UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING

INSTITUTE OF SOUND AND VIBRATION RESEARCH

Doctor of Philosophy

THE EFFECTS OF VIBRATION ON THE PERFORMANCE OF HUMAN OPERATORS IN CONTINUOUS MANUAL CONTROL SYSTEMS

by Christopher H. Lewis

The first part of this thesis comprises a review of current knowledge concerning the effects of vibration on manual control performance. This covers the incidence of known problems experienced in real vibration environments and the results of laboratory studies to determine the nature of these problems. The task and vibration variables which have been shown to affect the sensitivity of a task to vibration are discussed separately. Other sections are concerned with the measurement of continuous manual control or tracking performance in vibration environments, general conclusions about the nature and mechanisms of the effects of vibration on tracking and the application of these conclusions in the form of predictive models. The procedures and results of most of the laboratory studies of vibration and tracking performance are separately summarised as an appendix, as a convenient guide to the relevant literature.

Despite the range of interest and information that has been covered in the forty or so papers which have been reviewed, most of the general conclusions which can be drawn from the results of the research are not very far reaching and none are without disagreement. In addition to shortcomings in experimental methodology and measurement techniques very little consideration has been given to the great number of variables which may affect the sensitivities of manual control systems to vibration. It is concluded that the prediction of the effects of vibration on the control of projected systems and the identification of vibration effects in existing systems would benefit from an improved knowledge of the basic mechanisms by which vibration interferes with the performance of the human operator in manual control systems.

The second part of the thesis describes five experiments in which advanced performance measurement techniques are used to investigate the effects of vibration on the performance of a simple pursuit tracking task. Particular objectives of this research were to attempt to isolate some of the mechanisms by which vibration affects manual control performance and to determine the importance of possible interactions between control characteristics and vibration effects. Task variables investigated included control type and gain, and vibration variables included frequency level, duration, point of application and waveform.

The primary effects of vibration on the performance of the tracking task were found to be increases in tracking error variance due to vibration-induced control activity and increased operator-generated noise or remnant. The increase in remnant activity during low frequency vibration may be accounted for by increased perceptual noise caused by vibration-induced activity of the controlled element in the display, which is dependent on biodynamic factors and control gain. The effect is constant during vibration exposures up to one hour and there are no indications of any after-effect of vibration. The effect of a complex vibration waveform on the overall tracking error variance was successfully predicted from the root mean square sum of weighted frequency components of the vibration, however the results of predictions of individual error components indicates that caution should be exercised in the application of this conclusion.

I would like to express grateful thanks to all those who helped in the production of this thesis. Some of the research reported in the thesis was supported by the Procurement Executive, Ministry of Defence.

TABLE OF CONTENTS

1. GENERAL INTRODUCTION.

The human body is a complex system, comprised of a large number of hierarchically related subsystems which must be maintained in a stable balance if the whole is to function efficiently. Each human being, in turn, exists in a delicate balance with his environment and other parts of a much larger life system or ecosystem. The human system is only able to maintain its stability as long as it is able to adapt to changes in the environment: in other words it must possess an adequate variety of response, or have as many ways of countering outside disturbances as there are outside disturbances acting on it*.

A unique feature of man, compared to other life forms, is the way in which he is able to control his environment. The extent to which he has been able to control his environment is in proportion to the extent to which he has been able to harness and control external energy sources. However the use of external energy sources results in some side effects on the environment which are not particularly desirable. This thesis is concerned with the way in which one such side effect, vibration, can affect the performance of continuous manual control, or tracking, by a human operator. Manual tracking is the fine adjustment of a controlling device in continuous response to some command function, as in the control of vehicles of all kinds, externally powered tools and weapons.

In the past, the adaptability of the human operator in engineering systems has been exploited to a considerable degree by the designers of systems. Equipment was designed largely for engineering convenience and the operator had to match himself to the system as well as he could. However as equipment became more complex, the speed and variety of response expected from the operator was considerably increased and, in addition, he was often expected to perform under less natural environmental conditions. Around the time of the second world war it became obvious that the limits of human adaptation had been reached and exceeded, and that the performance, safety and health of human operators were being severely compromised. This realisation triggered off a revolutionary movement in science, led by such as Wiener, Rosenbleuth, Tustin and Craik, which was given added impetus by the urgency of the war effort. The revolution gained a new foothold after the war with the establishment of the new, multi-disciplinary sciences of Cybernetics and

Ergonomics and a great deal of knowledge has now been accumulated about the characteristics of the human operator which engineers can use to design systems which match the man. However even though quite a lot is known about the responses of the operator to some situations and environments, little is known about his responses to some others.

Human response to vibration is one area which has not been rigorously documented to date, in spite of problems in many real systems which can be related to vibration. One reason for this is that the effects of vibration are very complex and varied: some aspects have been studied closely although the quality of the results has been variable, while other aspects have been virtually ignored. The effects of vibration on manual control is one of the less well studied areas, whereas manual control performance without vibration has been extensively studied.

This thesis can be divided into two parts. The first part, which is comprised of chapters two and three, is a review of current knowledge concerning the effects of vibration on manual control and covers the incidence of known problems experienced in real vibration environments as well as the results of laboratory studies to determine the nature of the problem. It is evident from this review that the conclusions which can be drawn from most of the past work are not very far reaching. Furthermore there are a number of apparent contradictions between the results of different studies, making it very difficult to apply them in a general case. A number of shortcomings in experimental methodology which could have contributed to such contradictions are discussed in chapter three. It is concluded that the prediction of the effects of vibration on the control of projected systems and the isolation of vibration effects in existing systems would benefit from an improved knowledge of the basic mechanisms by which vibration interferes with the performance of the human operator in manual control systems. The second part of the thesis, which is comprised of the remaining seven chapters, describes five experiments which use advanced performance measurement techniques to attempt to isolate some of the mechanisms by which vibration affects the performance of human operators in manual control systems. Particular emphasis is placed on the possible effects of vibration on neuromuscular processes and on the interaction between control characteristics and vibration effects.

*See The Gaia Hypothesis by L. Margulis and J. Lovelock: in the Co-Evolution Quarterly, summer 1975.

2. VIBRATION IN THE ENVIRONMENT AND ITS EFFECTS ON HUMAN PERFORMANCE.

The sections of this chapter describe the nature and occurrence of whole-body vibration in the real world, and some ways in which it has been observed to affect human performance.

2.1 Characteristics of Vibration.

The term 'vibration' has been used to describe a number of varied phenomena. In the present context we will consider as vibration any sustained, structure borne disturbance applying a periodic or random, translational or rotational movement to the body or its parts, which is perceived by the senses other than hearing.

Vibration has frequency, magnitude and direction: all three parameters must be specified in order to describe a particular vibration. The simplest vibrations are characterized by periodic motions, which can be described by a time-varying function whose waveform exactly repeats itself at regular intervals. The time interval required for one complete repetition, or cycle, is the period, T, and the fundamental frequency, fo, is the number of periods per unit time. The simplest periodic vibration is simple harmonic motion, the displacement varying sinusoidally with one constant frequency. All other periodic motions can be resolved into a Fourier Series, consisting of a number of sinusoidal components, or harmonics, with various amplitudes and phases. The frequencies of the harmonic components are all integral multiples of the fundamental, fo.

Random vibration, however, does not contain periodic components, but consists of a statistical distribution over time of an infinite number of frequencies, amplitudes and phases. A third class of vibrations, which are not quite periodic and not quite random, are referred to as either almost periodic or pseudo random. These consist of a sum of sinusoidal components whose frequencies are not harmonically related.

The magnitude of a particular vibration can be measured in terms of displacement or its time derivatives, velocity and acceleration. Acceleration is usually the easiest to measure and is therefore the most frequently encountered term. Acceleration can be measured either in dimensional units such as ms^{-2}, or in non-dimensional g units where one g is equivalent to the acceleration of a free-falling body due to gravity and equal to 9.81 ms^{-2}. Acceleration, velocity and displacement may be defined by peak values or by the average or root mean square levels. These are related by the crest factor, which is defined as the ratio of peak amplitude to the root mean square level. Sinusoidal motions have a constant crest factor of $2^{\frac{1}{2}}$, but the crest factor of an irregular, random motion may be much higher.

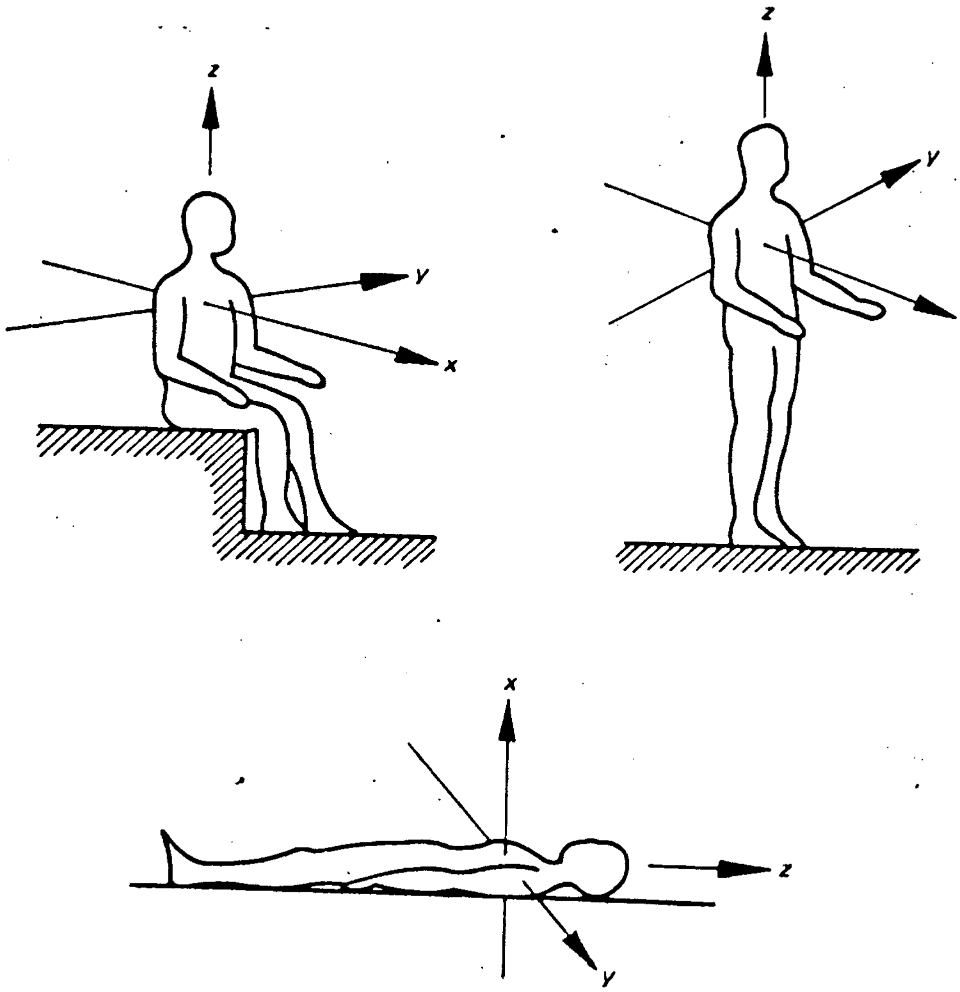
The direction of vibration acting on the human body can be defined relative to six orthogonal axes which have been defined by the International Standards Organisation (1974), hence any motion may be resolved into components in these six (three translational and three rotational) axes, which are defined in figure 2.1.1.

2.2. VIBRATION IN TRANSPORTATION.

Man is most commonly exposed to vibration in vehicles. Vibration in vehicles is generated by out-of-balance forces in moving parts within the vehicle or by external forces acting upon it from the atmosphere, terrain, etc. (see figure 2.2.1.). These vibrations are modified by the dynamics of the vehicle, which usually contains a number of resonant structures.

The data from Griffin (1974) shown in figure 2.2.3. gives typical rms vibration acceleration levels, measured in the three translational axes in various road vehicles. These data were obtained from spectra weighted according to the function proposed in the guide for the evaluation of human exposure to whole-body vibration by the International Standards Organisation (ISO,1974). These results indicate that average vibration acceleration levels in the vertical axis are typically greater than those in the horizontal axes, and as a consequence of this most of the vehicle vibration data published to date is for motion in the vertical axes only. However, some vehicles can exhibit fairly high acceleration levels in the horizontal axes. For instance, in helicopters there are large structures rotating in the horizontal plane, inducing considerable structural vibration in the lateral and longitudinal axes of the aircraft. Vibration spectra, measured at the floor of Sioux and Scout helicopters, by Griffin (1972), are given in figure 2.2.4. It can be seen that the vibration within the helicopter consists of a number of discrete components, varying only slightly in

FIG 2.1.1. Co-ordinate system for mechanical vibrations affecting humans (after ISO, 1974).



Translational vibration axes.	Rotational vibration axes.
x axis = back to chest.	roll = rotation about x axis.
y axis = right to left side.	pitch= rotation about y axis.
z axis = foot (or buttocks) to head.	yaw = rotation about z axis.

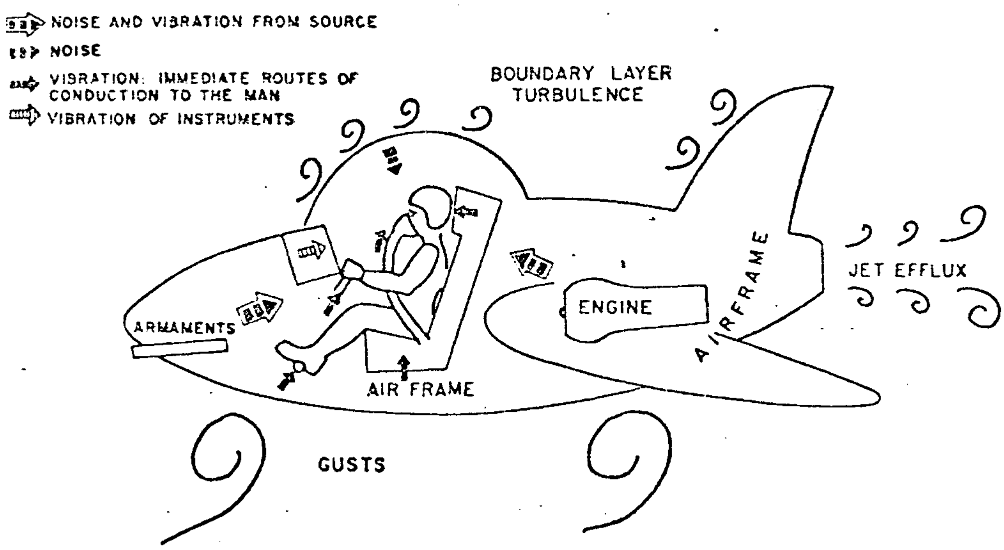
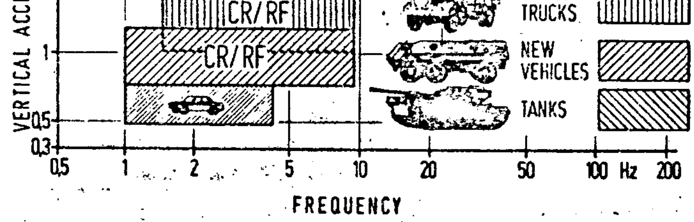


Diagram showing the principal sources and paths of conduction of vibration and noise to the pilot of a high-speed jet aircraft.

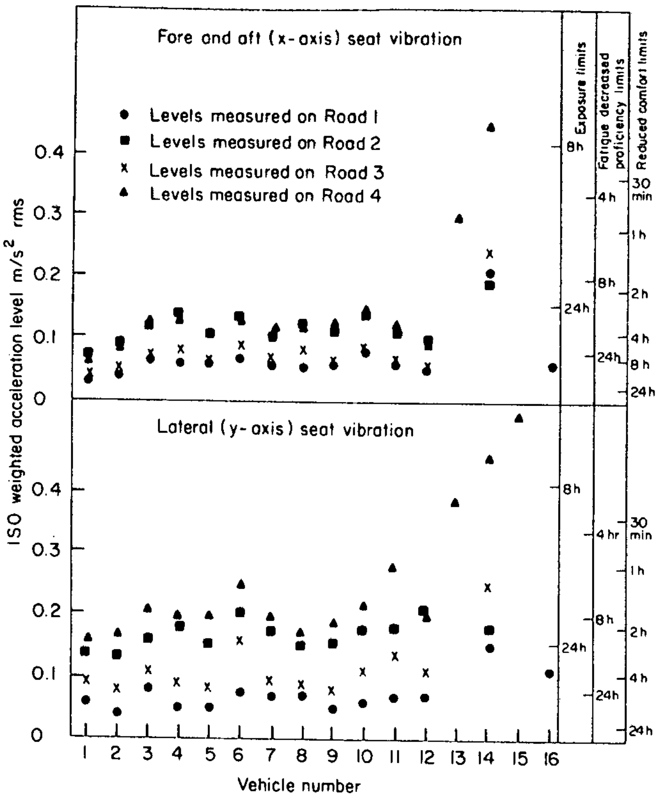
FIG 2.2.1. after Guignard (1965)



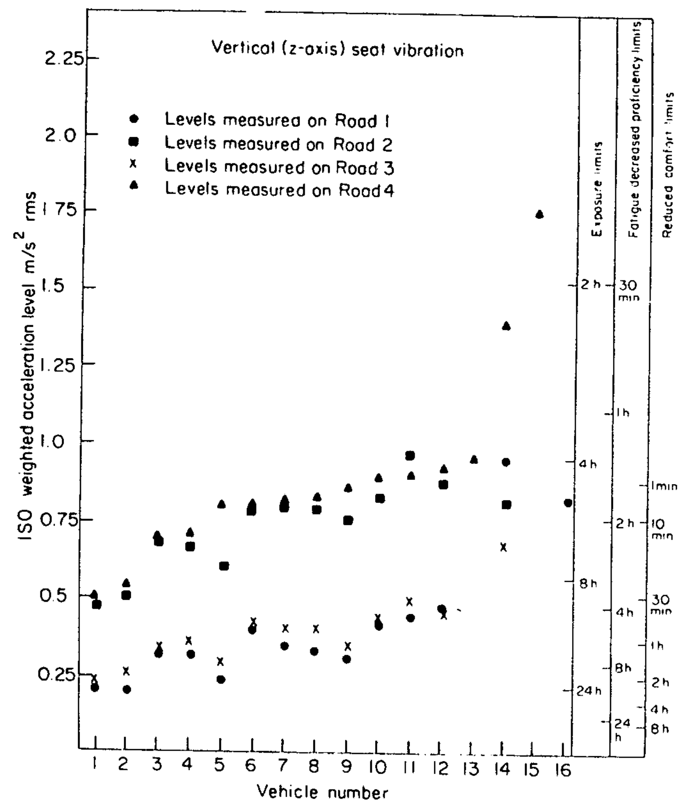
Vertical accelerations in military vehicles on different terrain surface

FIG 2.2.2. after Dupuis (1974)

FIG 2.2.3. after Griffin (1974).



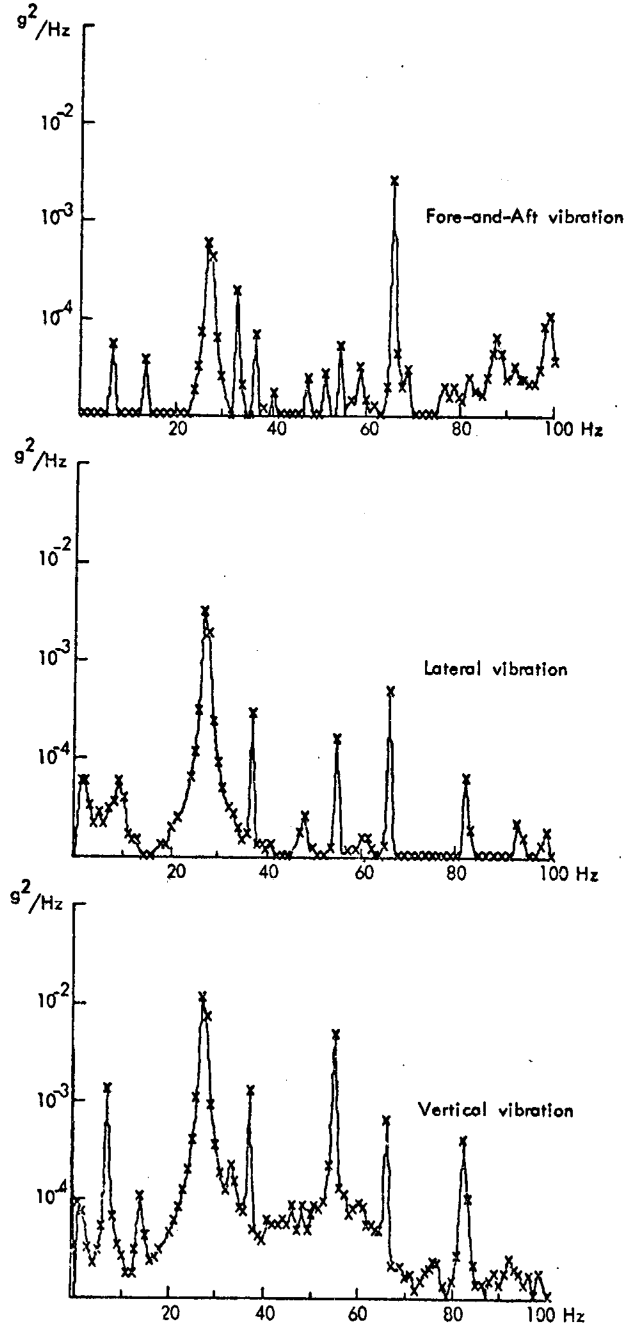
a. ISO weighted vibration levels measured on the seats of 16 vehicles in the horizontal directions



b. ISO weighted vibration levels measured on the seats of 16 vehicles in the vertical direction

Vehicle characteristics

Vehicle number	Description of vehicle	Engine capacity (cc)	Overall length (m)	Overall width (m)	Seat construction	Country of origin
1	Small low cost 5-door car	850	3·63	1·50	Metal and foam (bench)	France
2	Luxury car	2000	4.60	1.67	Mainly foam	UK
3	Family saloon	1593	4·27	1·70	Metal springs and foam	UK
4	Popular small car	1298	3·99	1·60	Metal springs and foam	UK
5	Estate	1498	4·30	1·59	Metal springs and foam	Sweden
6	Sports verson of popular small car	1998	3·88	1·52	Rubber and foam	UK
7	Popular light car	875	3·25	1·52	Rubber and foam	UK
8	Popular small car	1157	4·14	1·64	Metal springs and foam	UK
9	Popular small car	1500	4·06	1·55	Coiled metal springs	Germany
10	Small estate	1098	3·78	1·52	Rubber and foam	UK
11	Small van	1000	3·28	1·42	Metal springs and foam	UK
12	12 seat light bus	1724	4·39	1·88	Wood, metal, rubber and foam	UK
13	Double deck bus with 40 passengers.	Measurements middle top deck.			Light metal frame & foam seat	UK
14	Common 5995 cc truck (unladen) gross weight 9750 kg. Foam seat					UK
15	Single deck 48 seat bus with 12 passengers. Measurements on rear seat.				Foam seat	UK
16	Electric train (98 seats) 7 passengers, rear end of 3rd of 4 cars. length 19·32 m, width 2·82 m. Foam seat					UK



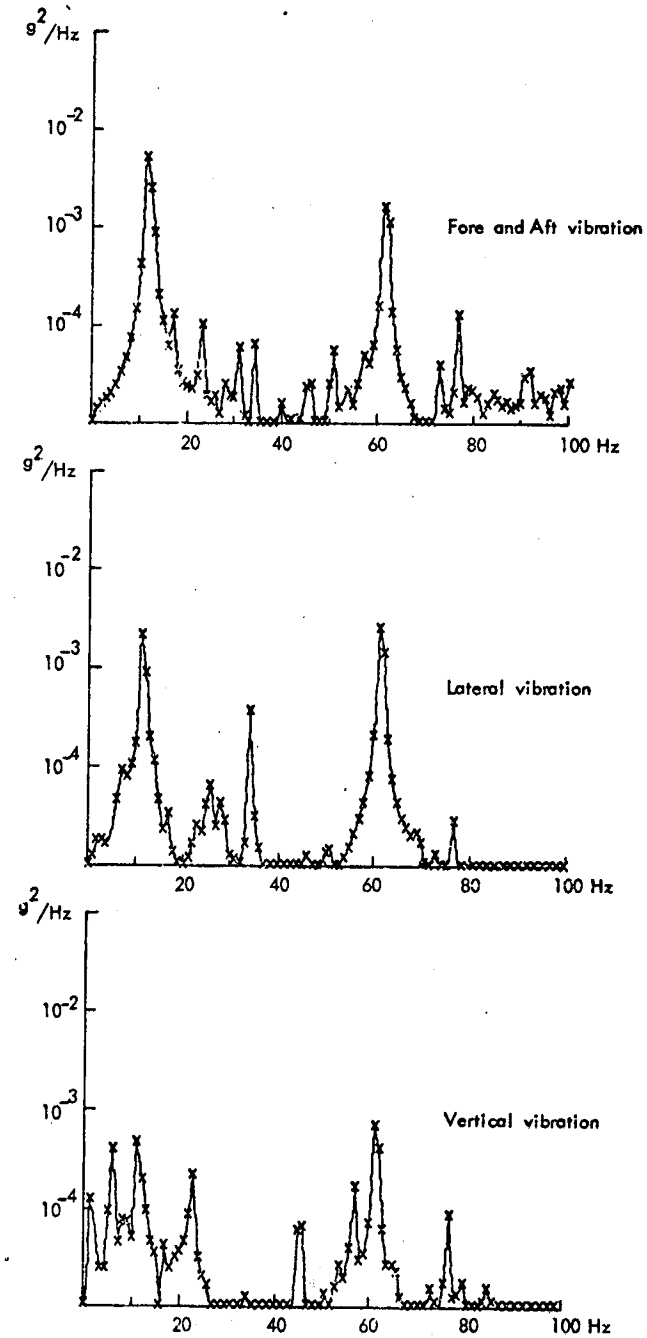


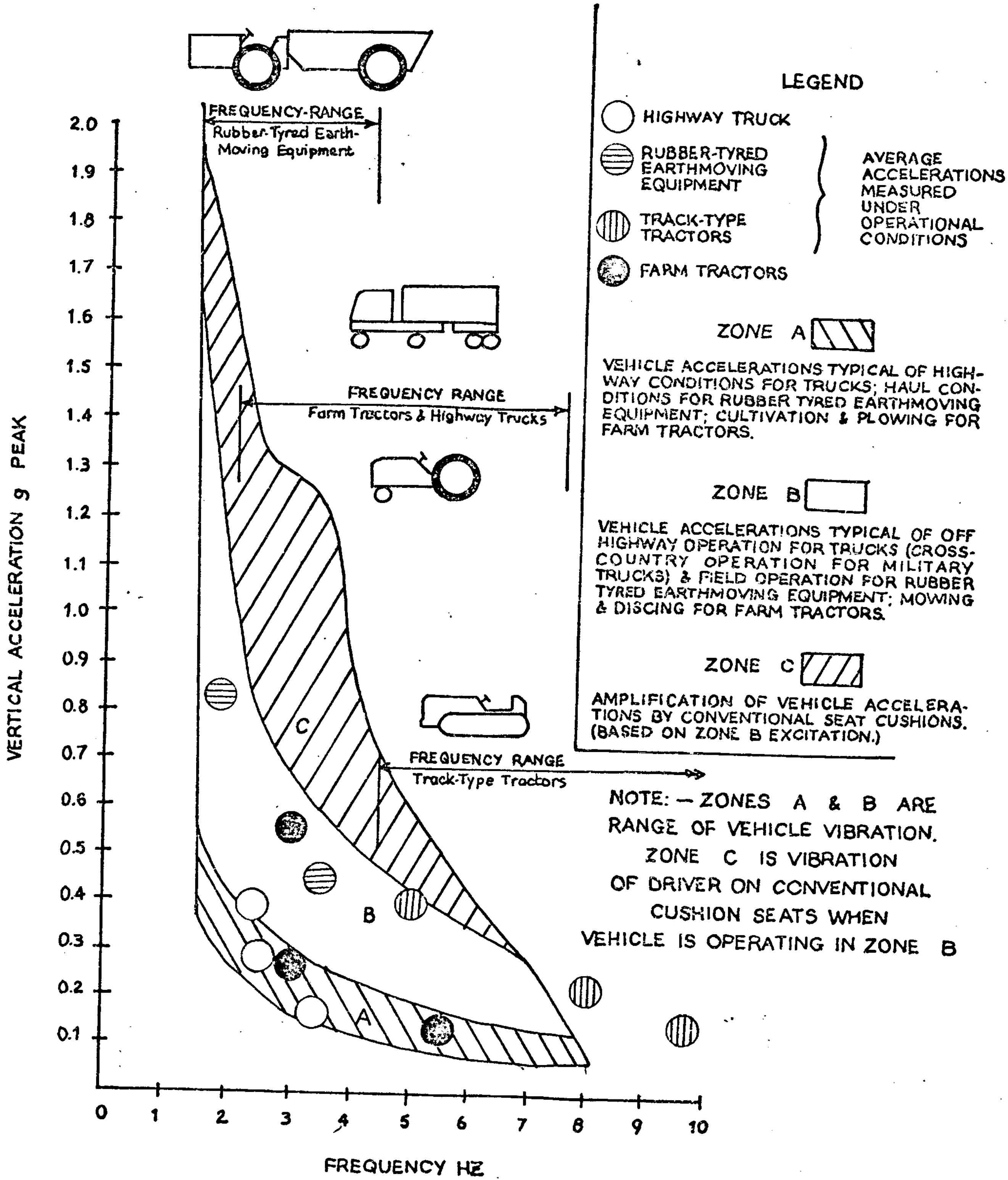
FIG 2.2.4. VIBRATION ACCELERATION SPECTRA AT THE FLOOR OF A SCOUT HELICOPTER DURING 100 kt FORWARD FLIGHT

VIBRATION ACCELERATION SPECTRA AT THE FLOOR OF A SIOUX HELICOPTER DURING 80kt FORWARD FLIGHT frequency: the low frequency components are produced by the main rotor and are dependant upon rotor frequency, R (R= 7Hz for the Scout), the rotor blade passage frequency (R x no. of rotor blades, or 28Hz for the Scout) and harmonics of these. In addition, higher frequency components depend on the tail rotor frequency (32 Hz for the Scout) and its harmonics, and the frequencies of rotation of engine and gearbox parts.

The vibration levels measured by Griffin (1972 and 1974) are typical of those which may be encountered in vehicles in normal, passenger-carrying roles. However, some special purpose vehicles are subjected to more severe environmental conditions, which are likely to induce higher levels of vibration. For instance, Dupuis (1974) has measured vibration acceleration in a number of military land vehicles in both on and off road conditions. The ranges of vertical vibrations found in a variety of wheeled and full-tracked vehicles are shown in figure 2.2.2. Peak acceleration levels of more than 1g were frequently measured in some trucks and tanks: at low frequencies these cause the driver to be lifted from his seat. Agricultural tractors and specialised construction equipment, due to their rigid suspensions and operation on rough surfaces, subject their operators to considerable low frequency acceleration levels (see figure 2.2.5.). In conventional tractors (Matthews, 1968, Hilton, 1970, Stayner, 1972) a large proportion of the vertical motion is concentrated around 3Hz (see figure 2.2.6.). Hilton has also recorded very pronounced roll, around 1.6 Hz.

In certain military operations strike aircraft are required to fly at high speeds, at very low altitude, in order to escape detection by radar. Turbulence is often severe near to the ground due to thermals, and eddies of surface wind caused by the friction of the earth's surface and interruption of flow by buildings, hills, trees, etc. An aircraft flying through turbulence is buffeted by random gusts of moving air, with a severity determined by the turbulence itself and the speed of the aircraft. Measurements made during low altitude, high speed flights in turbulent conditions (Forbes, 1959, Fraser, 1964, Wempe, 1965, Hornick and Lefritz, 1966 and Piranian, 1974a) reveal gust induced accelerations between 1 and 4Hz, which frequently exceed 1g peak. Fraser (1964) measured acceleration peaks at the heads of pilots of up to 4g, interspersed with repetitive impacts of the order of 0.5g at an average frequency of 2.35 per second. This buffeting also excites structural

FIG 2.2.5. Ranges of vertical(z axis) vibration levels in various on and off road vehicles, after Zach (1971).



bending modes in the airframe which are typically in the frequency range 4 to 18Hz.

