursor on the two-dimensional target tracking CRT. Both control devices were first-order rate controls. That is, the rate of cursor movement was proportional to the magnitude of the control inputs. The gain or sensitivity of the controls for the corresponding units of control input (force in ounces and displacement in degrees) is depicted in Figure 3-8. The gain function was exponentially shaped, similar to the target designation control (TDC) gain employed in the F-15 aircraft and proposed for the F-18 fighter aircraft. The modified technique for off-axis cursor position calculation, which was examined by Warner, et al, (1976), was used instead of the conventional technique. The modified technique measures both X- and Y-axes inputs and determines a resultant cursor movement. This technique provides the same control-display relationship as shown in Figure 3-8 for any direction. The conventional technique, used in the F-15 and A-7, measures and applies the nonlinear function separately for the X- and Y-axes which results in slower off-axis cursor movements for a given input magnitude.

3.3.2 Vibration Conditions - Three vibration conditions and a static condition were tested. All vibrations were random and occurred only in the Z-axis, vertical direction. The frequency range for each condition was 0.1 to 20 Hz. The plots of PSD, g^2/Hz versus frequency in Figure 3-9 illustrate the power distribution of the three vibration environments. Power spectral density (PSD) defines the power at discrete frequencies in the frequency band with the magnitude being expressed as g^2/Hz. Strip chart recordings of the displacement and accelerometer signals for these profiles are included in Appendix A. Figures 3-9A, B, and C indicate that the predominant energy was at 0.3 Hz for PSD A and PSD B, whereas the energy was fairly evenly distributed over the frequency range for PSD C. PSD A and B were shaped to correspond to the vibration environment of fighter/attack aircraft. The shapes of these power spectra were derived from current fighter aircraft flight test data. PSD A represents fighter aircraft response to moderate turbulence

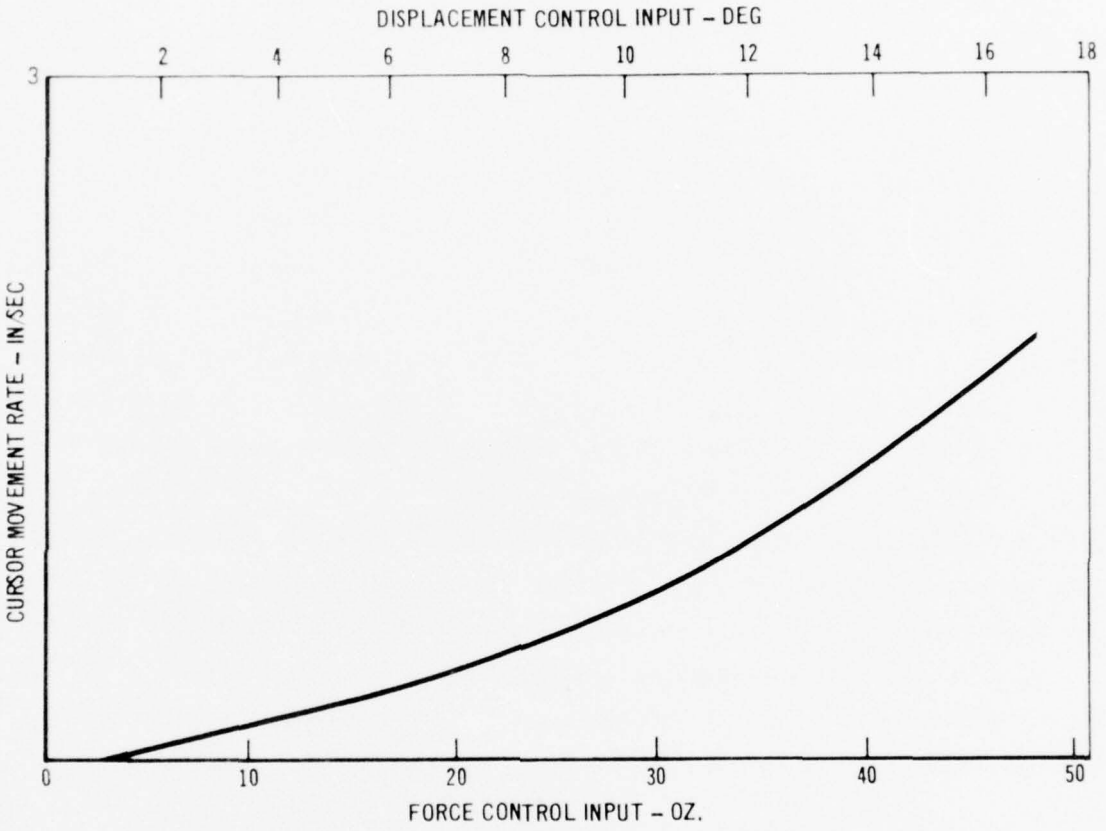


FIGURE 3–8 EXPONENTIAL CONTROL/DISPLAY FUNCTION

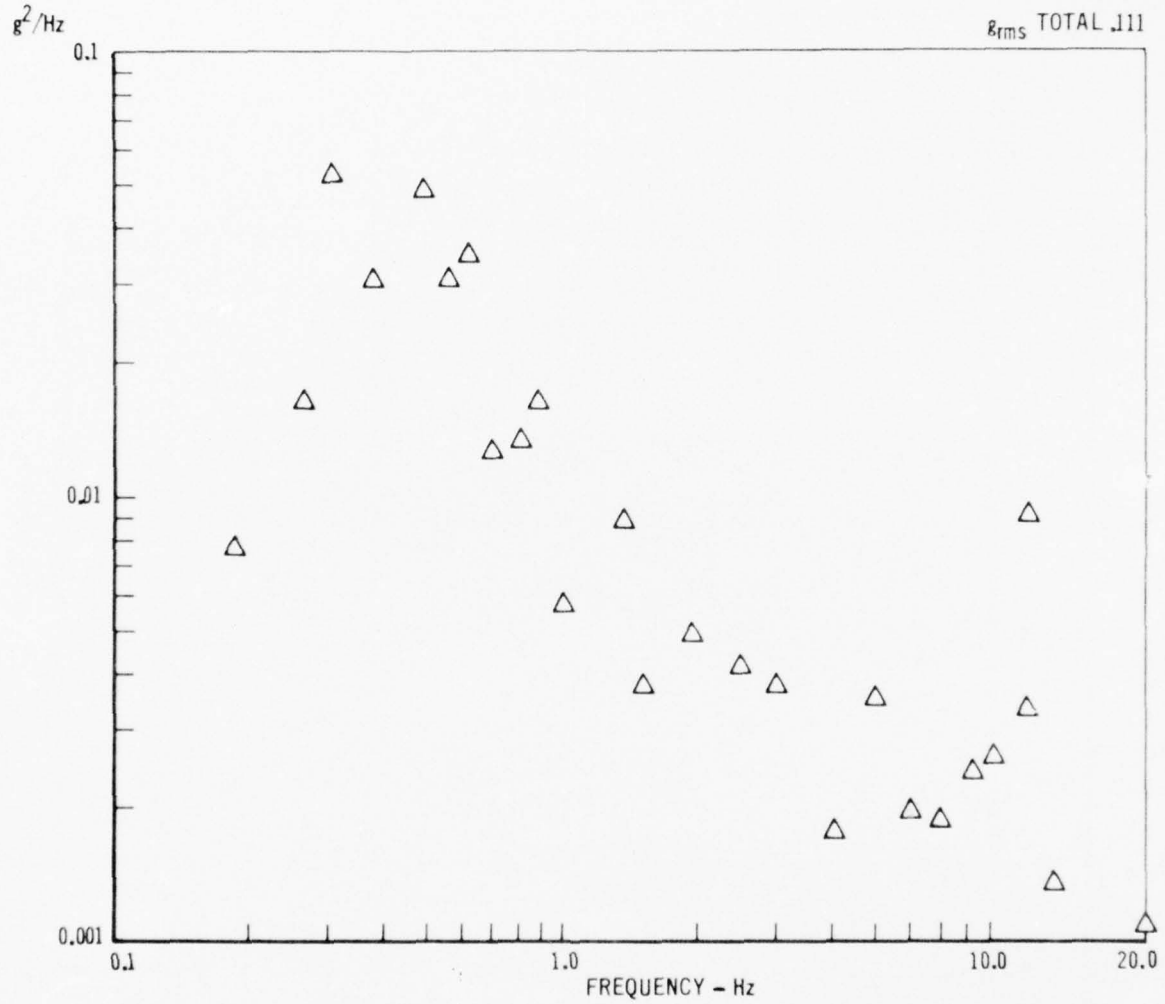


FIGURE 3-9A EXPERIMENTAL VIBRATION SPECTRA
(MODERATE TURBULENCE)

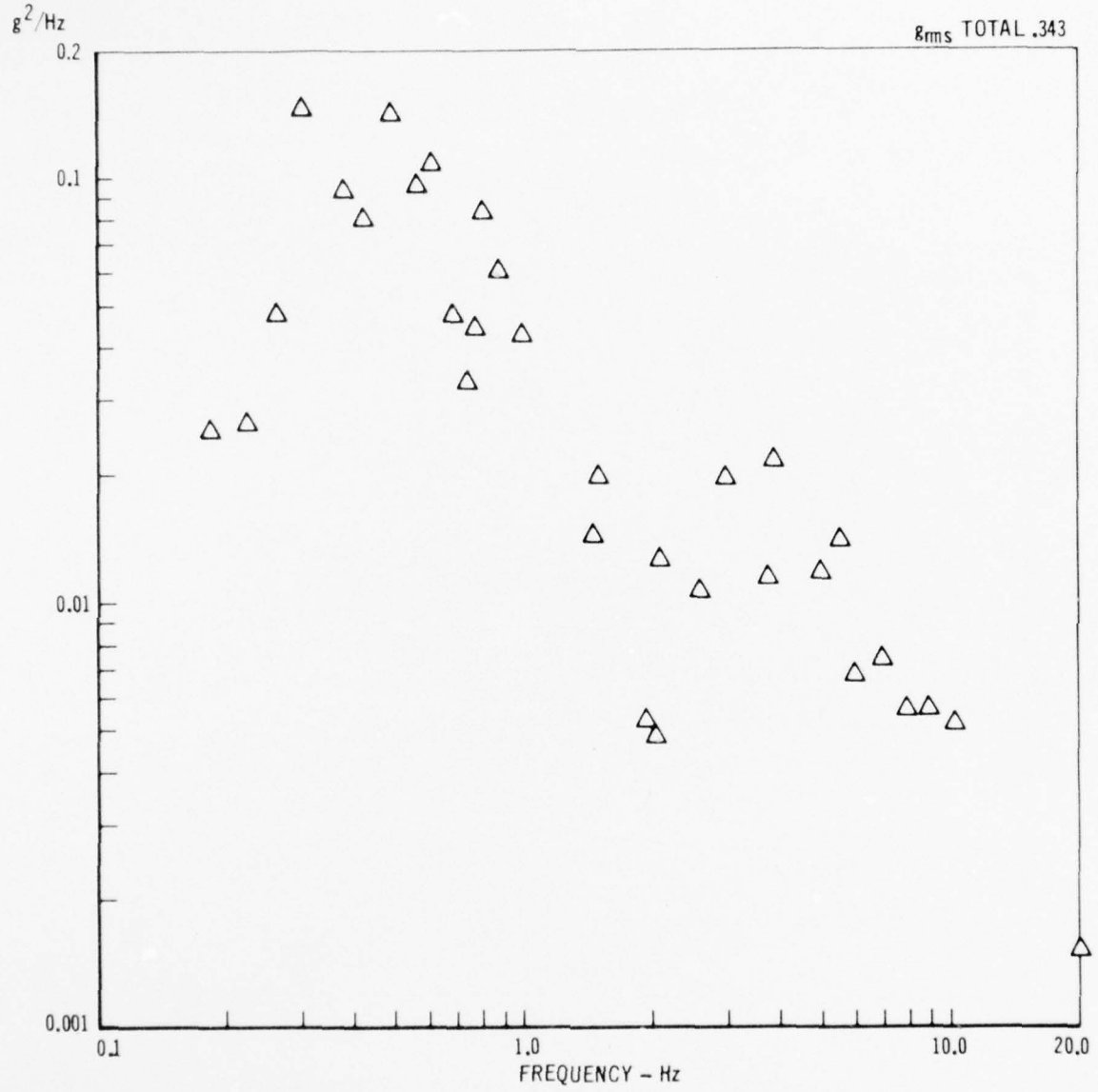


FIGURE 3-9B – EXPERIMENTAL VIBRATION SPECTRA
(HEAVY TURBULENCE)

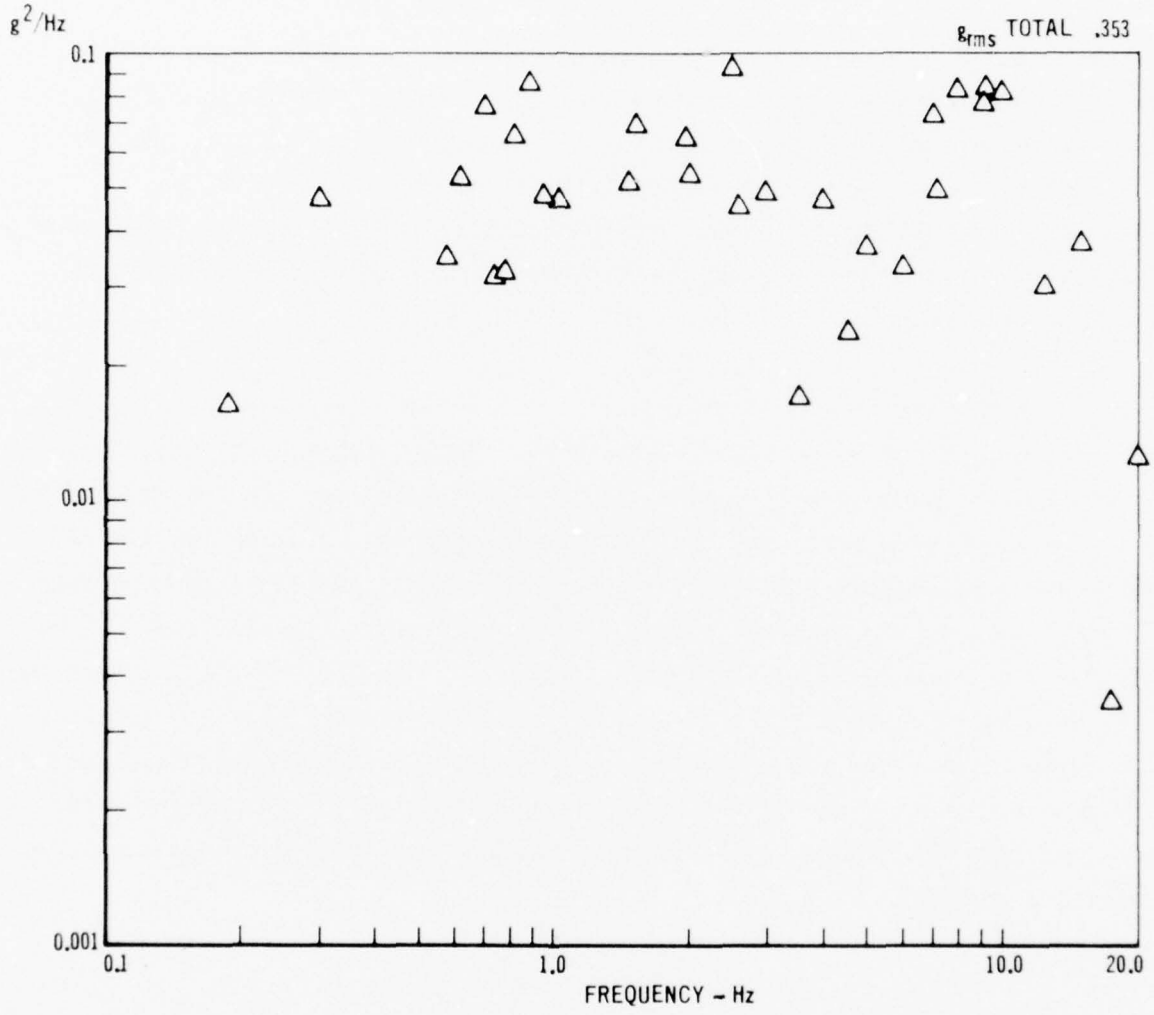


FIGURE 3-9C EXPERIMENTAL VIBRATION SPECTRA (BROADBAND)

conditions (≈ 5 ft/sec rms gust intensity), and PSD B corresponds to heavy turbulence conditions (≈ 16 ft/sec rms gust intensity). The 5 ft/sec (rms) gust value represents clear air turbulence at 10,000 feet altitude (Chalk, et al, 1967), and the 16 ft/sec (rms) value represents a conservative estimate of thunderstorm conditions. Chalk, et al, (1969), suggest a 21 ft/sec (rms) gust intensity to represent thunderstorm or severe turbulence; however, the performance of operational target tracking tasks in such an environment is unlikely. Thunderstorm gust intensities have also been reported as high as 110 ft/sec (rms) (Hitchcock and Morway, 1968). The 16 ft/sec (rms) gust intensity value was selected on the basis of being a reasonable value at which target tracking tasks would still be performed in a representative mission scenario and within the operational limitations of the motion base simulator.

3.3.3 Task Loading - The performance tasks in the investigation consisted of aircraft flight control and target tracking. During subject testing, these tasks were performed separately and in combination to provide for the evaluation of the effects on task performance. The relationship between task loading and flight control was measured by comparing performance on the flight control task with performance on the combined flight control and target tracking task. Since it was assumed that the combined tasks were inherently more difficult to perform than the separate tasks, both evaluations involved a comparison between two levels of task loading, a low workload condition corresponding to the separate tasks and a high workload condition corresponding to the combined tasks. The performance comparisons, the associated levels of task loading, and the performance measures are depicted in Table 3-3.

TABLE 3-3. TASK LOADING LEVELS

Performance Comparison	Task Loading Levels		Performance Measures Compared
	Low Workload	High Workload	
1.	Target Tracking (TT only)	Flight Control and Target Tracking	Target Tracking
2.	Flight Control (FC only)	Flight Control and Target Tracking (FC & TT)	Flight Control

The manner in which the experimental test trials were structured to provide the task loading conditions is described in Section 3.5.

3.4 Experimental Design - A three factorial, mixed experimental design (2 x 4 x 2) with repeated measures was utilized (Figure 3-10). The test matrix consisted of two levels of control type (force and displacement), four vibration conditions (static, moderate turbulence, heavy turbulence, and broadband vibration condition) and two levels of task loading (low and high) with repeated measures on the latter two factors. These factor levels combined to provide 16 test conditions. Each test participant was tested with one control type for the eight combinations of vibration and task loading.

3.5 Experimental Procedure - Each subject participated in one experimental session which lasted approximately 90 minutes. The subjects were randomly assigned to either the force or displacement control group, and the presentation order of the test conditions was counterbalanced across the test participants (Table 3-4).

Each subject received a standard set of instructions given by one of the experimenters. This briefing described the purpose of the study, the MBS system, the controls and displays, the task requirements, and experimental conditions. Subjects were instructed to fly a simulated weapons delivery mission segment that required the target tracking task with aircraft attitude and airspeed control under some of the test conditions. It was stressed that the tasks were of equal importance and that equal attention should be given to the three tasks, i.e., airspeed control, attitude control, and target tracking. Each pilot was given an opportunity to ask questions for clarification of any aspect of his task prior to the experimental trials.

A total of 25 performance trials were conducted during each experimental session. Of the total, nine were practice trials and 16 were experimental trials. Each trial was 2-1/2 minutes long and divided into two segments. As shown in Figure 3-11, for the first 30 seconds of both the low and high task loading conditions, the subjects were instructed to perform the aircraft attitude and airspeed tasks. The aircraft attitude task consisted of manipulation of the flight control stick in response to pitch/roll commands displayed by the horizontal and vertical pointer bars of the ADI. The bars were programmed to provide "fly to"

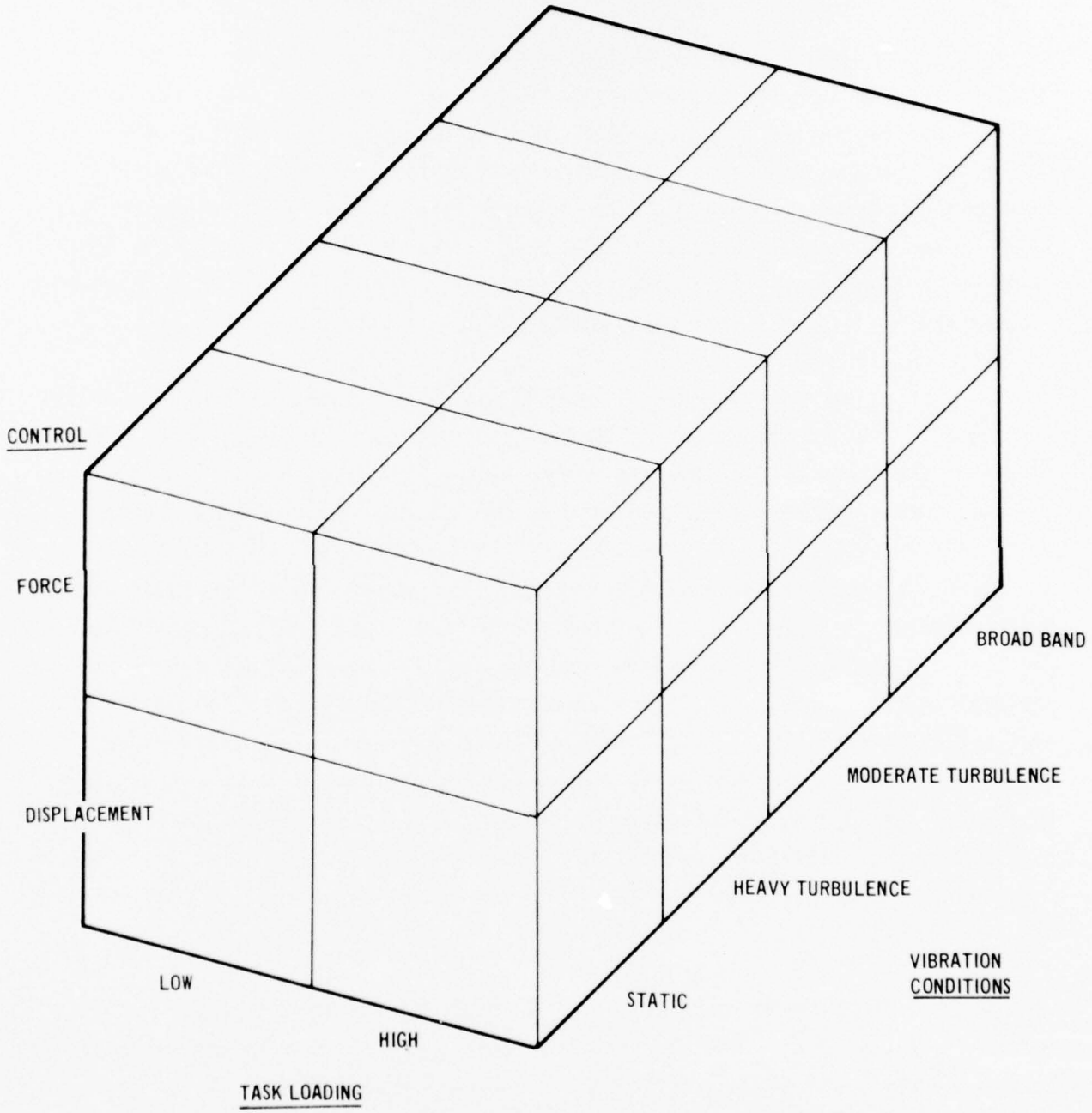


FIGURE 3-10 EXPERIMENTAL DESIGN

TABLE 3-4 PRESENTATION ORDER OF EXPERIMENTAL CONDITIONS

VIBRATION	STATIC				MOD. TURBULENCE				HEAVY TURBULENCE				BROADBAND			
TASK LOADING	LOW		HIGH		LOW		HIGH		LOW		HIGH		LOW		HIGH	
TARGET GROUP	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
ROLL-PITCH COMMANDS	C-1	C-2	A-1	B-2	C-3	A-3	A-1	B-2	B-3	C-1	A-1	B-2	C-2	C-3	A-1	B-2
EXPERIMENTAL CONDITION	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
SUBJECT*																
1 (2)	C	M	F	L	G	A	J	P	K	E	N	D	O	I	B	H
3 (4)	B	H	O	I	F	L	C	M	J	P	G	A	N	D	K	E
5 (6)	K	E	N	D	O	I	B	H	C	M	F	L	G	A	J	P
7 (8)	J	P	G	A	N	D	K	E	B	H	O	I	F	L	C	M
9 (10)	L	F	M	C	P	J	A	G	D	N	E	K	H	B	I	O
11 (12)	I	O	H	B	M	C	L	F	A	G	P	J	E	K	D	N
13 (14)	D	N	E	K	H	B	I	O	L	F	M	C	P	J	A	G
15 (16)	A	G	P	J	E	K	D	N	I	O	H	B	M	C	L	F

* Even = Force Control Group
Odd = Displacement Control Group

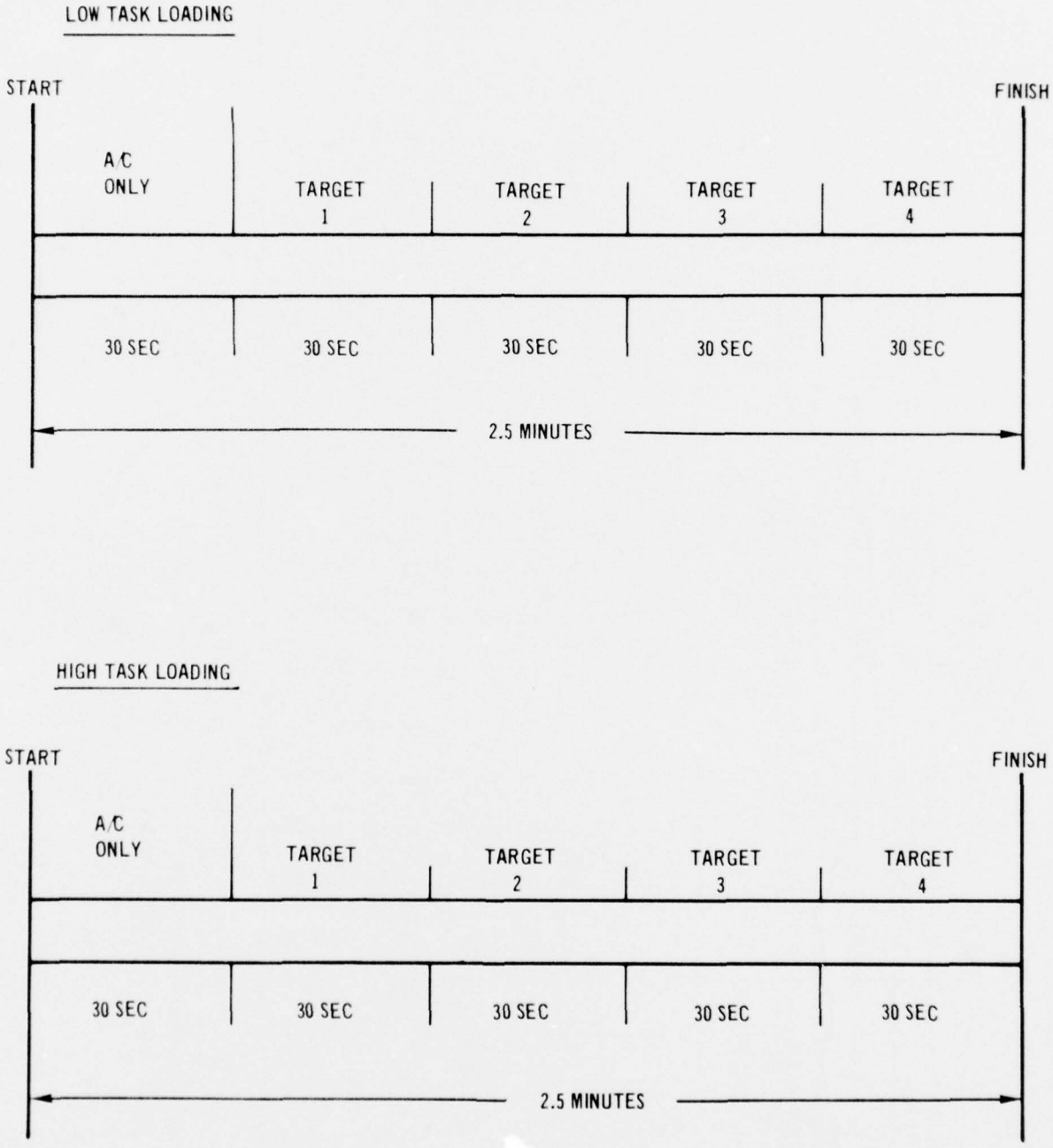


FIGURE 3-11 EXPERIMENTAL TRIAL TIME LINES

commands in such a manner that when the bars were centered over the aircraft symbol, the commanded attitude was achieved. The three sets of pitch and roll commands used in this study are illustrated in Figures A-4 and A-5 of Appendix A.

During the subsequent two minute segment, four targets appeared in succession for 30 sec each on the tracking CRT display. The targets moved at 0.1 inch/sec in a random pattern. The target positions and movements were identical to those used in the previous investigations and are illustrated in Figure A-6 and A-7. The subjects were requested to place the cursor over the target as quickly and as accurately as possible using the integrated tracking control, and then to depress the acquisition switch located on the flight stick grip to accomplish acquisition. The pilots were to continue to track the target until a new target appeared. Under the high task loading condition, they were instructed to attend to the aircraft attitude and airspeed tasks as well as target tracking giving equal attention to each task. The end of the trial was signalled by illumination of the indicator light.

Nine practice trials were given to each subject which proved adequate for familiarization training. The tasks to be performed and the vibration conditions provided in Table 3-5 show the breakdown of these trials. The 16 experimental trials consisted of the eight combinations of test conditions (two task loading x four vibration conditions) each being presented twice in a counterbalanced design (Table 3-4).

A short debriefing followed the end of the session. It required each subject to complete a questionnaire concerning the investigation and his previous target tracking experience (Appendix C). The subject was then given an opportunity to review and discuss any aspects of the study which he felt deserved further consideration. This concluded the test session.

TABLE 3-5 PRACTICE TRIALS CONDITIONS

TRIAL #	VIBRATION SPECTRA	TASK LOADING
1	Static	A/C Control Only
2	Static	Low
3	Static	High
4	Moderate Turbulence	Low
5	Moderate Turbulence	High
6	Heavy Turbulence	Low
7	Heavy Turbulence	High
8	Broadband	Low
9	Broadband	High

3.6 Performance Measures* - The aircraft attitude control task was a compensatory tracking task with simulated attack type aircraft dynamics. Three sets of pitch commands and three sets of roll commands were presented in a counterbalanced manner as the forcing functions for this task to limit subject memorization. Strip chart records of the pitch and roll commands can be found in Appendix A (Figures A-4 and A-5).

Data were recorded for the following measures of attitude and airspeed control:

- o RMS Pitch Error
- o RMS Roll Error
- o RMS Airspeed Error.

The RMS errors were computed from the difference (without regard to sign) between actual and command aircraft attitude represented on the ADI as the separation between the needles and the aircraft reticle. The errors were recorded in terms of degrees (Appendix B contains equivalent conversions in other metrics).

The airspeed control task was to maintain 300 kts. The error scores were based on the difference between the actual airspeed displayed on the indicator and 300 kts.

The target tracking task consisted of the acquisition and pursuit tracking of the simulated targets on the CRT display. The measures of task performance utilized included:

- o Target acquisition time
- o Error at acquisition
- o Overshoots before acquisition
- o Percent time on target
- o RMS X- and Y-axes and radial tracking error.

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*The authors recognize the presently accepted practice of reporting Metric rather than English units in research publications. However, English units were retained in this report because they are still the most common engineering measures in the United States and it was felt that they would facilitate the interpretation of the data by the readers to whom this research is directed, human factors and design engineers in the United States. Conversion factors to other metrics are provided in Appendix B.

Acquisition time was defined as the time in seconds from target appearance until the pilot "acquired" the target by depressing the acquisition button.

Error at acquisition was the absolute distance in inches between the center of the target and the cursor,when the acquisition button was depressed.

Overshoots before acquisition were measured as the number of times the cursor passed through a predetermined circular "window" 0.25 inch diameter around the target before acquisition.

Percent time on target represented the proportion of time the cursor was within the target window after the target had been acquired.

X- and Y- Axes tracking error was the vertical distance, in inches on the CRT, between the center of the target and the cursor.

These measures of target tracking provided extensive performance data on both the acquisition and tracking components of the target tracking task. Of the five measures used, the first three listed were target acquisition variables, and the latter two were target tracking variables. Although the various measures in each task component provided information on tracking efficiency, the variables were not equally weighted in terms of utility or importance. For the acquisition subtask, overshoots were secondary to acquisition time and error scores; and for the tracking subtask, percent time on target was secondary to the measures of tracking error. Overshoots were of secondary importance because rapid and accurate target acquisition was possible even with a relatively large number of overshoots. Furthermore, overshoots before acquisition represented only one of the many factors potentially affecting the time to acquire the targets; therefore, overshoots were subordinate to acquisition time. Time on target is a less effective index of proficiency because it does not take into account the magnitude of tracking error. In radar tracking missions, a large deviation is almost always worse than a smaller one. RMS errors are measures of tracking deviation and are the preferred method of scoring. RMS error also provides a measure of dispersion equivalent to the standard deviation with a mean deviation of zero.

3.7 Operational Applicability - A determined effort was made to provide a target tracking situation that was realistic and yet as generalizable as possible. With this goal in mind, task parameters and test variables were selected on the basis of present operational usage and future operational application. Thus, attack aircraft dynamics were simulated for the aircraft control tasks, and the target tracking task was configured so that a variety of target tracking mission scenarios could be represented while retaining a basis for comparison to existing tracking research data. Table 3-6 describes two mission scenarios which contain operational task elements comparable to the experimental tasks of this study. Again, the experimental tasks were designed to facilitate the application of the data to a variety of operational conditions. They were generalized tasks not necessarily suggesting one specific simulated operational situation. Table 3-7 describes the flight control and tracking task errors in terms of possible operational values.

TABLE 3-6 EXAMPLES OF SIMULATED MISSION SCENARIOS

TYPE OF TARGET:	GROUND (FIXED)	GROUND (MOVING)
TARGET SPEED*:	-	48 KTS
AIRCRAFT SPEED:	500 KTS	300 KTS
SENSOR TYPE:	RADAR (PPI)	E-O (STABILIZED)
DISPLAY SCALE:	5 NM	1.5° FOV
AIRCRAFT ALTITUDE:	10,000 FT.	10,000 FT.
AIRCRAFT-TARGET RANGE:	0 TO 5 NM	10 NM

* TARGET MOVEMENT ON SIMULATED DISPLAY = 0.1"/SEC (CONSTANT)

TABLE 3-7 OPERATIONAL EXAMPLES OF FLIGHT CONTROL AND TARGET TRACKING TASK ERRORS

	PERFORMANCE MEASURE	RESULTANT ERROR
FLIGHT CONTROL ERROR	1° PITCH ERROR (AT 300 KTS FOR 30 SEC)	ALTITUDE ERROR = 270 FT
	1° ROLL ERROR (AT 300 KTS FOR 30 SEC)	HEADING ERROR = 0.55° GROUNDPATH ERROR = 133 FT
TARGET TRACKING ERROR	0.01 INCH ACQUISITION OR TRACKING ERROR (RANGE = 10 MILES ; ALTITUDE = 10,000 FT.)	RADAR SENSOR = 180 FT
		TV SENSOR (5° FOV) = 106 FT*
		E-O SENSOR (1.5° FOV) = 30 FT*
		*AVERAGE ACROSS FOV

4.0 RESULTS

The presentation of the results is divided into three sections. The first section (4.1) is concerned with the relationship between the independent variables and target tracking performance. These data reflect the direct effects of the independent variables. The second section (4.2) examines the effects of the independent variables on aircraft attitude control and airspeed control representing the indirect effects of the target tracking variables. Section three (4.3) considers the subjective data obtained from the debriefing questionnaire. These data include the subjective ratings of the simulation program and previous target tracking experience.

4.1 Target Tracking Data Analyses - To analyze the direct effects of the independent variables, a three-factor analysis of variance (control types x task loading x vibration) with repeated measures on the last two factors, was conducted for each measure of target tracking performance. In the experimental design, all factors except subjects were considered as fixed. The appropriate a posteriori group comparisons were conducted where statistically significant main effects and interactions were observed. The overall means and standard deviations computed for each of the target tracking variables are provided in Table 4-1. Table 4-2 summarizes the significant effects obtained in the analyses of variance.

4.1.1 The Effects of Control Types - The analyses of variance indicated that the main effects of control type were statistically significant for the target tracking measure of percent time-on-target, $F(1,14) = 5.553$, $p < .05$. As illustrated in Figure 4-1, the force control was associated with higher percent time-on-target than the displacement control.

4.1.2 The Effects of Task Loading - The analyses of variance conducted on the measures of target tracking performance yielded statistically significant main effects of task loading summarized in Table 4-3. The comparison was between the low task loading level involving target tracking only, and the high task loading level which required target tracking and aircraft flight control.