Severe turbulence can also be generated at higher altitudes during atmospheric disturbances such as thunderstorms. A number of accidents and near-accidents, in recent years, involving large jet transport aircraft have been attributed to the effects of heavy turbulence (Ragland et al, 1964, Bray and Larsen, 1965, Bennett, 1971). Wasicko (1966) has measured acceleration power spectra at the pilot's station of long-nosed, flexible aircraft and reported peaks between 1 and 20 Hz, especially around 5Hz. The vibration time histories in figure 2.2.7. were obtained by Bray and Larsen, from a Boeing 720 in heavy turbulence. The predominantly low frequency, random motion is coloured, in the cockpit, by a 4Hz bending mode of the fuselage.

It should be noted that the point of measurement of vibration has not been the same in all of the above mentioned studies. Sometimes the vibration has been measured at the interface between the seat and the man, and sometimes at the floor or other point on the vehicle's structure The amount of vibration transmitted to the man from the vehicle is obviously dependant on the characteristics of his seat and other contacts with vibrating structures. The vibration of the various parts of the man's body is also dependant on the transmissibilty of the body itself. Below 100Hz the propagation of energy through the body is characterised by energy exchanges between lumped masses, as in a mass-spring-damper system. The transmission of vibration in such a system is frequency dependant. A number of major body resonances occur below 10Hz, especially from 3 to 8Hz for vertical vibration and up to about 4Hz for longitudinal and lateral vibration. The effect of these resonances is to amplify motion at the head and shoulders relative to the seat (see figure 2.2.8.). The amount of amplification at resonant frequencies is very variable, depending on phenotypic characteristics of individual bodies and variations in posture (Griffin,1975a). Low frequency body resonances are further exacerbated by the characteristics of the seats in most vehicles, which tend to have resonances at similar frequencies, especially for vertical motion. Rowlands (1973) has shown that the normal soft cushions used in aircrew seats give a vertical amplification of about 2 in the region 4 to 5Hz, but attenuate higher frequencies considerably. With lateral vibration there is a moderate amplification of 1.2 at 1Hz, but the next resonance is in the

Acceleration power spectral densities, tractor and seat

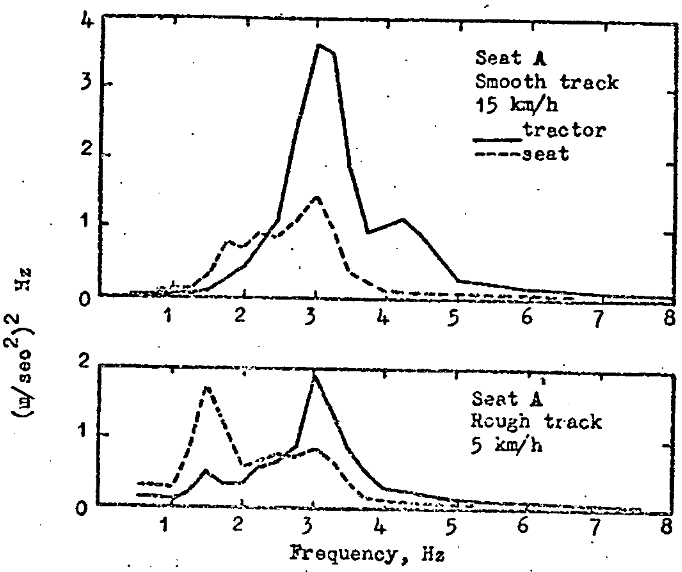


FIG 2.2.6. after Stayner (1971)

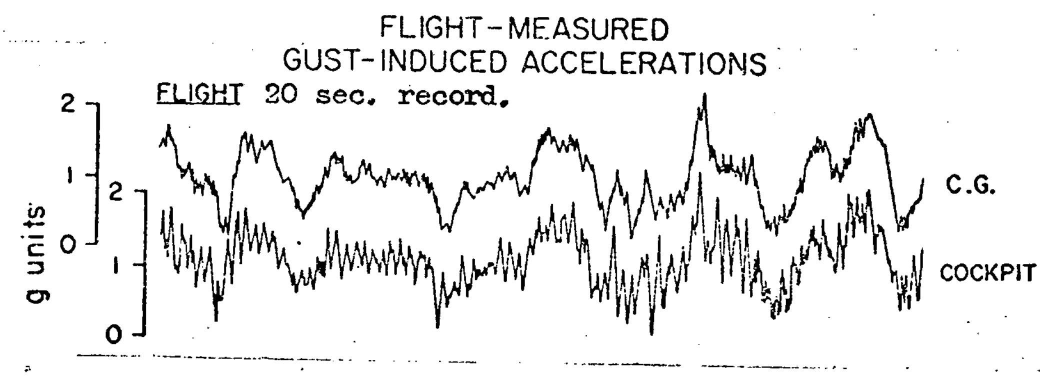
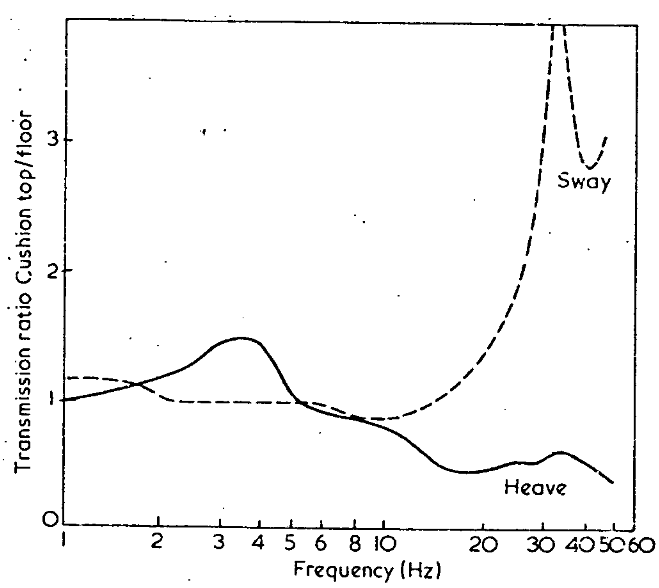


FIG 2.2.7. after Bray & Larsen (1965)



Helicopter seat vibration transmission. Cushion top to floor with 76 kg subject.

FIG 2.2.8. after Lovesey (1975)

region of 15Hz, where the amplification may be as high as 3. It can be seen from figure 2.2.5. that the transmission of vertical vibration by the seats in various wheeled vehicles is greatest in the 3 to 5Hz range. The transmissibilites of various car seats, measured by Griffin (1974), can be seen from figure 2.2.9. to exhibit similar resonances. The amplification of low frequency, vertical vibration can be considerably reduced by a well designed suspension seat (Strikeleather and Suggs, 1970, Zach, 1971). Suspension seats are now being fitted to some trucks and agricultural tractors. The performance of a suspension seat, compared to conventional seats is shown in figure 2.2.10.

Other important factors which may affect the transmission of vibration to the man are the geometry of the seat and of any restraining device such as a seat harness. Figure 2.2.11. shows the transmission of vertical vibration to a subject's head and shoulders from a rigid seat with a backrest, measured by Rowlands (1975). It can be seen that amplification of vertical motion in the region of 12Hz is considerably increased when the subject's back is in contact with the seat back, due to the additional vibration input to the upper part of his back. A full seat harness with shoulder straps may also be expected to result in higher levels of vibration at the head and shoulders due to transmission of vibration via the harness.

2.3 MANUAL CONTROL IN REAL AND SIMULATED VIBRATING ENVIRONMENTS.

One of the earliest observations of the effects of vibration on motor performance was made by Moss (1929 and 1931, reported by Guignard, 1965), who described increases in postural effort made by passengers who had been travelling in bumpy road vehicles. He suggested that the amount of sway in a passenger trying to stand to attention immediately following a ride could be roughly correlated with the quality of the vehicle's suspension and the length of the journey. Similarly, Swope and Brandenburg (1931, reported by Guignard, 1965), noticed that manual steadiness decreased after long car rides. Guignard (1965) commented that operators of pneumatic road drills are reputed to have difficulty, after a long spell of work, in raising a tankard to their lips - an action which is normally accomplished with practised smoothness!

Despite the high levels of vibration reported in some cases in the previous section, no field study appears to have been made of difficulties

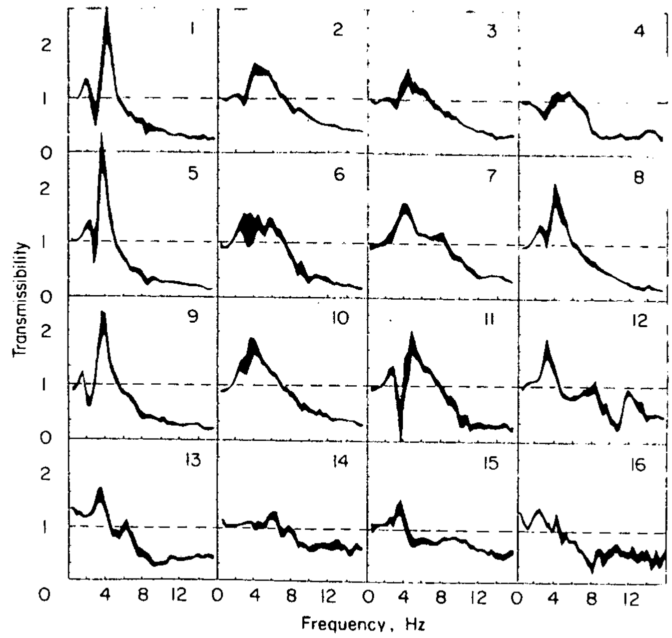
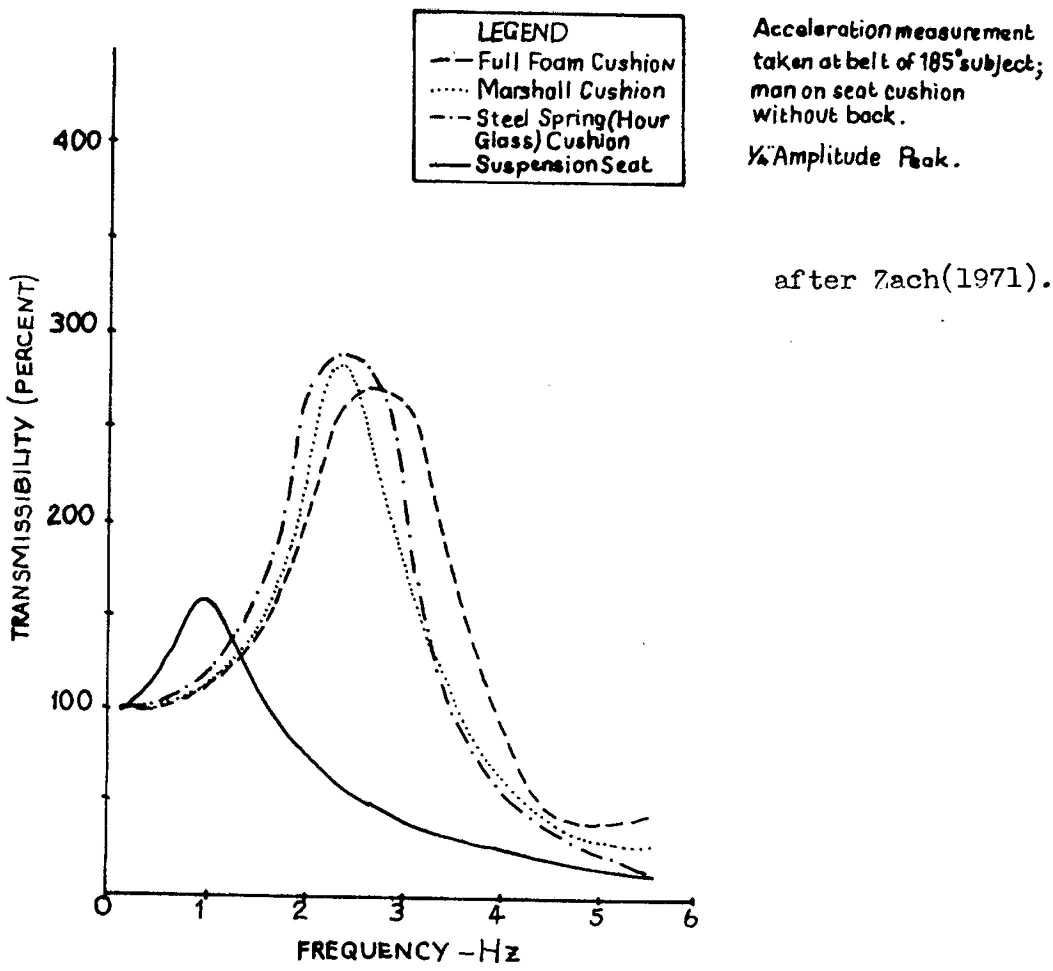


FIG 2.2.9. Vertical (z-axis) seat transmissibility in 16 vehicles. (black bands indicate the 10th to 90th % confidence interval, see vehicle key in figure 2.2.3.) after Griffin(1974).



after Zach(1971).

FIG 2.2.10. The frequency response of a purpose designed truck suspension seat, compared to conventional seat cushions, in the z-axis.

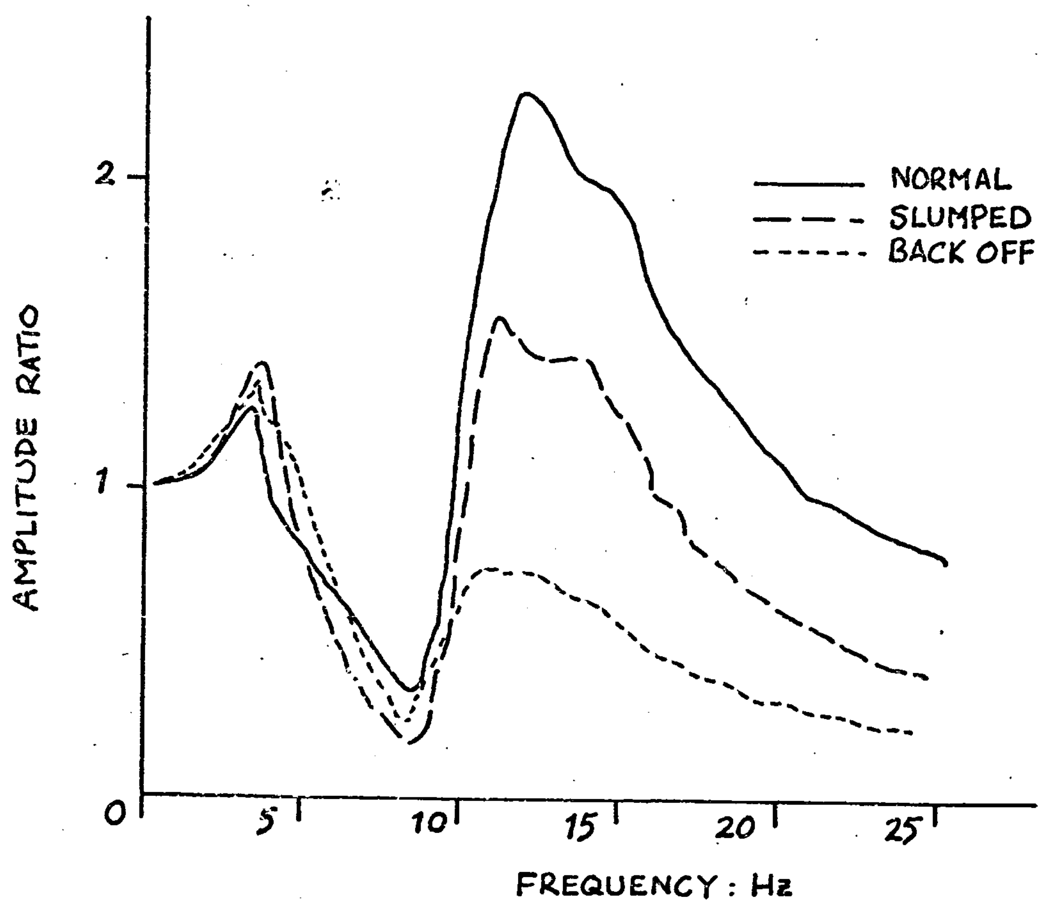


FIG 2.2.11. Head/seat frequency response for z axis vibration, with variations in sitting posture. after Rowlands (1975).

in the control of land vehicles due to vibration. Pathological studies, such as that by Fishbein and Salter (1950) indicate that in the long term, truck and tractor drivers are very susceptible to disorders of the spine and supporting structures, which might be due to intense jolting and vibration. It seems reasonable to suppose that vibration severe enough to do pathological damage to the operator is likely to affect his performance in some way. Concern has been expressed about the possible effect of duration of vibration in road vehicles. For instance, Ashley (1976) has commented that after seven hours of exposure to the noise and vibration environment of a truck, there is a significant increase in a driver's accident proneness. In a questionnaire survey by Oborne (1977) a number of passengers on trains, hovercraft and helicopters reported difficulty, due to the motion of the vehicles, in perceptual and motor activities such as reading, writing, eating and drinking.

Most of the research to date on the effects of vibration on the control of specific systems has been performed with aerospace systems in mind, the most obvious reason for this being that the task of controlling an aircraft tends to be particularly exacting, and the consequences of loss of control are more disastrous than in most other vehicles. On July 12, 1963, a Boeing 720B of United Airlines encountered severe turbulence in the cirrus portion of a thunderstorm. Control was lost and the aircraft entered a steep dive that was eventually terminated at 12000 feet, after an unanticipated loss of altitude of 25,000 feet. Earlier in 1963, a Northwest Airlines jet transport encountered severe turbulence in a thunderstorm shortly after take-off from Miami and crashed a few minutes later (Ragland et al, 1964). Subsequently, other commercial jet carriers have experienced difficulty in severe air turbulence, usually associated with thunderstorms, and have crashed or gone into steep dives from which recovery has been made only after alarming losses of altitude, and at least one instance of severe structural damage to the aircraft. Ragland et al (1964) and Bray and Larsen (1965) have observed pilot reaction to heavy turbulence during simulations of instrument flying in large jet transports. The simulators were able to reproduce controlled accelerations in the vertical, pitch and roll axis, and turbulence-induced disturbances in the vertical axis. The simulated control dynamics were those of a Boeing 720. The turbulence-induced disturbances were reproductions of flight recorder information during real flights in turbulence, including one in which control was actually lost. In each case the simulations were flown by both test pilots and regular airline pilots. The pilots reported that they had considerable difficulty in maintaining control in turbulent conditions due to two major effects. Firstly they experienced difficulty in scanning and reading the instruments due to visual blurring and confusion, and secondly because of involuntary and inappropriate stick movements. All pilots were able to maintain control in level flight, but this became increasingly difficult when flight path changes and other manoeuvres had to be performed.

Military aircraft are often required to perform quite complex manoeuvres in potentially turbulent conditions, especially during low altitude, high speed flight and air combat. During real low altitude, high speed flight tests of a Hunter 6 single seat jet fighter, pilots found terrain following difficult in bumpy conditions (Kerr et al, 1963). In severe turbulence pilots had the impression that the limits of control were being approached. The lateral-directional behaviour of the aircraft (skidding and yawing) worried the pilot not only from the point of view of possible loss of control, but also from concern for the structural integrity of the aircraft. On one occasion this forced him to abandon the sortie. Kerr et al also reported that when flying at mach 0.9 in heavy turbulence, pilots experienced frequent changes in fore and aft acceleration (shunting) which they found extremely distracting. In a study by Fraser et al (1964), three experienced pilots flew a T33 Silver Star aircraft at a speed of 400 knots and an altitude of less than 100 feet above a rough terrain. On two of the flights it became impossible for the pilot to read his watch, instruments or maps, and difficulty was reported in manipulating some of the controls. Legible writing, even under moderate turbulence, was impossible.

Piranian (1974b) performed a full flight simulation of target following at transonic speed by a Phantom aircraft. A 10Hz disturbance was applied, which was meant to simulate a structural bending mode of the aircraft excited by turbulence. Root mean square tracking error was found to be degraded only if the disturbance exceeded $\pm$ 0.5g, however in real flights (Kerr et al, 1963) pilots found disturbances of $\pm$ 0.5g at 1Hz intolerable. Flight simulator studies carried out by Wempe (1965) and Hornick and Lefritz (1966) demonstrated no clear effects, but Ragland et al (1964) have presented evidence to suggest that the rms error scores normally used in this type of study are somewhat insensitive and inappropriate for measuring this kind of performance. Besco (1961) did, however, demonstrate that rms error in 'flying' a simulator was significantly increased by turbulence-induced disturbances of 2 and 4 ft per second rms. (approximately 0.6 and 1.2 ms^{-1}).

Accelerations generated by the controlled motions of the aircraft itself can be very significant, especially when manoeuvring at high speed. These act in addition to other acceleration disturbances on the pilot. However, it has been clearly demonstrated in a number of flight simulations (Besco, 1961, Huddleston, 1966) that meaningful aircraft motions supply valuable feed-back information to pilots and that flying performance is degraded when motion cues from the aircraft are not present. Evidence that even non-meaningful motions can enhance performance in some circumstances comes from Jackson (1956). The performance of ten pilots was investigated by making continuous records of the altitude and heading of their aircraft during a series of fifteen hour flights. In the first two watches (out of four), pilots tended to fly more accurately and consistently in rough air than in calm air. In the last two watches they were adversely affected by turbulent conditions.

A survey of military helicopter crews was carried out by Rance and Chappelow (1974) in order to determine the scope and nature of problems due to helicopter vibration. The percentage-frequency of reports of effects of vibration on tasks and well-being, and the way in which turbulence and helicopter loads affect the number of reports, are shown in table 2.3.1. The major effects were often associated with hovering, or transition to or from the hover. It can be seen from table 2.3.1. that although visual tasks were most markedly affected by vibration, a significant number of direct effects on control were noted, especially in Sea King helicopters. It can also be seen that turbulence can increase the incidence of adverse effects on performance by up to 50% but that the loading of the aircraft makes no significant difference on reports of changes in performance.

PERCENTAGE FREQUENCY OF REPORTS OF EFFECTS ON TASKS AND WELL-BEING

AIRCRAFT Service Wt. (Kg)	EFFECTS			
	Reading	Communi-cations	Controlling	Well-being
HILLER 12E R.N. 1270	4	5	7	37
SIOUX (Bell 47) ARMY 1338	5	0	1	5
SIOUX R.A.F. 1338	0	4	0	17
SCOUT ARMY 2405	0	0	0	9
WASP R.N. 2495	6	10	6	6
WHIRLWIND R.N. 3629	2	5	0	18
WHIRLWIND R.A.F. 3629	9	9	9	18
WESSEX 3 R.N. 5715	19	4	4	27
WESSEX 2 R.A.F. 6120	19	6	2	17
PUMA R.A.F. 6400	20	1	8	21
SEA KING R.N. 9750	37	8	14	38

THE EFFECT OF TURBULENCE AND LOAD ON THE INCIDENCE OF REPORTS OF EFFECTS AND SYMPTOMS DUE TO VIBRATION (PERCENTAGE FREQUENCY)

		TURBULENCE		NO LOAD	LOAD
		NIL SLIGHT	MODERATE -SEVERE		
RN WESSEX	EFFECTS	12	24*	16	11
	SYMPTOMS	10	23*	13	9
RAF WESSEX	EFFECTS	11	10	11	11
	SYMPTOMS	7	9	8	8
PUMA	EFFECTS	11	17	10	13
	SYMPTOMS	5	5	4	7
SEA-KING	EFFECTS	20	31**	24	27
	SYMPTOMS	16	26***	20	23

* p<0.05   ** p<0.01   *** p<0.001

TABLE 2.3.1. Effects of helicopter vibration reported by aircrew. after Rance & Chappelow (1974).

3. A REVIEW OF LABORATORY STUDIES OF THE EFFECTS OF VIBRATION ON MANUAL CONTROL PERFORMANCE.

In the last section of the previous chapter some situations were discussed where vibration has been shown to, or is believed to, affect the performance of human operators in operational environments. It is not possible to make many general conclusions from observations made in such uncontrolled but real situations. This chapter presents a review of studies performed under controlled laboratory conditions of the effects of vibration on manual control.

Studies of the effects of vibration on continuous manual control may be divided into two categories. The first category includes studies of real vehicle guidance tasks, usually associated with aircraft, in either simulators or real flight conditions. The second includes studies of artificial tracking tasks performed under controlled laboratory conditions. The main distinction between these two categories is that in the former subjects have control over their motion input and may modify any disturbing motion by their control actions. In this review we are mainly concerned with laboratory experiments where the subject has no control over the motion, and vibration and task parameters can be easily and accurately controlled by the experimenter.

The next section of this chapter describes the important characteristics of a manual tracking system and discusses the measurement of tracking performance in vibrating environments: various important terms which will be used in the rest of this thesis are defined in this section. The effects of some important vibration variables are discussed in sections 3.2 to 3.5, and the effects of various task variables on the sensitivity to vibration of manual control activity are discussed in sections 3.6 to 3.9. Section 3.10 comprises general conclusions, and criticisms of the reviewed research and finally, some models of the effects of vibration on manual control are reviewed in section 3.11. The procedures and results of the various laboratory studies are separately summarised in tabular form in appendix A. Appendix A does not include studies where vibration has been combined with other environmental stresses, as these are described in detail in section 3.9.

3.1. THE MEASUREMENT OF THE EFFECTS OF VIBRATION ON MANUAL CONTROL PERFORMANCE.

The basic components of a manual control system, apart from the human operator, are the display, the control and the machine (see Figure 3.1.1.). The task of the operator is to match the actual system output, o(t), with a particular input or forcing function, i(t). The display is the means by which information about the actual and desired system output is presented to the operator, almost always in a visual form. In a pursuit tracking system the display contains separate representations of both the forcing function and system output. However in a compensatory tracking system there is only one moving element, representing the tracking error, e(t), or the difference between the actual and desired outputs.

The control translates the output of the human operator, which may be in the form of movement or force, into the electrical, mechanical or hydraulic form needed to control the machine. The relationship between the system (machine) output and the output of the control depends on the dynamics of the machine. The system output can be characterised by a mathematical derivative of the control output, which is determined by the order of the system, hence control of a zero order system is referred to as position control , a first order system as rate control and a second order system as acceleration control. In reality zero order systems are rare: for instance, consider the control of the altitude of an aircraft. In this case the control output is the elevator deflection. The elevator deflection determines the rate of change of pitch, therefore pitch control is a first order process. Providing forward speed is maintained (in reality the control of many systems involves more than one control loop) the pitch of the aircraft determines the rate of climb, or dive, or the rate of change of altitude. Altitude control can therefore be considered to be a second order process.

In the laboratory experiments reviewed here the forcing function, the control and the system outputs are represented by electrical voltages, which are usually displayed to the subject on a cathode ray oscilloscope screen. Machine dynamics are simulated by electronic circuits.

The scientific process has two parts. The first consists of controlled observations leading to the understanding of stable patterns of events. The observations should then be used, in the second part, to formulate general models which can be used to predict consequent events, given a set of antecedent conditions. Central to the process of controlled observation is the need for reliable and valid measures of human performance: an experimental observation is only as good as the method of measurement.

One of the many criticisms which have been levelled at experiments involving manual tracking in vibration is that performance criteria have been unrealistic and academic. (Harris and Shoenberger, 1965). In more than 70% of the studies reviewed in appendix A, tracking performance has been measured by integrated absolute tracking error or root mean square (r.m.s.) tracking error. There are important differences between tracking error measures and performance measures used in other human factors situations, in that they are distributed continuously in time and refer to the dispersion of the distributions they represent rather than central tendency. Tracking error is typically distributed symmetrically about a central point, which is usually zero whether performance is good or not, so it is the dispersion of errors about the central point rather than the central point itself which is of primary interest. The root mean square tracking error is a measure of error dispersion equivalent to the standard deviation of the tracking error distribution, and is given by

$$E_{rms} = \left\{ \frac{1}{T} \int_0^T (i(t)-o(t))^2 dt \right\}^{\frac{1}{2}}$$

The average absolute tracking error is also a measure of error dispersion, given by

$$E = \frac{1}{T} \int_0^T \left| i(t)-o(t) \right| dt$$

If the error distribution has a Gaussian form, as it probably does in most tracking tasks (Bahrick et al, 1957), average absolute error is a statistically reliable estimate of root mean square error, or the standard deviation of the error, and is therefore a good indicator of overall error dispersion (Kelly, 1969).

Measures of error dispersion such as integrated-absolute error scores have the advantage that they can be computed during the performance of the task using the simplest equipment. However, a measure of overall error dispersion gives information about the extent, but not about the type of errors and gives few clues as to their source, whereas the success or failure of a real system may be more sensitive to some types of errors than others. Moreover it is difficult to compare performance at different tasks with differing complexity and sensitivity using a simple error measure. For instance Ragland et al, (1964) have suggested that r.m.s. error scores are somewhat insensitive and inappropriate when considering the relevance of laboratory and simulator studies to real, operational control tasks.

Lewis (1974) used information transmission as a measure of tracking performance during vibration. In engineering terms the human operator performing a tracking task can be considered to be a communication channel. Information is transmitted from the display elements to the control, but some information will be lost due to perturbations of the signal by noise generated within the operator and by extraneous influences such as vibration. This idea has been developed by Cherry (1957) and Edwards (1967), who have shown that Communication Theory, developed by Shannon (1948) to assess the performance of noisy telecommunication channels, is applicable to the human operator (subject to certain conditions and limitations which are discussed in the papers by Cherry and Edwards). The input-output relations of the operator can be represented by the model in figure 3.1.2., which consists of a combination of linear transfer function and a noise generator. The transfer function, H(f), best approximates (in the mean-square difference sense) the response of the operator while the noise, or remnant, accounts for the part of the response, O(f), which is not linearly correlated with the input, I(f).

Shannon's seventeenth theorem (Shannon, 1948) states that the information capacity of a channel of bandwidth W perturbed by noise of power $N^2(f)$,* when the average transmitted power is limited to $S^2(f)$,* is given by

$$C = \int_W \log_2 \left\{ \frac{S^2(f) + N^2(f)}{N^2(f)} \right\} df \text{ bits/sec.}$$

where f denotes frequency. S(f) is the part of the output linearly

*Note that S(f) and N(f) have been expressed in units of volts, consistent with the terminology elsewhere in this thesis, whereas electrical power has units of volts^2.

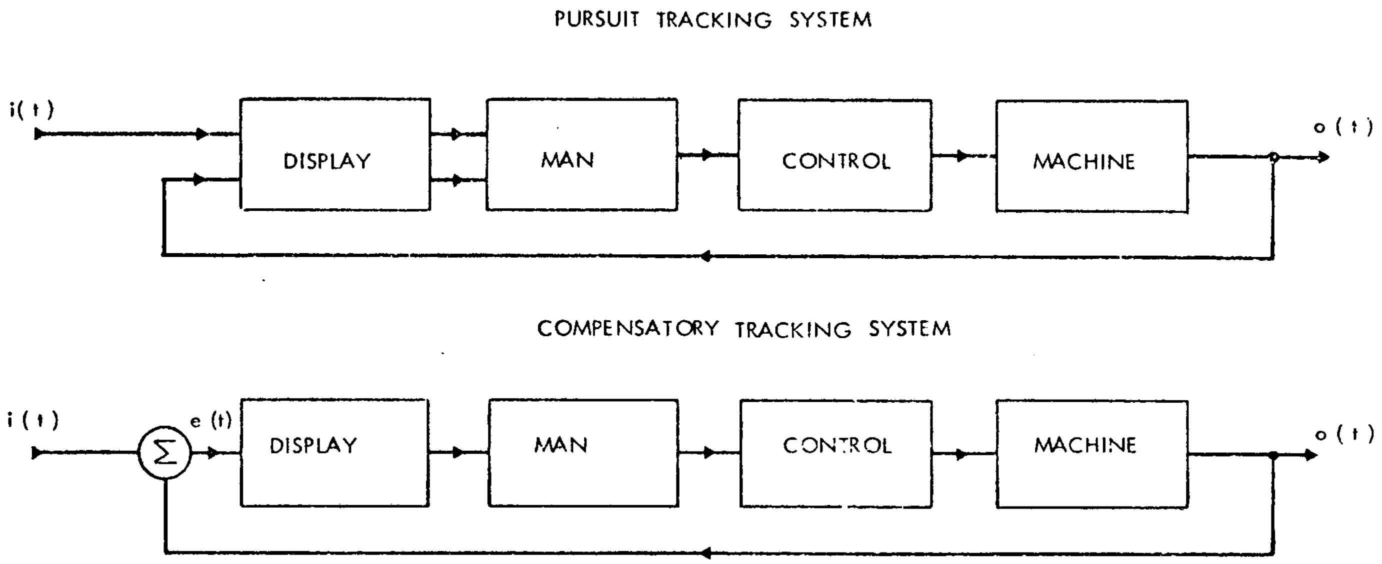


FIG 3.1.1. The basic components of a manual control system.

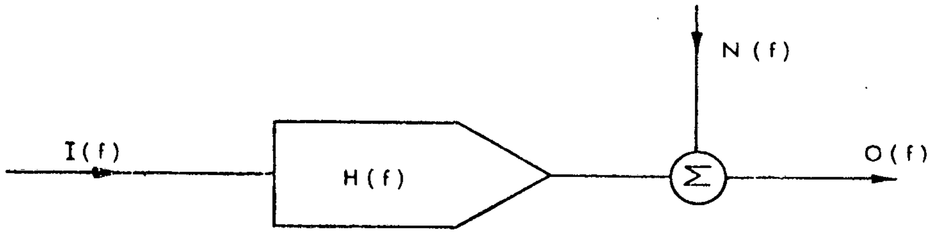


FIG 3.1.2. The human operator as a noisy communication channel.

correlated with the input and is equivalent to $I(f).H(f)$. The best estimate of the transfer function is given by

$$H(f) = \frac{G_{oi}(f)}{G_{ii}(f)}$$

where $G_{ii}(f)$ is the power spectral density of the input and $G_{oi}(f)$ is the cross power spectral density of input and output (see section 4.3.3).

It can be seen that the information channel capacity as expressed by Shannon's seventeenth theorem is a measure of coherence or correlation between input and output. It is more elegant than simple error measures. However it could not be easily calculated without the aid of a digital computer and it has a major shortcoming which could lead to misleading results when applied to a tracking task. A low coherence between input and output results in a low information capacity and obviously poor performance. On the other hand, a high coherence results in a large information capacity and implies a high level of performance. However this will not be the case if the transfer function is inappropriate. The transfer function describes the frequency response and response lags, or transmission delays, of the operator. It is possible to design a telecommunication channel with a relatively optimum transfer function; however the characteristics of the human operator cannot be 'engineered'.

In order to obtain optimum performance from a control system, the performance characteristics of the individual system components must be closely matched. As it is not possible to alter the design of the trained human operator, his significant response lags (up to 0.5 seconds according to Craik, 1947) and limited maximum frequency of response (little more than 5Hz for the 'freewheeling' hand according to Stark, Iida and Willis, 1961) impose severe limits on the systems design. Consequently there has been much interest in recent years in the measurement of the input/output relationships of the operator, in order to define design limits for the rest of the system.

Discontinuities such as threshold and saturation nonlinearities and shifts in attention over time are obvious in most human behaviour. However very stable and repeatable characteristics have been shown to be exhibited both within and between well trained and motivated subjects constrained to a continuous tracking task (McRuer and Graham, 1963). Providing the forcing function is within the controllable limits of the subject, his output is dominated by the linear* portion of his response (see the model in figure 3.1.1.). For instance, signal to noise ratios up to 20dB are typical in a variety of single loop, compensatory tracking tasks (Levison et al, 1969, Jex and Magdaleno, 1969). In these cases the remnant or noise portion of the response is typically a continuous and reasonably smooth spectrum, indicating no spectral lines which might be associated with periodic sampling or strongly nonlinear behaviour (McRuer and Krendel, 1974).

The effective linearity of response of human operators in continuous tracking tasks (note that the linear transfer function is not intended in any way to be a functional model of the human operator, but as a convenient mathematical approximation to his lumped responses and lags) permits the well developed theory of linear servomechanisms to be applied to manual control in the same way as it is to automatic control systems. Since the pioneering work by Tustin, thirty years ago, many measurements have been made of human operator transfer function parameters (the American literature refers to transfer functions as describing functions). Many of these have been concerned with aircraft control (e.g. McRuer et al, 1965), however, such measurement techniques have only recently been applied to the investigation of the effects of vibration on control. From the open loop transfer function, in a compensatory tracking task such as that in a study by Allen et al (1973), it is possible to determine the bandwidth of the system and the degree of system stability - a very important consideration when higher order systems are disturbed by vibration, particularly in vehicle control applications. Transfer function parameters are illustrated in Bode diagram form in Figure 3.1.3. with reference to data from Allen et al (1973). The gain crossover frequency determines the bandwidth of the control loop, and the phase crossover frequency represents the maximum possible closed-loop bandwidth if stability is to be maintained. The phase margin is the system stability margin, invoking the Nyquist

*A number of different concepts of linearity are in widespread use. The term has several different applications throughout this thesis but the exact meaning should be obvious from the particular context in which it is used. For a definition of linearity as applied to linear models of human operators see Licklider (1960).

criterion (Garner, 1968). As the phase margin approaches zero the closed-loop damping ratio vanishes and the control system approaches an unstable condition. There is no equivalent open-loop transfer function in a pursuit system, however Allen and Jex (1968) have shown that a compensatory loop closure does exist within the operator during pursuit tracking (i.e. the operator still responds predominantly to error).

When vibration is present, the output from the control system is likely to have some vibration-correlated activity superimposed upon it due to involuntary control movements induced by the vibration. The vibration can then be considered to be another input to the system. The amount of vibration-correlated activity in the operator's output is dependent upon a biodynamic transfer function (see figure 3.1.4.). Note that the output from the operator, including vibration-correlated activity, is operated upon by the control, or machine transfer function. Hence the system output, O(f), is given by

$$O(f) = \left(E(f).H_p(f) + V(f).H_v(f) + N(f)\right)H_c(f)$$

(The terms in the above equation are defined in figure 3.1.4.). Allen et al (1973) were able to use the relationship to quantify the contributions made to the total error variance by vibration-induced control activity, operator-generated noise or remnant, and tracking-input-correlated error, due to departures of the human operator transfer function from an ideal unity gain and zero phase lag in the frequency range of the forcing function. The input-correlated error reflects changes in the response lags and gain of the operator such as may occur with increased neuromuscular lags or voluntary changes in tracking strategy. The remnant portion of the output reflects noise and nonlinearities in perceptual and motor processes such as visual blurring, threshold nonlinearities, shifts in attention or increases in neuromuscular activation system noise. Transfer function measures can therefore give much more information about the type of errors, and provide more clues to error sources, however they are evaluated by complex fourier analysis procedures and require either extensive, special purpose analogue equipment, as is described by Allen and Jex (1972), or a digital computer.

Considerable advances have been made in recent years in the mathematical modelling of human operator transfer or describing functions (e.g. Licklider 1960, McRuer and Krendel 1974). Much interest has centred on the simple 'crossover model', which describes the open-loop

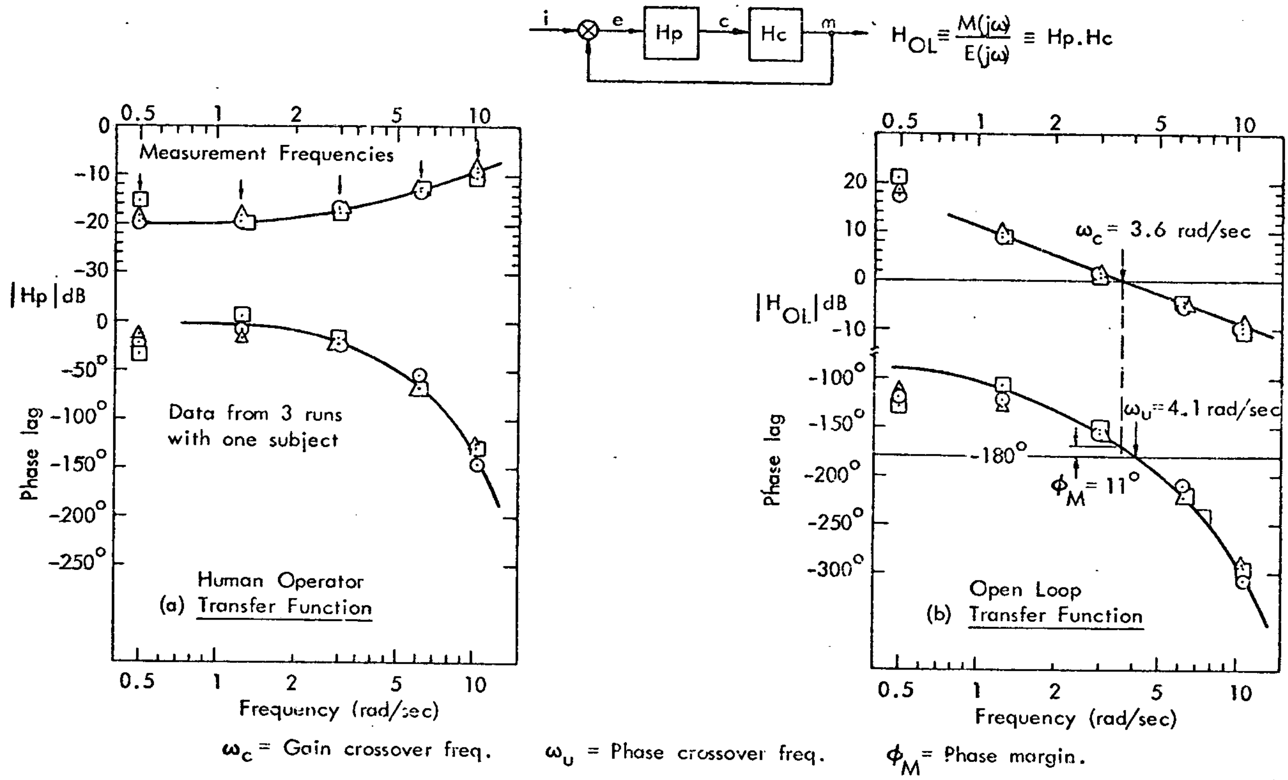


FIG 3.1.3 TYPICAL TRANSFER FUNCTION MEASUREMENTS AND PARAMETERS. (from Allen, Jex and Magdaleno 1973).

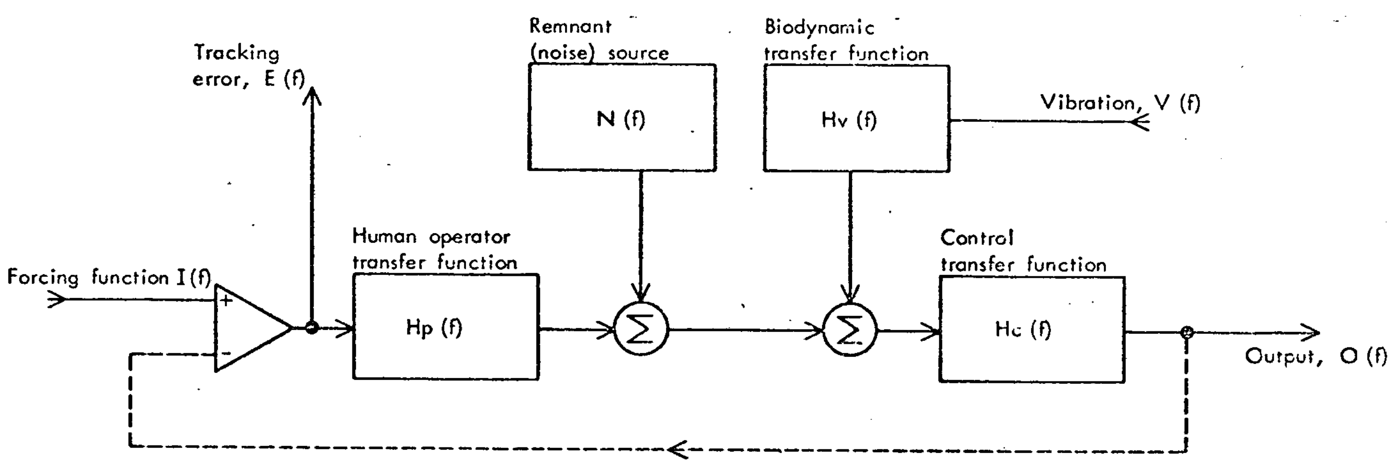


FIG 3.1.4 LINEAR MODEL OF A COMPENSATORY TRACKING SYSTEM

response pf the system M(s) in the region of gain and phase crossover frequencies, and has the form

$$M(s) = \frac{wc.e^{-\tau s}}{s}; \text{ near } wc$$

where wc is the gain crossover frequency and τ the operator's 'effective delay time'. The effective delay time is an approximation to the net response lag, which is the sum of the various delays and lags inherent in the perceptual, central and motor processes of the human operator. Since it is operator centred, unlike measures of tracking error which are very dependent on the configuration of a particular system, it is a useful measure of human operator performance. (Note that the term operator-centred does not mean that the effective time delay is not affected by different characteristics of the task or disturbance, but that it is a fundamental property of the human operator. This makes it possible to obtain more meaningful comparisons between performance with different tasks.)

The 'critical tracking task' developed by Systems Technology Inc. (Jex et al, 1966a, 1966b), which was used in the control location study by Shoenberger and Wilburn (1973), is a simple means of measuring the effective delay time directly. The critical task is a single-axis, compensatory tracking task with a first-order, divergent (unstable) controlled element. The dynamics are equivalent to a simple integrator with a positive feedback loop. The divergent time constant, or the degree of instability is determined by the gain of the positive feedback loop. To determine the effective delay time of the operator the degree of instability is progressively increased until the operator loses control and the controlled element is lost from the display: the effective delay time is then equivalent to the reciprocal of the divergent time constant at the instant when control was lost. The critical task can be considered to simulate a forward facing castor of negligible mass, pushed along a surface with increasing speed. As the point of contact of the wheel is ahead of the pivot point, any divergence from a straight path will progressively increase unless the pivot point is moved at least as far from the line as the error between the line and wheel contact point. Attempts to rapidly steer the wheel back to the line tend to result in oscillations which will increase with the forward speed of the castor until some speed is reached where control can no longer be maintained. Perturbations, tending to drive the wheel away from the line, may be provided by a random forcing function, or solely by the remnant or noise in the operator's control output.

The task has proved to be a useful indicator of stress imposed by secondary tasks and some other stresses (Jex, 1967) and has the advantage that it tightly constrains the operator's behaviour, therefore resulting in a small between trials variance. However, its effectiveness as an indicator of the effects of biodynamic stress is not yet proved, particularly since the effective delay time is related to the high frequency cut-off point of his tracking skill rather than tracking performance at normal frequencies.

Another new technique, which may find application in this area of research in the future, is adaptive tracking (Kelley, 1966, 1967). Adaptive tracking systems change their own difficulty level automatically in order to maintain a predetermined level of performance. The adaptive variable, which determines the level of difficulty of the task, may be a parameter of the forcing function (e.g. frequency), the task dynamics (e.g. control gain, instability of a divergent controlled element) or an external disturbance such as vibration. Negative feedback of tracking error is used to control the adaptive variable so that a low score will cause the level of difficulty to increase and vice versa.

Theoretically, using this technique with vibration level as the adaptive variable, it should be possible to quickly obtain equal performance contours for a large range of vibration frequencies. However, major difficulties in setting up a task with vibration as the adaptive variable are the finding of a suitable adaptive time constant and making the task sensitive to a wide enough range of vibration conditions (Johnston, 1976). There are also some doubts about using a task where the stress is effectively under the subject's control, in that he can reduce the level of stress by voluntary performing badly if he is not sufficiently motivated to do otherwise. Adaptive techniques have, however, been shown to be valuable in training situations: Lowes et al (1968) showed that adaptively trained pilots were more efficient when transferred to a flight simulation representing an aircraft in turbulent air than conventionally trained pilots.

Another weakness with the measures of error dispersion discussed earlier, is that they do not yield information concerning the shape of the distribution of tracking errors. If the error distribution has a Gaussian form and a zero central tendency the probability of 'hitting' a particular target may be quite high, even with a large error variance. However, if the error were to contain sinusoidal components of vibration breakthrough the distribution may become somewhat bi-modal. Bi-modal error distributions have also been known to occur in static conditions with certain combinations of high order task dynamics (McRuer and Krendel, 1974). If the error distribution has a bi-modal form, or is excessively plati-kurtic, and has a zero central tendency, the time on target may be quite low while there is still a relatively small error variance.

The above reasoning may appear to provide a good argument for using 'time on target' to measure performance, as in studies by Huddleston (1970), Lovesey (1971c). Rodrick (1972) and Wilson (1974). However, time on target scores are statistically much less reliable than root mean square or absolute error, moreover, their reliability varies greatly as a function of the size of the target zone (Kelley 1969). Time on target is a range measurement and has obvious applications for tasks such as weapon aiming and guidance, but Bahrick et al (2) have demonstrated that the time within a single target zone has limited value as an indicator of performance, particularly where wide variations in performance are to be measured. It is impossible to reliably generalise results between systems with different target zones due to differences in the dispersion and shape of the error distribution, however time on target scores for various target zones can be reliably predicted from the r.m.s. tracking error if the distribution is known (Bahrick et al 1957). It would therefore be helpful to the application of laboratory results to real systems if future experimenters reported the effects of vibration on the shape of error distributions as well as the error variance.

Summarising, the conclusions we are able to draw from many of the experiments reviewed in this chapter, particularly the earlier studies, are limited by their performance measures. Simple tracking error measures have proved useful for illustrating the overall effects of vibration and task parameters, as will be discussed in the following sections, but they cannot easily distinguish between the different mechanisms by which vibration may affect tracking performance. Moreover it is difficult to compare performance at different tasks, with differing complexity and sensitivity, using a simple error measure, for instance Ragland et al (1964) have suggested that r.m.s. error scores are somewhat insensitive and inappropriate when considering the relevance of laboratory and simulator studies to real operational control tasks. Measurement techniques have recently been developed which permit more complete analysis of the mechanisms of performance and which are less task centred. However more work is needed to determine the relevance of all such measures when attempting to predict performance in real systems.

3.2. THE EFFECT OF FREQUENCY OF WHOLE-BODY VIBRATION

For motions at less than 20 Hz there is fairly good agreement that performance decrements are related to the transmission of vibration through the body. For instance, Buckhout (1964) showed that for z axis vibration at 5, 7 and 11 Hz, tracking error in a two dimensional task was highly, positively correlated with transmission to the sternum. Also, Levison (1976) showed that performance decrements in a vertical tracking task were proportional to shoulder acceleration, with sinusoidal and random vibration in the z axis in the range 2 to 10 Hz.

In the z axis sinusoidal vibration generally produces the greatest decrements in tracking performance, for a given acceleration amplitude, at frequencies around 4 and 5 Hz; the decrement becoming progressively smaller as the frequency becomes higher or lower (Schmitz 1959; Forbes 1960; Parks 1961; Hornick 1962; Buckhout 1964; Harris and Shoenberger 1966; Nagasawa et al 1969; Lovesey 1971a; Shoenberger and Wilburn 1973). The same effect was demonstrated by Holland (1967) for narrow band, random, whole-body vibration. There are similar effects with vibration in the x and y axes. In these axes vibration appears to have the greatest effect on performance in the range 1 to 3 Hz (Hornick 1962; Shoenberger 1970; Allen et al 1973).

However Catterson et al (1962) concluded that performance is only a function of vibration level for z axis vibration from 2 to 15 Hz and Fraser et al (1961) found no significant effect of frequency in x, y or z axes from 2 to 12 Hz. The results of Catterson et al and Fraser et al are not necessarily in disagreement with those mentioned earlier as they specify vibration levels in terms of displacement, rather than acceleration, resulting in very high acceleration levels at the higher frequencies.

The results of Shurmer (1967) and Allen et al (1973) contain more serious anomalies. Performance of Shurmer's two dimensional, compensatory task was degraded more by 2 Hz, z axis vibration at $\pm$ 0.3 g than by 4 Hz vibration at the same level. He also reported that 4 Hz, y axis vibration at $\pm$ 0.1 g had a greater effect than a similar level of 2 Hz vibration - particularly on horizontal tracking performance. These results tend to conflict with data on the transmission of vibration through the body at these frequencies in y and z axes. With a single (vertical) axis compensatory task, Allen et al (1973) found that both remnant and input-correlated error variance increased with increasing frequency of z axis vibration, at $\pm$ 0.4 g, from 2 to 10 Hz. These results are not in accordance with transmission data for the same subjects which show that there was a marked peak in vibration transmitted to the shoulder, head and elbow at about 5 Hz, and the transmissibility fell off to less than unity at 10 Hz. Increases in response lags were noted in describing function data with 10 Hz vibration, and the authors conclude that the abnormally high performance decrements with 10 Hz vibration may be due to direct effects of vibration on the neuromuscular system.

The vibrations used in laboratory experiments have mostly been either sinusoidal or narrow-band random. However real environments are more likely to contain broad band and/or multiple frequency components. The current International Standard on human exposure to whole-body vibration (ISO 1974) recommends two ways of evaluating complex motions of this type: (i) evaluating the weighted r.m.s. acceleration level of each frequency component separately, and (ii) using a weighting filter. The second method has been found to work well when predicting the discomfort due to complex motions (Fothergill and Griffin 1977; Griffin 1976) and is recommended in the guide for the evaluation of human exposure to helicopter vibration proposed by Griffin (1975c), however there has been no experimental work to support either procedure for manual control performance.

Generally, effects of vibration on tracking performance can be expected to be highly correlated with transmission to the head and controlling limbs. This will be dependent on the location of vibration inputs to the body, body transmission phenomena and any restraining devices. It may also be modified by characteristics of the tracking system, such as the type of control, which will be discussed in later Sections of this chapter.

3.3. THE EFFECT OF LEVEL OF WHOLE-BODY VIBRATION

There is good agreement that, for a given vibration spectrum, performance is progressively degraded as the level of vibration is increased above a certain threshold of effect. This has been demonstrated for z axis vibration by Schmitz (1959), Fraser et al (1961), Parks (1961), Hornick (1962), Buckhout (1964), Harris et al (1964), Torle (1965), Weisz et al (1965), Harris and Shoenberger (1966), Shurmer (1969), Lovesey (1971), Bennett et al (1976), Lewis (1974); for y axis vibration by Fraser et al (1961), Hornick (1962), Shurmer (1969), and Shoenberger (1970); and for x axis vibration by Hornick (1962) and Shoenberger (1970). However Catterson et al (1962), with a zero order, compensatory task, found that performance was significantly improved by vibration in the frequency range 2 to 15 Hz at displacements of 0.065 inch (z) double amplitude, but significantly degraded by displacements of 0.13 inch (z) double amplitude.

The lowest level of vibration required to affect performance is very variable. For example Weisz et al (1966) failed to find an effect on the performance of a first order, dual axis, compensatory task, by 5 Hz vibration at 0.248 g (z) r.m.s., whereas Buckhout (1964) found that a similar task was degraded significantly by ± 0.26 g (z) (0.18 g r.m.s.) at 5 Hz and Harris and Shoenberger (1966), Shoenberger (1970) and Lovesey (1971a) have all reported significant increases in tracking error with ± 0.20 g (z) (0.14 g r.m.s.) vibration at 5 Hz.

It seems reasonable to draw the general conclusion that increases in vibration level, above some threshold of effect, will result in progressive degradation of performance. However because of the great number of task variables which may affect the performance of specific systems during vibration, some of which will be discussed in this review, it is not reasonable to expect to be able to discover an absolute threshold of effect, above which performance is affected by vibration and below which it is not.

3.4. THE EFFECT OF AXIS OF WHOLE-BODY VIBRATION

The only two studies in which the effects of x, y and z axis vibration have been directly compared are Fraser et al (1961), with a zero order, two dimensional, compensatory tracking task, and Shoenberger (1970), with a first order, two dimensional, compensatory task.

The results of Fraser et al indicate that with vibration in the frequency range 2 - 12 Hz, horizontal tracking performance was affected more by y axis vibration than by z axis vibration at the same displacement. Vertical tracking was affected more by z axis vibration than by y axis vibration. Vibration in the x axis had no effect on either horizontal or vertical tracking.

Shoenberger also showed that for constant accelerations over the range 1 to 11 Hz, y axis vibration degraded horizontal tracking performance to a much greater extent than vibration in either of the other two axes. This difference was especially pronounced in the 1 to 5 Hz range. The effects of x and z axis vibration on horizontal tracking were similar over this frequency range. For vibration frequencies of 1 and 3 Hz, vertical tracking performance was also degraded to a greater extent by y axis vibration than by x or z axis vibration, although the percentage increase in tracking error as a result of y axis vibration was considerably smaller for vertical than for horizontal tracking. Vibration in the x and z axes degraded vertical tracking performance to a greater extent than horizontal tracking performance. This is in agreement with the results for z axis motion reported by Fraser et al. However, unlike Fraser et al, Shoenberger found that x axis vibration caused greater increases in vertical tracking error than the same level of vibration in the z axis for every frequency except 11 Hz.

Shoenberger concluded that, because y axis vibration resulted in larger increases in horizontal tracking error and vibration in the z and x axes caused larger increases in vertical tracking error, mechanical interference with perceptual processes and hand control is a primary mechanism responsible for decrements produced by short duration whole-body vibration on tasks of this nature. The very large decrements in performance due to y axis vibration were attributed to the ineffectiveness of the conventional support and restraint system in this axis: despite a full seat harness large side to side movements were noted in almost all body parts. Allen et al (1973) have also reported very large increases in tracking error in a roll axis tracking task with a lightly-sprung control stick, due to y axis vibration. They reported that the low frequency y axis vibration induced large control stick movements, mainly due to limb-control stick 'bobweight' effects which lead to subjectively reported uncertainty in control position and to an order of magnitude increase in remnant. Shoenberger (1970) suggested that performance under these conditions could be improved by the use of specialised support and restraint systems for the limbs and torso.

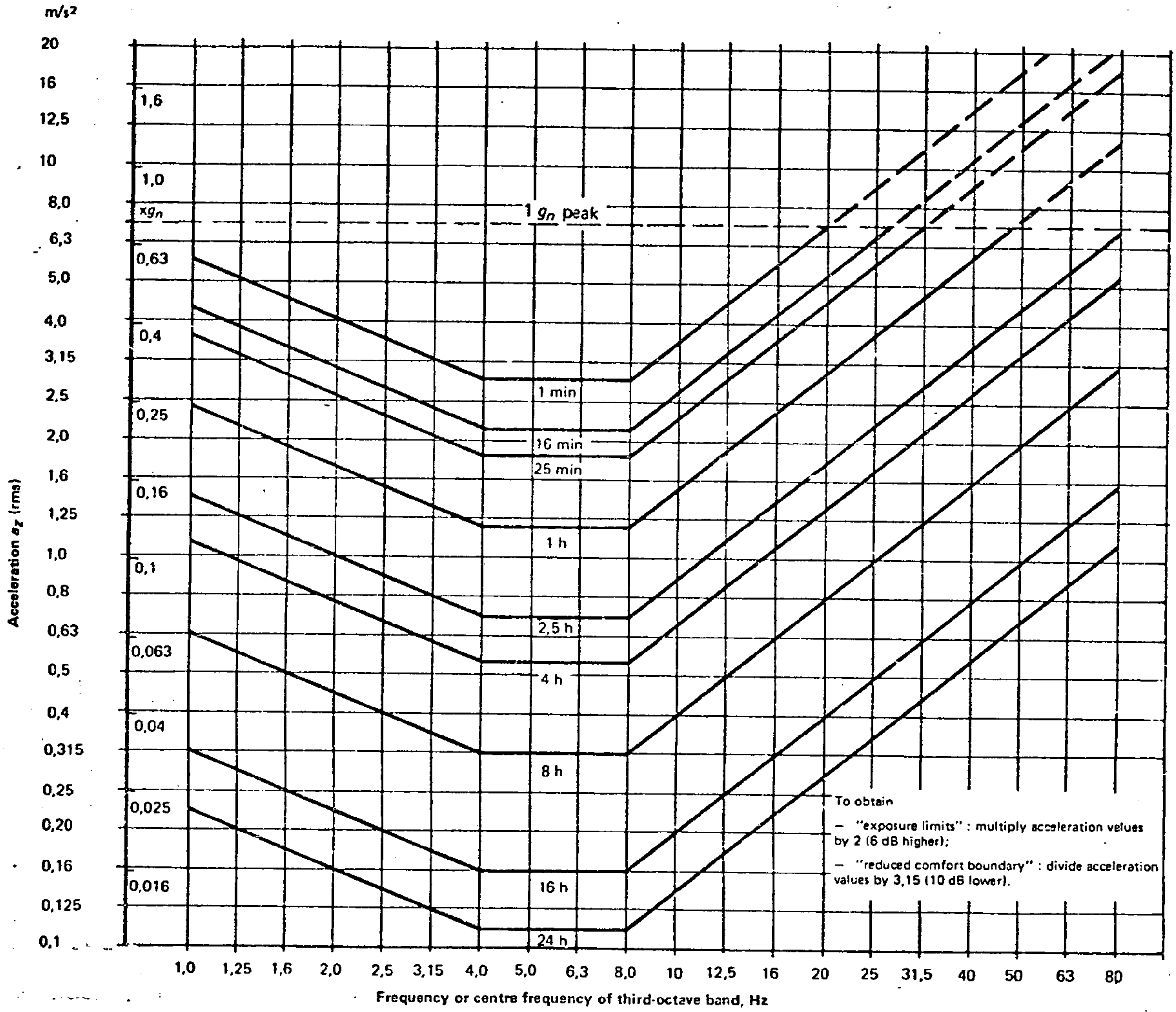
Multiple axis vibration environments have been investigated by Shurmer (1969) and Lovesey (1971a, 1971b, 1971c). Lovesey (1971a) concludes that for combinations of z and y axis vibration at 3, 5 or 7 Hz, percentage decrements in tracking error are equal to the product of the decrements produced by each vibration axis alone. For two and three axis combinations of 2 and 4 Hz vibration in the x, y and roll axes Shurmer (1969) also proposes that the total performance decrement is equal to the weighted product of those with each axis alone. Recent proposals to the International Standards Organisation suggest that the effect of multiple axis motion is similar to the effect of a single axis motion at a level corresponding to the root mean square sum of the weighted levels in each axis - again, this is a procedure which has been shown to be appropriate in subjective work by Griffin and Whitham (1976), but has not yet been shown to be appropriate to manual control performance.

Generally the largest decrements in tracking performance can be expected to be caused by vibration in the same direction as the sensitive axes of the control and display. However the effects of motion in any particular axis are likely to be largely dependent on the dynamics of the task.

3.5. THE EFFECT OF DURATION OF VIBRATION

One of the more controversial issues regarding human response to vibration is that of the effects of duration of vibration exposures. The form of the 'fatigue decreased proficiency' limits proposed by the International Standards Organisation, 1974, suggests the effects of vibration on performance are time dependent, the tolerable acceleration level decreasing with exposure time (see figure 3.5.1.). The validity of the fatigue proficiency limits has been investigated by Wilkinson and Gray (1974) and Guignard et al (1976). Wilkinson and Gray exposed subjects to continuous, 5 Hz z axis vibration at 1.2 m/s^2 r.m.s. (a level equivalent to the ISO 1 hour FDP boundary) for a period of three hours, while they performed zero order compensatory tracking, vigilance, visual search and handwriting tasks. There were six 3 minute tracking runs spread over the course of a three hour session with vibration and a similar session without vibration. Tracking performance was actually found to improve during each session and the improvement was more marked, though not significantly so, during vibration compared to static control sessions. These improvements may be partially due to learning effects, but subjects did attend several practice sessions before the experiment. Guignard et al required subjects to perform a battery of tasks similar to those of Wilkinson and Gray, including zero order, compensatory tracking with a pedal control, for periods between 16 minutes and 8 hours, whilst exposed to sinusoidal z axis vibration at 2, 4 and 8 Hz at levels corresponding to the ISO fatigue decreased proficiency limit for that particular period of exposure. There were no significant changes in performance of any of the tasks.

Wilkinson and Gray (1974) suggest that one setting in which there may be some support for the ISO proposals is where vibration is associated with continuous performance of one task. Hornick (1962) found that performance of a continuous control task, including tracking with a steering wheel and a pedal control and choice reaction time, deteriorated significantly within half-hour exposures to sinusoidal vibration in the range 1.5 to 5.5 Hz in the x, y or z axis. (The levels employed by Hornick correspond to fatigue decreased proficiency levels between 1 minute and 16 hours). However Schmitz (1959), with similar tasks and similar levels of z axis sinusoidal vibration, discovered no significant effect of time within a one and a half hour, continuous exposure although tracking error in post-vibration trials was greater than in pre-vibration trials. Holland (1967) exposed subjects continuously for six hours to narrow-band random, z axis vibration although fifteen minute rests from the two axis, compensatory tracking task were given within every hour of exposure. Average hourly errors were significantly different, but not always in the direction of the



Longitudinal (a_z) acceleration limits as a function of frequency and exposure time; "fatigue-decreased proficiency boundary"

FIG 3.5.1 from ISO (1974)

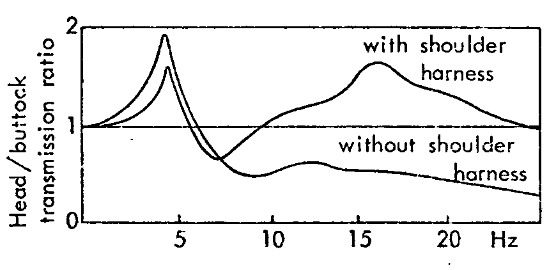


FIG 3.7.1 THE EFFECT OF WEARING A SHOULDER HARNESS UPON BODY VIBRATION TRANSMISSION IN THE Z AXIS (after Lovesey, 1975)

expected increase with time.