TABLE 4-1 MEANS AND STANDARD DEVIATIONS OF PERFORMANCE MEASURES AS A FUNCTION OF THE INDEPENDENT VARIABLES

DEPENDENT VARIABLE	MEASURE	CONTROL				VIBRATION			
		DISPLACEMENT	FORCE	LOW	HIGH	STATIC	MODERATE TURBULENCE	HEAVY TURBULENCE	BROAD BAND
Acquisition Time (Sec)	$\bar{X}$	3.83	3.25	3.53	3.54	3.61	3.47	3.52	3.56
	S.D.	1.30	.54	.87	1.18	1.10	1.19	.91	.97
Acquisition Error (Inches)	$\bar{X}$	.082	.065	.062	.085	.053	.056	.093	.092
	S.D.	.070	.029	.029	.070	.018	.023	.091	.039
RMS X Error (Inches)	$\bar{X}$	.108	.081	.057	.133	.077	.092	.102	.108
	S.D.	.078	.047	.029	.071	.043	.076	.065	.073
RMS Y Error (Inches)	$\bar{X}$	.122	.080	.059	.143	.077	.094	.108	.125
	S.D.	.092	.048	.028	.085	.053	.078	.066	.096
RMS Radial Error (Inches)	$\bar{X}$	.167	.116	.084	.200	.111	.135	.151	.169
	S.D.	.124	.067	.040	.114	.068	.113	.094	.123
Time on Target (Percent)	$\bar{X}$	68.0	78.9	89.0	57.9	80.7	77.0	69.9	66.2
	S.D.	22.0	18.9	9.8	17.7	18.0	20.5	21.9	21.9
Overshoots (#)	$\bar{X}$	.441	.272	.310	.404	.186	.315	.402	.525
	S.D.	.405	.352	.367	.404	.303	.365	.405	.404
RMS Pitch Error (Degrees)	$\bar{X}$	1.98	2.71	1.92	2.77	2.02	1.98	2.39	2.69
	S.D.	.67	1.76	.91	1.62	.89	1.15	1.43	1.82
RMS Roll Error (Degrees)	$\bar{X}$	2.13	1.78	3.33	2.37	1.93	1.98	1.93	1.96
	S.D.	.93	.62	2.25	.88	.61	.91	.92	.78
RMS Airspeed Error (Knots)	$\bar{X}$	10.1	16.6	10.4	16.4	12.6	11.9	13.7	15.3
	S.D.	5.3	10.4	6.1	10.2	8.3	5.2	10.0	11.0

TABLE 4-2 SUMMARY OF SIGNIFICANT ANALYSIS OF VARIANCE EFFECTS FOR TARGET TRACKING PERFORMANCE MEASURES

ANALYSIS OF VARIANCE	TARGET TRACKING PERFORMANCE MEASURES						
	ACQUISITION TIME	ACQUISITION ERROR	PERCENT TIME ON TARGET	RMS RADIAL ERROR	RMS X-AXIS ERROR	RMS Y-AXIS ERROR	OVERSHOOTS BEFORE ACQUISITION
BETWEEN OBSERVERS							
CONTROLS (C)	NS	NS	$p < 0.05$	NS	NS	NS	NS
WITHIN OBSERVERS							
TASK LOADING (T)	NS	$p < 0.05$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	NS
C X T	NS	NS	NS	NS	NS	NS	NS
VIBRATION (V)	NS	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
C X V	NS	NS	NS	NS	NS	NS	NS
T X V	NS	NS	$p < 0.05$	NS	NS	NS	NS
C X T X V	NS	NS	NS	NS	NS	NS	NS

NOTE: NS - NON-SIGNIFICANT

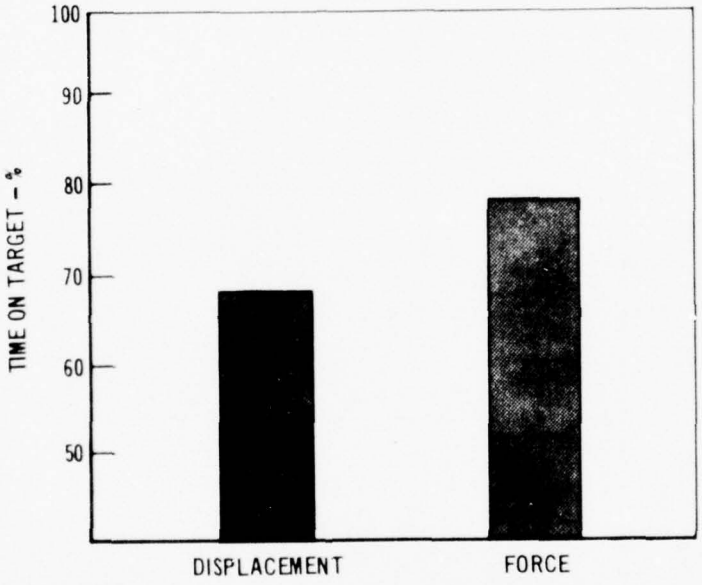

FIGURE 4–1 TIME ON TARGET AS A FUNCTION OF CONTROL TYPE

TABLE 4-3. SIGNIFICANT TASK LOADING MAIN EFFECTS FOR TARGET TRACKING PERFORMANCE MEASURES

Performance Measure	F	df	p	Superior Task Loading Level
Acquisition Error	7.838	1, 14	< 0.05	Low
Percent Time on Target	133.295	1, 14	< 0.01	Low
RMS X-Axis Error	43.272	1, 14	< 0.01	Low
RMS Y-Axis Error	31.369	1, 14	< 0.01	Low
RMS Radial Error	35.72	1, 14	< 0.01	Low

Figures 4-2 through 4-6 illustrate the magnitude of the differences between the means for the two task loading levels. The data clearly show that the low task loading level yields consistently superior target tracking performance than the high task loading level. A significant interaction between task loading and vibration was also found. This interaction and related a posteriori tests are described in Section 4.1.4.

4.1.3 The Effects of Vibration - Statistically significant main effects of vibration were obtained in the analyses of variance of the target tracking performance measures. These are summarized in Table 4-4.

The mean values corresponding to the three vibration conditions and the static control condition are depicted in Figures 4-7 through 4-12 for these performance measures. Tests of the differences between the vibration and static conditions were conducted by application of the Scheffe test. The significant group comparsions ($p < 0.05$) obtained in these tests are provided in Tables 4-5 through 4-10. The results of these tests indicate that:

a. The effects of the low amplitude, narrow-band vibration on target tracking performance were not significantly different from the static condition.

b. The effects of the high amplitude, narrow-band vibration and broadband vibration conditions did not differ significantly in terms of target tracking performance.

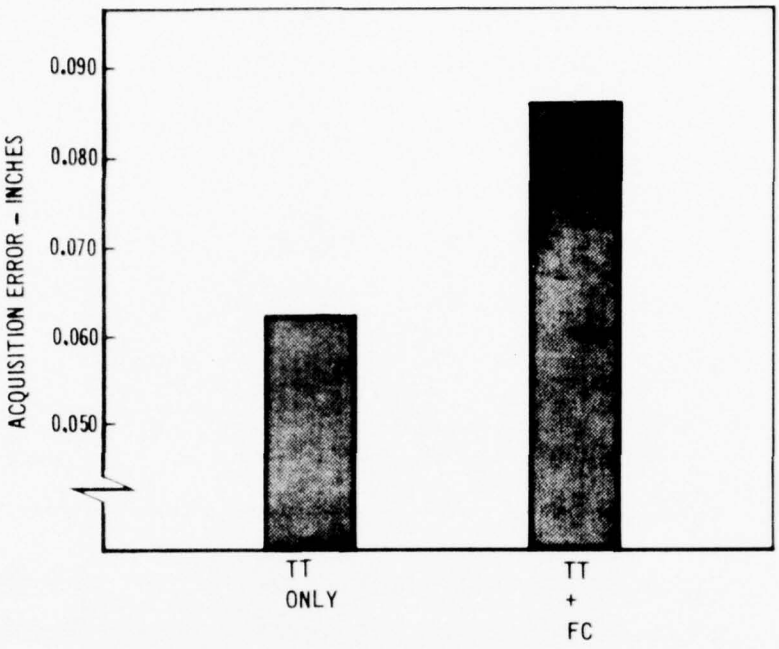

FIGURE 4-2 ACQUISITION ERROR AS A FUNCTION OF TASK LOADING

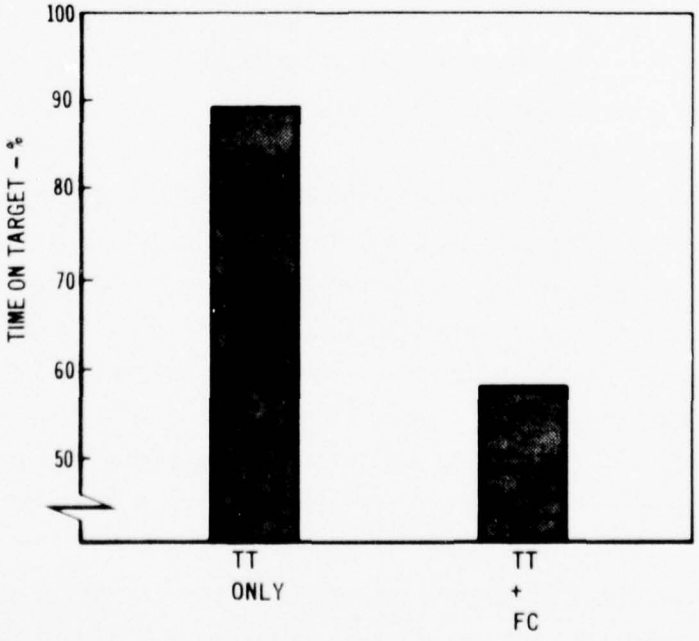

FIGURE 4-3 TIME ON TARGET AS FUNCTION OF TASK LOADING

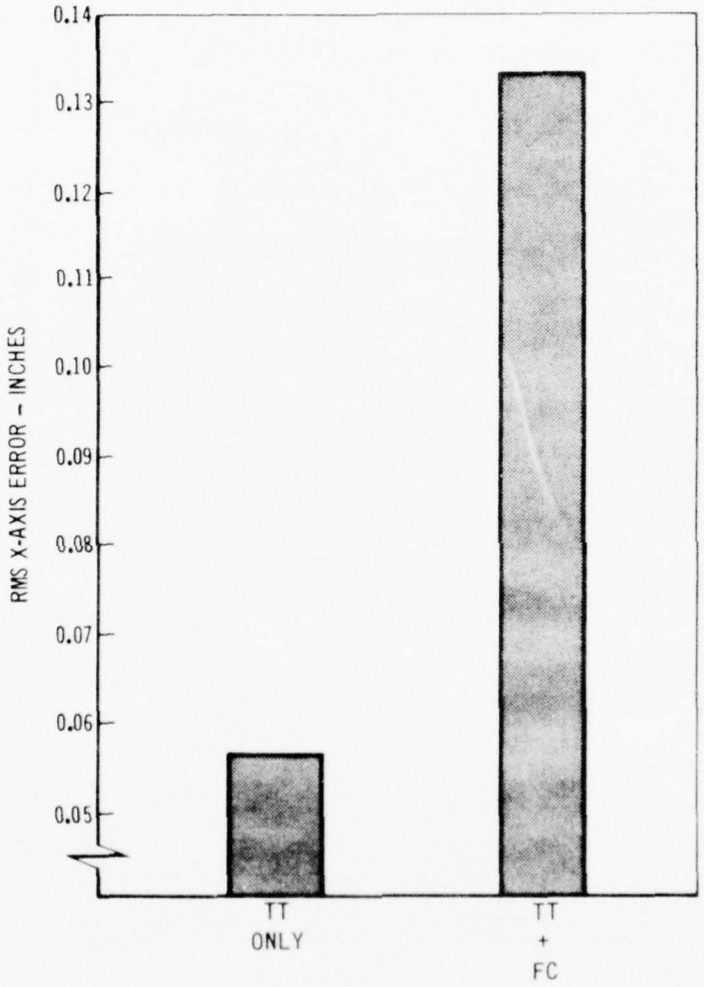

FIGURE 4-4 RMS X-AXIS ERROR AS A FUNCTION OF TASK LOADING

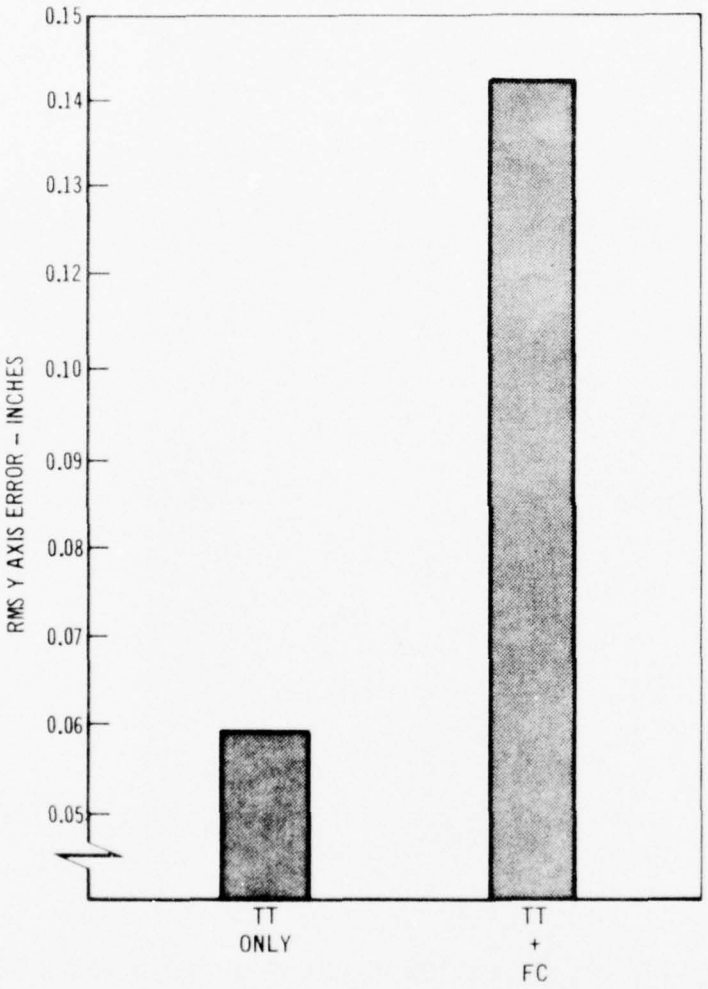

FIGURE 4–5 RMS Y-AXIS ERROR AS A FUNCTION OF TASK LOADING

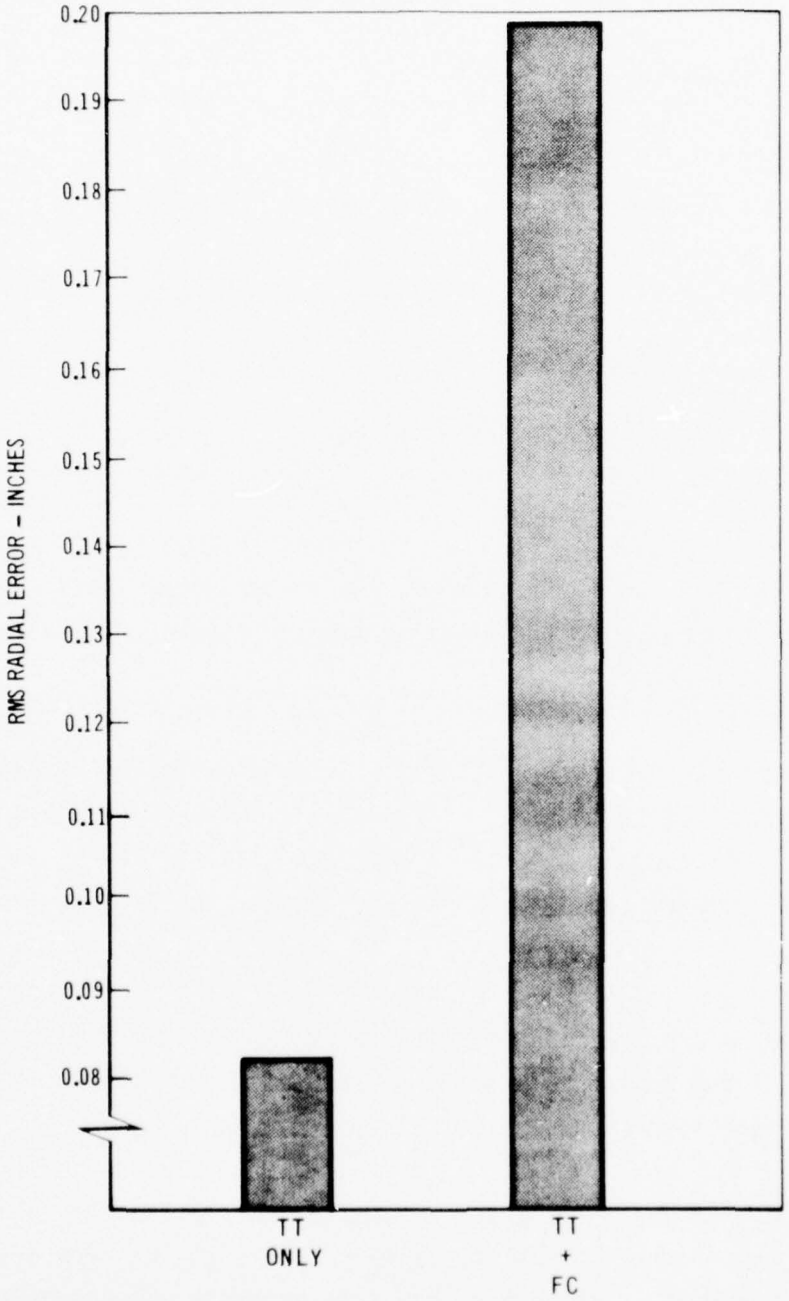

FIGURE 4-6 RMS RADIAL ERROR AS A FUNCTION OF TASK LOADING

TABLE 4-4. SIGNIFICANT VIBRATION MAIN EFFECTS FOR TARGET TRACKING PERFORMANCE MEASURES

Performance Measures	F	df	p
Acquisition Error	11.477	3, 42	< 0.01
Overshoots before Acquisition	7.484	3, 42	< 0.01
RMS X-Axis Error	3.436	3, 42	< 0.05
RMS Y-Axis Error	9.153	3, 42	< 0.01
RMS Radial Error	6.018	3, 42	< 0.01
Percent Time on Target	19.857	3, 42	< 0.01

c. Target tracking performance was significantly impaired by exposure to the high amplitude, narrow-band vibration, and broadband vibration conditions compared to the low amplitude narrow-band vibration and static condition.

Based on these results, it appears that the detrimental performance effects of the vibration conditions tested were primarily a function of the overall acceleration level (g_{rms}) of the power spectra rather than the particular shape of the power spectra. In summary, the higher the g_{rms} level, the greater the performance decrement.

A significant interaction involving vibration was obtained from the analysis of variance in addition to the main effects. This interaction and the corresponding group comparisons are described in the following section.

4.1.4 Target Tracking Interaction Effects - The analysis of variance (Table 4-2) revealed a significant two-way interaction ($p < 0.05$) between task loading and vibration. Therefore, a posteriori statistical tests were performed to determine significant differences between group means. The Scheffe test was applied for these group comparisons.