No clear general conclusions can be drawn concerning the effect of long-term vibration due to the variations and contradictions in the results of experimental studies such as those cited above. Those contradictions may be at least partially due to variations and deficiencies in experimental methodology. In the experiment by Schmitz and by Hornick static performance (i.e. performance in the absence of vibration) was measured before and after each vibration exposure, but there were no complete control conditions for the same period as the vibration exposures. This makes meaningful comparison of performance in static and vibration conditions for any particular exposure time impossible. Schmitz, Hornick and Holland all employed secondary tasks, in addition to the main tracking tasks, in all of the experimental conditions. In these cases interactions between the primary and secondary tasks may have masked the effect of vibration on either task alone (see section 3.8.).

Weisz et al (44) found that when subjects were required to perform a tracking task continuously for 20 minutes, performance significantly deteriorated over the period in both static and vibration conditions, however when one minute rests from the task were given at 5 minute intervals performance levels remained constant throughout the 20 minute vibration exposure. The basic problem associated with tasks of long duration appears to be one of arousal and motivation. If laboratory subjects are not sufficiently motivated, they are unlikely to maintain a sufficient level of attention to the task over long time periods. In some cases, as in Wilkinson and Gray (1974), subjects may be able to maintain their performance better while exposed to vibration due to the arousing nature of vibration stimuli. Confirmation of the arousing nature of the vibration stimulus comes from Jackson (1956 - see section 2.3.), who investigated records of altitude and heading of aircraft during a series of fifteen hour flights by ten pilots. During the first half of the flights pilots tended to fly more accurately and consistently in rough air than in calm air. However in the latter parts of the flights they were adversely affected by turbulent conditions, which seems to indicate some interaction between fatigue and vibration. In simulated low altitude, high speed flight, Hornick and LeFritz (1966) found that pilots were able to maintain their performance levels for four hours whilst subject to random vibration (1-12 Hz) at levels up to 0.2g(z) r.m.s.

Khalil and Ayoub (1970) and Dudek et al (1973) have described experiments in which subjects performed a tracking task for periods of one or two hours under various work/rest schedules from 5 minutes on and 5 off to 60 minutes on and 60 off. During continuous vibration the best overall performances were obtained with alternative work/rest periods of 30 minutes, but in static conditions the shortest work/rest periods turned out to be optimum. As the length of the work/rest periods increased, the difference in performance between static and vibration conditions became progressively less, until with 60 minute work/rest periods the overall performance was better during vibration than in static conditions.

To conclude, there is no clear evidence to support the concept of time dependent fatigue decreased proficiency limits, as proposed by the International Standards Organisation, for continuous manual control tasks. However it is possible that some results have been confounded by variations and deficiencies in experimental methodology. During some moderate exposures, up to several hours, vibration may even compensate for the effects of fatigue by increasing arousal.

3.6. COMPARISONS BETWEEN DIFFERENT CONTROLS AND CONTROL LOCATIONS

Of the 41 studies of manual tracking listed in appendix 4, 36 have used a joystick control. Aircraft type, centre mounted sticks were used in 10 studies and side mounted sticks in 28 studies: there were only 3 comparisons of stick location. There were 43 displacement (isotonic and spring centred) sticks, 10 isometric (force) sticks and one viscously damped stick: stick characteristics were compared in 10 studies.

Conventional centre sticks are normally large devices, requiring operation by the whole forearm, compared with miniature side mounted joysticks which are normally mounted on a seat armrest for operation by the hand. Gibbs (1962) and Hammerton and Tickner (1966) have provided data to show that, under static conditions in the laboratory, hand operated controls perform consistently better than arm, finger or thumb operated controls with a wide range of system gains and dynamics: a result which seems to favour the miniature, hand operated, side mounted joystick. These results may not be applicable in vibration environments, where the greater dynamic range and damping that it is possible to build into a large stick may reduce the effect of vibration transmitted to the control. However Soliday and Schohan (1965) found that in conditions of moderate to severe buffetting, during simulated low altitude, high speed flight, pilots were better able to maintain a constant terrain clearance altitude using a miniature side-stick than with a conventional, large aircraft centre-stick.

All three laboratory studies of the effect of control location have compared identical controls in centre and side locations and all the comparisons have been made with z-axis vibration only. Levison and Houck (1975) compared spring centred and isometric sticks - each with three gains - in centre and side locations during complex vibration (frequency components in the range 2 to 10 Hz) and found no difference in overall performance between any of the sticks or locations. Holland (1967) compared miniature, isometric sticks in each location and found that the centre-stick performed significantly better than the side stick during narrow-band random vibration with peaks at 2 or 5 Hz. However caution should be exercised in the interpretation of this result as tracking runs with the centre stick always preceeded those with the side stick, and were for a much shorter duration.

Shoenberger and Wilburn (1973) found that the best control location depended on the frequency of the vibration. Subjects' 'effective time delay' in the Systems Technology Inc. Critical Task described in section 3.1. (Jex et al, 1966a, 1966b) was lower with the side-stick during 2 Hz vibration, but the centre-stick performed slightly better with 6 Hz vibration and significantly better with 10 Hz vibration. The authors commented that the large performance decrement with the side stick at 10 Hz may be due to transmission of vibration to the subject's hand via the armrest which was provided at the side location (see Section 4.2 on the effects of restraining devices).

In static conditions, isometric (force) controls have been shown to have a superior performance to pure isotonic (displacement) and spring centred controls in a wide variety of systems (Gibbs 1954; Burke and Gibbs 1965; Ziegler and Chernikoff 1968; Mehr 1973) however several studies have shown that this may not be true in vibration environments. Isometric joysticks have been shown to be more affected by vibration than isotonic joysticks in both zero order* tasks (Shurmer 1969) and first order tasks (Levison 1976). One reason for this

* See definition on p. 21.

may be that isometric controls have been generally more susceptible to vibration breakthrough (vibration-correlated tracking error due to transmission of vibration to the control) than displacement controls, particularly at vibration frequencies greater than about 5 Hz (Allen et al 1973; Levison and Houck 1975; Levison 1976). Note that vibration breakthrough will contribute less to the total error variance in first, or higher, order systems due to attenuation by machine dynamics (Levison and Houck 1975; Levison 1976): each integration process in the machine dynamics represents a 6 dB per octave attenuation of control output.

Spring centred controls have similar dynamic properties to isometric controls, however Lewis (1974) compared tracking performance with a pure isotonic stick and a spring centred stick with two spring constants during combined 3, 5 and 8 Hz vibration and found that the spring centred controls were less sensitive to vibration breakthrough, and resulted in smaller increases in remnant due to vibration, compared with the isotonic control. The stick with the larger spring constant performed best in these respects. The greater susceptibility of isometric controls to the effects of vibration, particularly breakthrough, may be due to the absence of or low frictional damping, which is present to a greater or lesser extent in all displacement controls. The actual sensitivity of any particular control to breakthrough at a particular vibration frequency is of course proportional to the gain of the control. Gibbs (1962) has shown that in static conditions control gain has a pronounced effect on the performance of tracking systems, with a variety of dynamics. However the relative gain of the controls does not seem to have been considered in the various studies comparing different controls under vibration.

Controls other than joysticks have been used in 5 studies. Pedal controls have been used by Schmitz (1959); Hornick (1962); Hansson and Suggs (1973); Bennett et al (1976) and Giugnard et al (1976); steering wheels by Schmitz (1959) and Hornick (1962). The results of these studies indicate that pedals and steering wheels are affected by vibration in much the same way as joystick controls. Hansson and Suggs (1973) found no significant differences between tracking errors with sticks and a pedal, with vibration frequencies of 1.6 to 4.5 Hz, in a group of male subjects; but in a female group more vibration was transmitted to the pedal than the sticks.

There has not been enough comparative experimentation to enable effective general conclusions to be reached about the relative performance of different types of controls under vibration, however if control in two axes is required some kind of joystick or roller-ball control is essential. Regarding the dynamic properties of the control, more comparative research is needed which takes into account the possible effects of control gain on the relative effeciency of different control dynamics under vibration.

3.7. THE EFFECTS OF BODY RESTRAINTS AND POSTURAL VARIABLES

In many of the studies reviewed here, subjects have been strapped into their seats similarly to aircrew. However, only Lovesey (1971a, 1971b, 1971c) has considered the effect that the addition of a harness may have on the sensitivity of tracking performance to vibration. In Lovesey (1971c) the sum of maximum deviations either side of the target in a positioning task was greater when subjects wore a restraining harness than with no restraints during vibration in x and y axes at 2 and 2.7 Hz. Lovesey (1971b) showed that vertical tracking error variance during x and y axis vibration at 3.5 and 7 Hz was greater with a full harness, but horizontal tracking was improved. Harness effects can be explained in terms of effects on body transmission. The shoulder straps of a full harness hold the body against the seat back, providing an additional vibration input through the upper back and increasing the transmission of z axis vibration to the head and shoulders, especially at higher frequencies (Lovesey 1975, see Figure 3.7.1.). However the effect of y axis vibration, which has severe effects on horizontal tracking at low frequencies, may be reduced by the extra support given to the body by a full harness (Shoenberger 1970, see Section 3.4.).

Torle (1965) investigated the effect of providing small and large armrests for the subject's tracking arm during random)0.2 to 5 Hz), z axis vibration. A comparison of tracking performance without an armrest with that obtained using a small or large armrest showed a marked difference in favour of the support when vibration was present. The two types of armrest appeared to have similar effects. The results of Shoenberger and Wilburn (1973) indicate that the effects of armrests may be frequency dependent. Performance of the Systems Technology Inc. Critical Task was better with a side mounted stick with padded armrest than with an identical, centre mounted stick with no armrest during 2 Hz z axis vibration, but the centre stick was slightly better with 6 Hz vibration and significantly better at 10 Hz. The larger performance decrement at 10 Hz was attributed to transmission of vibration to the subject's tracking hand via the armrest.

Griffin (1975a) has shown that the transmission of z axis vibration to the head is highly dependent on variations in sitting posture. Performance decrements due to vibration have been shown to be highly correlated with body transmission, so we can expect posture to be an important variable in studies of tracking performance. Only Bennett et al (1976) have so far incorporated postural variables in an experiment. Subjects performed zero order, continuous, compensatory tracking with a foot pedal control, whilst subject to sinusoidal (6 Hz) and random (0.5 Hz) vibration in the z axis. The results indicate that performance under vibration was marginally better with a semi-reclined seat position, compared with an upright position.

The effects of body restraints, postural variables and other factors affecting body transmissibility is an important area of research which has been largely overlooked in performance studies. Much more work is needed before realistic general conclusions can be reached regarding the optimum characteristics for the seats and other restraining devices.

3.8. THE VISUAL CONNECTION: THE EFFECT OF DISPLAY VARIABLES

Relative motion between head and display has been shown by Huddleston (1970) to cause decrements in tracking performance. Huddleston reported significant reductions in time on target, with a two axis, zero order, compensatory tracking task due to apparent motion of the display in the frequency range 1 to 10 Hz. The effect of vibration was greatest for frequencies between 3 and 6 Hz, where a change of viewing strategy from pursuit eye movements to fixation on nodal images was apparent. Visual disturbance will be exacerbated by any seating configuration or restraining device which results in increased vibration transmission to the head (see section 3.7.). Wilson (1974), using the same task as Huddleston but with whole-body vibration in the range 2 to 10 Hz and a static display, has shown that the effects of vibration can be reduced when the display is viewed through a collimated lens, especially with 4 to 6 Hz vibration. (The collimated lens produces a virtual image of the display at infinity. For linear motion of the eye or display relative angular movement between the two is reduced as the distance between them increases, therefore collimation of the display could enhance visual acuity under vibration - see Griffin and Lewis, 1978). Compensatory eye movements evoked by the vestibulo-occular reflex during very low frequency (0.04 Hz) angular motion of both operator and display, in yaw, have also been shown by Gilson et al (1970) to result in significant decrements in tracking performance. Compensatory eye movements may also be evoked by linear motion, however Fraser et al (1961) reported that tracking performance during whole-body vibration in the 3 translational axes at frequencies from 2 to 12 Hz was slightly better with a moving, compared to a static, display but at these frequencies head motion is unlikely to be the same as display motion, even with a moving display.

It should be noted at this stage that the tracking displays employed in the experiments by Gilson et al (1970); Huddleston (1970) and Wilson (1974) were small, 4 cm diameter, cross pointer indicators which may be similar to some aircraft instruments, but are not typical of the relatively large oscilloscope screens used in many other experiments reviewed here. Tasks involving the perception of fine details are very susceptible to the effects of vibration (see, for instance, a review of the effects of vibration on visual acuity by Griffin and Lewis, 1978). However research has shown that a relatively small increase in the size of a test object can result in a large decrease in sensitivity to vibration: O'Hanlon and Griffin (1971) observed a 75% reduction in error in a 'Landolt C' reading task after only a 25% increase in character size.

The importance to tracking performance of an efficient visual connection between display and eyes is obvious, however the susceptibility of a task to vibration-induced visual disturbances will depend on such factors as display size, viewing distance and transmission of vibration to the head. Visual disturbances are not likely to be a significant factor in the degradation of performance by vibration where relatively large displays are used, as in most of the studies reviewed in this chapter, or where the display is distant from the operator. Systems are likely to be especially resistant to visual disturbances if the display elements move in an axis orthogonal to that of the vibration.

3.9. THE EFFECT OF WORKLOAD AND OTHER STRESSES

Environments in which vibration is the sole environmental stress acting on human operators are quite rare. Vibration is almost invariably associated with acoustic noise, and in such circumstances as high-performance aircraft and military vehicles these are likely to be accompanied by heat or cold, acceleration, impacts, workload, fatigue, mission stress and the impediments of clothing etc.

Some experiments have required subjects to perform secondary tasks concurrently with the main tracking task, either in an effort to make the control task more realistic or, as in the case of Holland (1967), to increase the sensitivity of measurement of performance by occupying the 'reserve channel capacity' of the subject. Poulton (1965) has suggested that a secondary task can have an effect similar to increasing the difficulty of the primary task. However he points out that the additional task should engage different receptors and effectors to ensure that competition between the tasks does not occur in the sense and the effector organs, as it may have done in Holland's tracking and choice reaction time tasks. The imposition of additional workload stress, which may have an unknown interaction with vibration, makes the interpretation of such studies difficult. For instance Weisz et al (1965) showed that tracking performance decrements under 5 Hz vibration were disproportionately greater when subjects were required to perform secondary tasks than when they were not. This suggests that the secondary task produces additional workload stress which interacts with the vibration stress to degrade tracking performance.

Decrements in tracking performance due to vibration have usually been attributed to specific, mechanical interference. Tasks which do not demand fine visual acuity or manipulation of a control have generally been found to be unaffected by vibration conditions which caused marked degradation of tracking performance (Shoenberger 1967). In the earlier discussion of the effect of duration of vibration exposure it was noted that vibration can serve to maintain arousal during long periods of continuous tracking. For example the significant improvement in tracking performance with low levels of vibration which was reported by Catterson et al (1962) can also be taken as evidence of increased arousal. Noise, heat and sleep loss, as non-specific stresses, are also known to affect certain aspects of human performance, although the mechanisms involved are not well understood. Broadbent (1963) has presented evidence which suggests that noise is over-arousing and sleep loss is under-arousing, the two effects partially cancelling each other in some situations. Heat, however appears to impair performance by a separate mechanism and produces different effects from the other two stresses.

The effects of a combination of filtered white noise and whole-body vibration on manual tracking have been investigated by Harris and Shoenberger (1970); Sommer and Harris (1972, 1973) and Harris and Sommer (1973). The task in all these studies was first order, compensatory tracking in two axes, identical to the task in Shoenberger (1970), run concurrently with a choice reaction time task. Each trial was 19 minutes long and was divided into four 4 minute blocks with 1 minute rests between blocks. Harris and Shoenberger (1970) found that 5 Hz vibration at ± 0.25 g (z) significantly degraded horizontal and vertical tracking while 110 dB noise (compared with an 85 dB control condition) significantly degraded only vertical tracking. When noise and vibration were combined the effect of noise was additive to that of vibration. Noise had no effect on the choice reaction time task. Sommer and Harris (1972) have described an extension of this study, in which the effect of vibration frequency was investigated. The vibration conditions were 5 Hz at ± 0.25 g (z), 7 Hz at ± 0.30 g (z) and 11 Hz at ± 0.50 g (z). 110 dB white noise was used as before, but the control condition was reduced to 60 dB. Tracking performance was significantly degraded by all the vibration conditions, with the greatest effect at 11 Hz. However in this experiment there was no effect of noise at 110 dB, compared with 60 dB, with or without vibration.

Sommer and Harris (1973) have also reported an experiment where 6 Hz vibration at ± 0.1 g (z) was combined with 100 dB white noise, compared to a 60 dB control condition. In addition to a significant effect of vibration on both horizontal and vertical tracking performance there was a significant noise by vibration interaction indicating that performance was better, during vibration, with noise at 100 dB than at 60 dB. Noise alone had no effect on performance. Harris and Sommer (1973) repeated this experiment with the noise condition increased to 110 dBA. In this experiment noise significantly degraded tracking performance and the effects of combinations of noise and vibration were again additive and performance was degraded more, during vibration, with noise at 110 dB than at 60 dB. Therefore it appears that increasing the noise level from 100 to 110 dB changed the interaction with vibration from a subtractive to an additive effect. The interaction between noise and vibration is complex and cannot be simply explained by an arousal theory. It is normally assumed that as arousal is increased performance is improved up to a certain point and then deteriorates as the man becomes over-aroused. The effect of increasing noise level during whole-body vibration in the above experiments is compatible with this model, however the effect of noise alone is quite different. Sommer and Harris (1973) have suggested that the subtractive effect of vibration and 100 dB noise may be due to an inhibiting effect on other sense modalities by noise, but the additive effect of 110 dB noise makes this difficult to accept.

Grether et al (1971) and Grether (1972) have reported two manual control experiments where heat stress was combined with noise and vibration. Subjects were required to perform first order, compensatory tracking in two dimensions, concurrently with choice reaction time and voice tasks. The levels of stress conditions used in both experiments were 5 Hz vibration at $\pm$ 0.3 g (z); filtered white noise at 85 and 105 dB; and dry-bulb temperatures of 72 and 120^{o} F. In the first experiment there was one control condition, three conditions where each stress was presented singly and a triple-stress combination. The primary impairment of tracking performance was produced by vibration; there was a slight impairment by heat but noise had no effect. However performance was slightly better during the combined stress condition than with vibration alone. Similar results were obtained for choice reaction time. The second experiment was similar to the first except that only four stress combinations were presented. These were a control condition, vibration alone, heat and vibration, and noise, heat and vibration. Again, the greatest decrements in tracking performance occurred with vibration only. There was less impairment of performance when heat was combined with vibration, and still less with all three stresses. Unlike performance measures, subjective ratings of stress increased with the number of stresses.

Although there is considerable agreement between the results of the above laboratory studies, their scope is somewhat limited and it would be dangerous to attempt to generalise conclusions to other tasks, stresses or even levels of the same stress without an understanding of the mechanisms involved. More research is needed into basic mechanisms of non-specific stress effects before questions can be answered satisfactorily.

3.10 GENERAL CONCLUSIONS AND SHORTCOMINGS OF STUDIES OF THE EFFECTS OF VIBRATION ON MANUAL CONTROL

The conclusions which can be drawn from the results of most of the forty or so studies reviewed in this chapter are not very far-reaching: some reasons for this have been discussed in section 3.1, on performance measurement. Moreover it can be seen from the discussions in preceding sections that there are a number of apparent contradictions between the results of different studies, severely limiting general conclusions. A number of shortcomings in experimental methodology appear to contribute to such contradictions. Methodological shortcomings in some of the research include the lack of proper control conditions (see section 3.5); the use of secondary tasks which may have complex interactions with performance at the primary task (see sections 3.5 and 3.9); the use of independent groups of subjects to test different experimental conditions with little attempt to control variability in biodynamic and other factors between groups; and in some cases, lack of adequate practice conditions leading to the possible confounding of results with learning effects. Other variations in experimental technique which may cause apparently conflicting results include the use of different terms to define the vibration stimulus (some experimenters refer to the displacement of the motion and others to acceleration - see section 3.2) and the use of different performance measures such as time-on-target as opposed to average error (see section 3.1).

It is evident that many task and workstation variables may have large effects on the way vibration affects control, however many of these variables have been incompletely or ambiguously specified in much of the literature. In some cases this ambiguity even extends to the reporting of the vibration stimulus, particularly in studies involving flight simulators (e.g. Besco, 1961, Soliday and Schohan, 1965) where the vibration environment is specified in terms of gust velocities and the dynamic characteristics of the simulated aircraft, making definition of the vibration spectrum nearly impossible. This ambiguity in reporting appears to be symptomatic of a more basic lack of definition of the goals of the research. General questions have been asked, such as 'how is tracking performance related to the amplitude, frequency, duration, etc. of whole-body vibration?' but very specific systems have been set up in the laboratory to answer these non-specific questions and in most cases very few of the variables which may affect the sensitivity of manual control systems to vibration have even been acknowledged.

The previous sections of this chapter are an attempt to extract from the confusion, where data is available, general trends in the effects of some important vibration and task variables. It has generally been observed that decrements in tracking performance due to low frequency, whole-body vibration are highly correlated with the transmission of vibration to the shoulders, controlling limbs and head. The largest performance decrements occur when the motion is in the same direction as the sensitive axes of the control and display and when the frequency of the motion is in the region of major body resonances. The effects are particularly great when there is little effective restraint for movements of the body in the direction of motion, as is typically the case for y axis vibration (Shoenberger 1970). Therefore any changes in the seat, restraint systems or controls which are likely to result in changes in the vibration inputs or the transmission of vibration through the man are also likely to affect the sensitivity of the tracking system to vibration. These observations have led Forbes (1960), Shoenberger (1970) and others to conclude that the effects of vibration on manual control are due to a combination of involuntary movements of the controlling limbs, induced by jolting and shoulder-girdle resonance, and impairments in visual acuity.

Until approximately five years ago the only performance measures used by experimenters in this area of research were simple average error and time-on-target scores, which do not permit a thorough analysis of the mechanisms of vibration interference with tracking performance. However with the recently increasing availability of data processing hardware it should now be possible to investigate these mechanisms in much greater depth. For instance, recent research has shown that only a relatively small proportion of the increase in tracking error under vibration can typically be correlated with the disturbing vibration (Allen et al 1973, Lewis 1974, Levison 1976). The visual aspect of the tracking tasks in these studies was quite robust: all of them used large oscilloscope displays and in the study by Lewis the controlled element and target moved in an axis orthogonal to the vibration disturbance. This leads to the conclusion that vibration can have other adverse effects on control performance than simple mechanical interference or visual disturbances. The importance to tracking performance of efficient visual feedback is obvious, but the visual control loop is not the only one involved in the performance of a tracking task. Lewis (1974) has pointed out that important neuromuscular control loops, involving proprioceptive feedback, may also be affected by vibration. Lewis noticed that high levels of vertical, whole-body vibration (with 3, 5 and 8 Hz frequency components) induced peaks of fairly periodic remnant activity in the output of some subjects. This activity was most marked when the subjects were tracking with a free-moving isotonic control stick and was significantly reduced when spring centring was added to the control. Since all other details of the task, including the display gain, were the same with both isotonic and spring-centred controls, Lewis concluded that the effect was neuromuscular in origin. He compared the periodicities in the subjects' responses under vibration to the oscillations which occur in servo-mechanisms with delayed or inadequately damped feedback.

Other experimenters have also found that the primary effect of vibration is to cause an increase in the remnant, or nonlinear, portion of the operator's response. (Allen et al 1973, Lewis 1976). Levison (1974) was able to re-analyse the lateral (y-axis) vibration experiment by Allen et al (1973) and fit the data to an 'optimal control model' (see section 3.11). Levison found that while low frequency remnant activity (below 0.3 Hz) was consistent with increases in perceptual, or observation noise, the remnant activity above 0.3 Hz best fitted the model with a large increase in motor noise, or neuromuscular remnant. Subjects in the study by Allen et al (1973) reported 'neuromuscular sluggishness' during some conditions of vertical, whole-body vibration. Transfer function measures also revealed increases in response lags which, the authors suggested, could have been due to some direct interference with neuromuscular actuation process. In some cases noise introduced into kinaesthetic senses of position and force, by vibration-induced activity in the controlling limb, may mask relevant cues of control displacement or force. For instance, in the experiment by Allen et al (1973) involving y-axis vibration (referred to above), during roll axis tracking with a lightly sprung stick, subjects reported that the large control stick movements induced by low frequency y-axis vibration resulted in considerable uncertainty about the null position of the control. There is also some physiological evidence to show that vibration of the body can directly affect reflex activity of the limbs and kinaesthetic feedback mechanisms. This is discussed in some detail in appendix B.

In addition to the direct, specific effects of vibration discussed above, evidence has been presented in section 3.9 to show that vibration can act as a non-specific stress, similarly to noise, heat, etc. There may therefore be complex interactions between the effects of vibration and other non-specific stresses in the environment of the human operator. The mechanisms by which vibration affects manual control performance will be discussed in greater detail in succeeding chapters of this thesis.

It can be seen from the discussions so far in this chapter that the effects of vibration on manual control performance are particularly complex and if the effects of operational vibrations on any real or projected system are to be predicted with any accuracy it is necessary to consider a great many variables. Because of this complexity, fairly extensive model structures are necessary in order to answer questions concerning the effects of vibration on any particular system. In the next, final section of this chapter the formulation of general models will be considered in the light of observations made so far.

3.11 MODELLING THE EFFECTS OF VIBRATION

Having made our observations and measurements, we need to make general sense of them in the form of predictive models. The simplest form of model of performance in vibration environments consists of a simple frequency weighting function indicating the relative effect of different vibration frequencies on performance. Because of the way characteristics of vibration and tasks interact, simple weighting functions are not sufficient to predict actual performance decrements in a general case. However they have proved useful for establishing desirable boundaries for vibration levels in environments where a number of different tasks may be performed. Examples of such limits are the fatigue decreased proficiency boundaries proposed by the International Standards Organisation (1974), and the guide for the evaluation of human exposure to helicopter vibration proposed by Griffin (1975c).

A taxonomic model of human operator processes contributing to performance in vibration has been described by Lewis (1974), a modified form of which is illustrated in Figure 3.11.1. He proposed that it

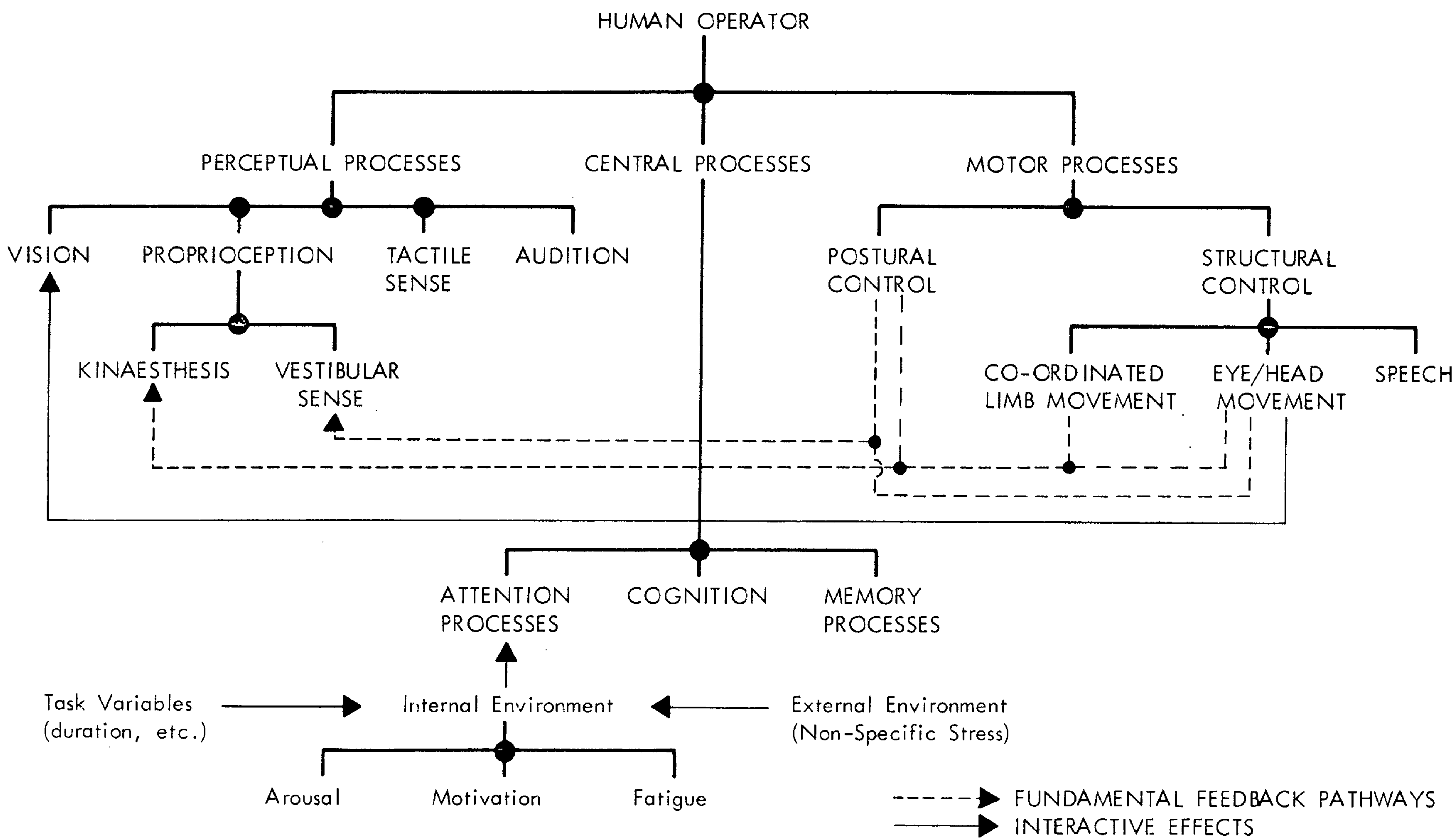


FIG 3.11.1 MODIFIED TAXONOMIC MODEL OF HUMAN OPERATOR PROCESSES WHICH MAY BE AFFECTED BY VIBRATION.

Modified from Lewis (1974)

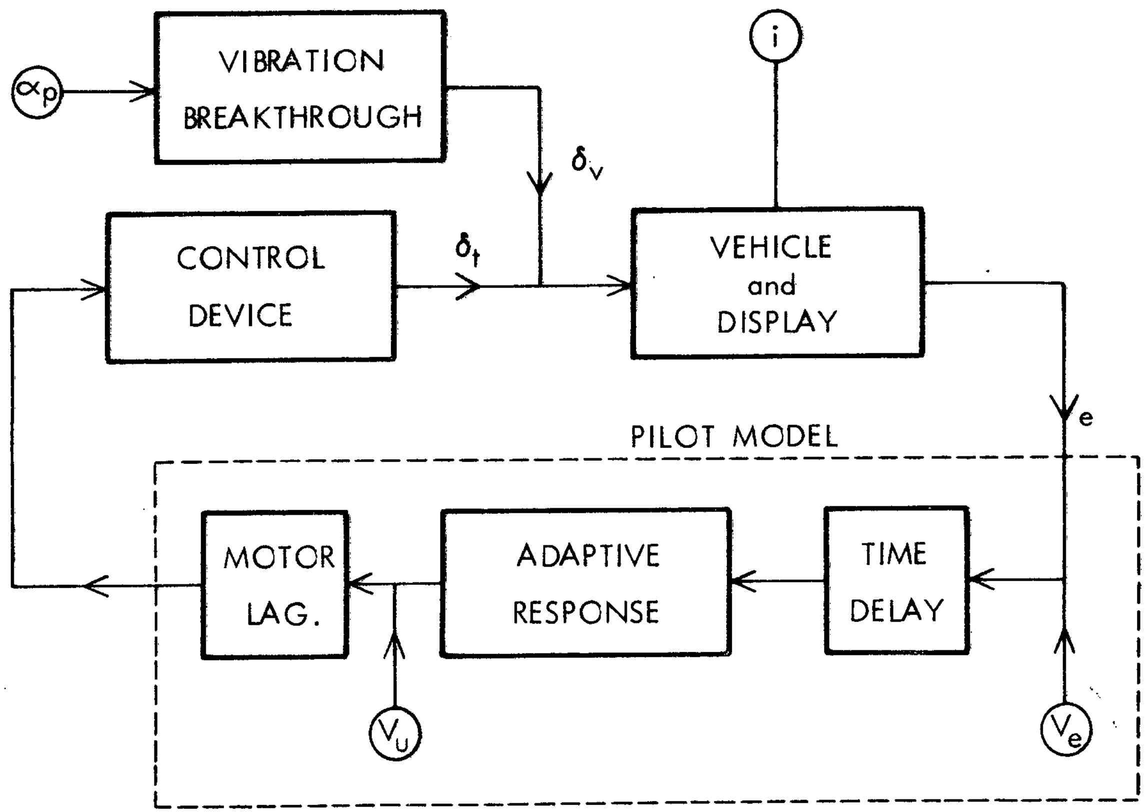
should be possible to determine the effects of vibration on the various component processes of the human operator, then the gross effects of vibration on a particular task could be predicted by determining the contribution of the various processes to the performance of the task, and integrating the effects at the subsystem level. The model is not intended to be a rigorous predictor of system performance in a quantitative sense, but it is thought to have application in pointing out possible weak points in planned systems and specific areas in which knowledge needs to be improved, as well as providing orientation for further research.

Probably the best developed models of the human operator in tracking tasks are the so-called 'quasi-linear' models of the input-output relations of the operator. These include mathematical representations of linear transfer functions, such as were defined in section 3.1 and remnant, which describes the nonlinear portion of the operator's response. These models have been extensively reviewed by Licklider (1960) and by McRuer and Krendel (1974). In the study of manual control performance during sinusoidal vibration by Allen et al (1973), parameters were fitted to the simple 'crossover model', described in section 3.1, which describe the open-loop frequency response of the operator in the region of gain and phase crossover frequencies. Quasi-linear operator models are black-box representations, which merely approximate certain aspects of the operator's response: they are not representative of the actual mechanisms of the operator in any way. Such models, which express the performance of human operators in engineering terms, are useful to the control engineer who needs to know the operator's transfer function in so far as it limits the system design. Of course these models can only be safely applied in situations similar to the laboratory conditions under which data for the model were gathered, however there are other serious limitations to their application due to inadequacies in the modelling techniques, which cannot successfully account for certain important characteristics of the human operator. The theory assumes that the operator performs similarly to an error correction servomechanism and cannot satisfactorilly account for the human operator's ability to base his response on information from many different sources, received via several channels, or for his memory, planning and prediction processes. Consequently this type of model is only really applicable to narrowly constrained tracking tasks, such as compensatory tracking of a single channel, randomly appearing forcing function (Kelley 1969).

Another important problem of modelling transfer functions of human systems is that the human operator is highly adaptive and can change his strategy in order to partially compensate for disturbances. An 'Optimal Control' model, similar to that developed by Kleinman et al (1971), has been shown to be successful in predicting the effects of vibration on a tracking task used by Levison and Houck (1975) and Levison (1976). The application of the model is subject to the same restrictions as other quasi-linear models, however in addition to vibration level and spectral shape, it does take account of vehicle dynamics, tracking input characteristics, control characteristics, display gain, performance requirements and attention to the task. The structure of the model is illustrated in Figure 3.11.2. The key idea underlying the optimal control model is the assumption that the well trained, motivated human operator behaves in a near optimal manner, subject to his inherent limitations: specific operator characteristics are predicted by solving a multi-factor optimization problem.

'Biodynamic' models of individual parts of the human operator system, such as those described by Von Gierke (1973) have made some contribution to the understanding of the mechanisms of manual control. These models are in the form of mathematical or mechanical analogues which perform similarly to the processes of the human operator. Models of vibration breakthrough dynamics have been described by Allen et al (1973), and more recently progress has been made in the modelling of perceptual and motor processes contributing to increases in tracking remnant with vibration (Jex 1974). Models of vibration breakthrough and visual/motor dynamics due to Jex (1974) are illustrated in Figure 3.11.3. Because of the great number of biodynamic systems involved in determining the effects of vibration of tracking performance, such models are bound to be extremely complex. Most models of this type are also very system and situation specific since the complexity of the model tends to be proportional to its generality. However this type of model is useful in a descriptive, as well as mathematically quantitative sense, as it can provide useful clues to the operation of the actual mechanisms of the human operator.

A problem with the concept of quantitative models such as the biodynamic and optimal control models described above is that they



i = forcing function
e = tracking error
α_p = vibration input
δ_t = intended control output to minimise error
δ_v = vibration induced control output
V_e = observation noise
V_u = motor noise

FIG 3.11.2 "OPTIMAL CONTROL" MODEL OF PILOT/VEHICLE SYSTEM (after Levison, 1976)

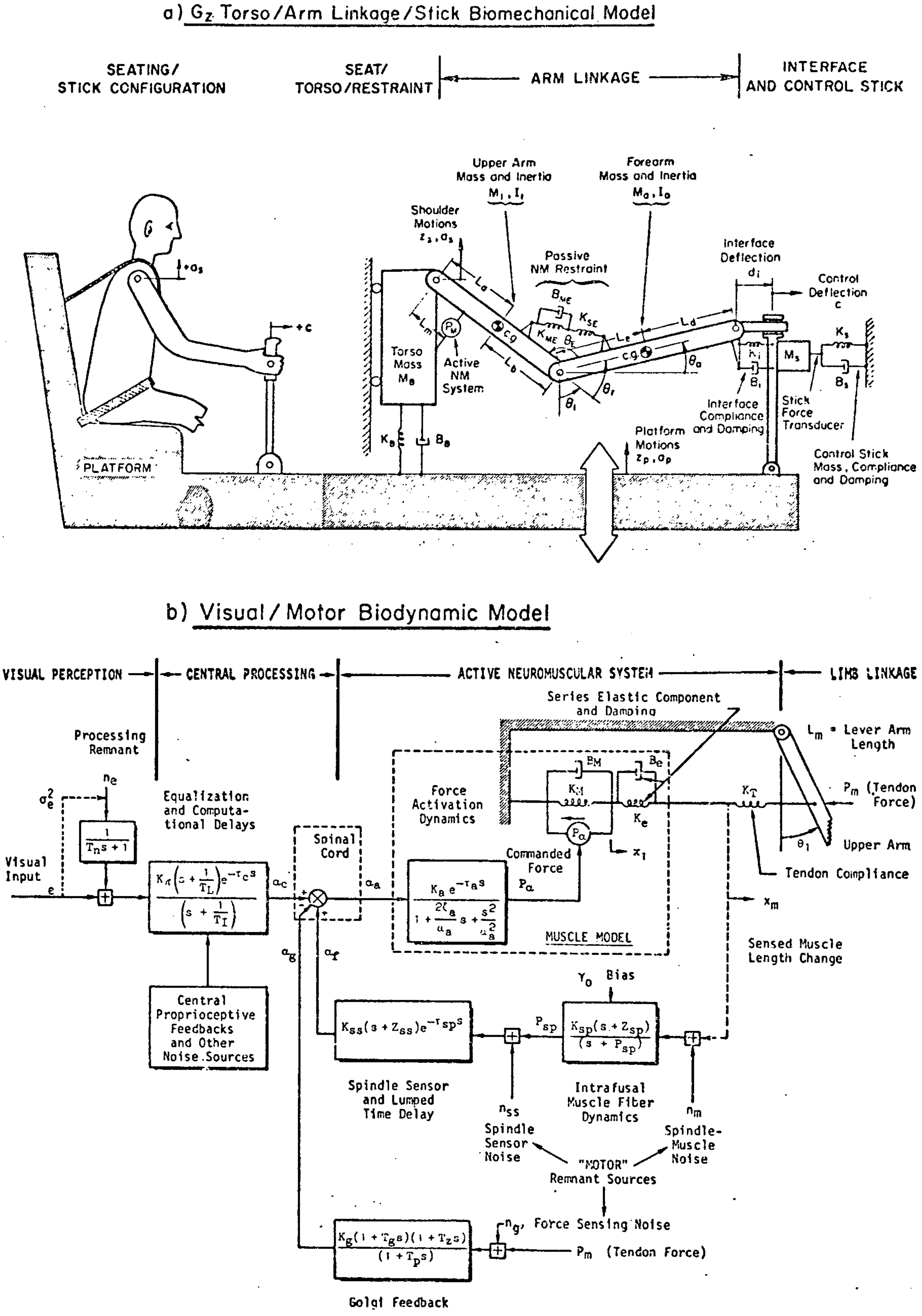


FIG 3.11.3 MODELS FOR VERTICAL VIBRATION EFFECTS ON PITCH CONTROL.

(after Jex, 1974)

describe the performance of an 'average' man, who rarely exists in reality. Individual variability in task performance is large and there are large differences between individuals in the effects of vibration on performance. The importance of these differences will vary from system to system so it is desirable that they should be quantified. Of course any predictive model is only as good as the data upon which it is based. There are still large gaps in available knowledge which must be filled before it is possible to predict the effects of vibration on performance in a general sense.

It can be seen from the above discussion that human performance in vibration environments can be represented by a variety of different model structures. The most useful form for such a model depends on its intended application. There have been several attempts in recent years to create quantitative mathematical models of the effects of vibration on human performance, but these have only been applicable in very specific situations. It is doubtful whether a comprehensive predictive model in a quantitative sense will be possible for some time due to the complexity of the human operator and the shortcomings of the presently available modelling techniques, as well as large gaps in our understanding of the mechanisms by which vibration affects manual control. It is obviously folly to model something which is not very well understood, so a greater research effort needs to be made in the near future towards understanding how vibration affects performance, and how other important properties of the task, workstation and environment interact with its effects. Until more comprehensive quantitative model structures become available this information could be used to refine descriptive models of the human operator, such as the taxonomic model structure proposed by Lewis (1974), which should prove to be useful aids in the isolation of the effects of vibration in systems and the consequent improvement of weak points in them.

4. INTRODUCTION TO EXPERIMENTATION

One of the most important conclusions that can be drawn from the results of the research reviewed in chapter three is that there is an as yet unfulfilled need for knowledge of the basic mechanisms by which vibration interferes with the performance of the human operator in manual control systems. Apart from providing the necessary groundwork for general predictive models, such knowledge would aid the understanding of interactions between components in the system, such as restraining devices or controls, and the effects of vibration. It would also aid the analysis of vibration effects in the system, providing clues to the location of effects and to what may be done to alleviate them. The mechanisms by which vibration can affect continuous manual control performance are investigated more thoroughly in the experiments reported in the rest of this thesis. Particular objectives of this research are to further investigate the hypothesis proposed by Lewis (1974) (see section 3.10), that interference with the kinaesthetic feedback processes mediating neuromuscular action is a primary cause of degraded performance in vibration environments, and to determine the importance of possible interaction between control characteristics and vibration effects.

This chapter describes the nature of the task, apparatus details and performance measures used in the experiments which are described in succeeding chapters.

4.1. THE TRACKING TASK

The task employed in all the experiments reported in this thesis consisted of zero order pursuit tracking (displacement of controlled element in direct proportion to control output) of a continuous forcing function. The forcing function appeared as random noise, approximating a 0 to 1 Hz rectangular spectrum. In the first four experiments the task was unidimensional, the forcing function and control elements moving in the lateral horizontal axis. The task in experiment five was two-dimensional, horizontal and vertical movements being produced by lateral and fore-and-aft control movements respectively. The tracking controls were side-arm joysticks or knobs, and were manipulated by the subjects' right hands (all the subjects were right-handed.) The control dynamics were either isotonic (constant force:

the control output is proportional to control displacement), isometric (constant displacement: the control output is proportional to applied force) or spring centred (combining isotonic and isometric characteristics). Vibration was in the vertical (e) axis only, and applied to either the subject's seat or to the control.

Zero order pursuit tracking, which is the simplest possible tracking task configuration, was used in order to minimise perceptual and central loads on the subjects, which may have confounded the primary, specific effects of vibration (see section 3.9.). The tracking task used in these experiments should also be resistant to direct vibration interference with the visual interface between the subject and the task as the oscilloscope display was relatively large (see section 3.8.). This should be particularly true of the single axis task, used in the first four experiments, as in this case the sensitive axis of the display is orthogonal to the applied vibration. However, because of the loosely coupled nature of the limbs, vertical vibration of the seat or control can be expected to result in significant amounts of vibration-correlated activity in other translational axes at the hand, as has been demonstrated in other experiments, using the same task configuration, which are reviewed in chapter three. The controls in most vehicles move in horizontal or rotational axes only, so this task configuration has some practical significance.

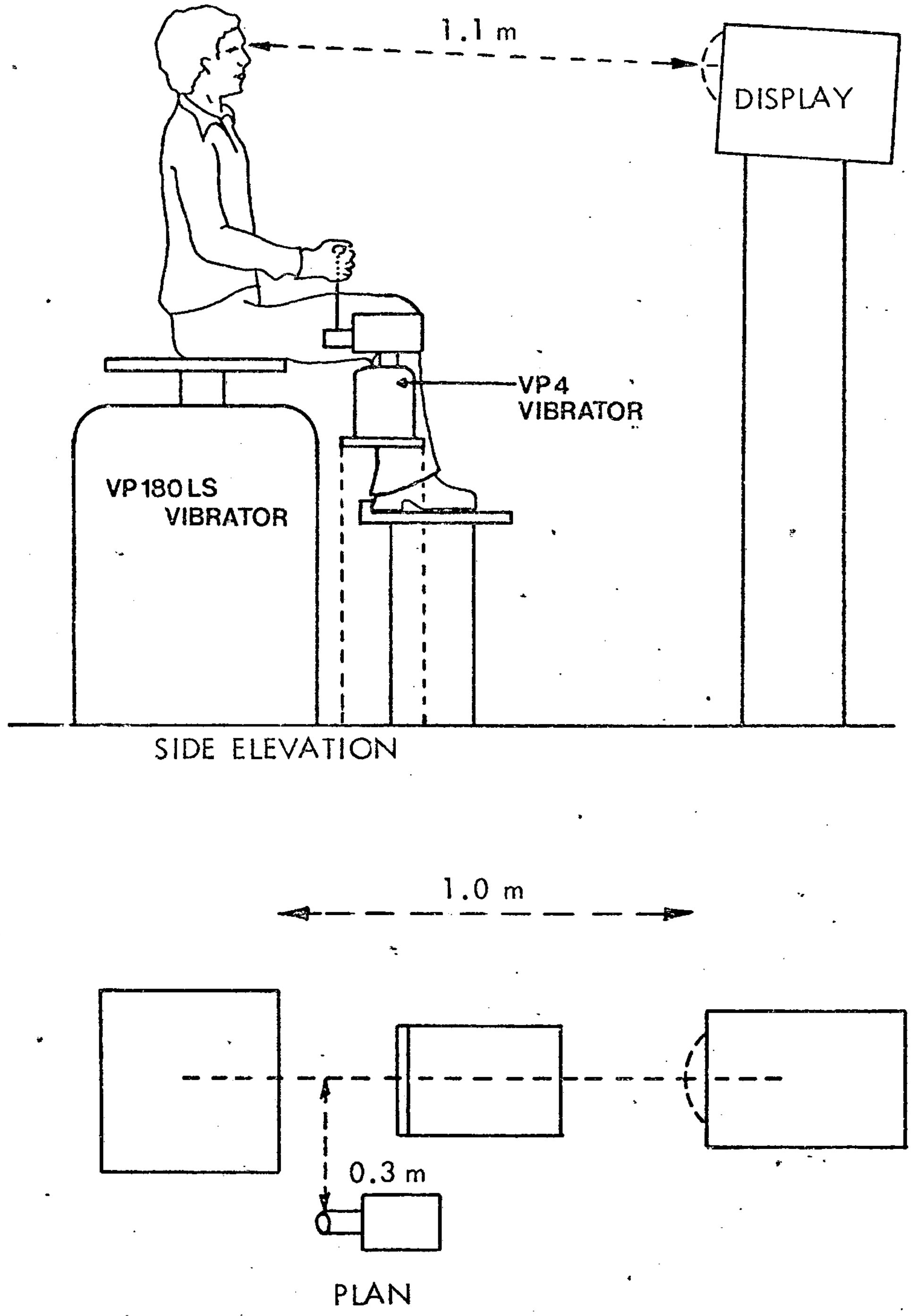
The next section comprises a detailed description of the apparatus, including control station dimensions and details of the generation of the forcing function and vibration conditions.

4.2. APPARATUS.

(i) The Control Station

In experiments one to four the subjects sat on a flat, hard seat with no back-rest which was mounted on a Derritron VP180LS electrodynamic vibrator. Their feet rested on a stationary footrest, the height of which was adjusted so that the upper legs were horizontal. The tracking control was mounted to the right of the seat and arranged so that the subject's right hand, in which the control was held, was at approximately waist height. The control mechanism was mounted on a Derritron VP4 electrodynamic vibrator, so that vertical (z-axis) vibration could be applied to either the control or the seat. The layout and dimensions of

FIG 4.2.1. PLAN AND ELEVATION OF CONTROL STATION.



the control station are shown in figures 4.2.1. and 4.2.2.

In experiment five a different seat was used. This was a hard, wooden seat with a back rest and integral footrest. The geometry of the seat and the position of the feet on the footrest were similar to that in a Westland Sea King helicopter (Grimster et al, 1974). The subjects were restrained by a tight, five point harness (two shoulder, two lap and a negative-G strap, joined by a quick-release buckle at the waist). The tracking control was mounted in a similar position relative to the subject as in the first four experiments, but was rigidly attached to the seat frame. The position of the display relative to the subject was unchanged. The configuration of the seat, harness and control is illustrated in figures 4.2.3. and 4.2.4.

The control station was screened from rest of the laboratory by heavy black curtains. The apparatus for the control of the task and vibration was located with the experimenter in a control room to the rear of the control station, so that the subject could be observed from behind. The view of the control station from the control room is shown in figure 4.2.5. The intake of cooling air by the vibrators produced a constant broadband noise (55 dB(A) at the subject's head), which was present throughout all of the experimental sessions. The experiments were all carried out in normal room lighting.

(ii) The Tracking Controls.

The tracking controls used in the first four experiments were various combinations of isotonic, isometric and spring-centred joysticks, and isotonic and isometric knobs. The joystick controls were 100mm long and sensitive to displacement or force in a lateral, horizontal axis. A knob at the end of the stick was gripped in the palm of the subject's hand. The knob controls were 12mm thick aluminium discs, 100mm in diameter, mounted in a plane parallel to the face of the display. The knobs were gripped by the fingers around the circumference. The isotonic and spring-centred controls were mounted on potentiometer shafts: frictional resistance to movement was negligible. Spring centring was provided by elastic springs, attached to a crank on the potentiometer shaft. The shaft upon which the isometric controls were mounted was attached to a horizontal cantilever. Silicon semi-conductor strain guages (the electrical resistance of the strain guages is sensitive to very small changes in length) were mounted on the upper and lower surfaces of the central portion of the cantilever, in order to detect

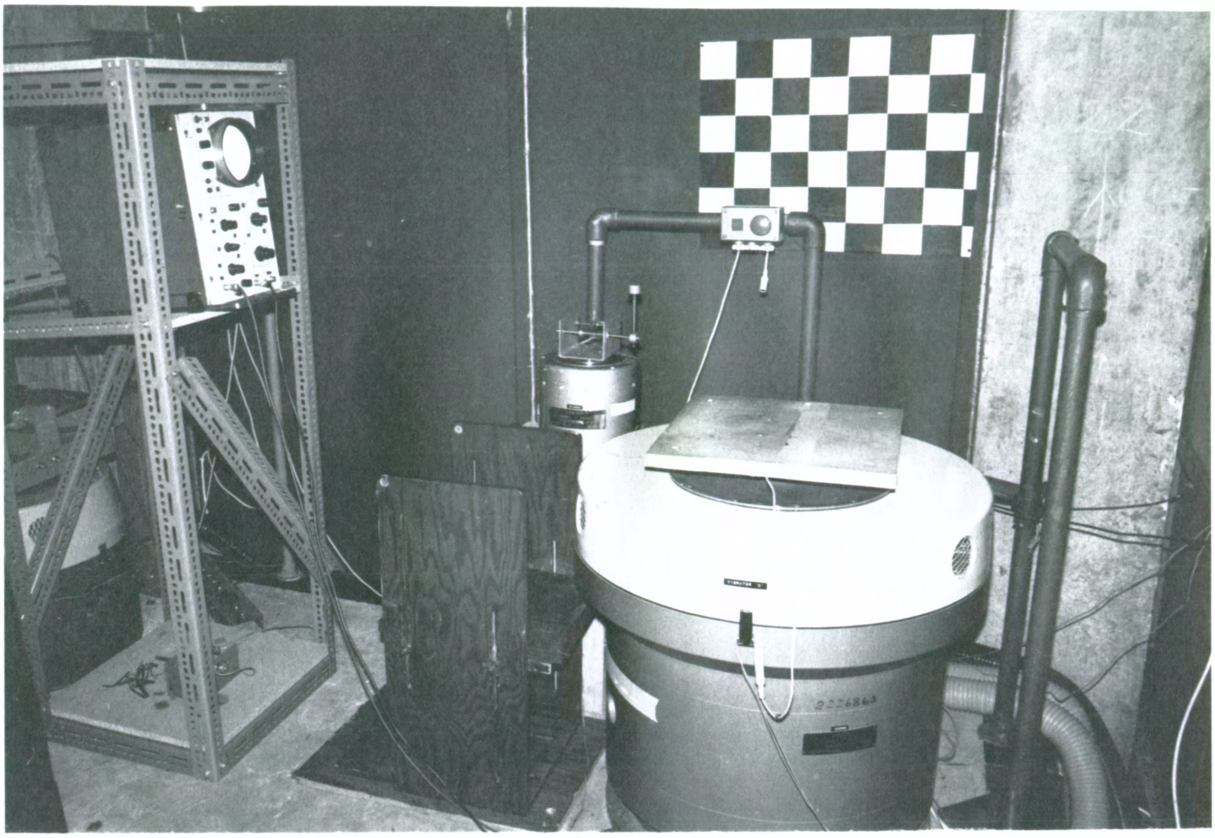


FIG 4.2.2.   The control station in experiments 1-4.

FIG 4.2.3.   Configuration of seat, control and harness in experiment 5.

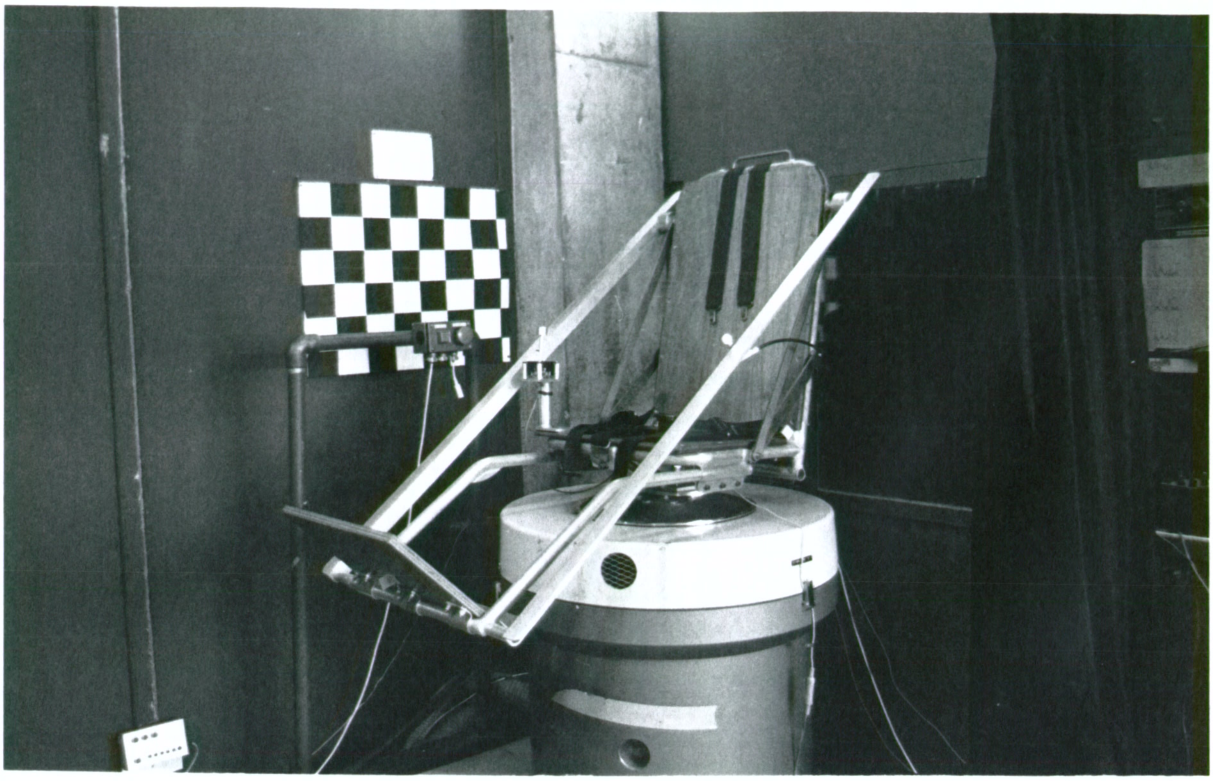


FIG 4.2.4. Details of the simulated helicopter seat and two-axis control used in experiment 5.

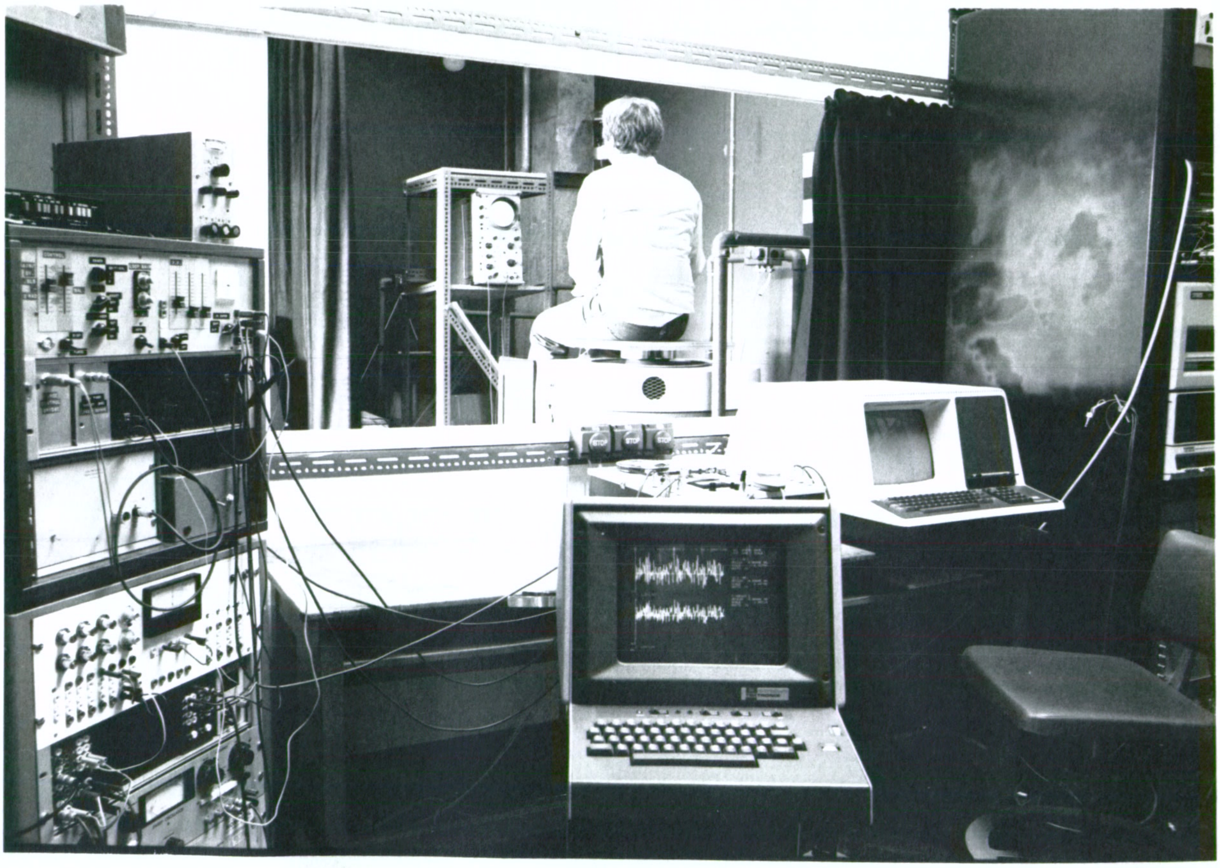


FIG 4.2.5. Experimenter's view of the control station.

the bending moments produced by torsion in the control shaft. The details of the isotonic and isometric control mechanisms can be seen from figures 4.2.6. and 4.2.7.

The tracking control used in experiment five was a two axis isotonic joystick, sensitive to horizontal displacements in the lateral and longitudinal (fore and aft) axes. The joystick was an identical size and shape to that in previous experiments. The joystick was mounted on a ball joint, and deflected two orthogonal cranks which were attached to potentiometer shafts. This arrangement resulted in slightly more frictional resistance to movement than the single axis case, although this was still too small to measure. The moment of inertia of each of the joystick controls was approximately 6 $Kg.cm^2$ and that of the knob controls was approximately 3.75 $Kg.cm^2$. Details of this control are shown in figure 4.2.8.

The output potentiometers of the isotonic controls and the strain guages on the isotonic control formed half of a resistance bridge network which was completed by a balance potentiometer. The output of the resistance bridge was buffered and amplified to produce a voltage proportional to displacement (in the case of the isotonic controls) or applied force (in the case of the isometric controls). The sensitivity of the amplifier could be varied to give a wide range of control gains. The control and display electronics were programmed on a special purpose analogue computer, which was designed and built by the author. The circuit of the control amplifier is given in figure 4.2.9.

(iii) Display and Task Generation.

The display was a Tektronix 502A dual beam oscilloscope, with a very short persistance (white, T.V. type) phosphor. The forcing function was represented by a moving circle (diameter 5mm) and the controlled element by a vertical line (length 5mm). The maximum excursion of the forcing function on the screen was $\pm$ 50mm in the horizontal and vertical axes. Note that in experiments one to four only the horizontal axis was used. As the display oscilloscope was not equipped with independent horizontal deflection amplifiers it was necessary to multiplex the signals representing the controlled element and the forcing function into a single channel, which was displayed using one beam only. The multiplexing was achieved by

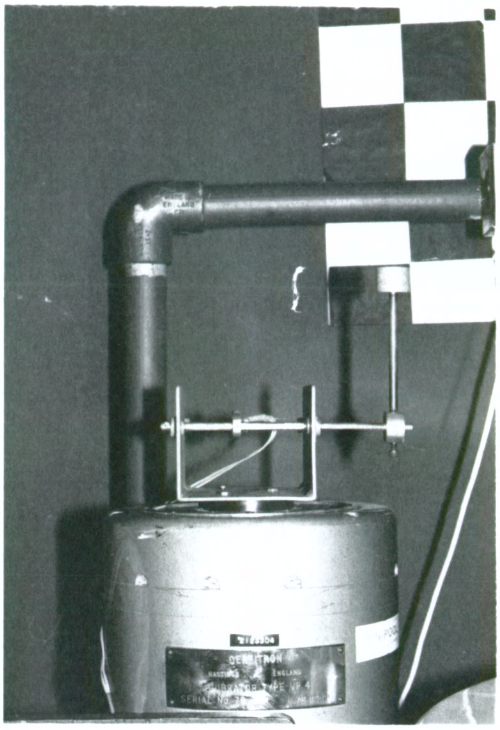


FIG 4.2.6a. Side view of the single-axis isometric control mechanism.