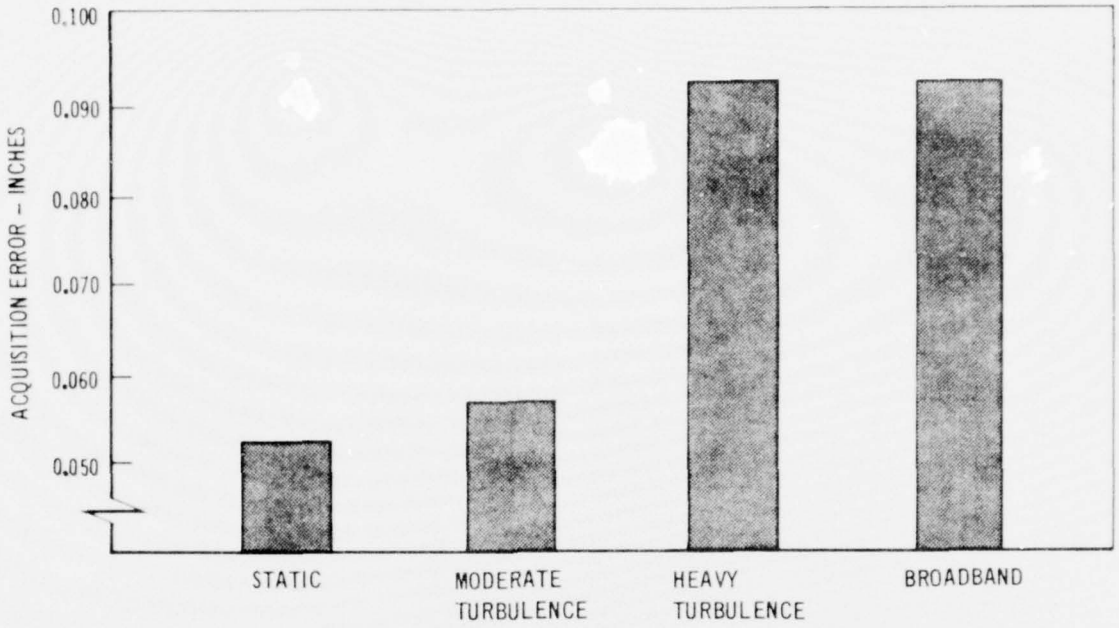

FIGURE 4-7 ACQUISITION ERROR AS A FUNCTION OF VIBRATION CONDITION

TABLE 4-5 SIGNIFICANT GROUP COMPARISONS FOR VIBRATION MAIN EFFECT ON ACQUISITION ERROR

COMPARISON	MEAN DIFFERENCE	CRITICAL VALUES*	SUPERIOR CONDITION
STATIC - PSD B	0.040	0.027	STATIC
STATIC - PSD C	0.039	0.027	STATIC
PSD A - PSD B	0.036	0.027	PSD A

*$p < 0.05$

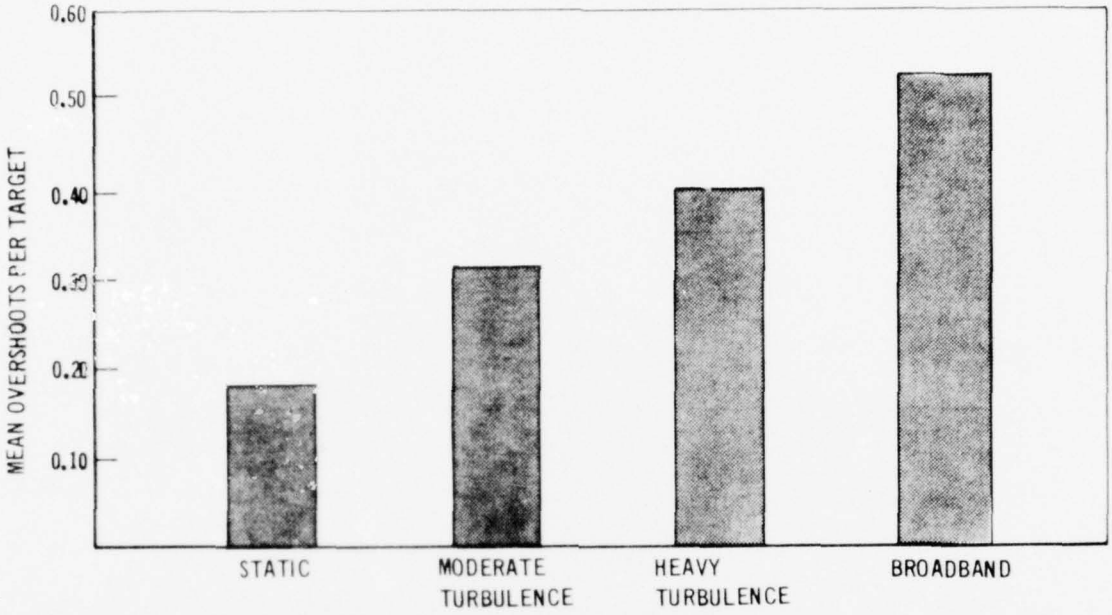

FIGURE 4-8 OVERSHOOTS AS A FUNCTION OF VIBRATION CONDITIONS

TABLE 4-6 SIGNIFICANT GROUP COMPARISONS FOR VIBRATION MAIN EFFECT FOR OVERSHOOTS

COMPARISON	MEAN DIFFERENCE	CRITICAL VALUE*	SUPERIOR CONDITION
STATIC - PSD B	0.217	0.216	STATIC
STATIC - PSD C	0.340	0.216	STATIC

* $p < 0.05$

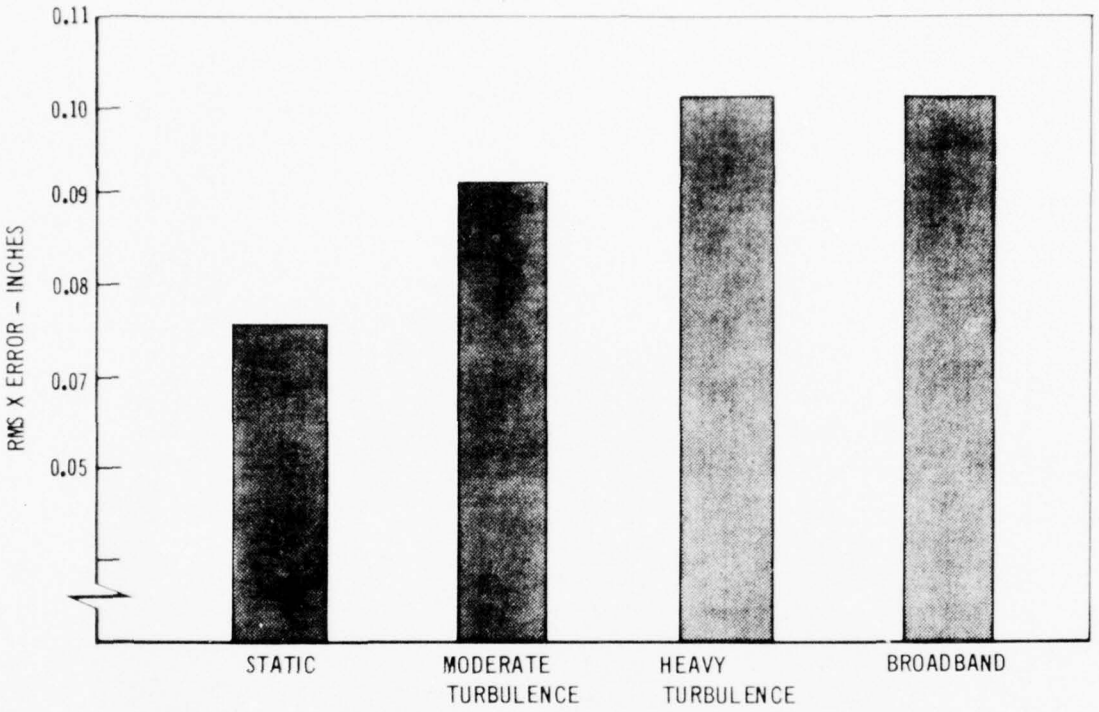

FIGURE 4-9 RMS X-AXIS ERROR AS A FUNCTION OF VIBRATION CONDITION

TABLE 4-7 SIGNIFICANT GROUP COMPARISONS FOR VIBRATION MAIN EFFECT ON RMS X-AXIS ERROR

COMPARISON	MEAN DIFFERENCE	CRITICAL VALUE*	SUPERIOR CONDITION
STATIC-PSD C	0.031	0.030	STATIC

* $p < 0.05$

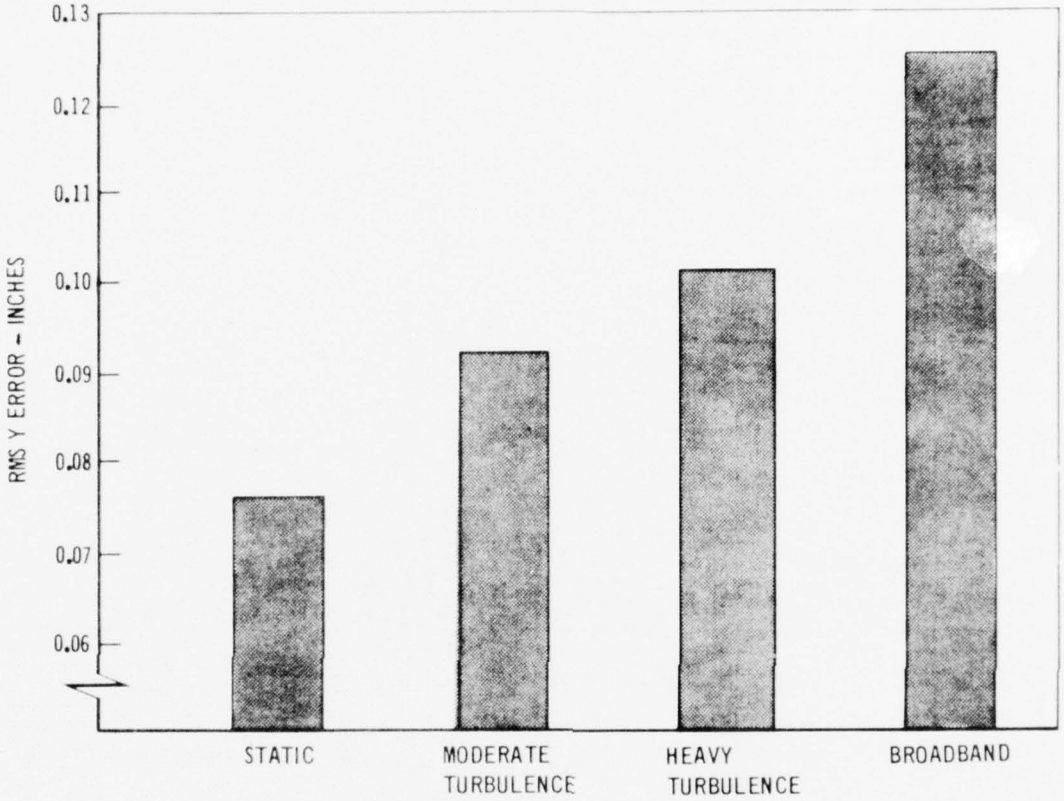

FIGURE 4-10 RMS Y-AXIS ERROR AS A FUNCTION OF VIBRATION CONDITIONS

TABLE 4-8 SIGNIFICANT GROUP COMPARISONS FOR VIBRATION MAIN EFFECT ON RMS Y-AXIS ERROR

COMPARISON	MEAN DIFFERENCE	CRITICAL VALUE*	SUPERIOR CONDITION
STATIC - PSD B	0.031	0.028	STATIC
STATIC - PSD C	0.048	0.028	STATIC
PSD A - PSD C	0.032	0.028	PSD A

*$p < 0.05$

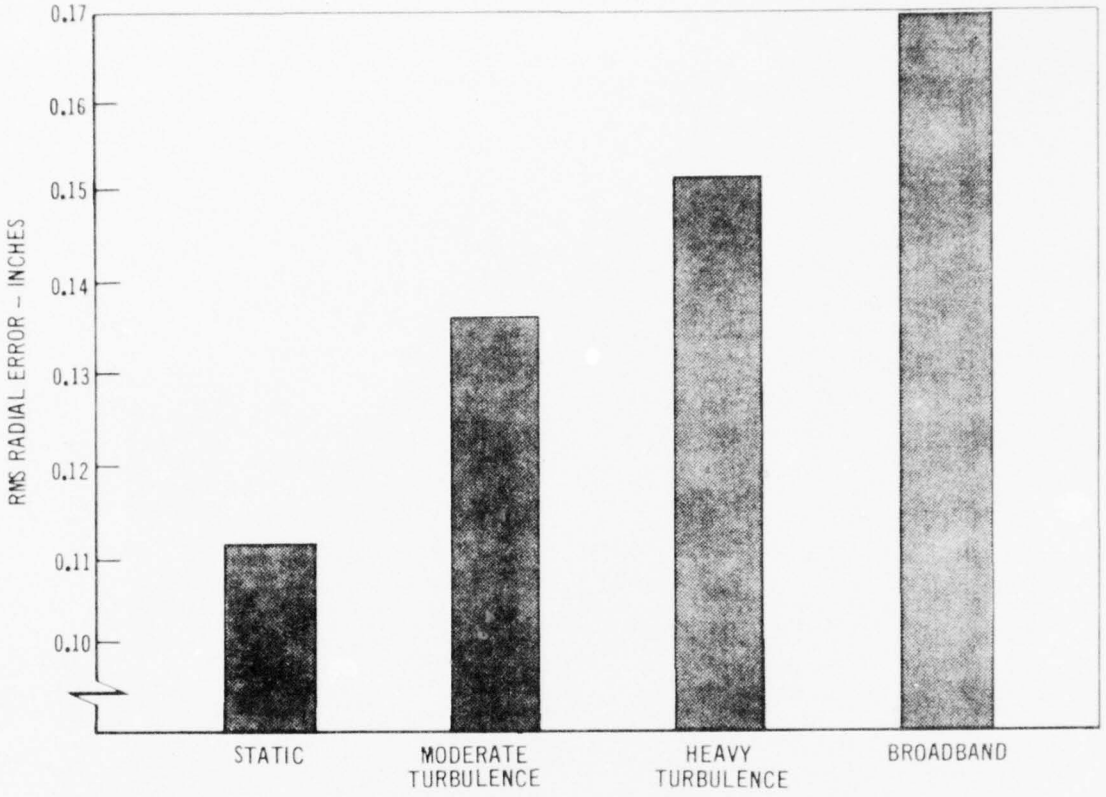

FIGURE 4–11 RMS RADIAL ERROR AS A FUNCTION OF VIBRATION CONDITIONS

TABLE 4-9 SIGNIFICANT GROUP COMPARISONS FOR VIBRATION MAIN EFFECT ON RMS RADIAL ERROR

COMPARISON	MEAN DIFFERENCE	CRITICAL VALUE*	SUPERIOR CONDITION
STATIC - PSD B	0.041	0.040	STATIC
STATIC - PSD C	0.058	0.040	STATIC

*$p < 0.05$

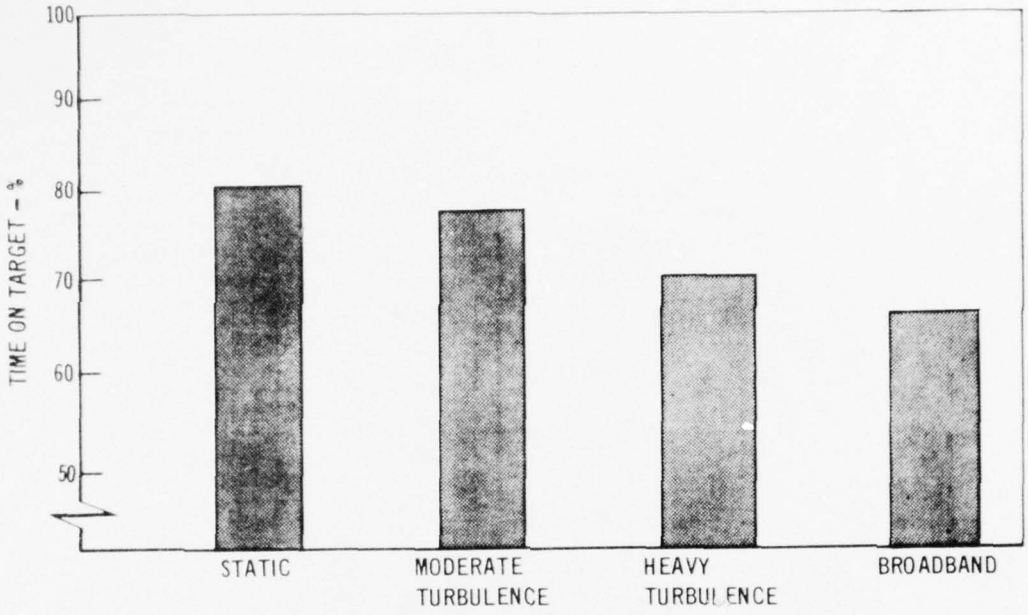

FIGURE 4-12 TIME ON TARGET AS A FUNCTION OF VIBRATION CONDITIONS

TABLE 4-10 SIGNIFICANT GROUP COMPARISONS FOR VIBRATION MAIN EFFECT ON PERCENT TIME ON TARGET

COMPARISON	MEAN DIFFERENCE	CRITICAL VALUE *	SUPERIOR CONDITION
STATIC - PSD B	10.818	6.093	STATIC
STATIC - PSD C	14.472	6.093	STATIC
PSD A - PSD B	7.143	6.093	STATIC
PSD A - PSD C	10.798	6.093	STATIC

* $p < 0.05$

In the Sheffe tests, all possible comparisons between paired means in a logical grouping were tested. In this report, only the statistically significant ($p < 0.05$) mean comparisons are reported. The significant interactions and the results of the a posteriori group comparisons are shown in Table 4-11 and graphically illustrated in Figure 4-13. All comparisons between the low and high task loading conditions showed that significantly higher percent time on target was associated with the low task loading condition, the same results found for the main effects (Section 4.1.2). The comparisons between the vibration conditions found identical results under the high task loading condition as were found in the main effects comparisons (Table 4-5). Again, there were no significant performance differences found between the static and moderate turbulence conditions nor between the heavy turbulence and broadband conditions. Similarily, under the low task loading conditions, no significant difference was obtained between the static and moderate turbulence conditions nor between the moderate and heavy turbulence conditions.

4.2 Aircraft Attitude and Airspeed Control Analyses - In order to assess the indirect effects of the independent variables, a three factor analysis of variance with repeated measures was conducted for each measure of aircraft control. The significant effects derived from these analyses are summarized in Table 4-12.

4.2.1 The Effects of Control Types - A statistically significant effect of control types on aircraft control was obtained for RMS airspeed error ($p < 0.05$). As graphically illustrated in Figure 4-14, RMS airspeed error indicated superior performance of the displacement control condition over the force control condition.

4.2.2 The Effects of Task Loading - Task loading conditions significantly affected all of the aircraft control variables ($p < 0.01$). As shown in Figures 4-15 and 4-16, aircraft control performance under the low task loading level was clearly superior to the high task loading condition.

4.2.3 The Effects of Vibration - A statistically significant effect of vibration on aircraft control performance was obtained for rms pitch error ($p < 0.05$). The corresponding a posteriori paired comparisons tests indicated that only the difference in rms pitch error between the static and the broadband conditions was significant (mean differences = 0.676, $p < 0.05$). As illustrated in Figure 4-17, the lowest rms pitch error was associated with the static condition.

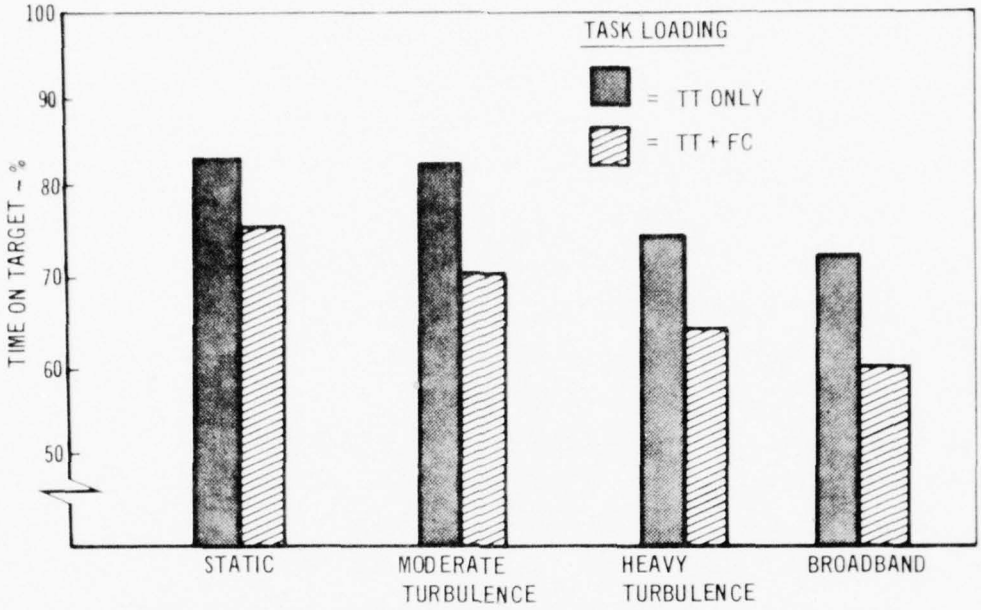

FIGURE 4-13 TIME ON TARGET AS A FUNCTION OF TASK LOADING AND VIBRATION CONDITIONS

TABLE 4-11 SIGNIFICANT GROUP COMPARISONS FOR PERCENT TIME ON TARGET WITH TASK LOADING X VIBRATION INTERACTION

TASK LOAD LEVEL COMPARISON	VIBRATION	MEAN DIFFERENCE	CRITICAL VALUE *	SUPERIOR CONDITION
LOW - HIGH	STATIC	28.721	6.276	LOW
LOW - HIGH	PSD A	30.769	6.276	LOW
LOW - HIGH	PSD B	35.791	6.276	LOW
LOW - HIGH	PSD C	28.980	6.276	LOW

TASK LOADING	VIBRATION COMPARISON	MEAN DIFFERENCE	CRITICAL VALUE *	SUPERIOR CONDITION
LOW	STATIC - PSD B	7.284	6.942	STATIC
	STATIC - PSD C	14.343	6.942	STATIC
	PSD A - PSD C	11.692	6.942	PSD A
	PSD B - PSD C	7.060	6.942	PSD B
HIGH	STATIC - PSD B	14.353	6.942	STATIC
	STATIC - PSD C	14.602	6.942	STATIC
	PSD A - PSD B	9.654	6.942	PSD A
	PSD A - PSD C	9.903	6.942	PSD A

* $p < 0.05$

TABLE 4-12 SUMMARY OF SIGNIFICANT ANALYSIS OF VARIANCE EFFECTS FOR AIRCRAFT CONTROL PERFORMANCE MEASURES

ANALYSIS OF VARIANCE EFFECTS	FLIGHT CONTROL PERFORMANCE MEASURES		
	RMS PITCH ERROR	RMS ROLL ERROR	RMS AIRSPEED ERROR
BETWEEN OBSERVERS			
CONTROLS (C)			$p < 0.05$
WITHIN OBSERVERS			
TASK LOADING (T)	$p < 0.01$	$p < 0.01$	$p < 0.01$
C X T			
VIBRATION (V)	$p < 0.05$		
C X V			
T X V			
C X T X V			

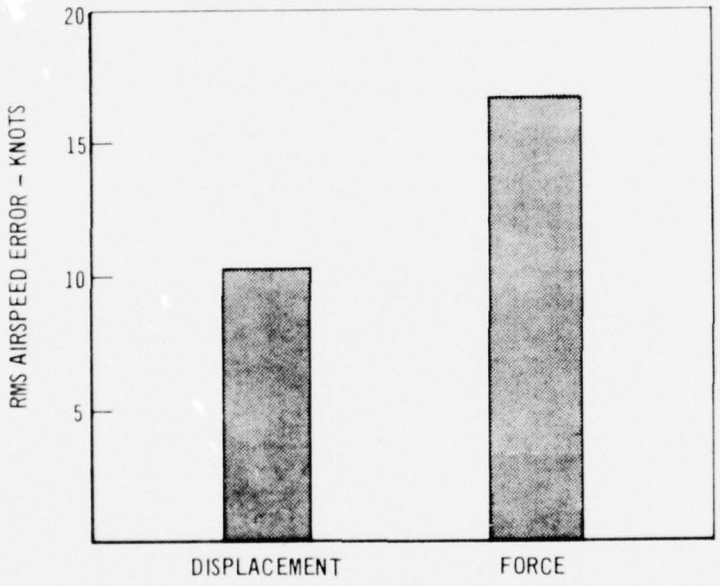

FIGURE 4-14 RMS AIRSPEED ERROR AS A FUNCTION OF CONTROL TYPE

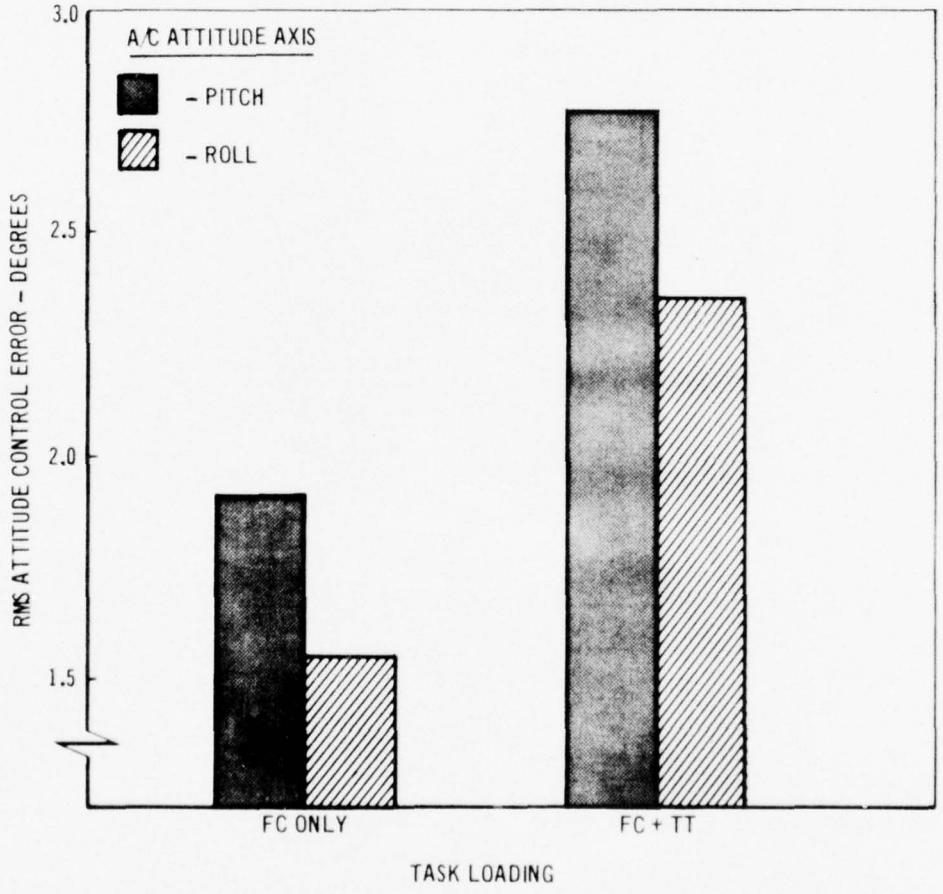

FIGURE 4-15 RMS AIRCRAFT ATTITUDE CONTROL ERROR AS A FUNCTION OF TASK LOADING

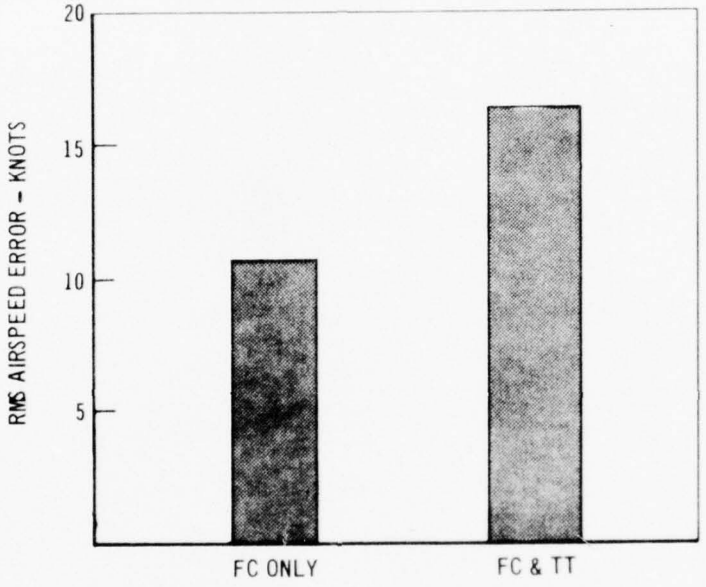

FIGURE 4–16 RMS AIRSPEED ERROR AS A FUNCTION OF TASK LOADING

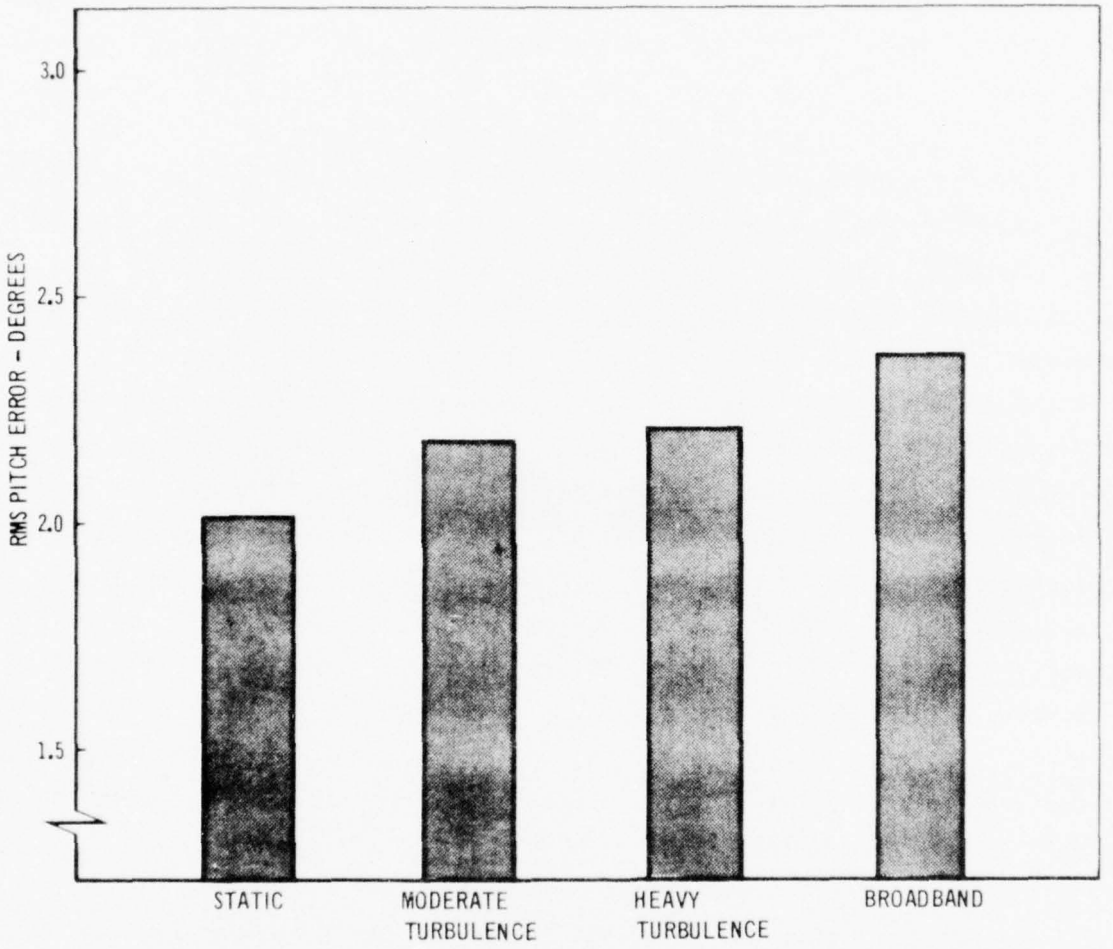

FIGURE 4-17 RMS PITCH ERROR AS A FUNCTION OF VIBRATION CONDITION

4.2.4 Aircraft Control Interaction Effects - No two or three way interactions of the independent variables were obtained for the aircraft control measures.

4.3 Pilot Questionnaire Responses - Immediately following the experimental session, the subjects were asked to complete a debriefing questionnaire (Appendix C). The results of the evaluation of the questionnaire data are discussed in subsequent paragraphs.

4.3.1 Subjective Ratings - Using the debriefing questionnaire, the subjects were asked to rate the workload levels, aircraft control and motion fidelity, and the motion predictability aspects of the study. As shown in Figure 4-18, there was a general rating trend toward increasing workload as the magnitude of the vibration increased. These data support the performance data results described in paragraphs 4.1.3 and 4.2.3. These subjective data also suggest that the workload levels for the flight control only and the target tracking only conditions (low task loading) were about the same; but the combination of these tasks, the high task loading condition, was more demanding than either of the single task conditions. The latter finding corresponds to results of the effects of task loading on the target tracking and aircraft control performance (paragraphs 4.1.2 and 4.2.2). Ratings of the aircraft control fidelity (Figure 4-19) indicate that the pitch/roll dynamics were of acceptable fidelity with the related airspeed control dynamics slightly less realistic. The motion fidelity ratings indicated that the broadband condition was the most realistic (Figure 4-20). Figure 4-21 suggests that the motion was predictable to some extent for all of the vibration conditions.

4.3.2 Motion Sickness - Only four of the 16 subjects indicated that they had experienced any motion sickness during the experiment. In all of these cases, the motion sickness was mild and was induced by the heavy turbulence condition, according to their reports.

4.3.3 Control Activity - Motion Anticipation - The subjects were asked if they modified their control behavior in anticipation of the cockpit motions. A majority of the pilots indicated that they did not modify their tracking behavior. Some of the pilots, however, indicated that they occasionally anticipated the motion by hurrying or delaying their control inputs.