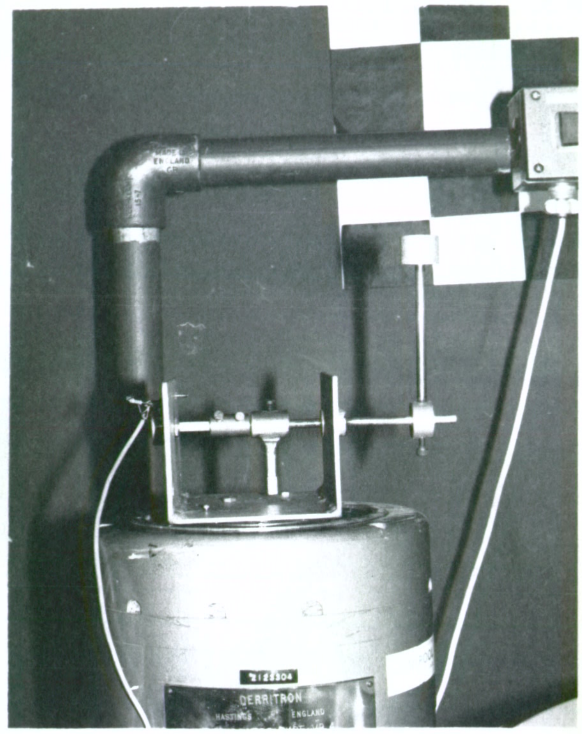


FIG 4.2.7a. Side view of the single-axis isotonic control mechanism.

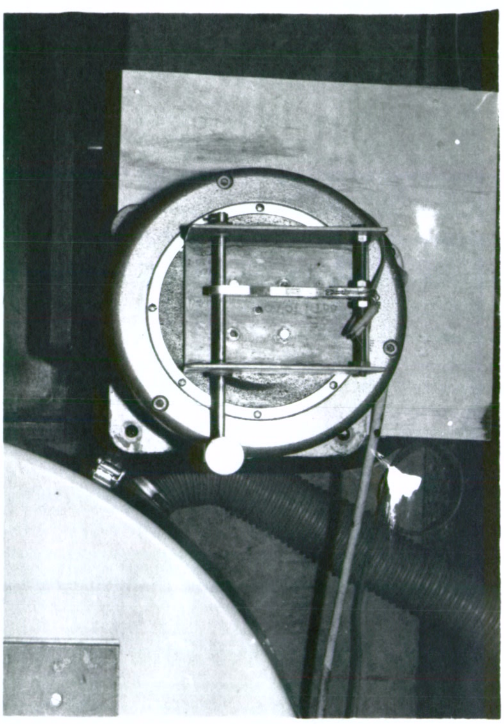


FIG 4.2.6b. Plan view of the single-axis isometric control mechanism.

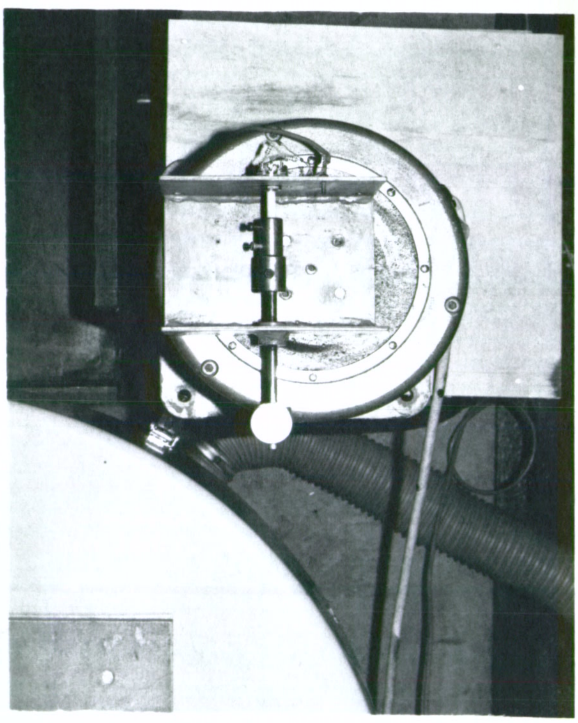


FIG 4.2.7b. Plan view of the single-axis isotonic control mechanism.

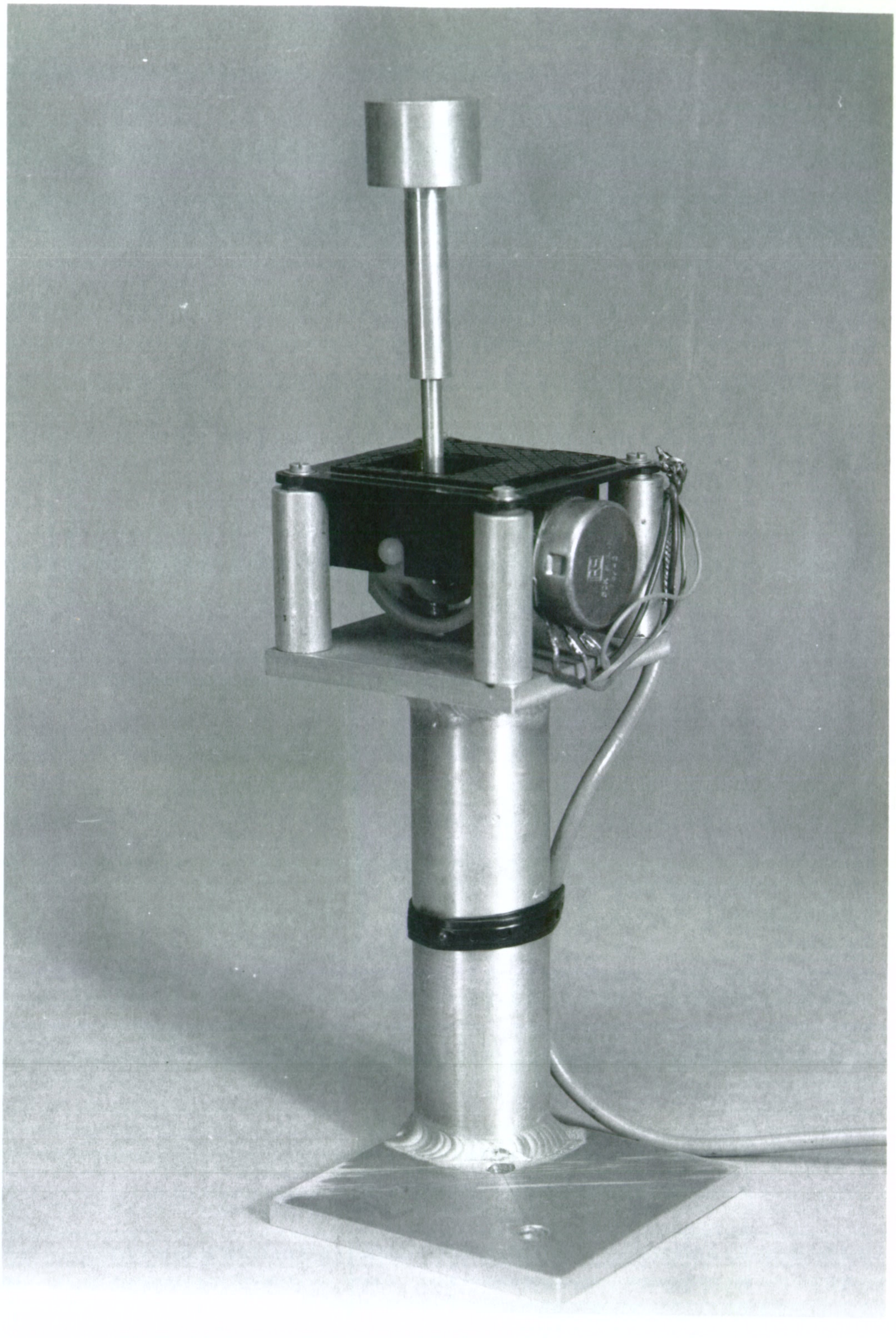


FIG 4.2.8. Details of the two-axis isotonic control mechanism.

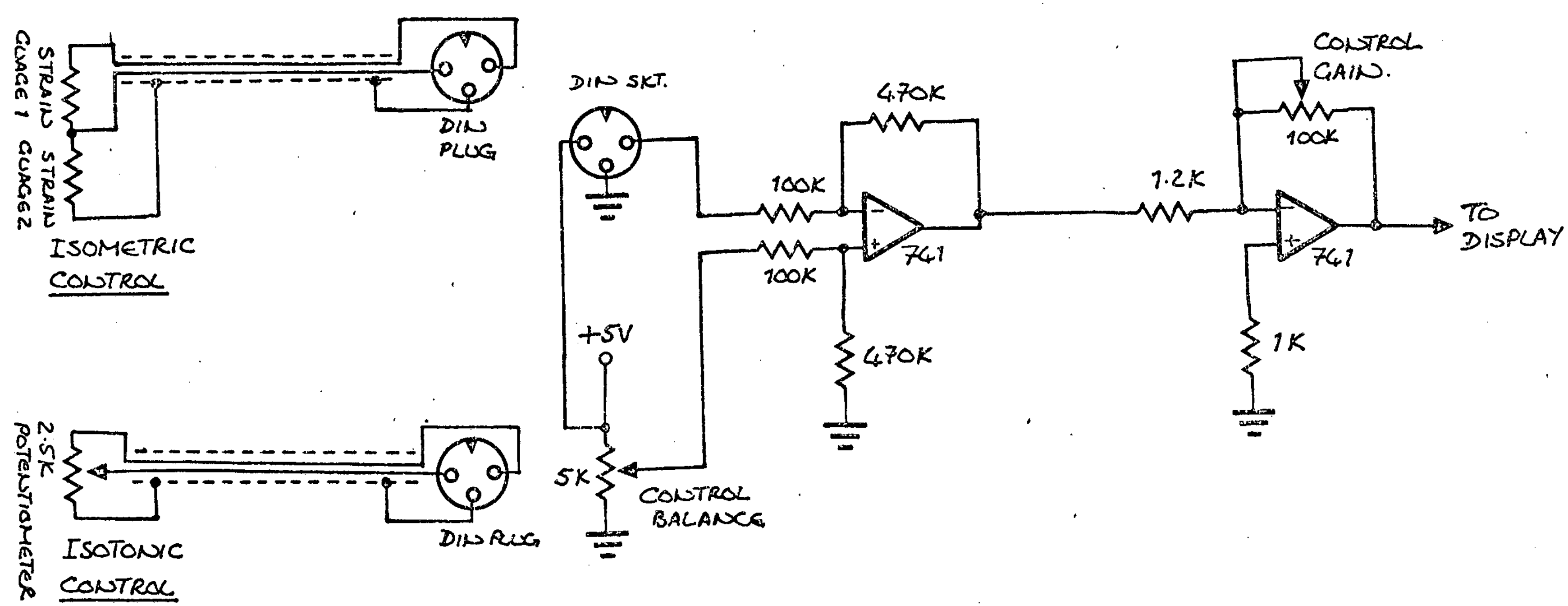


FIG 4.2.9. CONTROL AMPLIFIER CIRCUIT (one channel only shown).

chopping between the two signals with a frequency of approximately 10KHz. The target circle and line were generated by adding 5KHz sine and cosine signals to the vertical and horizontal deflections of the forcing function and the vertical deflection of the controlled element. Details of the target generation and multiplexing circuit are shown in figure 4.2.10.

The forcing function was generated by passing a random noise signal through a low pass filter. The filter had a fourth order Chebychev response and was designed to have a -3dB point at 0.9 Hz followed by an initial slope of -34dB per octave and a final slope of -24dB per octave, with a ripple order of 0.5 dB (Bronzite, 1970). The measured response indicated an attenuation of 20dB at 1.5 Hz. For the first four experiments (single axis task only) the filter was driven by a thermal noise generator, but for the two axis task in experiment five separate filters were used to drive the forcing function in horizontal and vertical directions, each filter being driven by an independent pseudo-random binary sequence generator. The pseudo-random binary sequence generators consisted of 15 stage shift registers with exclusive-OR feedback from the first and final stages and were clocked at 25 Hz (Barnes et al, 1973). Using this arrangement the output from any stage of the shift register consists of an apparently random sequence of binary signals. However, identical sequences are repeated after 32676 clock periods, or every 22 minutes. The resulting signal has a flat spectrum extending to almost half the clock frequency with a similar probability density function to that of band limited random noise (Anderson et al, 1973). Pseudo-random sequences also have the advantage that they are repeatable, lacking the long term statistical variations of true random noise. The sequences driving the horizontal and vertical motions appeared uncorrelated. Circuit details for the low-pass filters and pseudo-random binary sequence generators are shown in figure 4.2.11. and the power spectral density and probability density functions for each axis of the forcing function are shown in figure 4.2.12. The power spectra and probability density functions were similar with both random and pseudo-random driving signals.

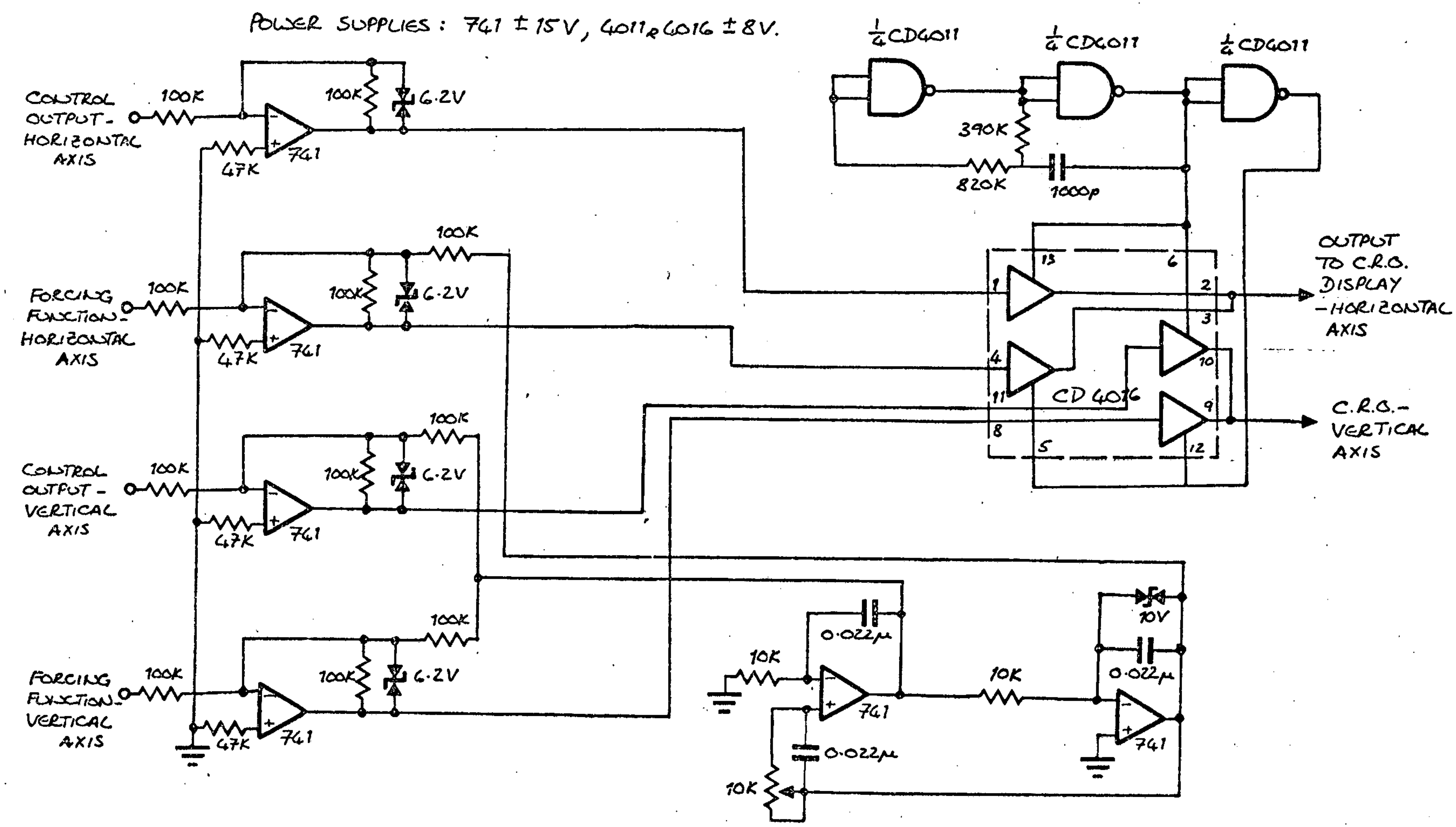


FIG 4.2.10. THE TARGET GENERATOR AND DISPLAY MULTIPLEXING CIRCUIT.

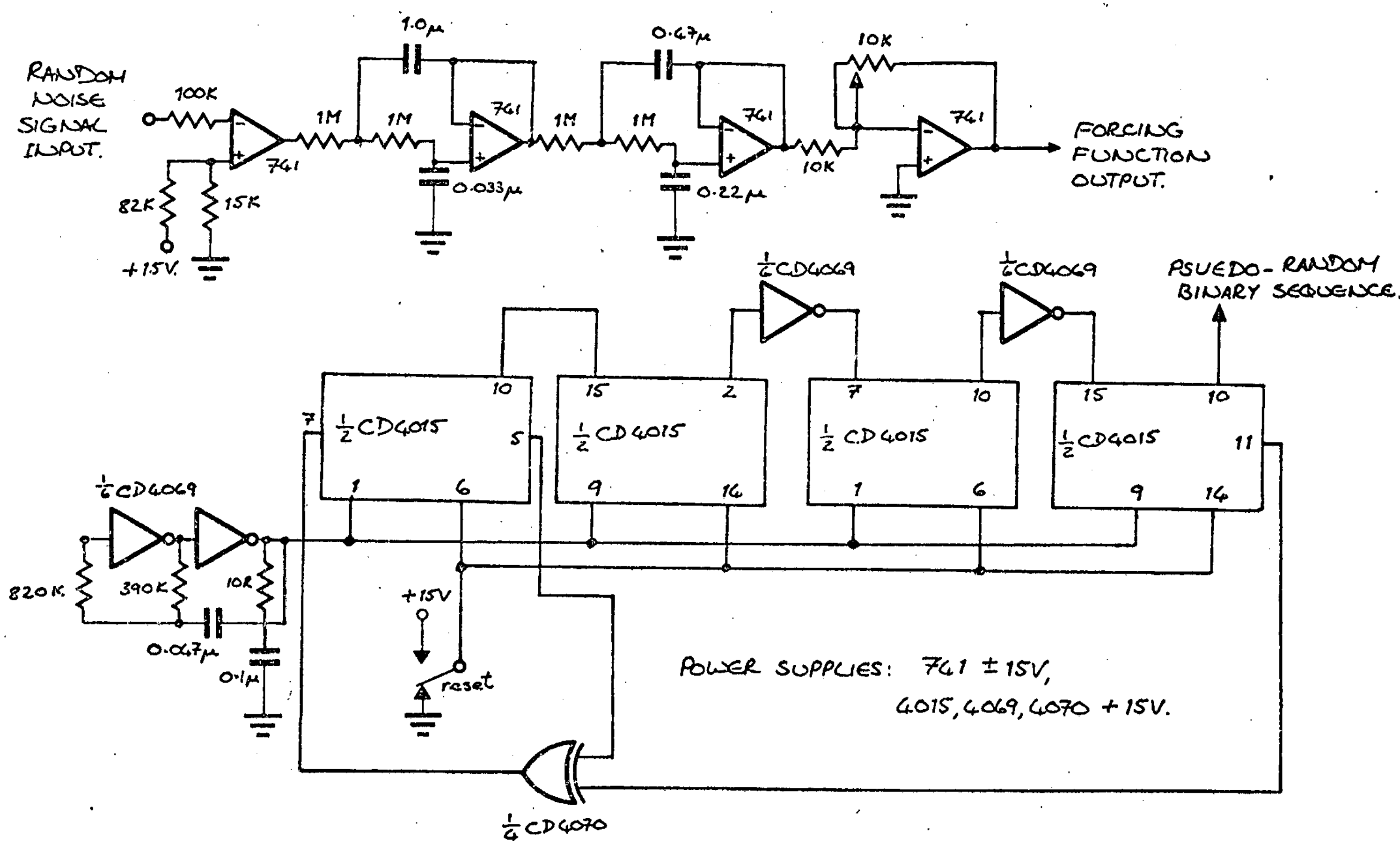


FIG 4.2.11. THE FORCING FUNCTION GENERATOR AND SHAPING FILTER (one channel only shown).

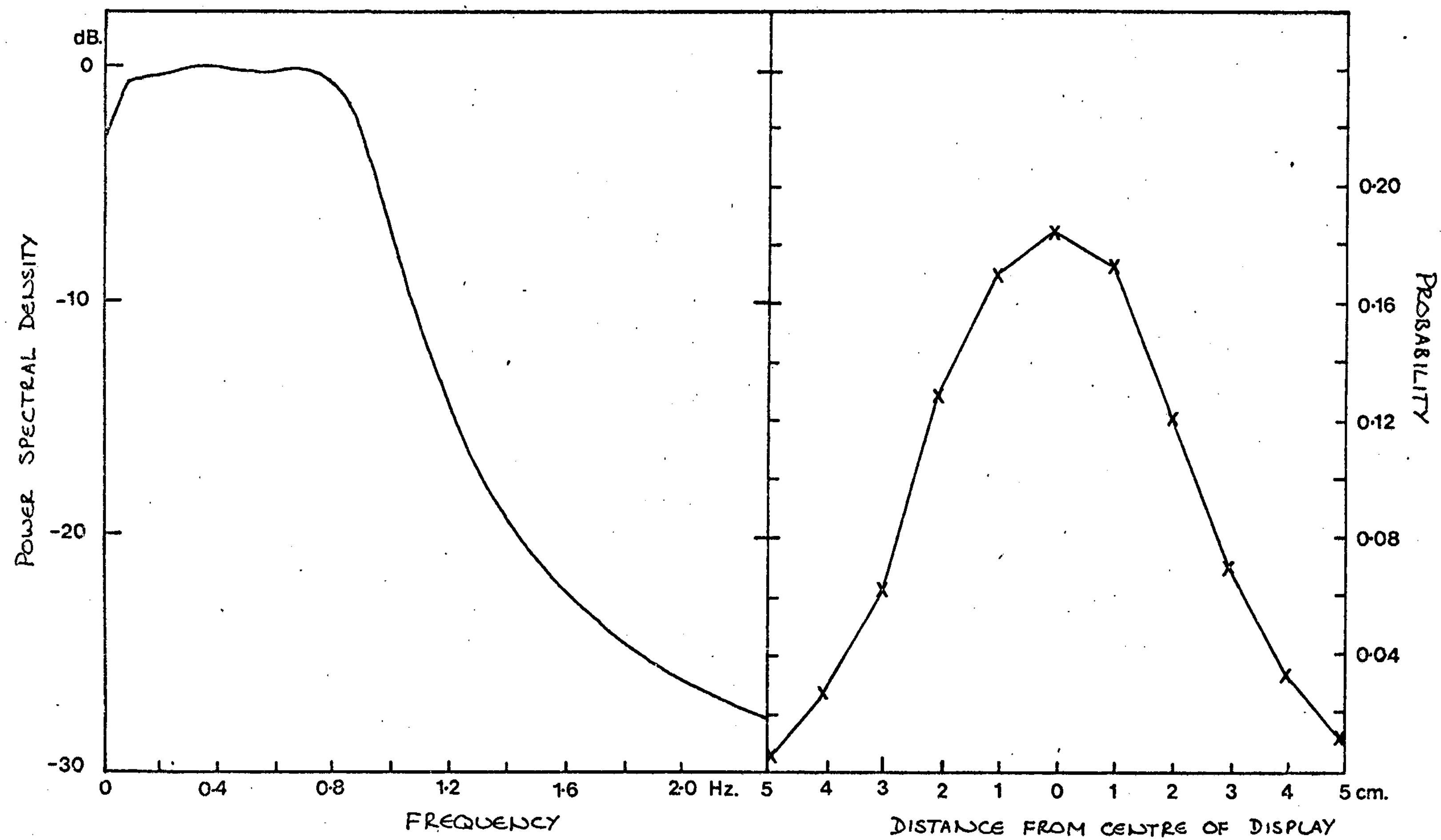


FIG 4.2.12. POWER SPECTRUM AND PROBABILITY DENSITY OF FORCING FUNCTION.

(iv) Vibration Control.

The two vibrators used in the experiments were electrodynamic types. The VP180LS vibrator, which was used for the whole-body vibration conditions, was driven by a Derritron 1500 watt, solid state power amplifier. Safety features in this system include displacement limit cut-outs on the vibrator and a variable current limit cut-out on the amplifier. Emergency stop buttons were also located next to the control station and in the control room. The smaller, VP4 vibrator which was used to vibrate the control in experiments two and three, was driven by a Derritron 100 watt, solid state power amplifier. Harmonic distortion of the acceleration output of the VP180LS is about 15% at 3Hz and decreases with increasing frequency. Harmonic distortion of the acceleration output of the VP4 is less than 10% at all frequencies used in these experiments.

Vibration levels were monitored via Endevco 2265-20 piezo-resistive accelerometers, which were firmly attached to the hard seat and to the control mechanism. The pre-amplified outputs from the accelerometers were passed through an r.m.s. to D.C. conversion module, giving the true r.m.s. acceleration, which was displayed on a digital voltmeter. The vibrator amplifiers could be driven by any electrical signal source of sufficient level. The acceleration output of the vibrator for a given level of input signal to the amplifier is dependent on load impedance. Therefore the signal levels have to be individually set up for different subjects. Furthermore fluctuations in load impedance, which may result from changes in posture (in the case of whole-body vibration) or force exerted on the control (in the case of control vibration), produce fluctuations in the acceleration output. These fluctuations are only generally significant, however, with the less powerful VP4 vibrator. In order to compensate for these fluctuations and to aid the accurate setting up of vibration levels, a closed-loop control system was devised. This used negative feedback from the accelerometer to automatically adjust the level of the input signal to the vibrator, in order to maintain the r.m.s. acceleration level equal to a pre-set reference level. The circuit can only be used for sinusoidal inputs, so the complex vibration conditions used in experiment five had to be set up manually. However the control circuit also proved very useful for measuring vibration transmissibilities (see chapters 6 and 9) using a sine-sweep input. In this case the

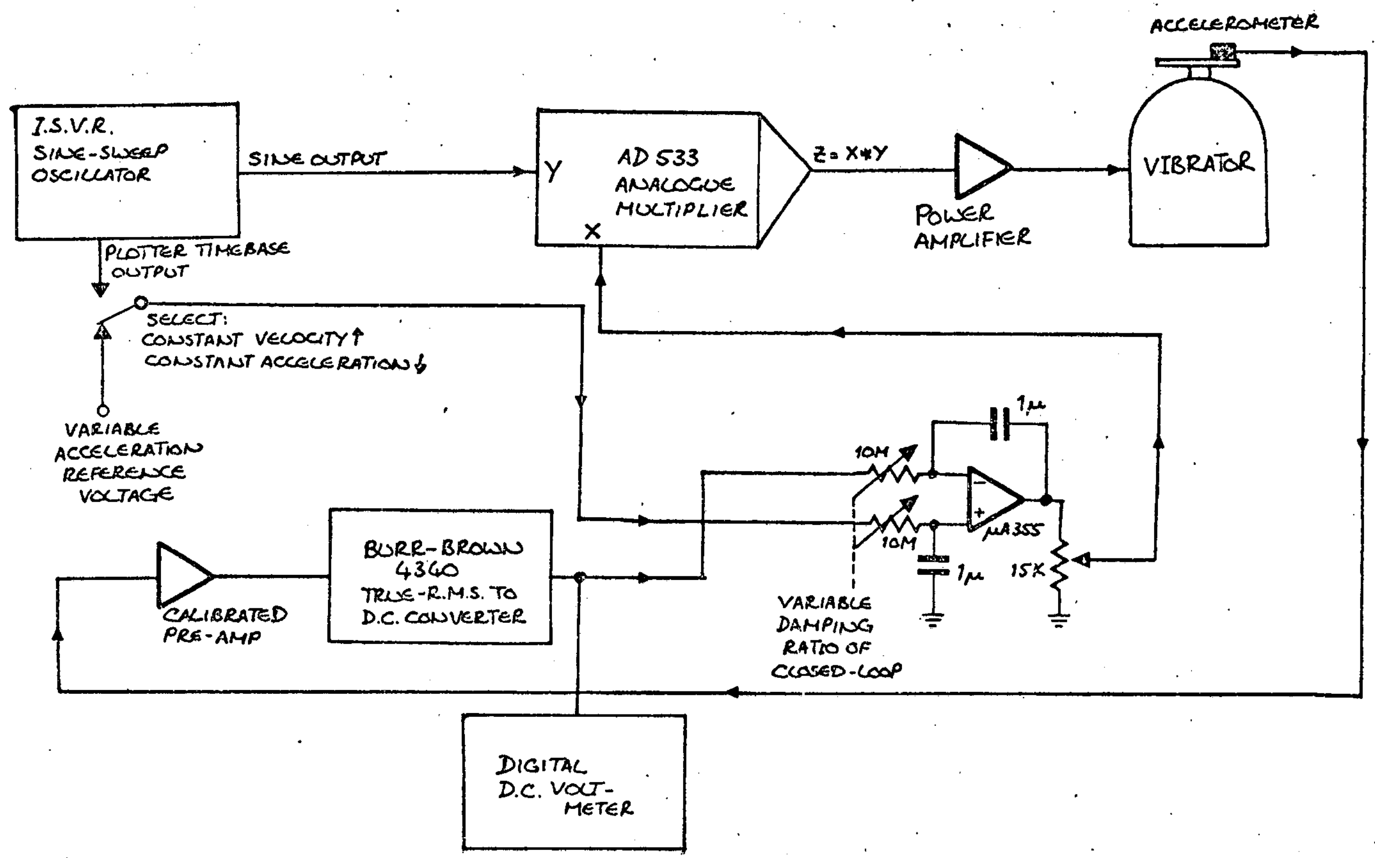


FIG 4.2.13. THE VIBRATION CONTROL SYSTEM

frequency of the vibrator input is swept linearly over a preset range, within a given time period (this was accomplished by a commercial sine-sweep oscillator). The acceleration reference voltage can either be kept constant, equalising the frequency response of the vibrator over the frequency range of the sweep, or varied in proportion to the vibration frequency (by connecting the reference input to the X-Y plotter timebase output from the oscillator), giving a constant velocity acceleration response. Circuit details of the vibration control system are given in figure 4.2.13.

4.3. PERFORMANCE MEASURES

(i) Theoretical Considerations.

The output, y(t), of an ideal, constant parameter, linear system, subject to excitation x(t) is given by

$$y(t) = \int_{-\infty}^{\infty} h(\tau).x(t-\tau).d\tau \qquad \text{(a)}$$

where $h(\tau)$ is the impulse response of the system. The Fourier transform of $h(\tau)$ is the transfer function, or frequency response of the system; hence in the frequency domain

$$Y(f) = H(f).X(f) \qquad \text{(b)}$$

where Y(f), H(f) and X(f) are Fourier transforms of y(t), $h(\tau)$ and x(t) respectively. We have already seen that the human operator in a continuous tracking tracking loop may be represented by a linear system with an internal noise generator. Consider the system in figure 4.3.1., in which a random noise process, n(t) is injected at the output. The output, in the frequency domain, will be given by

$$Y(f) = H(f).X(f) + N(f) \qquad \text{(c)}$$

where N(f) is the Fourier transform of n(t). The Fourier transforms are all complex-valued quantities, representing the amplitude and phase relationships of the frequency components of the time-varying signals. However the power spectral density, $G_{xx}(f)$, of a time varying signal x(t) is a real quantity, and is equivalent to

$$G_{xx}(f) = \lim_{T\to\infty} \frac{X(f).X^*(f)}{2T} \qquad \text{(d)}$$

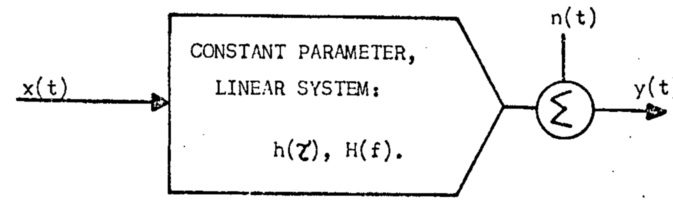


FIG 4.3.1. REPRESENTATION OF A LINEAR SYSTEM WITH NOISE, WITH THE NOISE PROCESS INJECTED AT THE SYSTEM OUTPUT.