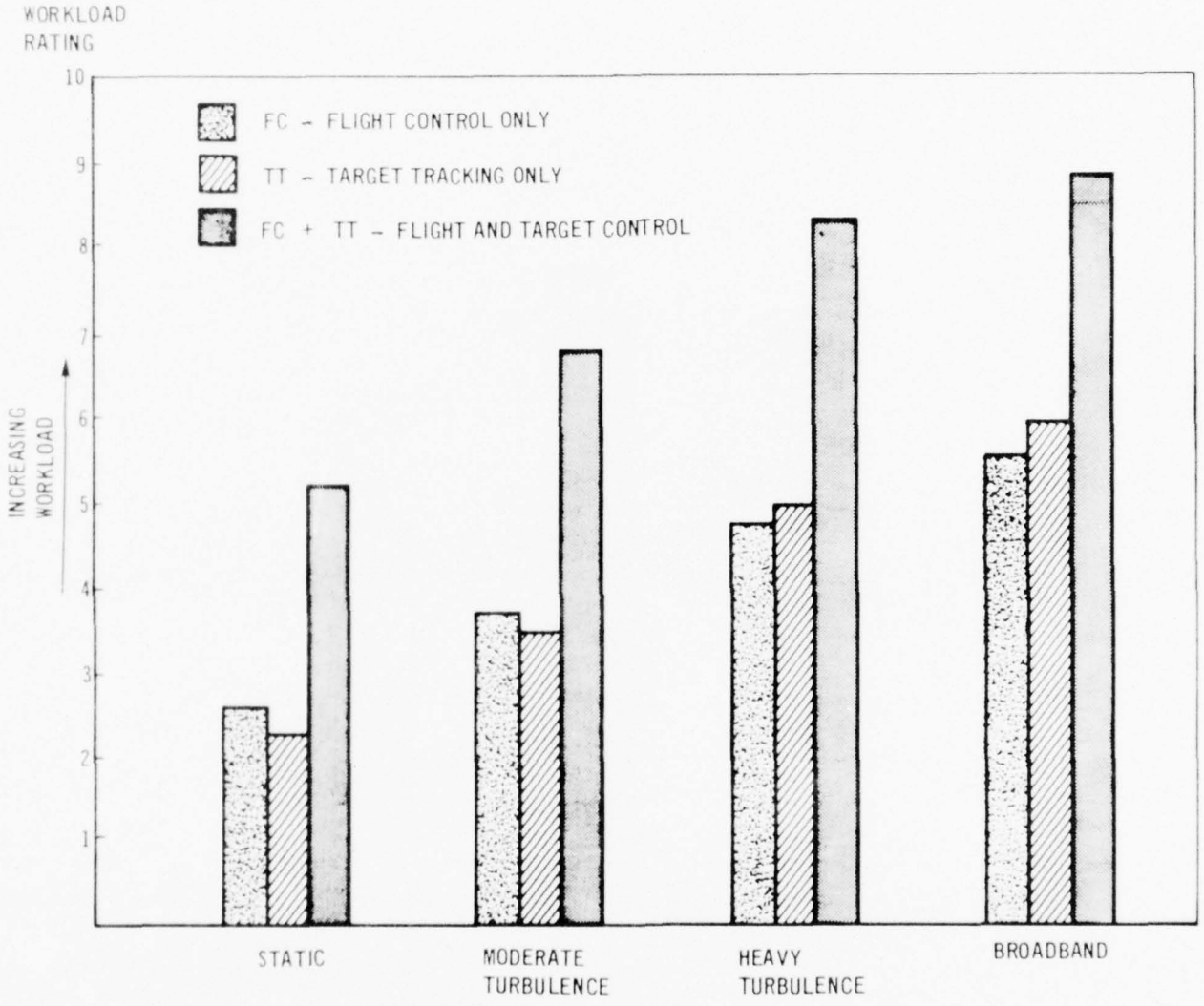

FIGURE 4-18 MEAN PILOT WORKLOAD RATINGS AS A FUNCTION OF TASK LOADING AND VIBRATION CONDITION

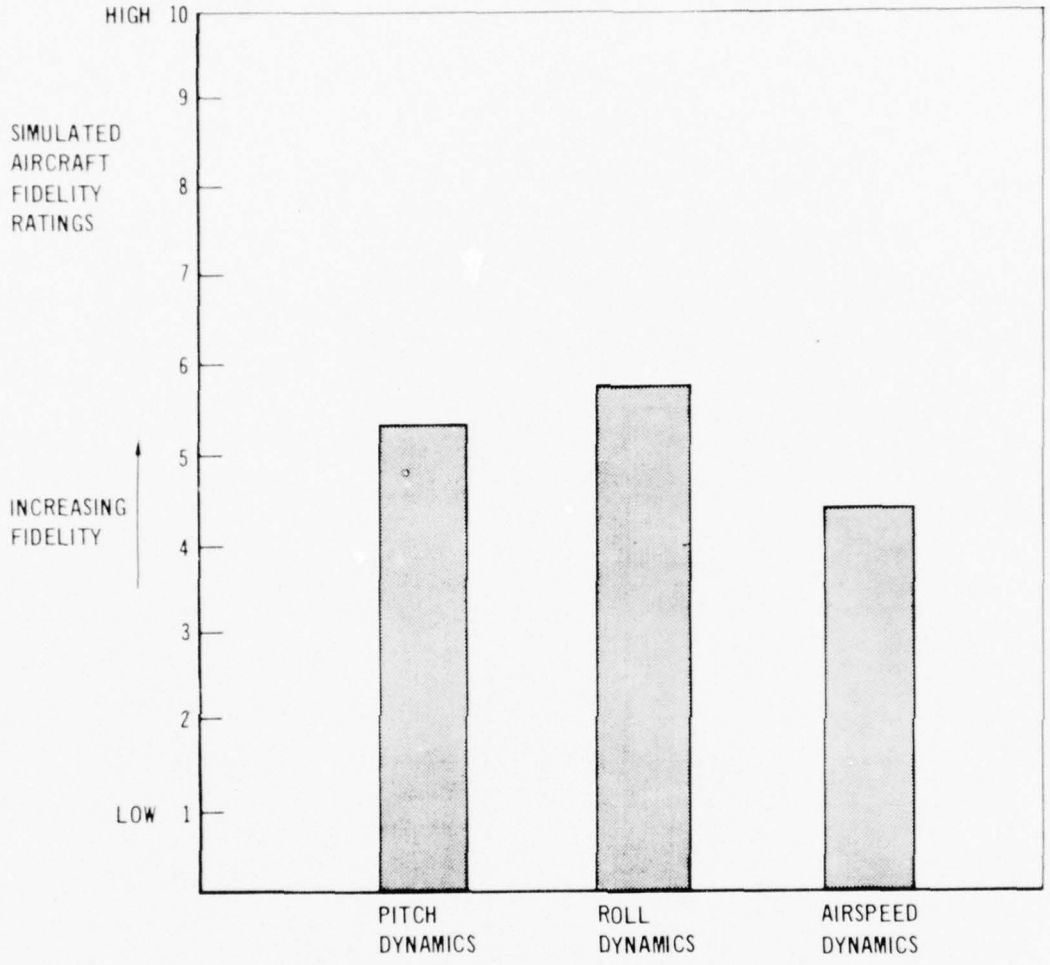

FIGURE 4–19 MEAN SIMULATED AIRCRAFT DYNAMICS FIDELITY RATINGS

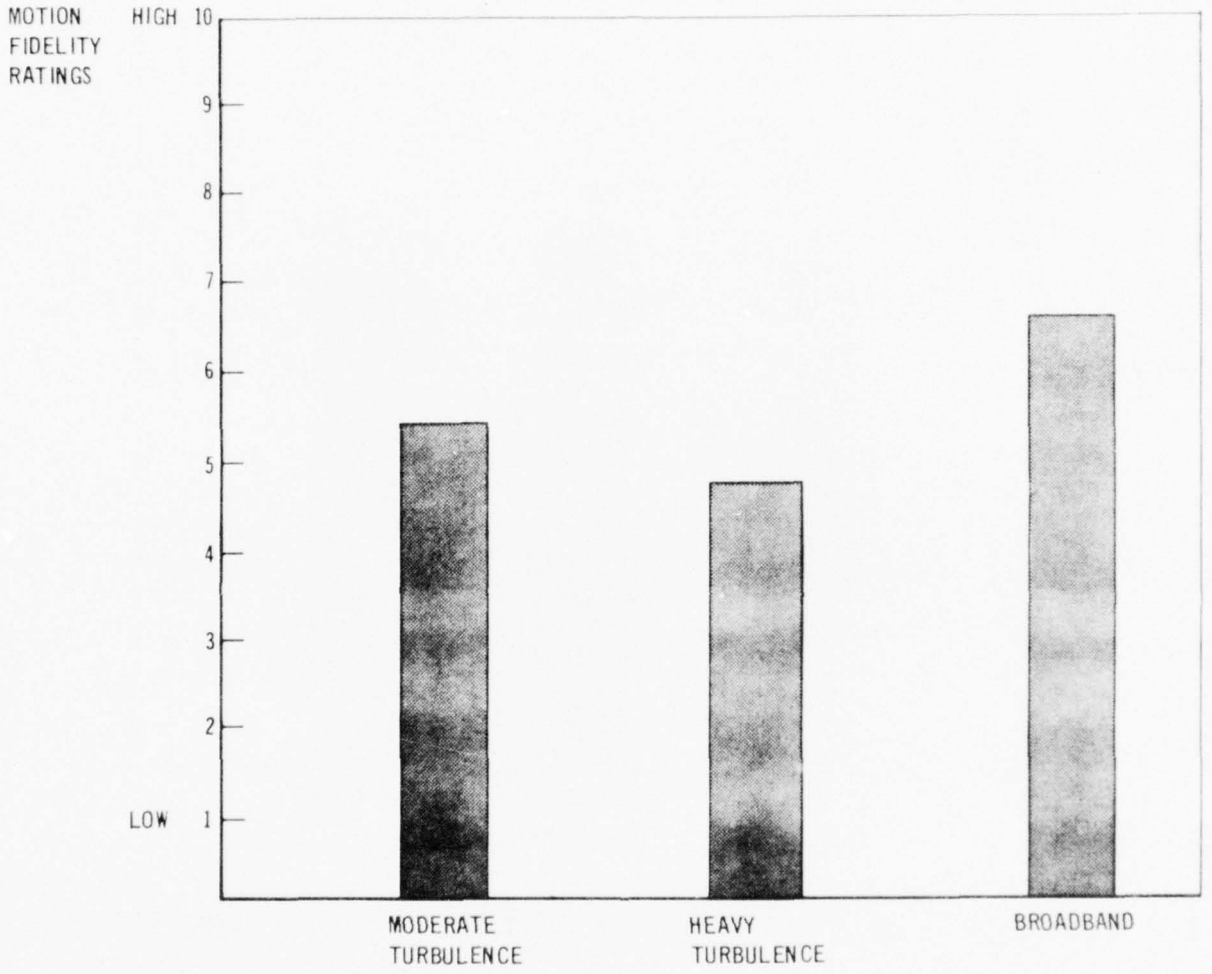

FIGURE 4-20 MEAN MOTION FIDELITY RATINGS

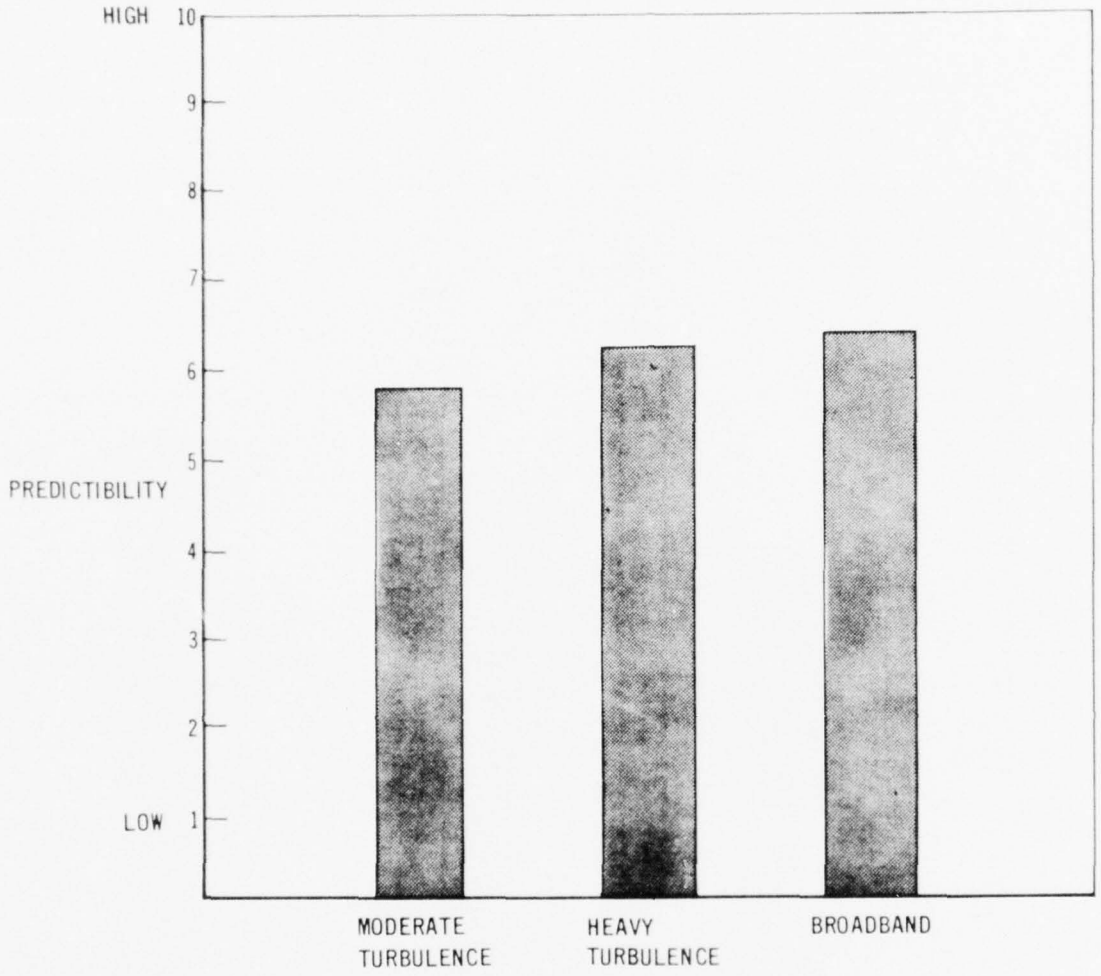

FIGURE 4-21 MEAN PREDICTABILITY RATINGS OF VIBRATION CONDITIONS

4.3.4 Aircraft and Target Tracking Experience - Nearly all subjects (14 of 16) had previous target tracking experience for air-to-air and air-to-ground scenarios in simulator and actual flight training missions. The background data indicated that the subjects were highly experienced pilots with a flight experience range of 1000 to 9000 flight hours and an average of approximately 3900 hours.

5.0 DISCUSSION

It is apparent from the results that control type, task loading, and vibration significantly affected both target tracking and aircraft control performance.

The target tracking variables suggest that the force control was associated with better performance than the displacement control; however, only the time-on-target score indicated statistically significant differences (see Tables 4-1 and 4-2). The time-on-target scores for the force control were 16 percent higher than the displacement control scores. While time-on-target may not be considered as sensitive as RMS tracking error (Poulton, 1974), it is comparable to operational measures such as gun/missile envelope time or time within radar gate. The data suggested a trend toward better performance with the force control across both the task loading and vibration conditions. These data tend to corroborate the findings of Lewis and Griffith (1976) which suggest that force cues are more important than displacement cues in tracking, particularly under whole-body vibration.

The control type variable was also found to influence aircraft airspeed performance. However, in this instance, the lower error score was associated with the displacement control. The 6 Kt. differential between the mean airspeed error scores for the force and displacement controls is less than the 10 Kt. range represented by one division of the airspeed indicator (Figure 3-4). Operationally, this performance differential may not be significant depending upon the mission requirements.

The lack of interaction between control types and vibration is also noteworthy. The differences between the control types were consistent whether under static or vibration conditions.

The performance data do not indicate an overall preference for either control type. While the force control did appear to provide better tracking performance, the data were consistent for only one of the four tracking measures, and apparently, at the expense of airspeed performance. Therefore, selection of control type cannot be made based only on performance.

The levels of task loading significantly affected target tracking and aircraft control performance. Pilot performance under the low task loading conditions was superior in all cases to the high task loading condition. The main effects of task loading were found to be significant ($p < .01$) for nearly all of the target tracking variables[1] which suggests a general decrement in target tracking performance when the aircraft control task was simultaneously required with target tracking. Similar effects were found for all of the aircraft control performance measures ($p < .01$). In each case, aircraft control performance was significantly degraded when the target tracking task was added. These findings are not unexpected since analyses of the data from the earlier related target tracking studies have suggested similar effects of task loading (Drennen, et al, 1976). Of particular interest is the lack of significant interaction effects between task loading and vibration. The effects of task loading were constant across the vibration conditions with one exception. The vibration and task loading conditions affected performance independently. Also, task loading did not interact with control type.

The effects of vibration on performance were also found to be statistically significant. The main effects of vibration affected all of the target tracking variables ($p < .01$). The higher vibration intensity environments caused decrements in tracking performance. The posteriori tests indicated that the heavy turbulence and broadband vibration conditions (0.35 g_{rms}) were associated with decreased tracking proficiency as compared to the static and moderate turbulence (0.11 g_{rms}) conditions. These findings support the results of the studies of Rustenburg (1971) and Bramaghim (1974). As illustrated in Figure 2-4, a performance decrement threshold is defined in terms of intensity and frequency of vertical vibration. In the 0.2-0.4 Hz region, it is suggested that the vibration intensity must be above 0.2 g_{rms} before peformance will be impaired. The vibration levels described by the moderate and heavy turbulence conditions were predominately within this very low frequency range (Figure 3-8). As indicated in paragraph 4.1.3, the performance under the moderate turbulence condition (0.11 g_{rms}) was not significantly different from the static condition, but the heavy turbulence condition (0.35 g_{rms})

[1]The lack of variation in the acquisition time scores permits more meaningful analyses of the acquisition error scores because the confounding influence of the speed-accuracy tradeoff is minimal, that is, acquisition time scores remained relatively stable across experimental conditions.

did significantly decrease tracking proficiency. The a posteriori tests also indicated that the heavy turbulence and broadband vibration conditions did not significantly differ in their effect upon performance. This finding suggests that vibration spectra with the same vibrational intensity (g_{rms}) may have similar performance effects despite their dissimilar spectral distributions.

The spectra in this study may have caused equivalent performance decrements because of the interaction of their frequency components and human tolerance to those components. As shown in Figure 3-8, the heavy turbulence spectra was concentrated in the 0.2-0.4 Hz region while the broadband spectra was equally distributed across the 0.1 to 20 Hz range. Human tolerance to vertical vibration is illustrated in Figure 2-4 and indicates a low performance decrement threshold in the 0.2 to 0.6 Hz range. With the concentration of vibratory energy in the 0.2-0.4 Hz range and the relatively low decrement threshold, the heavy turbulence spectra appears to have interfered with task performance to the same degree as the broadband spectra.

The subjective data from the debriefing questionnaire yielded estimates of the pilot workload levels associated with the experimental conditions and estimates of the fidelity of the simulation. As described in Section 4.3.1, the estimates of workload varied for the experimental conditions in a manner similar to the performance data. As shown in Figure 4-18, workload increased with increasing task loading and vibration.

From the ratings of the motion fidelity, the broadband vibration condition was rated as most representative of the simulated flight environment, though the turbulence conditions were based upon in-flight aircraft gust responses. This disparity was found because the desired vibration spectra was repeated every 20 seconds to provide the same vibration environment across the trial segments (see Appendix A). This motion repetition was performed to enable valid comparisons between trial segments and because of the operational limitations of the motion base simulator. In actual flight, the vibration spectra of a given 20-second segment may not be representative of the vibration spectra for the entire flight profile due to varying atmospheric conditions. While the vibration conditions were rated as periodic and moderately predictable (Figure 4-21), the pilot subjects' control strategies did not vary as a result of the dynamic repetition (Section 4.3.3).

In planning this investigation, the experimenters recognized that the fidelity of simulation would be compromised to some degree as a result of the open-loop vibration technique for implementation. However, this was determined to be the better approach in light of two other factors, namely the increased experimental control provided and, to a lesser extent, equipment constraints. It is felt that the vibration conditions did provide adequate motion environments for the study of selected variables, and that the validity of the data and subsequent analyses were not compromised. Several of the subjects indicated that the open-loop nature of the vibrational motion did influence their rating of the motion fidelity. They felt that a closed-loop system, where the crew station motion would also respond to pilot control inputs, would have been more realistic.

The effects of open-loop versus closed-loop motion on pilot performance have not been firmly established and should be examined to facilitate the effective, accurate application of past and current vibration research to operational vehicular systems. If a vibration system could be developed which provides open-loop or closed-loop response with good experimental control of the vibration spectra for both modes, that is an "adaptive" vibration system, their individual effects and the resultant impact for both past and current vibration research could be ascertained.

6.0 CONCLUSIONS

On the basis of the results obtained from this investigation, the following conclusions have been drawn:

- Target tracking performance employing the force control was superior to tracking performance with the displacement control for the time-on-target dependent variable.
- Better airspeed performance was obtained when tracking using the displacement control versus the force control.
- There were no consistent performance differences to suggest the overall superiority of either control type.
- The moderate turbulence (0.11 g_{rms}) did not differentially affect performance from the static condition, but the heavy turbulence and broadband vibration (0.35 g_{rms}) caused similar significant tracking performance decrements.
- Very low frequency vertical vibration (0.2-0.4 Hz) significantly affected pilot performance for target tracking performance measures depending upon the vibration intensity.
- The effects of vibration did not interact with the effects of control type or task loading.
- The high task loading condition, where target tracking and aircraft control were performed simultaneously, resulted in degraded performance, as compared to the low task loading conditions where only one of the tasks was performed.
- Subjective workload ratings increased as task loading and vibration increased.

7.0 PROGRAM OVERVIEW

This study represents the last of a four-phase research effort to examine, systematically, control simplification and integration techniques for the enhancement of aircrew performance.

Specifically, the total program objective was to identify the effects of various tracking control characteristics on pilot performance in manual target tracking tasks. In Phases I-III, a static, part-task flight simulator was utilized while a motion base flight simulator was used in Phase IV (ref. Section 3.2).

During testing, pilot subjects performed target tracking and aircraft control tasks separately for low task loading levels and simultaneously for high task loading levels. Following completion of each experimental session, the subject was administered a debriefing questionnaire. An overview of the experimental conditions that were evaluated is provided in Table 7-1, and the results of the four-phase manual controls program are summarized in Table 7-2.

In the initial phase of the research program, Phase I, force and displacement target tracking controls were compared which were either integrated into the throttle control or independently located (Curtin, et al, 1973). The pilot subjects performed the tasks with and without flight gloves. The results indicated that the displacement control promoted more rapid target acquisition than the force control, but there were no differences in performance between the two controls for time-on-target or tracking error. The integrated control configuration was found to yield more accurate target tracking than the independent control placement. Wearing flight gloves did not affect tracking performance relative to the no-glove test condition. In this study, a repeated measures design was used in which the pilots performed the target tracking task with both the force and displacement controls. The order of presentation of these control types was observed to have a significant effect on pilot performance. When the force control was used first, target tracking was more efficient than when the displacement control was used first. The effects of the independent variables on aircraft pitch, roll, and airspeed control were also analyzed. The results revealed that there were no significant differences among the experimental conditions on the aircraft control tasks. Analysis of the debriefing questionnaire data indicated that the pilots preferred the integrated control configuration and the force control device.

TABLE 7-1

MANUAL CONTROLS PROGRAM OVERVIEW

	PHASE I	PHASE II	PHASE III	PHASE IV
EXPERIMENTAL CONDITIONS				
1. EXPERIMENTAL DESIGN	2X2X2X2 MIXED DESIGN (REPEATED MEASURES ON FIRST THREE FACTORS)	2X2X3X3 MIXED DESIGN (REPEATED MEASURES ON LAST TWO FACTORS)	2X2X2X3 MIXED DESIGN (REPEATED MEASURES ON LAST TWO FACTORS)	2X2X4 MIXED DESIGN (REPEATED MEASURES ON LAST TWO FACTORS)
2. NUMBER OF PILOTS (MILITARY RATED)	16	16	24	16
3. NUMBER OF TRIALS	12 (4 PRACTICE, 8 EXPERIMENTAL)	18 (6 PRACTICE, 12 EXPERIMENTAL)	18 (6 PRACTICE, 12 EXPERIMENTAL)	25 (9 PRACTICE, 16 EXPERIMENTAL)
CONTROL CHARACTERISTICS				
1. CONTROL TYPES	FORCE VS. DISPLACEMENT	FORCE VS. DISPLACEMENT	FORCE VS. DISPLACEMENT	FORCE VS. DISPLACEMENT
2. OUTPUT FUNCTIONS	LINEAR	STEP VS. LINEAR	STEP VS. EXPONENTIAL	EXPONENTIAL
3. CONTROL PLACEMENT	INDEPENDENT VS. INTEGRATED			
4. CONTROL/DISPLAY GAINS	LOW	LOW VS. MEDIUM VS. HIGH	LOW VS. MEDIUM VS. HIGH	MEDIUM
5. FLIGHT GEAR	GLOVES VS. NO-GLOVES	-	-	-
6. TARGET CHARACTERISTICS	-	THREE TARGET SPEEDS	-	-
7. CALCULATION TECHNIQUES	-	-	CONVENTIONAL VS. MODIFIED	MODIFIED
PERFORMANCE TASKS	A/C ATTITUDE, AIRSPEED, AND TARGET TRACKING	A/C ATTITUDE AND TRAGET TRACKING	A/C ATTITUDE, AIRSPEED, AND TARGET TRACKING	A/C ATTITUDE, AIRSPEED AND TARGET TRACKING
TEST ENVIRONMENT	STATIC	STATIC	STATIC	o STATIC o MODERATE TURBULENCE ($.11g_{rms}$) o HEAVY TURBULENCE ($.35g_{rms}$) o BROADBAND ($.35g_{rms}$)

TABLE 7-2 MANUAL CONTROLS PROGRAM RESULTS

PHASE I	PHASE II	PHASE III	PHASE IV
TARGET TRACKING TASK o Control Types: Displacement control promoted more rapid target acquisition than force control. o Control Placement: Integrated controls yielded more accurate target tracking than independent controls. o Flight Gear: No differences in performance between gloves and no-gloves. o Presentation Order: Significant differences in presentation order occurred between control types (force control first yielded better tracking performance).	TARGET TRACKING TASK o Control Types: - No significant main effects. - Force control was superior to displacement control in interactions with output functions for acquisition time, acquisition error, and time on target. o Output Functions: - Linear function resulted in smaller acquisition errors than step function. - Step function produced faster target acquisition and more time on target than the linear function when both were combined with force control. o Target Speed: Increasing target speed decreased tracking performance. o Control/Display Gains: - Medium gain produced more rapid target acquisition than the low and high gains. - Gains interacted with output functions and target speeds.	TARGET TRACKING TASK o Control Types: - No significant main effects. - Force control was superior to displacement control in interaction with gains for percent time on target. o Output Functions: No significant main effects or group comparisons in interactions. o Calculation Technique: Modified technique consistently yielded more efficient target tracking performance than conventional technique. o Control/Display Gains: - Medium and high gains resulted in more rapid target acquisition and accurate target tracking. - Low gain resulted in fewer acquisition overshoots and greater percent time on target. - Gains interacted with control types, output functions, and calculation techniques.	TARGET TRACKING TASK o Control Types: - The force control was superior to the displacement control. o Task Loading: - The high task loading condition, simultaneous target tracking and aircraft control, was associated with performance decrements from the low task loading conditions where the tasks were performed separately. - Task loading did not interact with vibration. o Vibration: - The heavy turbulence and broadband spectra (.35 g_{rms}) significantly impaired tracking performance. - The moderate turbulence (.11 g_{rms}) did not significantly impair tracking performance.
AIRCRAFT CONTROL TASK Aircraft control was not affected by the various target tracking variables.	AIRCRAFT CONTROL TASK Aircraft control was significantly related to output functions, target speeds, and control/display gains; but not control types.	AIRCRAFT CONTROL TASK Aircraft control was differentially affected by output functions, calculation techniques, and control/display gains; but not control types.	AIRCRAFT CONTROL TASK Aircraft control was differentially affected by control types, task loading and vibration conditions.
DEBRIEFING QUESTIONNAIRE o Integrated tracking controls was the preferred configuration. o Force control was preferred to the displacement control.	DEBRIEFING QUESTIONNAIRE o Displacement control with step function considered undesirable for operational application. o No consistent preferences for other three control type/output function combinations.	DEBRIEFING QUESTIONNAIRE o Pilot workload was slightly to moderately more than in "real-world" o Pilots preferred the modified calculation technique and the medium control/display gain.	

The Phase II investigation examined various control and display characteristics in relation to the throttle integrated control device[1] that was used in the first research phase (McGuinness, et al, 1974). The experimental variables included two types of control action (force and displacement), two control output functions (linear and step), three control/display gains, and three target speeds. With respect to control action, an evaluation of the data revealed that there were no significant main effects, but control action was found to interact with output functions to yield significantly different effects on target tracking performance. In the interactions, it was observed that the force control was superior to the displacement control with the step output function for acquisition time, acquisition error, and time-on-target. There were no significant differences in target tracking between the force and displacement controls with the linear output function. With regard to output functions, a significant main effect obtained in the analyses of variance revealed that the linear function was associated with significantly smaller acquisition errors than the step function. For the control action versus output function interactions, the step function produced faster target acquisition time and increased time-on-target scores than the linear function when both of these outputs were compared in relation to the force control. There were no differences between output functions with the displacement control. The results associated with control/display gains and target speeds emphasized the importance of interactions in this study, since the characteristic effects of these conditions were dependent upon the variables with which they were combined. In general, increasing the speed of the targets decreased tracking performance, and the medium control gain produced more efficient performance than the low and high gain conditions. In contrast to Phase I, aircraft flight control performance was affected by the experimental variables. It was observed that aircraft control was differentially affected by output functions, target speeds, and control/display gains. In the debriefing questionnaire administered after completion of the test session, the pilots consistently indicated that the displacement control with the step output function was undesirable for operational implementation. The ratings for the remaining three combinations of controls and output functions yielded no consistent preferences.

[1]The same integrated force control was used for all four phases. However, for the integrated displacement control, a four-position trim switch was used for Phase I, while a miniature springloaded joystick was used in Phases II, III, and IV.

Phase III was designed to study the effects of cursor control calculation techniques, step and exponential output function, and control/display gains on pilot performance employing the integrated force and displacement controls. One major result from this investigation was that the modified calculation technique significantly improved tracking performance as compared to the conventional calculation technique for the two nonlinear output functions. No meaningful performance differences were found between control types or output functions. Control/display gains had significant main and interaction effects on subject pilot performance. In general, the medium and high gains resulted in more rapid target acquisition and increased target tracking accuracy, whereas, the low gain resulted in fewer acquisition overshoots and higher percent of time-on-target scores. In this study phase, aircraft flight control performance was differentially affected by the calculation techniques, output functions, and control/display gains, but control types did not have a differential effect upon performance. The debriefing questionnaire indicated that the pilot workload experienced for total task performance was moderately beyond the normal workload encountered under actual flight conditions. Subjects also expressed a preference for the modified calculation technique and the medium control/display gain.

As described in the body of this report, the final phase of this research effort examined the use of the integrated tracking controls under several vibration environments. This study examined the pilot performance with the force and displacement tracking controls under static and three vertical open-loop vibration conditions. The moderate and heavy turbulence vibration conditions were representative of fighter/attack aircraft response to turbulent atmospheric conditions and were characterized by random vibration (0.1 to 20.0 Hz) concentrated in the 0.2 to 0.4 Hz range. The intensities of the moderate and heavy turbulence conditions were 0.11 g_{rms} and 0.35 g_{rms} respectively. The broadband vibration condition also had a 0.35 g_{rms} intensity, but was equally distributed across the 0.2 to 20 Hz range. The motion base simulator described in Section 3.2 contained the simulated crew station and, through the five degree of freedom motion system, provided the selected vibration spectra. The target tracking and aircraft control tasks were performed either separately (low task loading) or simultaneously (high task loading). The results of this study indicated that the force control provided superior target tracking

performance as compared to the displacement control. The high task loading condition significantly decreased pilot performance of the target tracking and aircraft control tasks when compared to the low task loading conditions where the tasks were performed independently. The high amplitude (0.35 g_{rms}) vibration conditions (heavy turbulence and broadband) significantly degraded subject performance when compared to the static and low amplitude vibration conditions. The moderate turbulence did not differentially affect pilot performance compared to the static condition, nor did the heavy turbulence and broadband vibration conditions differ in their effects on performance. These findings suggest that very low frequency vibration, less than 10 Hz, can significantly affect performance, depending upon the intensity level. Also, dissimilar vibration spectra can have similar effects upon operator performance depending upon vibration intensity and individual tolerance to the spectral frequency components.

A residual benefit from this program is a survey of target tracking controls and their operational applications for secondary flight tracking tasks (Drennen, 1976). Detailed information is presented which describes the types of controls and their characteristics for present U.S. attack/fighter aircraft. Anomalies and inadequacies related to current applications are discussed concomitant with recent, pertinent research. Future applications of similar controls and potential research areas are also described.

In summary, the results of this four phase program indicate that the integration of secondary tracking controls into the throttles can significantly improve pilot performance and that the characteristics of these controls can significantly affect aircraft control performance, as well as target tracking performance.

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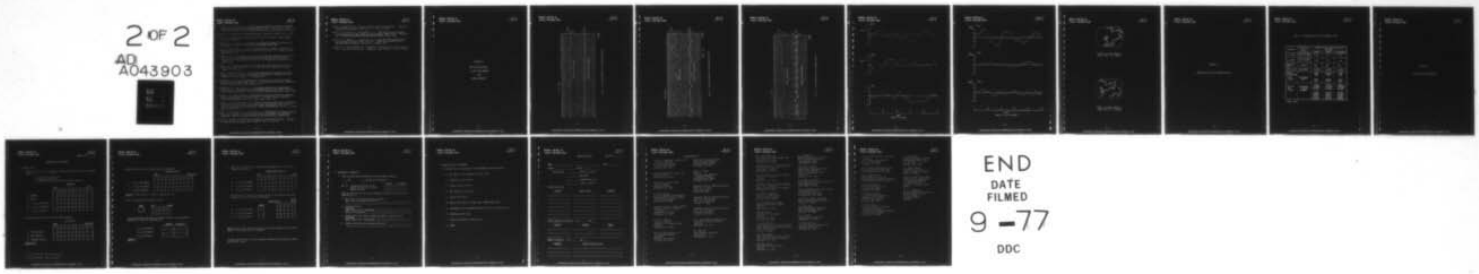

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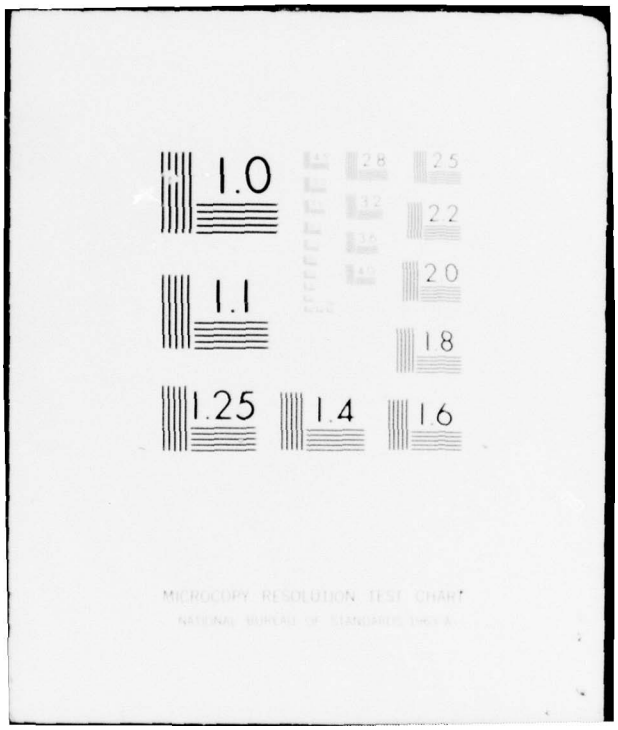
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APPENDIX A