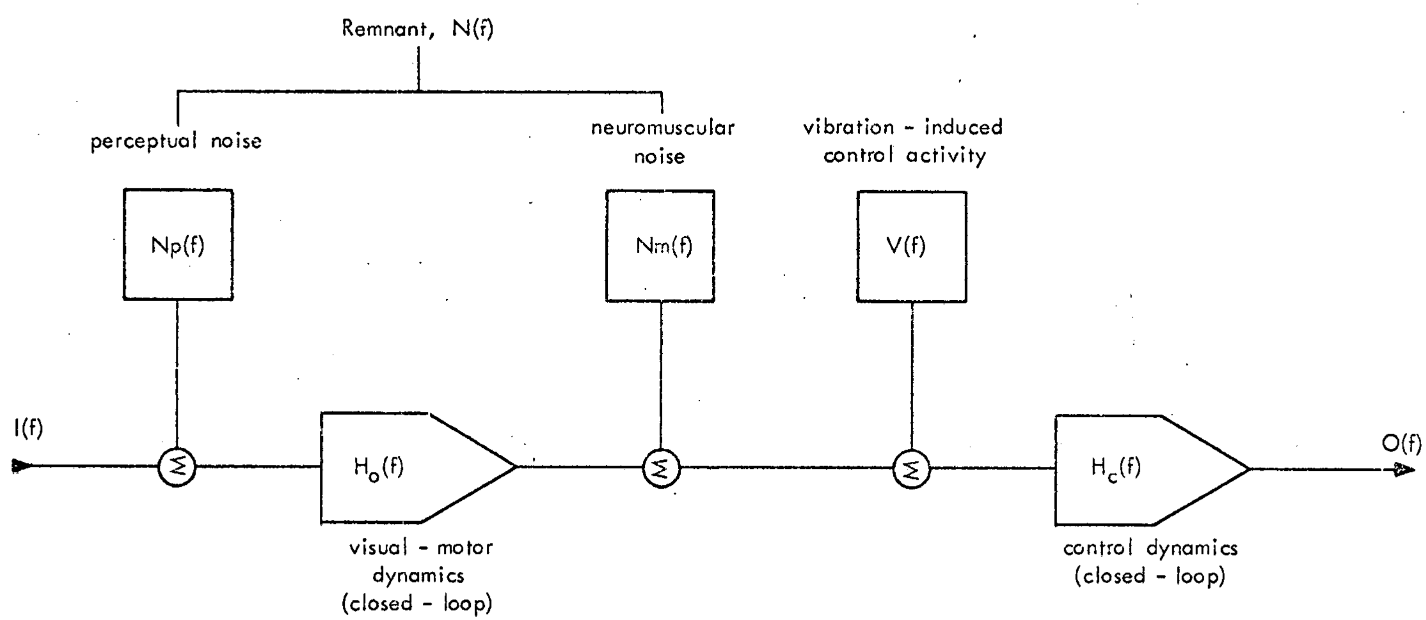


FIG 4.3.2. THE HUMAN OPERATOR AS A COMMUNICATION CHANNEL WITH NOISE.
I(f) and O(f) are fourier transforms of i(t) and o(t) respectively.

where * denotes the complex conjugate. $X(f).X^*(f)$ is equivalent to $X^2(f)$, therefore assuming that the input and noise are uncorrelated (and therefore their cross-spectral products are zero) equation (c) can be expressed as

$$G_{yy}(f) = G_{xx}(f).H^2(f) + G_{nn}(f) \tag{e}$$

where $G_{yy}(f)$ and $G_{nn}(f)$ are power spectral densities of $y(t)$ and $n(t)$ respectively. The best estimate of the transfer function in the least square error sense (Bendat and Piersol, 1966, pp 209) is given by

$$H(f) = \frac{G_{yx}(f)}{G_{xx}(f)} \tag{f}$$

where $G_{yx}(f)$ is the cross power spectral density between $x(t)$ and $y(t)$, and is equivalent to

$$G_{yx}(f) = \lim_{T\to\infty} \frac{X(f).Y(f)}{2T} \tag{g}$$

$H(f)$ is a complex-valued quantity, which can be expressed in the form

$$|H(f)|.e^{-i\phi(f)}$$

where the modulus, $H(f)$, describes the gain, or frequency response characteristics of the linear part of the system output and the phase factor, $\phi(f)$, describes the phase difference between the system output and input. Combining equations (e) and (f) gives

$$G_{yy}(f) = \frac{G^2_{yx}(f)}{G_{xx}(f)} + G_{nn}(f) \tag{h}$$

Therefore the best estimate of the power spectral density of the noise, $n(t)$, is given by

$$G_{nn}(f) = G_{yy}(f) - \frac{G^2_{yx}(f)}{G_{xx}(f)}$$

$$= G_{yy}(f).(1 - \gamma^2_{yx}(f)) \tag{i}$$

where $$\gamma^2_{yx}(f) = \frac{|G_{yx}(f)\ ^2|}{G_{xx}(f).\ G_{yy}(f)}$$

$\gamma^2_{yx}(f)$ is the squared coherence function between the system input, x(t), and the output, y(t). It is a real-valued quantity and for all f, satisfies

$$0 \leqslant \gamma^2_{yx}(f) \leqslant 1$$

It can be seen that the squared coherence function is a measure of linear correlation, and represents the proportion of power in the system output which is linearly correlated with the system input.

So far we have considered only the situation where noise is injected at the output of a linear system, whereas in the human operator noise is likely to originate in both perceptual (input) and motor (output) processes. Moreover the system output will be modified by the transfer function of the controlling device. Consider the linear model of a pursuit tracking system shown in figure 4.3.2. The closed-loop transfer function, H(f), which describes the linear portion of the operator's output is $H_o(f).H_c(f)$. Note that in a zero order task $H_c(f)$ is constant for all f, and the closed-loop transfer function is directly proportional to $H_o(f)$. The control output is given by (assuming no vibration input)

$$O(f) = I(f).H(f) + N(f) \qquad (j)$$

where N(f), or the uncorrelated remnant in the control output due to the operator's internal noise sources, is given by

$$N(f) = N_p(f).H_o(f).H_c(f)+N_m(f).H_c(f) \qquad (k)$$

It follows from equation (j) that

$$G_{oo}(f) = G_{ii}(f).H^2(f) + G_{nn}(f) \qquad (l)$$

where $G_{oo}(f)$, $G_{ii}(f)$ and $G_{nn}(f)$ are power spectral densities of input i(t), output o(t) and remnant n(t) respectively. The best estimate of the (closed-loop) transfer function is given by

$$H(f) = H_o(f).H_c(f) = \frac{G_{oi}(f)}{G_{ii}(f)}$$

where $G_{oi}(f)$ is the cross power spectral density of input and output.

The tracking error at time t is given by

$$e(t) = i(t) - o(t) \qquad (m)$$

e(t) is made up of all the remnant, or noise activity, n(t) and a component, c(t), which is linearly correlated with the input i(t). Hence

$$e(t) = c(t) + n(t) \qquad (n)$$

and

$$G_{ee}(f) = G_{cc}(f) + G_{cn}(f) + G_{nc}(f) + G_{nn}(f)$$

$$= G_{cc}(f) + G_{nn}(f) + 2|G_{nc}(f)| \qquad (o)$$

however since c(t) and n(t) are independent and uncorrelated the cross-power spectral products are assumed to be zero, and equation (o) reduces to

$$G_{ee}(f) = G_{cc}(f) + G_{nn}(f) \qquad (p)$$

If the operator and/or the control is being subjected to vibration, the forces transmitted to the man/control interface will induce some control activity which is correlated with the vibration input to the system. The power in the 'vibration breakthrough' or vibration-correlated error, $G_{vv}(f)$, is a further addition to the total tracking error power, hence

$$G_{ee}(f) = G_{cc}(f) + G_{nn}(f) + G_{vv}(f) \qquad (q)$$

Referring to equation (i) the best estimates of the error power components can be obtained from the following relationships:

$$G_{cc}(f) = G_{ee}(f).\gamma^2_{ei}(f) \qquad (r)$$

$$G_{vv}(f) = G_{ee}(f).\gamma^2_{ev}(f) \qquad (s)$$

$$G_{nn}(f) = G_{ee}(f).(1 - \gamma^2_{ei}(f) - \gamma^2_{ev}(f)) \qquad (t)$$

Where $\gamma^2_{ei}(f)$ is the squared coherency between the tracking error and the input or forcing function, and $\gamma^2_{ev}(f)$ is the squared coherency between the tracking error and the vibration input. If the frequency bandwidth of the vibration is separate from that of the remnant, $G_{vv}(f)$ may be calculated more simply from

$$G_{vv}(f) = G_{ee}(f)(1 - \gamma^2_{ei}(f)) \qquad (u)$$

where f is the frequency of the vibration.

The total variance or mean square value of the tracking error, over the frequency range f_1 to f_2, is given by

$$\sigma_e^2 = \int_{f_1}^{f_2} G_{ee}(f).df$$

$$= \int_{f_1}^{f_2} G_{cc}(f).df + \int_{f_1}^{f_2} G_{nn}(f).df + \int_{f_1}^{f_2} G_{vv}(f).df \qquad (w)$$

$$= \sigma_c^2 + \sigma_n^2 + \sigma_v^2 \qquad (x)$$

The variance of the input-correlated error, σ_c^2, reflects the linearity of the operator's response as indicated by his closed-loop transfer function, $H_o(f)$. If the transfer function was ideal, with unity gain and zero phase lags at all frequencies, the mean square input-correlated error would be zero. Hence increases in input-correlated error may be due to response lags, as a consequence of neuro-muscular lags or perceptual/central factors such as attention, or departures from unity gain due to frequency response limitations, voluntary changes in strategy to minimise the effects of response lags, vibration-induced control actions or nonlinear behaviour.

The variance of the vibration-correlated error, or vibration breakthrough, σ_v^2, depends on the gain and dynamic properties of the control, as well as the transmission of vibration through the body.

Increases in remnant variance, σ_n^2, or the portion of the operator's response which is not linearly related to either the forcing function or the vibration, may have perceptual/central (perceptual remnant) or neuromuscular (motor remnant) origins. Perceptual remnant reflects threshold and range nonlinearities and perceptual noise due to such factors as shifts in attention and limitations in visual acuity as a consequence of differential motion between the display and eye. Motor remnant reflects neuromuscular actuation noise, which may be due to noise in associated proprioceptive feedback networks or to other noise sources such as postural and action tremor. Unfortunately the above analysis techniques cannot distinguish between perceptual and motor contributions to the total remnant power. However it can be seen from equation (k) that the contributions of both perceptual and motor remnant are proportional to the control transfer function, $H_c(f)$, whereas the perceptual remnant is also proportional to the human operator transfer function, $H_o(f)$. Within the limits of their respective dynamic ranges the gain of the human operator, at any particular frequency, should be effectively inversely proportional to the gain of the control; since any increase in control gain will be compensated by a decrease in human operator output in order to maintain a constant overall closed-loop gain in the system. Therefore the contribution of motor remnant to the total remnant power will be proportional to control gain, but the perceptual remnant will be effectively independent of gain variations. Hence an indication of the relative proportions of perceptual and motor remnant may be obtained by determining the sensitivity of the overall remnant variance to changes in control gain.

The primary performance measures evaluated in the five experiments were the total error variance, the variances of input-correlated error, remnant and vibration breakthrough, and the human-operator transfer function, resolved into modulus and phase (Note that in each case the measured transfer function was $H(f) = H_o(f).H_c(f)$). These measures were estimated from the time histories of the forcing function and control output, using fast Fourier transform techniques, by the digital computers at the Data Analysis Centre in the Institute of Sound and Vibration Research.

(ii) The Computor Analysis of Tracking Performance.

The computer system at the Data Analysis Centre has an extensive library of programs, developed at I.S.V.R., for the analysis of time-varying data. The data is stored on magnetic disc, in the form of a file of numbers and a control block containing information concerning units and other parameters. Each of the analysis programs takes one or more data files, operates on them and produces an output file of results which may be listed, displayed in graphical form or used as the input for another analysis. Extensive analysis routines are performed by connecting the appropriate analysis programs together as subroutines in 'jobs', which are written in a Fortran-type control language. Programs are available for most common analyses, such as Fourier transforms, power spectra, cross spectra, auto-correlation, curve-fitting, probability functions, etc., as well as programs for the acquisition of analog data, and the arithmetic manipulation and display of data files. In addition, certain users may install their own programs, written in Fortran IV, into the system. The author has written several programs to carry out statistical analyses which were used in the analyses of the experimental results: these are reproduced in appendix C.

At the time of running experiment one, the computer system consisted of a Marconi Myriad MkII computer with disc memory, two 12 bit analogue to digital converters, incremental graph plotter and a paper tape reader and punch. Communication with the computer was via a teletype terminal. During experimental runs the forcing function and control output were recorded on a Racal-Thermionic T-3000 FM tape recorder. The recorded signals were later simultaneously digitised and transferred to magnetic disc prior to further analysis.

Between experiments one and two the computer system was replaced by a new PDP 11/50 computer. This computer works in a time sharing mode, handling up eight Tektronix 4010 visual display terminals with graphics capability and several teletype and non-graphics visual display terminals. The computer is equipped with disc memory, two 14 bit analogue to digital converters (with multiplexing for up to 16 data channels), incremental graph plotter, line printer and a magnetic tape unit. Terminals can be used in laboratories at various locations on the University campus, which are equipped with communication lines to the computer. The Tektronix terminals have four channel line driver amplifiers built into them which transmit analogue data directly to the analogue to digital converters. Hence it was possible, with this system, to dispense with the FM tape recorder and to relay the forcing function and control output signals directly to the computer during experimental runs.

The performance measures described earlier in this section are all based on power spectral and cross spectral density functions. These were evaluated using standard, Data Analysis Centre programs. The programs use the fast Fourier transform (Mercer, 1973) to evaluate the expressions in equations (d) and (g). Note that the expression is only strictly true as the time T, over which the Fourier transforms are evaluated, tends towards infinity: direct use of the expression gives a statistically unreliable estimate as it is based on only two degrees of freedom. The statistical accuracy is improved in the computer programs by ensemble averaging of successive time slices of the time history and by averaging across adjacent frequency bands. The number of degrees of freedom of an estimate of the power spectral or cross spectral density function is given by the expression

$$2\left(\frac{2N}{L} - 1\right) \qquad (y)$$

where N is the number of samples in the time history and L is the length (no. of samples) of each Fourier transform, which is always a power of 2.

$$L = \frac{S}{R} \qquad (z)$$

where S is the sampling rate of the time history and R is the frequency resolution of the power spectral or cross spectral density estimate. It can be seen that the number of degrees of freedom are effectively proportional to the number of data samples and the frequency resolution of the estimate. Hence a compromise must be reached between the fineness of the frequency resolution and the statistical accuracy. An indication of the magnitude of the errors in amplitude of a spectral density estimate is given by table 4.3.1., after Mercer (1973). The number of degrees of freedom of the spectral density estimates obtained from the results of the five experiments reported here was between 66 and 176.

A block diagram of the complete analysis procedure is given in figure 4.3.3. For details of sampling rates and numbers of samples for the analog to digital conversions, and of the frequency bandwidths of the estimates of error variance components, see the details of the individual experiments.

TABLE 4.3.1. DEGREES OF FREEDOM AS FUNCTION OF ACCURACY AND CONFIDENCE LEVEL.

	ACCURACY			
CONFIDENCE LEVEL	±5 dB	±2½ dB	±1 dB	±½ dB
40%	-	3	11	42
60%	2	5	28	105
80%	4	11	63	250
90%	5	18	104	410
96%	8	27	161	640
98%	10	34	207	820

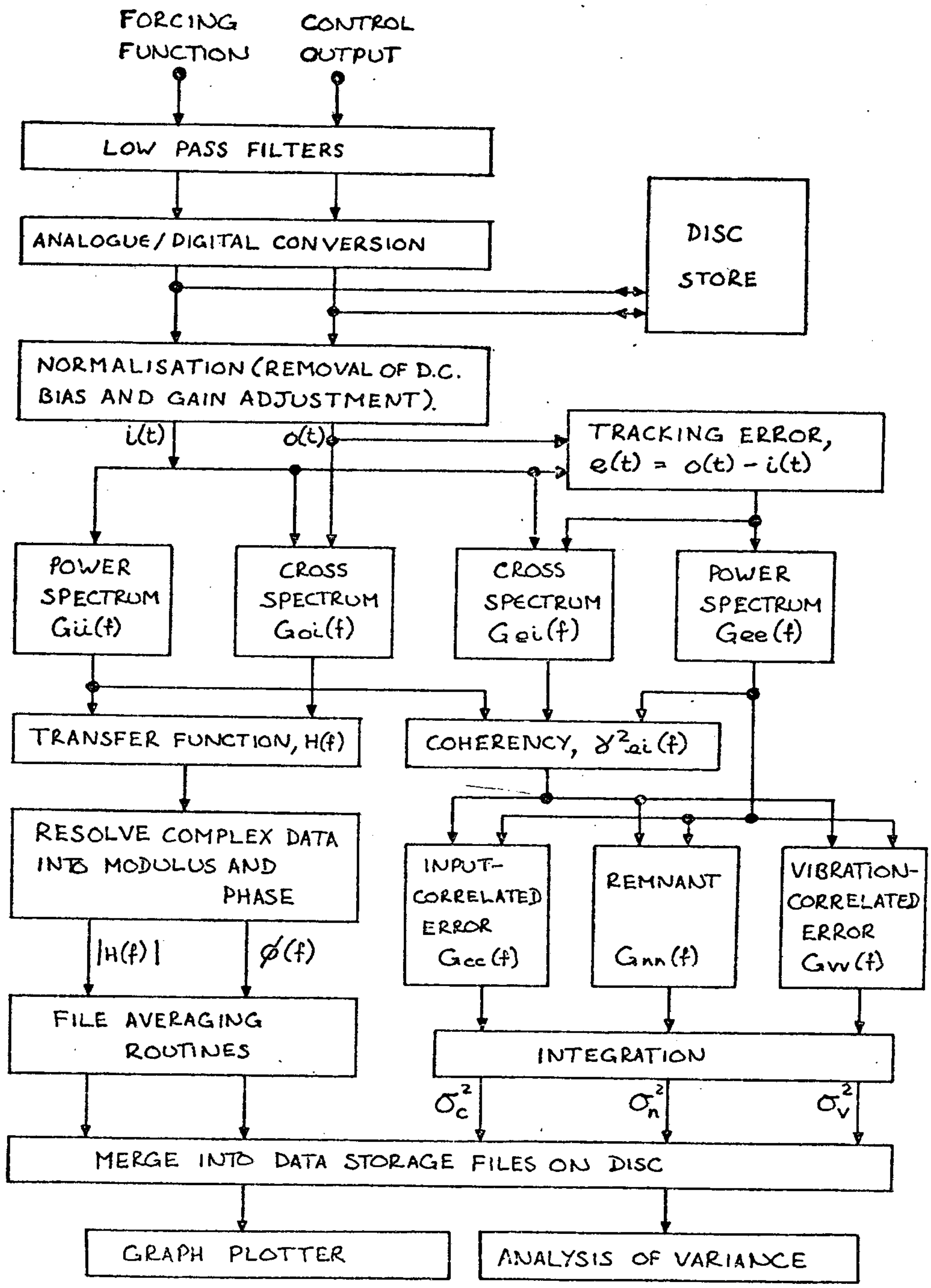


FIG 4.3.3. FLOW CHART OF THE DATA ANALYSIS PROCEDURE PROGRAMMED ON THE COMPUTER.

The frequency bandwidth of a power spectral density analysis is given by half the sampling rate of the analogue to digital conversion. If the analogue process contains significant power at frequencies greater than half the data sampling rate the power spectral estimates at certain lower frequencies will be in error due to the phenomenon known as aliasing. When aliasing occurs, power at higher frequencies is folded back, about the upper cut-off point of the analysis, to appear at lower frequencies (Bendat and Piersol, 1966, pp 279). The lowest sampling rate used in the series of experiments described here was 10 samples per second, giving an upper frequency cut-off point of 5Hz for the spectral analysis (Experiment 4, described in chapter 8). The forcing function for the tracking task in all the experiments contained no significant power beyond 3Hz, however in the case of experiments 2 and 3 the control output could have contained significant power beyond the upper frequency cut-off point due to vibration breakthrough to the control. The data sampling rate for the data in experiments 2 and 3 was 20 samples per second, giving a cut-off point of 10Hz. The highest vibration frequency used in experiment 3 was 16Hz and in experiment 2 was 64Hz. In every case the control output was filtered by a second order RC process, with the 3 dB point at 10Hz, before recording or digitizing.* This reduced the power in the control output due to 32Hz and 64Hz vibration breakthrough to insignificant levels, but significant power could still occur at 16Hz during the higher levels of 16Hz vibration. The 16Hz vibration breakthrough folded back about the 10Hz cut-off frequency to form a peak in the error spectrum at 4Hz, and as the upper limit of the transfer function, remnant and input-correlated error measures was 3Hz it was possible to ignore the contribution of the aliased power to the mean square tracking error measures.

* This was not the case during sine-sweep measures of vibration transmission to the controls, described in section 6.6.

5. EXPERIMENT ONE: THE INTERACTION OF CONTROL GAIN AND THE EFFECTS OF VIBRATION

5.1. INTRODUCTION

Experimental evidence presented in section 3.6. suggests that, despite their generally superior performance in static conditions, isometric joystick controls are affected more by vibration than isotonic joysticks. There is particular evidence that isometric controls are more susceptible to vibration-induced stick activity, resulting in a relatively large amount of vibration-correlated tracking error. It was also pointed out in section 3.6. that the amount of vibration-correlated activity, or breakthrough, in the control output depends on the control gain. In static conditions there is an optimum gain for all controls, at which tracking errors are minimized (Gibbs, 1962): comparisons between performances using different controls is optimized. However there is no mention of control gains having been optimized in any of the reports of studies reviewed in section 3.6., comparing different controls in vibration conditions.

Where there is a significant amount of breakthrough in the control output, the control gain at which the overall tracking error is minimized should be lower in vibration conditions than in static conditions. If the vibration frequency is sufficiently high it may be possible to reduce the breakthrough by filtering the control output. However filtering is only likely to be successful if the vibration frequency is the forcing function, otherwise phase shifts may be introduced into the control response at forcing function frequencies, which may further degrade tracking performance.

Lewis (1974) has shown that whole-body vibration can also result in increases in error variance at frequencies other than those of the vibration. In the study by Lewis (1974) vertical (z-axis) whole-body vibration (with 3, 5 and 8Hz frequency components) was observed to induce noise, or remnant activity at frequencies around 2Hz and below. Lewis hypothesized that this activity was made up primarily of motor remnant, due to interference by vibration with neuromuscular actuation processes (see section 3.10.). Levison (1974) has also presented evidence of increases in motor remnant, at 0.3Hz and above, in vibration conditions. As this activity occurs at frequencies well within the normal bandwidth of the operator's control processes it cannot be successfully filtered out. Motor remnant has been shown, in section 4.3., to be dependent on control gain; so that even if breakthrough is not taken into account the optimum control gain is likely to be lower in vibration conditions than in static conditions.

All of the studies described in chapter three in which frequency analyses of tracking errors were made were performed with joystick type controls only. Although vibration of the seat in any one of the three translational axes is likely to result in significant activity at the hand in all three translational axes, due to the loosely coupled nature of the shoulder girdle/arm system, it may not result in much rotational motion at the hand (wrist). Controls actuated by rotation of the hand about the wrist may therefore be less sensitive to vibration-induced activity or breakthrough than joystick controls.

The four objectives of the experiment described in this chapter were (i) to establish optimum gain conditions for four different controls in preparation for further experimentation: (ii) to determine how variations in control gain affect the sensitivity of tracking performance to vertical (z-axis) whole-body vibration at 4Hz; (iii) to further investigate the hypothesis proposed by Lewis (1974) that interference with the kinaesthetic feedback mechanisms involved in neuromuscular control loops is a principal means by which vibration degrades manual control performance; and (iv) to test the hypothesis that with translational whole-body vibration, rotary controls will be less sensitive to vibration-induced control activity than joystick controls.

Vibration at 4Hz was used in this experiment as this frequency is in the range of whole-body resonances for vertical vibration and may be expected to have a large effect on performance.

5.2. SUBJECTS

Four, right-handed, male subjects took part in the experiment. All were full-time students or research workers and their ages ranged from 18 to 26 years. Two of the subjects had previous experience of both manual tracking and human vibration experiments. Further details of the subjects are given in appendix D. The subjects received payment of £1.00 for their attendance at each of the three practice and four experimental sessions.

The use of more than four subjects could have lead to more precise and even more statistically significant results. However in view of the large amount of data processing carried out on the results of each experimental run, the limited data storage space available on the computer and the exploratory nature of the first experiments it was felt that more useful results could be obtained, within the time available for experimentation, with a relatively small number of well-trained subjects. This approach was also adopted with experiments two and three, which are described in the succeeding chapters.

5.3. PROCEDURE

The four controls used in this experiment were the single-axis isotonic and isometric joysticks and the isotonic and isometric knobs. The controls, and the single-axis, zero order, pursuit tracking task are described in detail in section 4.2. The two vibration conditions employed in the experiment were static and 4Hz whole-body vibration at 0.75 ms^{-2} r.m.s. The controls were not vibrated.

The optimum range of gains for each control was determined by pilot experimentation, in which the experimenter served as the subject. The four gains, for each control, presented in the experiment were chosen to cover this range: these are given in table 5.3.1.

Experiment one was run as four separate sub-experiments: one for each of the four controls. Each of these sub-experiments was run on separate days. In addition to the four experimental sessions, subjects attended three practice sessions. For the practice sessions the subjects were divided into two groups of two: one group practiced with the isotonic stick in the first session and the isometric stick in the second, while the other group practiced first with isometric stick and second with the isotonic stick. Each practice session consisted of sixteen 120 second tracking runs, with 120 second rest between consecutive runs. The sixteen runs were divided into four blocks: all four gains were presented, in a balanced order, within each block. The third session, for all the subjects, was the isotonic stick experiment (Experiment 1A) and the fourth session was the isometric stick experiment (Experiment 1B). The fifth session consisted of a third practice session, during which all the subjects practiced with the knob controls. There were again sixteen runs divided into four blocks. The group which had practiced

TABLE 5.3.1

CONTROL GAINS

	ISOTONIC STICK	ISOMETRIC STICK	ISOTONIC KNOB	ISOMETRIC KNOB
G1	12.5 cms/radian	2.5 cms/kg at tip	12.5 cms/radian	2.5 cms/kg along tangent
G2	25.0 cms/radian	5.0 cms/kg at tip	25.0 cms/radian	5.0 cms/kg along tangent
G3	37.5 cms/radian	7.5 cms/kg at tip	37.5 cms/radian	7.5 cms/kg along tangent
G4	50.0 cms/radian	10.0 cms/kg at tip	50.0 cms/radian	10.0 cms/kg along tangent

first with the isometric stick, practiced with the isotonic knob for the first two blocks and the isometric knob for the last two. The other group practiced with the controls in the reverse order. The sixth and seventh sessions for all subjects were the isotonic knob experiment (Experiment 1C) and the isometric knob experiment (Experiment 1D) respectively. Each experimental session consisted of eight 330 second tracking runs, with 150 seconds rest between consecutive runs. The four control gains and two vibration conditions being presented in balanced order.

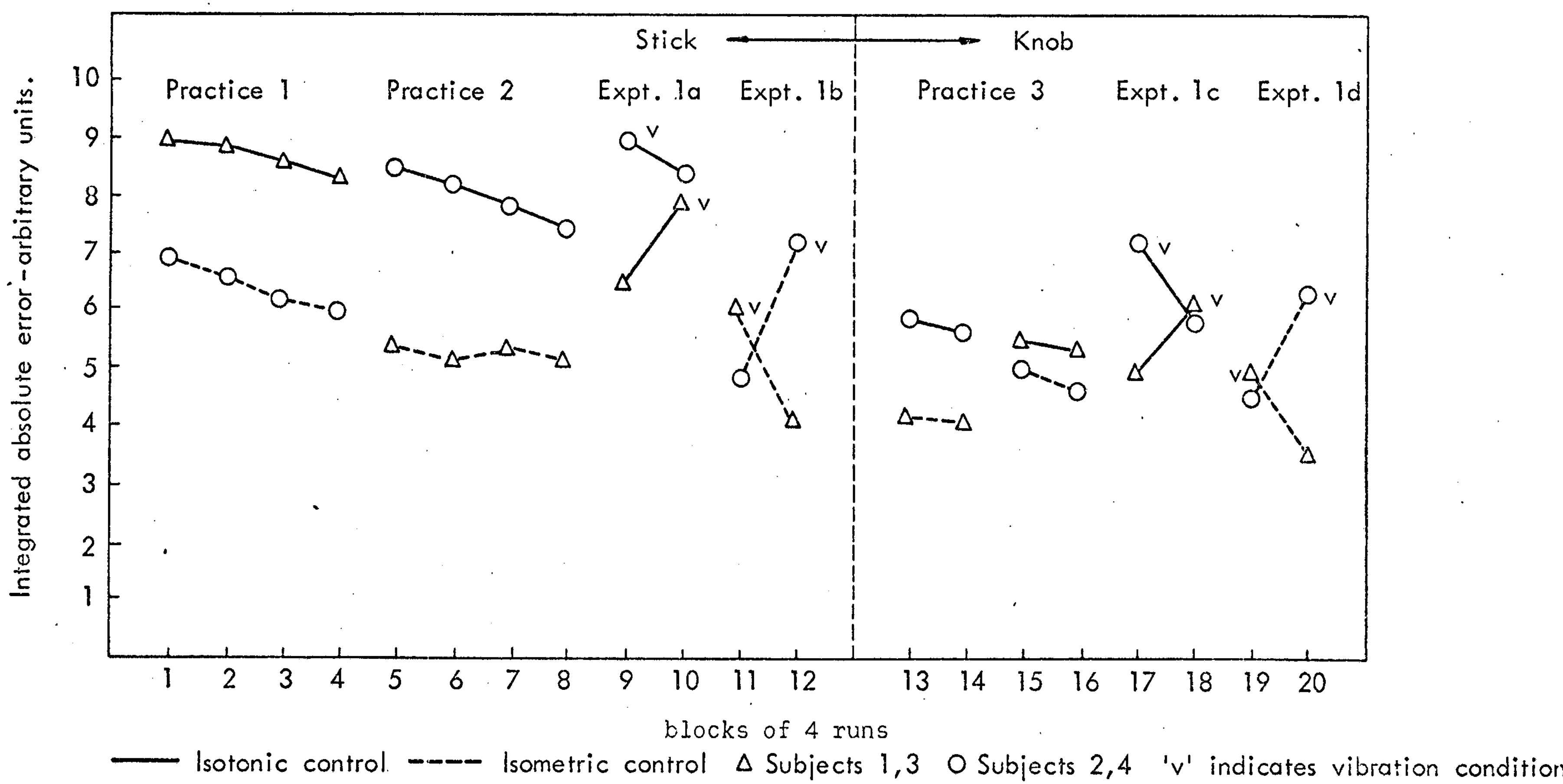
During both practice and experimental sessions performance was monitored by integrated absolute error, obtained by rectifying and integrating the tracking error signal. This measure was not very reliable as considerable problems were encountered with drift in the integrator, nevertheless it gives some indication of the development of performance during the practice sessions. During the experimental sessions both the control output and forcing function were recorded on a Racal-Thermionic T3000 FM tape recorder. These were later digitised and transferred to magnetic disc for computer analysis. The transfer function measures and the variance of the various tracking error components described in section 4.3. were evaluated for the last 210 seconds of each tracking run.

The sampling rate of the analogue to digital conversion was 25 samples per second for each channel. The actual resolution of the spectral analyses was 0.098 Hz, giving 78 degrees of freedom.