CREW STATION MOTION, FLIGHT PATH COMMAND AND TARGET MOVEMENTS

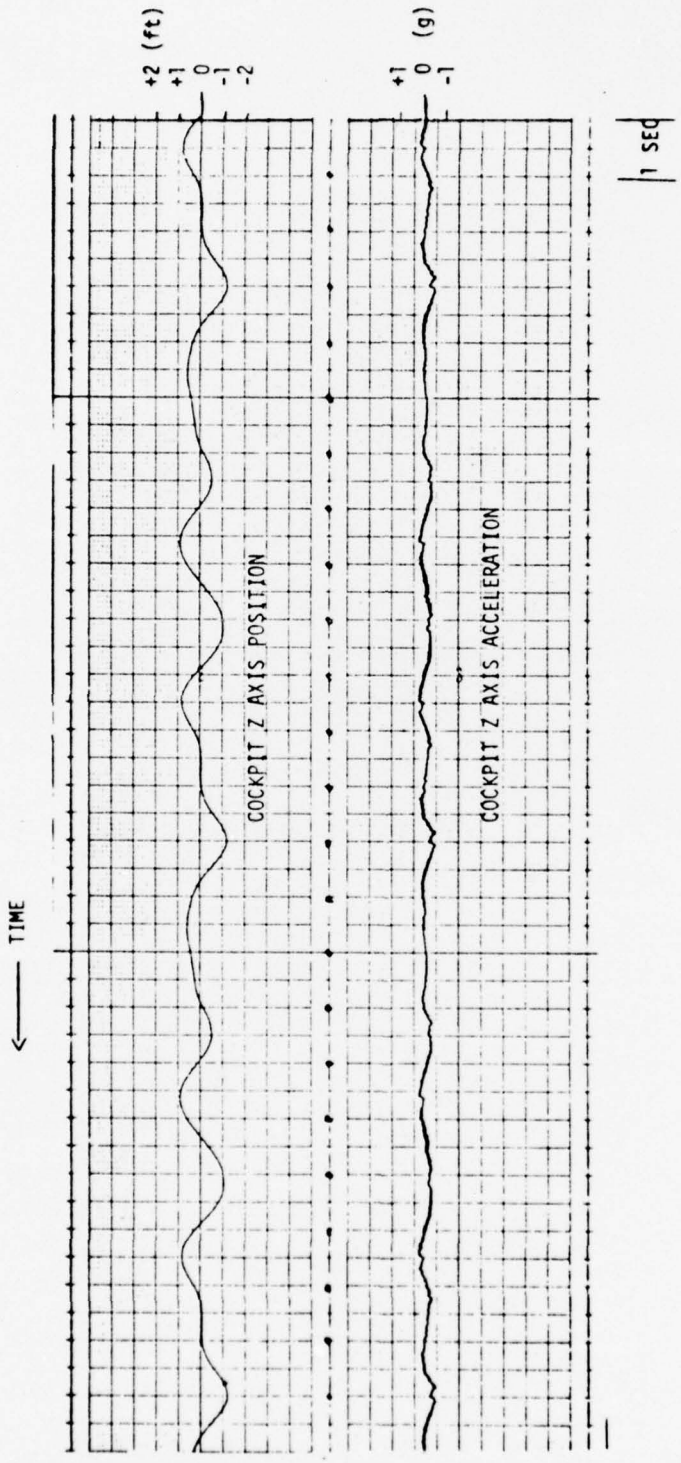

FIGURE A-1 STRIP CHART RECORDING OF LIGHT TURBULENCE CONDITION

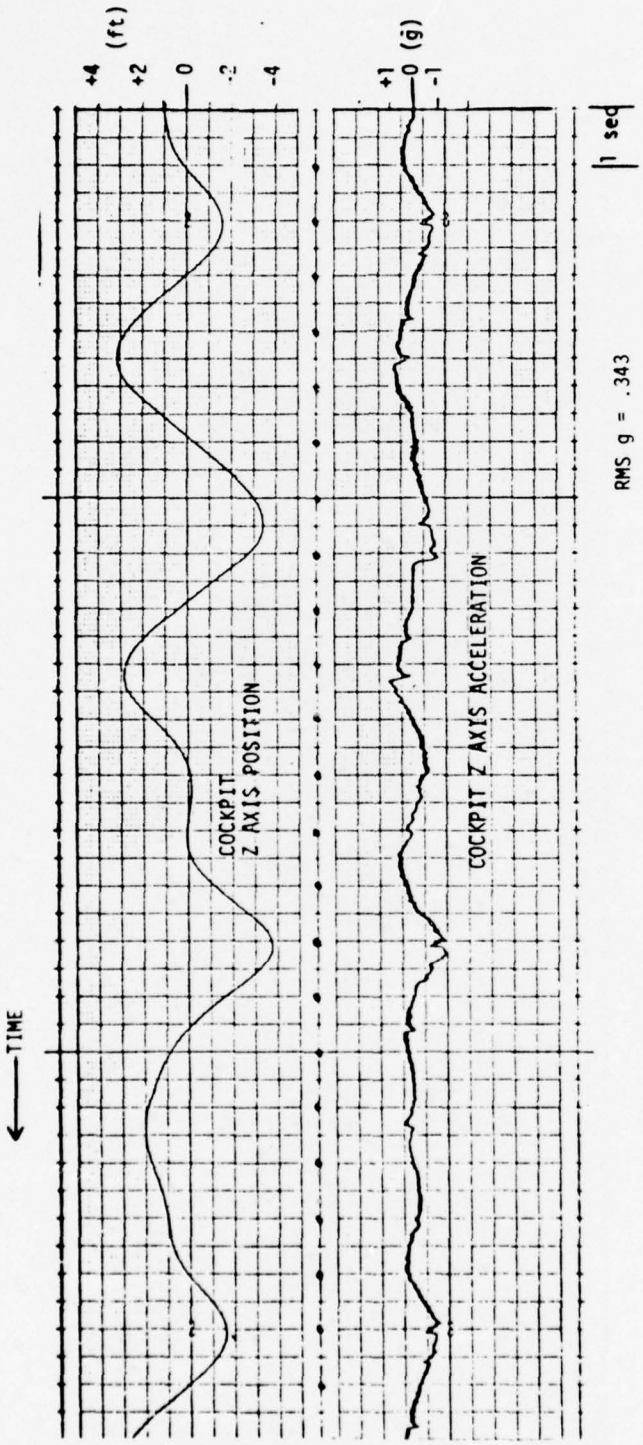

FIGURE A-2 STRIP CHART RECORDING OF HEAVY TURBULENCE CONDITION

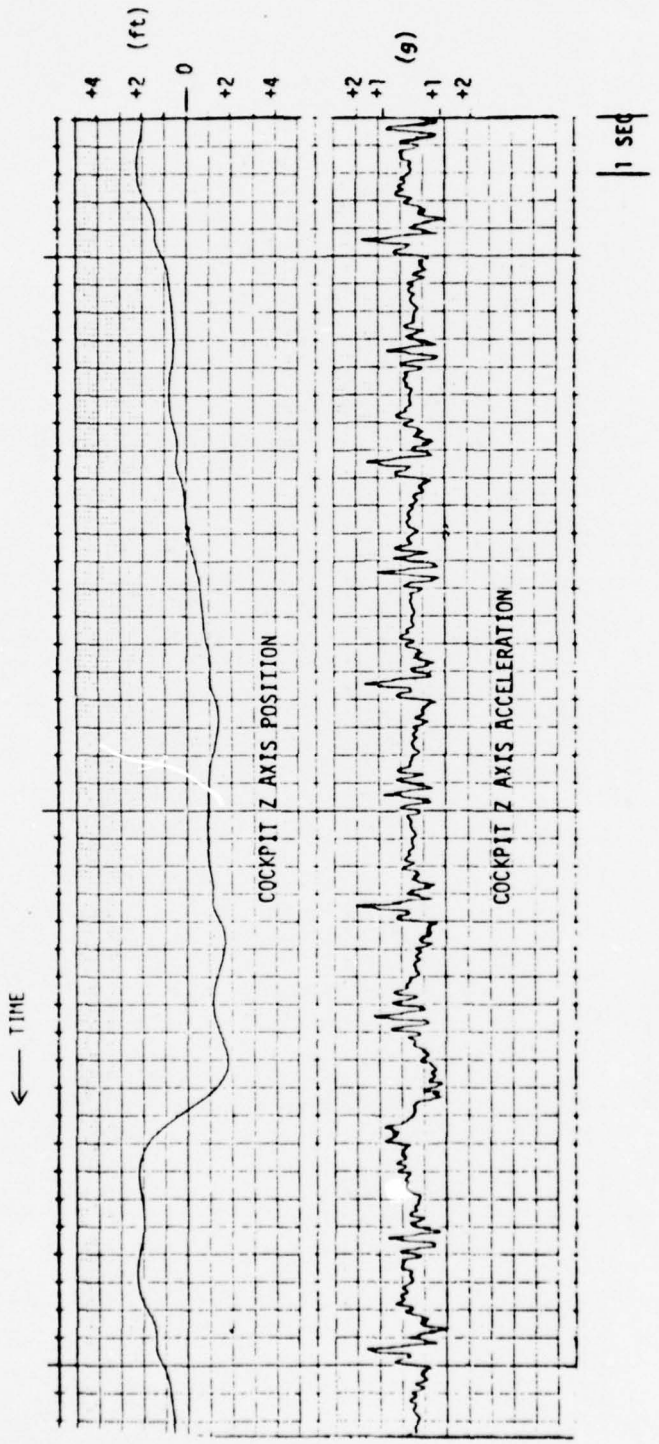

FIGURE A-3 STRIP CHARTING RECORDING OF BROADBAND CONDITION

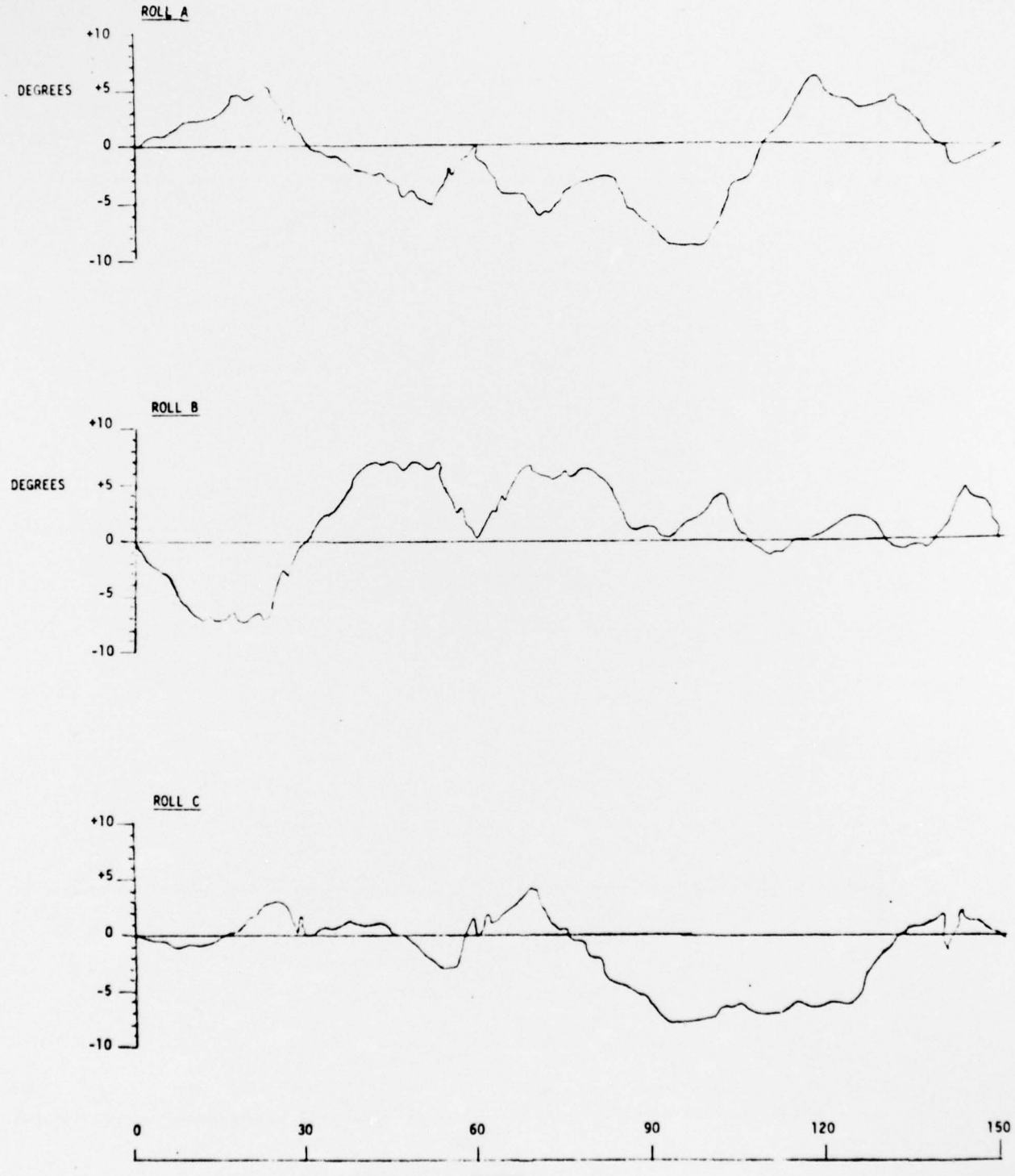

FIGURE A-4 ROLL COMMANDS

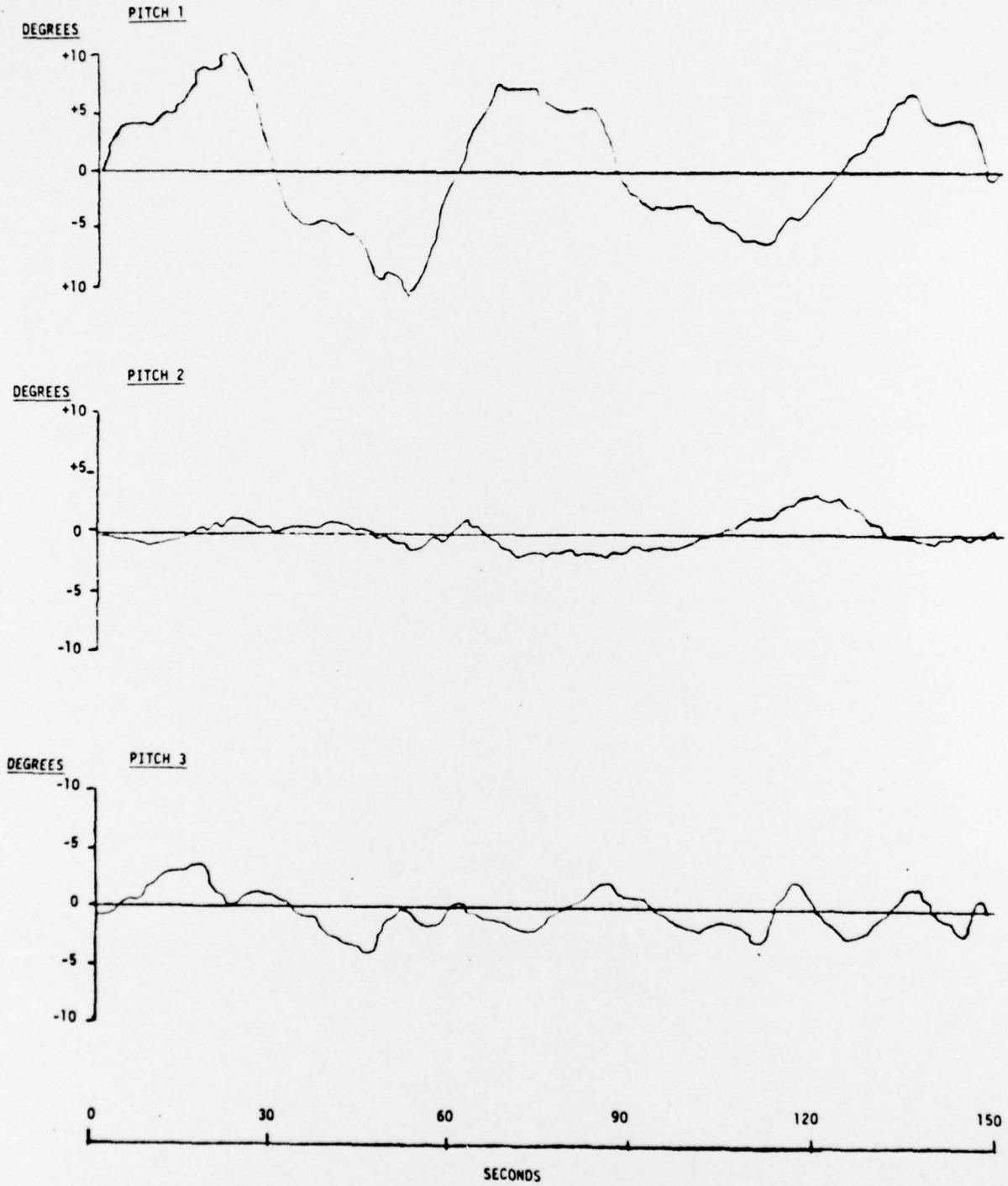

FIGURE A-5 PITCH ATTITUDE COMMANDS

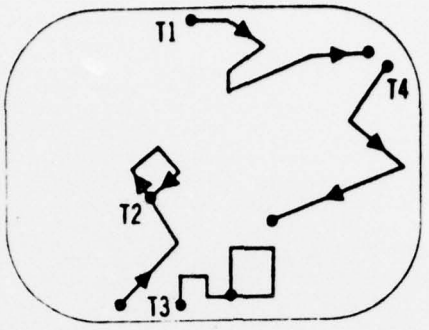

FIGURE A-6 TARGET GROUP I
TARGET SPEED = 0.1 IN./SEC

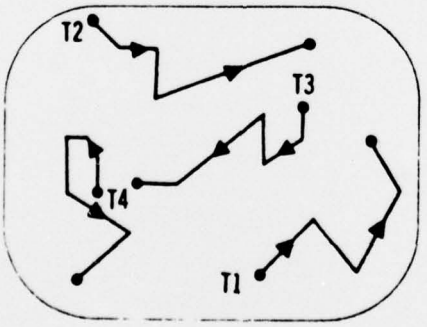

FIGURE A-7 TARGET GROUP II
TARGET SPEED = 0.1 IN./SEC

APPENDIX B

CONVERSION TABLE FOR ALTERNATIVE UNITS

TABLE B-1 CONVERSION TABLE FOR ALTERNATIVE UNITS

VARIABLES	REPORTED UNITS WITH UNITY VALUES	ALTERNATIVE UNITS WITH EQUIVALENT VALUES (VISUAL ARC)		
		MINUTES	DEGREES	MILLIRADIANS
PITCH ERROR	1^0 PITCH ATTITUDE (.063 IN. ON ADI)	7.413	.124	2.156
ROLL ERROR	1^0 ROLL ATTITUDE (.033 IN. ON ADI)	3.914	.065	1.139
ACQUISITION ERROR	1 IN. ON CRT	118.6	1.976	34.5
TARGET SPEED	IN/SEC ON CRT	118.6/SEC	1.976/SEC	34.5/SEC
CONTROL/ DISPLAY RATIOS:		2.5/SEC / OZ.	0.0415/SEC / OZ.	7.2/SEC / OZ.
a. FORCE - CONTROL	IN/SEC ON CRT / 48 OZ	40/SEC / LB	0.667/SEC / LB	1.2/SEC / LB
b. DISPLACEMENT CONTROL	IN/SEC ON CRT / 17^0 CONTROL MOVEMENT	7/SEC / 1^0 CONTROL MOVEMENT	0.116/SEC / 1^0 CONTROL MOVEMENT	2.0/SEC / 1^0 CONTROL MOVEMENT
		400/SEC / RADIAN OF CONTROL MOVEMENT	6.65/SEC / RADIAN OF CONTROL MOVEMENT	115.9/SEC / RADIAN OF CONTROL MOVEMENT

*1 INCH = 2.54 cm

APPENDIX C

DEBRIEFING QUESTIONNAIRES

SUBJECT NO. _____

DEBRIEFING QUESTIONNAIRE

A. RATING SCALES

1. Rate the level of pilot workload for each task under each test environment. Where:

   1 = A/C flight control only
   2 = target tracking only
   3 = combined A/C flight control and target tracking

WORKLOAD

	LOW								HIGH
1	2	3	4	5	6	7	8	9	10
		2		1	3				

a. Example
b. Static
c. .11 g_{rms} Narrowband*
d. .35 g_{rms} Narrowband*
e. .35 g_{rms} Broadband

2. Rate the fidelity of the aircraft flight dynamics.

A/C FIDELITY

	POOR								EXCELLENT
1	2	3	4	5	6	7	8	9	10

a. Pitch Response
b. Roll Response
c. Airspeed Response

IMPROVEMENTS?

* .11 g_{rms} Narrowband = Moderate Turbulence
  .35 g_{rms} Narrowband = Heavy Turbulence

3. Rate the fidelity of the three dynamic environments.

MOTION FIDELITY

	POOR									EXCELLENT
	1	2	3	4	5	6	7	8	9	10
a. .11 g_{rms} Narrowband										
b. .35 g_{rms} Narrowband										
c. .35 g_{rms} Broadband										

COMMENTS? (Applicability, severity, regularity, etc.)

4. Did you experience any motion sickness?

NONE	MILD				SEVERE
	1	2	3	4	5

If you experienced some degree of motion sickness, which vibration condition(s) induced or aggravated it?

	INDUCED	AGGRAVATED
.11 g_{rms} Narrowband		
.35 g_{rms} Narrowband		
.35 g_{rms} Broadband		

COMMENTS?

5. Rate the predictability of the motion characteristics for the three vibration conditions.

MOTION PREDICTABILITY

	LOW 1	2	3	4	5	6	7	8	9	HIGH 10
a. .11 g_{rms} Narrowband										
b. .35 g_{rms} Narrowband										
c. .35 g_{rms} Broadband										

Did you hurry or delay your control inputs in anticipation of cockpit motions within each vibration condition?

	NEVER	OCCASIONALLY 1	2	3	4	QUITE OFTEN 5
a. .11 g_{rms} Narrowband						
b. .35 g_{rms} Narrowband						
c. .35 g_{rms} Broadband						

Which control inputs did you hurry or delay in anticipation of the cockpit motions? Which were hurried? Delayed?

To what cockpit motions in each vibration condition did you hurry or delay your control inputs?

B. BACKGROUND INFORMATION

1. Have you previously performed any similar target tracking?

___ Yes _____ No (Go on to Section C)

Was it:	AIR/AIR	AIR/GROUND
simulator practice missions	_____	_____
actual A/C practice missions	_____	
combat missions	_____	

What was the nature of the target tracking situation as you previously experienced it?

a. A/C flight control during target tracking:
What aircraft and mode (A/A, A/G)? _____
_____

b. Tracking control:
Placement? _____
Hand, finger, etc., controlled? _____
Force or displacement? _____

c. Target acquisition button (target designator, target lock-on):
Placement? _____
Hand, finger, etc., controlled? _____

d. Target tracking display and mode (A/A, A/G): _____
_____

C. SUGGESTIONS FOR IMPROVEMENT

1. Do you have any suggestions for improvement of the experiment?

a. A/C control stick (dynamics, forces, etc.):

b. Target Designator button:

c. Target tracking control:

d. ADI commanded flying task:

e. Target CRT display:

f. Motion characteristics (open loop, closed loop, etc.)

g. Experimental test procedures (practice trials, test runs, etc.):

h. Airspeed control task:

i. Throttle (placement, design, etc.):

j. Other:

PILOT DATA SHEET SUB NO. _____ __

NAME _____ DATE _____

HEIGHT: _____ WEIGHT: _____

AFFILIATION: _____ MCAIR TEST PILOT

_____ MILITARY

_____ ENGINEERING PILOT

_____ OTHER - SPECIFY

FLIGHT EXPERIENCE:

AIRCRAFT	HOURS LOGGED	CURRENT?

FLIGHT SIMULATOR EXPERIENCE: YES _____ NO _____

FACILITY	PURPOSE	HOURS

COMBAT EXPERIENCE: YES _____ NO _____

AIRCRAFT	TYPE OF MISSION FLOWN

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