5.4. RESULTS AND DISCUSSION OF TRACKING ERROR MEASURES.

The effect of practice on the mean integrated absolute error scores (averaged over the four control gains) are shown in figure 5.4.1. It can be seen that there was some positive transfer of training from the isotonic stick to the isometric stick, but hardly any from isometric to isotonic. Some caution is necessary in interpreting this result as each data point is based on only two subjects and an inaccurate measurement system, nevertheless other researchers have also observed a much greater transfer from the generally less efficient isotonic controls to isometric controls than from isometric to isotonic (see for instance Gibbs, 1954). Gibbs,(1954) suggested that this result was due to differences in the kinaesthetic feedback mediating isometric

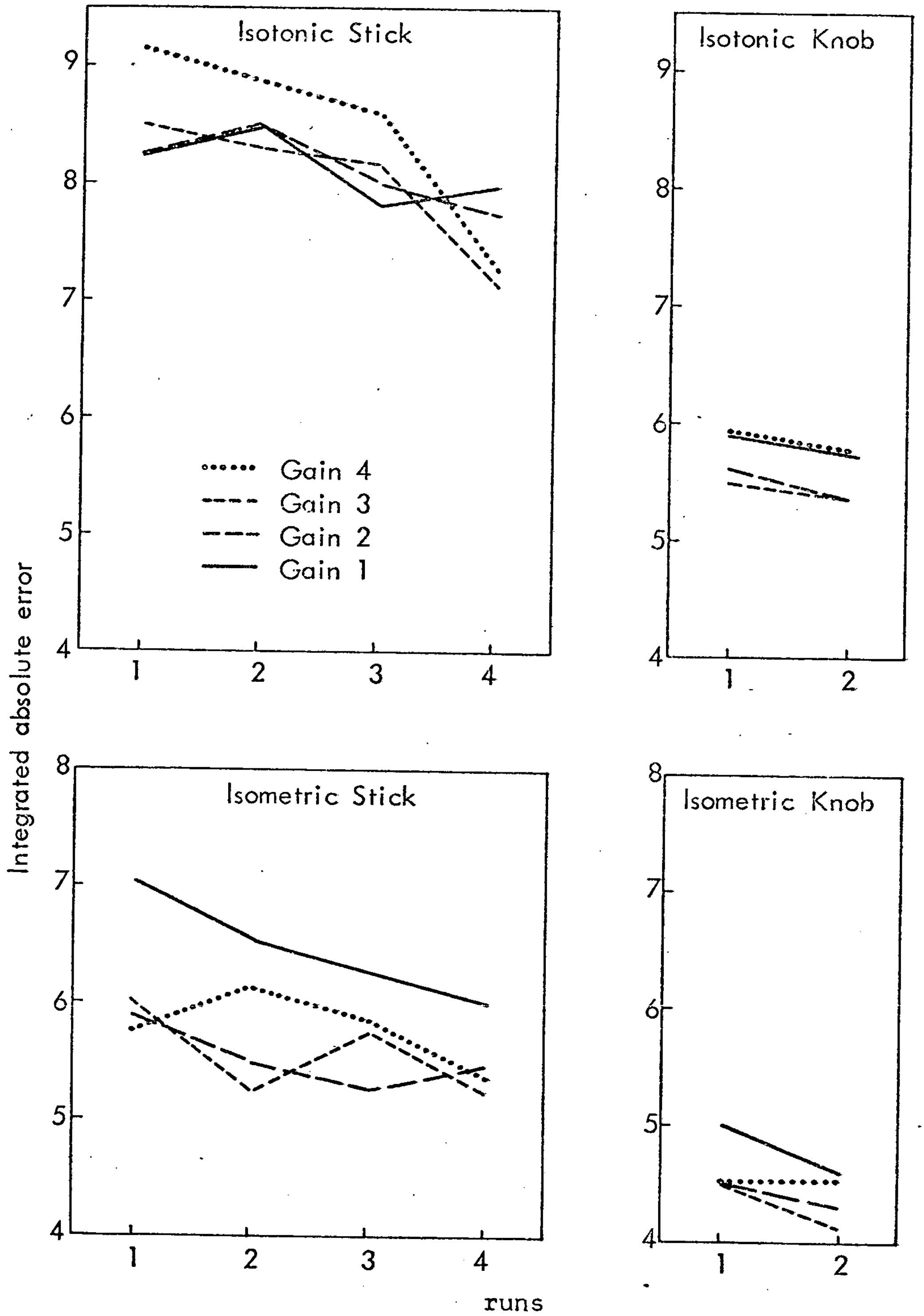
FIG 5.4.1.



SERIES ONE EXPERIMENTS : INTEGRATED ERROR DURING PRACTICE AND EXPERIMENTAL SESSIONS

: MEANS FOR 4 GAINS AND 2 SUBJECTS.

FIG 5.4.2.



INTEGRATED ERROR DURING PRACTICE SESSIONS FOR EACH CONTROL GAIN. MEAN FOR 4 SUBJECTS.

and isotonic contractions. He put forward the hypothesis that kinaesthetic feedback available during isometric contraction is more meaningfully related to their control output than that available during isotonic contraction (see appendix B). Interactions between the effect of control gain and practice are shown in figure 5.4.2. Unpracticed subjects using the isotonic control were able to perform best with the lower control gains, but at the end of the practice period they performed best with a higher control gain. With a low control gain, larger movements are required to produce a given control output, making a greater amount of kinaesthetic feedback available to the subject and enabling him to more accurately control his actions. However larger control movements will also have the disadvantages of greater movement times and greater inertial forces opposing changes in the direction of movement, so as the subject learns to make more efficient use of smaller amounts of kinaesthetic feedback he will be able to perform better with higher control gain. Less interaction is evident between gain and practice with the isometric stick. This may be interpreted as evidence to support Gibbs' (1954) hypothesis, indicating that subjects are able to make more efficient use of kinaesthetic cues at the beginning of the practice period.

The average, mean square tracking error components, or variances of the error components, for the four controls, are illustrated in the profiles in figures 5.4.3. to 5.4.6. A two factor, mixed effects analysis of variance with randomnized blocks was carried out on each of the error components (except vibration-correlated error) for each control (extreme caution should be exercised in comparing performances between controls as the order of presentation of the controls was not balanced in the experimental sessions, and there is an indication that unequal transfer of training took place between the controls). ANOVA summary tables for the error components from experiment 1A (isotonic stick) are given in tables 5.4.1a to 5.4.1c; from experiment 1B (isometric stick) in tables 5.4.2a to 5.4.2c; from experiment 1C (isotonic knob) in tables 5.4.3a to 5.4.3c and from experiment 1D (isometric knob) in tables 5.4.4a to 5.4.4c.

It can be seen from the mean square error profiles that similar levels of vibration-correlated error or breakthrough were produced with the rotary controls as with the joysticks wver the range of control gains investigated. This is inconsistent with the hypothesis put forward earlier and indicates that significant rotational motions can

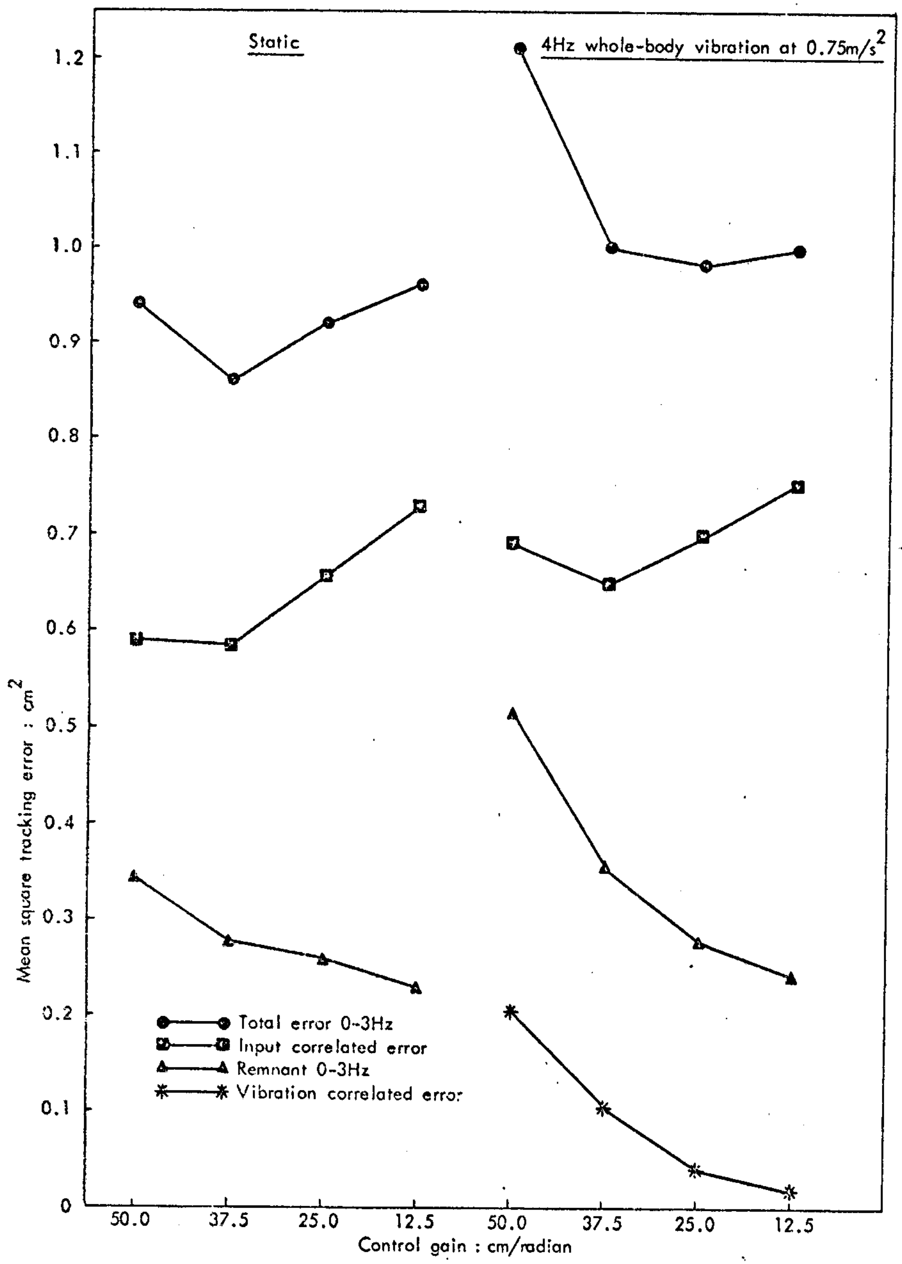


FIG 5.4.3. ISOTONIC STICK : MEAN PERFORMANCE

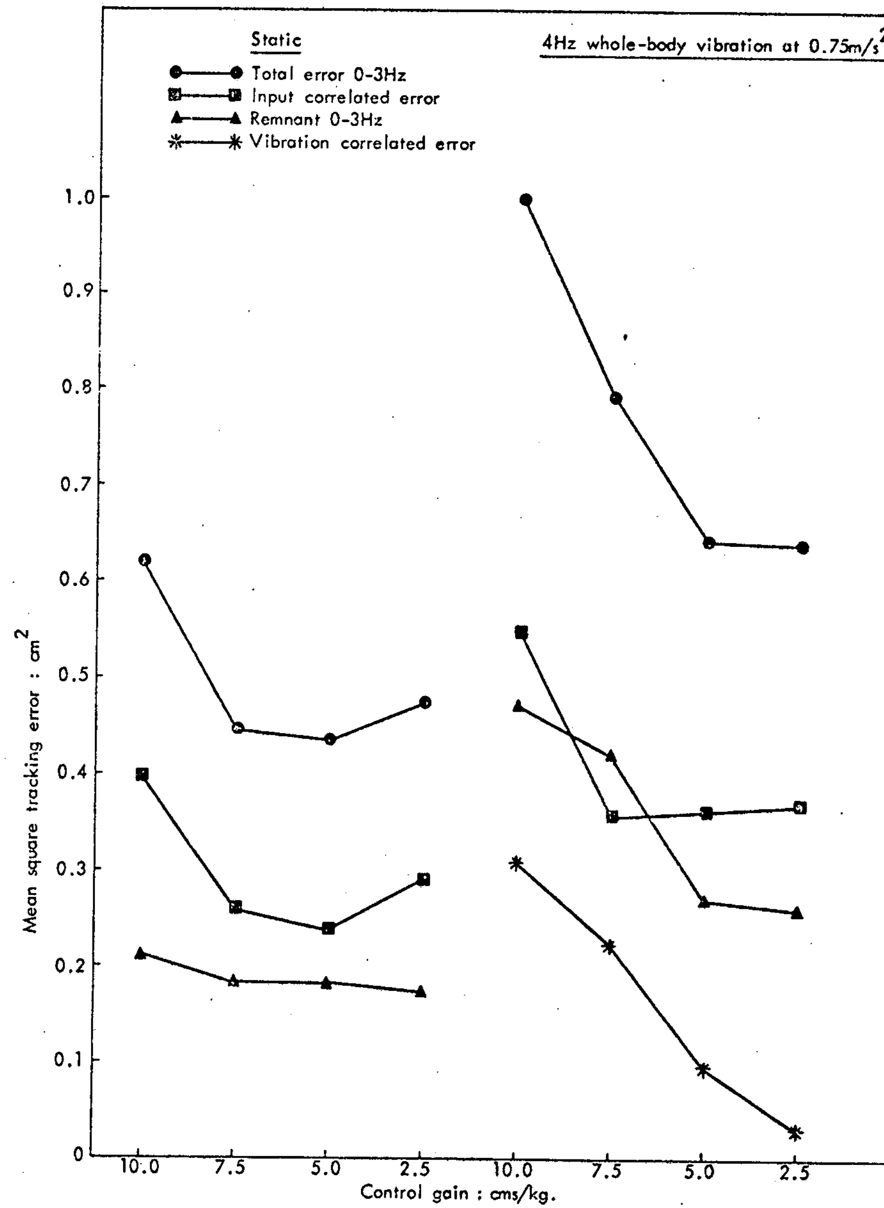


FIG 5.4.4. ISOMETRIC STICK : MEAN PERFORMANCE

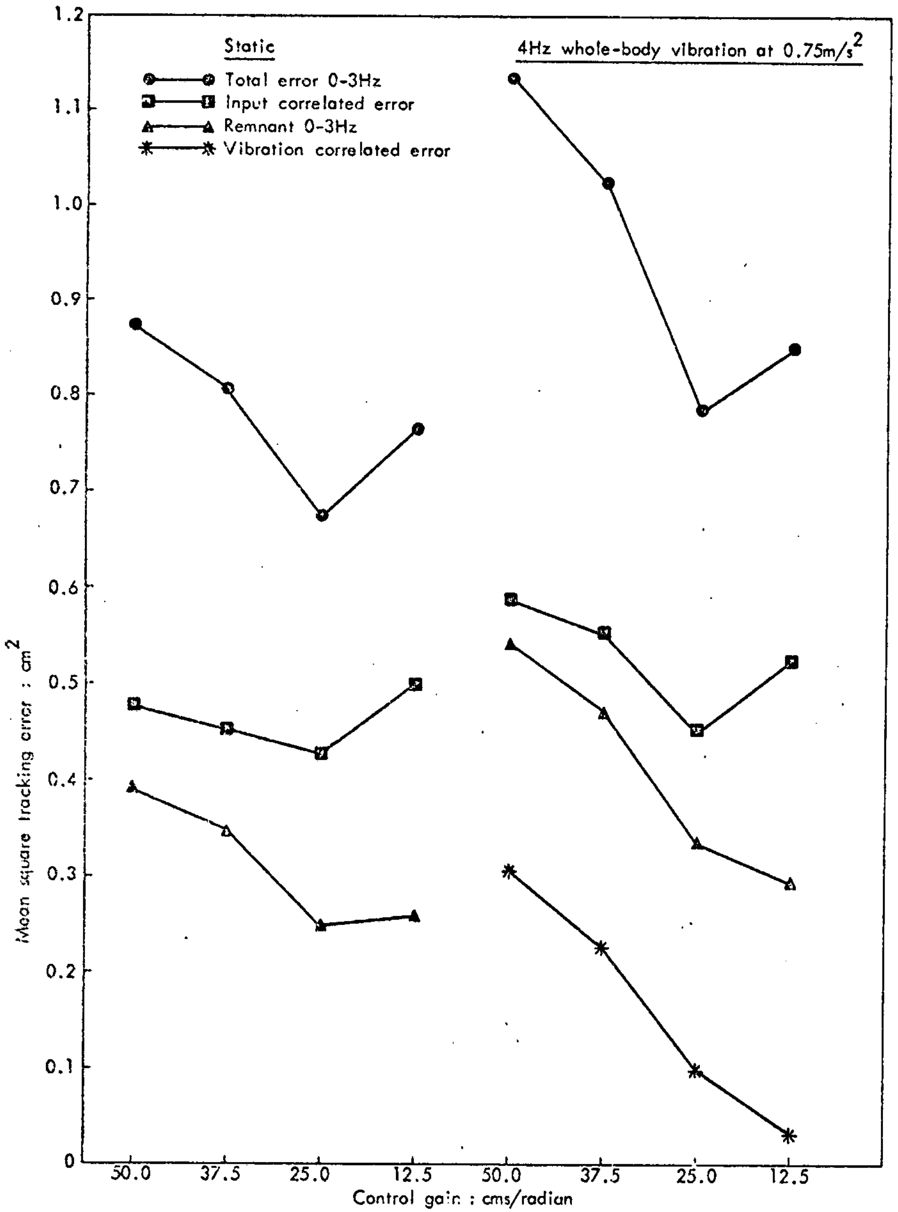


FIG 5.4.5 ISOTONIC KNOB : MEAN PERFORMANCE

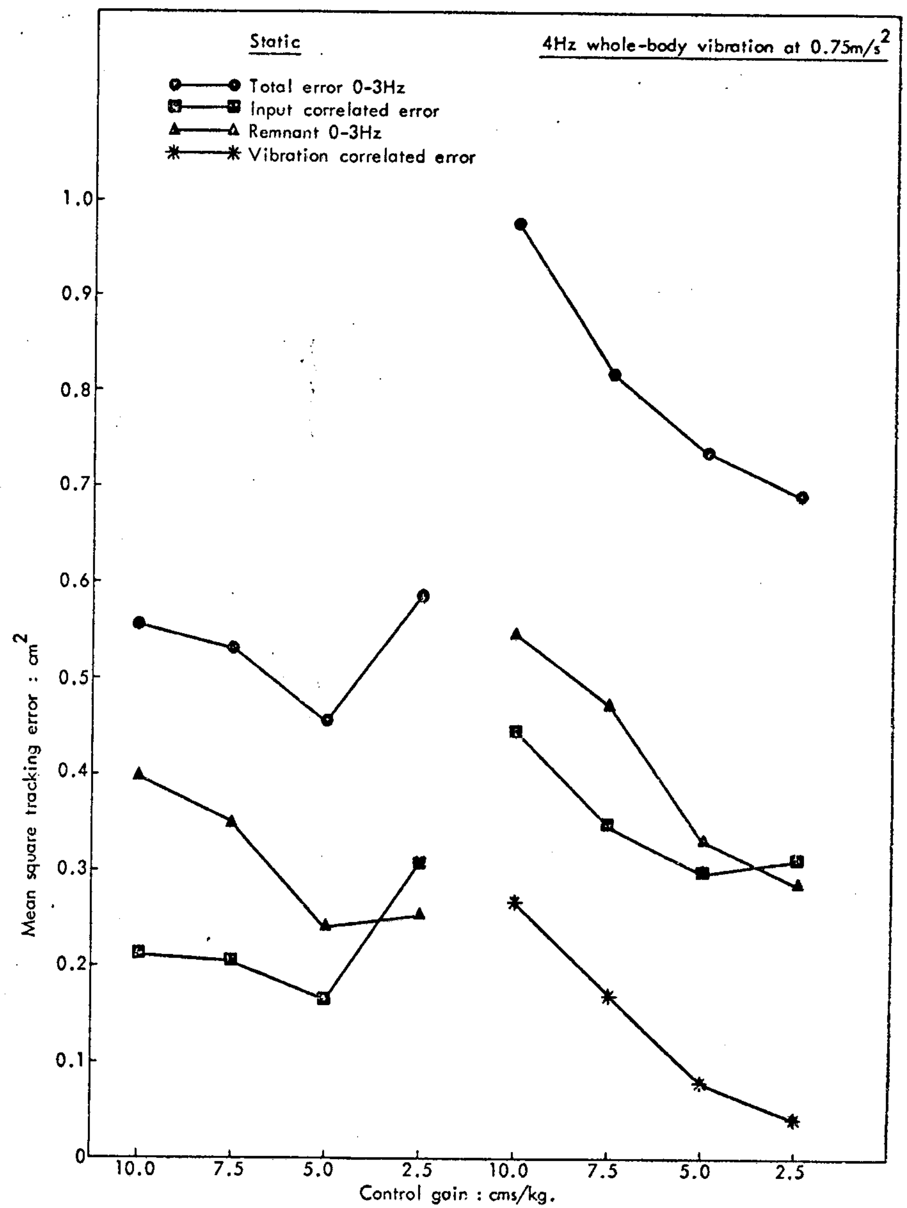


FIG 5.4.6. ISOMETRIC KNOB : MEAN PERFORMANCE

TABLE 5.4.1. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 1A.

Treatments: S = Subjects, G = Control Gain, V = Vibration.

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

Source	SS	DF	MS	F RATIO	p
S	0.12466E 14	3	0.41554E 13	65.82	0.01
G	0.55016E 12	3	0.18339E 12	3.04	0.1
V	0.90614E 12	1	0.90614E 12	9.34	0.1
G x V	0.40504E 12	3	0.13501E 12	2.46	ns
RESIDUAL	0.13257E 13	21	0.63127E 11		
G x S	0.54190E 12	9	0.60212E 11		
V x S	0.29075E 12	3	0.96916E 11		
G x V x S	0.49302E 12	9	0.54779E 11		

(b) MEAN SQUARE INPUT_CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.88034E 13	3	0.29345E 13	57.92	0.01
G	0.44943E 12	3	0.14981E 12	5.63	0.05
V	0.18640E 12	1	0.18640E 12	0.92	ns
G x V	0.34452E 11	3	0.11484E 11	0.47	ns
RESIDUAL	0.10639E 13	21	0.50660E 11		
G x S	0.23948E 12	9	0.26609E 11		
V x S	0.60770E 12	3	0.20257E 12		
G x V x S	0.21669E 12	9	0.24077E 11		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.34042E 12	3	0.11347E 12	4.31	0.01
G	0.11007E 13	3	0.36690E 12	13.05	0.01
V	0.27053E 12	1	0.27053E 12	4.33	ns
G x V	0.20704E 12	3	0.69012E 11	5.55	0.05
RESIDUAL	0.55209E 12	21	0.26290E 11		
G x S	0.25291E 12	9	0.28102E 11		
V x S	0.18740E 12	3	0.62465E 11		
G x V x S	0.11178E 12	9	0.12420E 11		
Simple Main Effects					
V at G1	0.19562E 10	1	0.19562E 10	0.03	ns
V at G2	0.49402E 10	1	0.49402E 10	0.07	ns
V at G3	0.10089E 12	1	0.10039E 12	1.62	ns
V at G4	0.23699E 13	1	0.23699E 13	37.93	0.01

*note: The multiplier 'E n' signifies x 10^n.

TABLE 5.4.2. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 1B.

Treatments: S = Subjects, G = Control Gain, V = Vibration.

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.25840E 13	3	0.86134E 12	5.29	0.01
G	0.25633E 13	3	0.85445E 12	3.58	0.1
V	0.42568E 13	1	0.42568E 13	23.70	0.05
G x V	0.51807E 12	3	0.17269E 12	2.11	ns
RESIDUAL	0.34163E 13	21	0.16268E 12		
G x S	0.21422E 13	9	0.23803E 12		
V x S	0.53867E 12	3	0.17956E 12		
G x V x S	0.73534E 12	9	0.81704E 11		

(b) MEAN SQUARE INPUT-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.93564E 12	3	0.31188E 12	2.42	ns
G	0.10426E 13	3	0.34754E 12	1.36	ns
V	0.69724E 12	1	0.69724E 12	8.40	0.1
G x V	0.50783E 11	3	0.16928E 11	0.89	ns
RESIDUAL	0.27030E 13	21	0.12871E 12		
G x S	0.22837E 13	9	0.25374E 12		
V x S	0.24873E 12	3	0.82910E 11		
G x V x S	0.17056E 12	9	0.18951E 11		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.60126E 12	3	0.20042E 12	6.32	0.01
G	0.49213E 12	3	0.16404E 12	5.46	0.05
V	0.15085E 13	1	0.15085E 13	39.34	0.01
G x V	0.33571E 12	3	0.11190E 12	3.59	0.1
RESIDUAL	0.66555E 12	21	0.31693E 11		
G x S	0.27040E 12	9	0.30044E 11		
V x S	0.11503E 12	3	0.38345E 11		
G x V x S	0.28012E 12	9	0.31124E 11		
Simple Main Effects					
V at G1	0.11381E 12	1	0.11381E 12	2.96	ns
V at G2	0.98080E 11	1	0.98080E 11	2.55	ns
V at G3	0.76347E 12	1	0.76347E 12	19.91	0.05
V at G4	0.86889E 12	1	0.86889E 12	22.65	0.05

*note: the multiplier 'E n' signifies x 10^n.

TABLE 5.4.3. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 1C.

Treatments: S = Subjects, G = Control Gain, V = Vibration.

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.43874E 13	3	0.14625E 13	20.18	0.01
G	0.21498E 13	3	0.71661E 12	13.89	0.01
V	0.14155E 13	1	0.14155E 13	9.03	0.1
G x V	0.26823E 12	3	0.89411E 11	1.36	ns
RESIDUAL	0.15217E 13	21	0.72462E 11		
G x S	0.46414E 12	9	0.51571E 11		
V x S	0.46980E 12	3	0.15660E 12		
G x V x S	0.58776E 12	9	0.65306E 11		

(b) MEAN SQUARE INPUT-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.17240E 13	3	0.57466E 12	21.66	0.01
G	0.28377E 12	3	0.94589E 11	4.14	0.05
V	0.26581E 12	1	0.26581E 12	6.09	0.1
G x V	0.63883E 11	3	0.21294E 11	0.86	ns
RESIDUAL	0.55701E 12	21	0.26524E 11		
G x S	0.20540E 12	9	0.22822E 11		
V x S	0.13085E 12	3	0.43615E 11		
G x V x S	0.22076E 12	9	0.24529E 11		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.12974E 13	3	0.43248E 12	15.07	0.01
G	0.13167E 13	3	0.43891E 12	20.57	0.01
V	0.45452E 12	1	0.45452E 12	5.81	0.1
G x V	0.97335E 11	3	0.32445E 11	1.65	ns
RESIDUAL	0.60265E 12	21	0.28698E 11		
G x S	0.19199E 12	9	0.21332E 11		
V x S	0.23440E 12	3	0.78134E 11		
G x V x S	0.17626E 12	9	0.19585E 11		
Simple Main Effects					
V at G1	0.10160E 11	1	0.10160E 11	0.13	ns
V at G2	0.91292E 11	1	0.91292E 11	1.16	ns
V at G3	0.18559E 12	1	0.18559E 12	2.37	ns
V at G4	0.26477E 12	1	0.26477E 12	3.39	ns

*note: the multiplier 'E n' signifies x 10^n.

TABLE 5.4.4. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 1D.

Treatments: S = Subjects, G = Control Gain, V = Vibration.

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.71565E 13	3	0.23855E 13	17.52	
G	0.78648E 12	3	0.26216E 12	1.87	ns
V	0.38325E 13	1	0.38325E 13	14.13	0.05
G x V	0.59759E 12	3	0.19919E 12	2.28	ns
RESIDUAL	0.28588E 13	21	0.13613E 12		
G x S	0.12607E 13	9	0.14007E 12		
V x S	0.81331E 12	3	0.27110E 12		
G x V x S	0.78480E 12	9	0.87200E 11		

(b) MEAN SQUARE INPUT-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.12310E 13	3	0.41032E 12	3.71	
G	0.29592E 12	3	0.98639E 11	1.23	ns
V	0.10566E 13	1	0.10566E 13	3.10	ns
G x V	0.32944E 12	3	0.10981E 12	1.69	ns
RESIDUAL	0.23215E 13	21	0.11055E 12		
G x S	0.71957E 12	9	0.79952E 11		
V x S	0.10194E 13	3	0.33982E 12		
G x V x S	0.58243E 12	9	0.64715E 11		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.12974E 13	3	0.43248E 12	15.07	
G	0.13167E 13	3	0.43891E 12	20.57	0.05
V	0.45452E 12	1	0.45452E 12	5.81	0.1
G x V	0.97335E 11	3	0.32445E 11	1.65	ns
RESIDUAL	0.60265E 12	21	0.28698E 11		
G x S	0.19199E 12	9	0.21332E 11		
V x S	0.23440E 12	3	0.78134E 11		
G x V x S	0.17626E 12	9	0.19585E 11		
Simple Main Effects.					
V at G1	0.10160E 11	1	0.10160E 11	0.13	ns
V at G2	0.91292E 11	1	0.91292E 11	1.17	ns
V at G3	0.18559E 12	1	0.18559E 12	2.37	ns
V at G4	0.26477E 12	1	0.26477E 12	3.39	ns

*note: the multiplier 'E n' signifies x 10^n.

be found in a controlling limb by translational whole-body vibration at the seat.

With this tracking system it appears that minimum remnant is generally produced at a lower gain than for minimum input-correlated error. Therefore the gain for which the overall tracking error is minimized is a compromise between input-correlated error and remnant. The overall effect of control gain on remnant was significant ($p<0.05$) for all four controls but the effect of gain on input-correlated error was significant only for the isotonic controls.

Of more interest than the overall main effects of gain and vibration are interactions between them. There was a significant interaction between vibration and control gain for remnant with the isotonic stick and an interaction approaching significance (i.e., $p<0.1$) for remnant with the isometric stick. Tests for the significance of simple main effects of vibration at each control gain were carried out for each control and the results are shown in tables 5.4.1c to 5.4.4c. The remnant was significantly increased by vibration at the highest gain for the isotonic stick and at the higher two gains with the isometric stick, but not at lower gains. The remnant with the knob controls was similarly more affected by vibration with higher control gains, but the effect only approaches significance (i.e. $p<0.1$) at the highest gains.

The effect of vibration on input-correlated error is not significant with any of the controls, although the effect does approach significance ($p<0.1$) with the isometric stick and isotonic knob, but only at the higher control gains. The major effect of vibration on this task, apart from vibration-correlated error due to direct vibration-induced stick activity, is to cause an increase in remnant which appears to be proportional to the gain of the control. According to the models developed in section 4.3., only the motor portion of the remnant, or the noise developed in neuromuscular actuation processes, is dependent on control gain. Therefore this result supports the hypothesis that vibration degrades control performance by direct interference with neuromuscular control loops.

The control gains adopted for further experimentation were those for which the mean total error was minimized under static conditions: these were G3 for the isotonic stick and G2 for the isometric stick. The error profiles show that the optimum control gain with reference

TABLE 5.4.5

CONTROL GAINS AT WHICH LOWEST TRACKING ERROR VARIANCES OCCURRED FOR INDIVIDUAL SUBJECTS.

	STATIC	VIBRATION	
	min. 0-3Hz error	min. 0-3Hz error	min. 0-5Hz error
ISOTONIC STICK			
S1	G2	G2	G2
S2	G3	G3	G2
S3	G3	G2	G1
S4	G3	G2	G1
ISOMETRIC STICK			
S1	G2	G2	G2
S2	G2	G2	G1
S3	G2	G1	G1
S4	G3	G1	G1
ISOTONIC KNOB			
S1	G3	G2	G1
S2	G2	G2	G2
S3	G2	G2	G1
S4	G2	G1	G1
ISOMETRIC KNOB			
S1	G2	G1	G1
S2	G1	G1	G1
S3	G4	G3	G2
S4	G2	G1	G1

to minimum total error below 3Hz was lower in most cases with vibration than in static conditions, due to the effect of vibration on remnant. Higher levels of vibration are likely to favour an even lower control gain, and if the additional contribution of vibration-correlated error is added to the total error below 3Hz this effect will be much more pronounced. (Note that the total error variance under vibration is the sum of total error below 3Hz and vibration-correlated error.) However, vibration-induced stick activity will contribute less to the overall tracking error in rate, or higher order control systems, due to the attenuation of higher frequencies by the system dynamics. It can be clearly seen from Table 5.4.5. that the individual subjects exhibit similar trends to those in the mean data.

5.5. RESULTS AND DISCUSSION OF TRANSFER FUNCTION MEASURES.

Mean transfer functions for static and vibration conditions are compared for each gain condition with the isotonic and isometric sticks and with the isometric knob in figures 5.5.1. to 5.5.3. respectively. (It was not possible to complete the transfer function analysis for the isotonic knob due to the replacement of the computer system.) There were no observed consistent differences between transfer functions measured in static and vibration conditions for any of the controls. There is also little difference between transfer functions with the isometric stick and isometric knob, but much larger high frequency phase lags were produced with the isotonic stick than with the isometric controls.

The phase lags in the transfer functions are an accumulation of all the relevant perceptual, central and motor delays in the human operator. Some lag in response is inevitable with the present system due to the unpredictable nature of the forcing function. However, the moving, isotonic controls are subject to extra delays due to inertia and friction, which tend to oppose the initiation and halting of movements. These extra delays are reflected in the larger input-correlated errors produced by the isotonic controls. It can be seen from figure 5.5.4. that decreasing the gain of the isotonic stick in static conditions, thereby increasing the size of control movements, resulted in greater response lags and in some reduction in gain at higher transfer function frequencies. It has also been suggested (Gibbs,

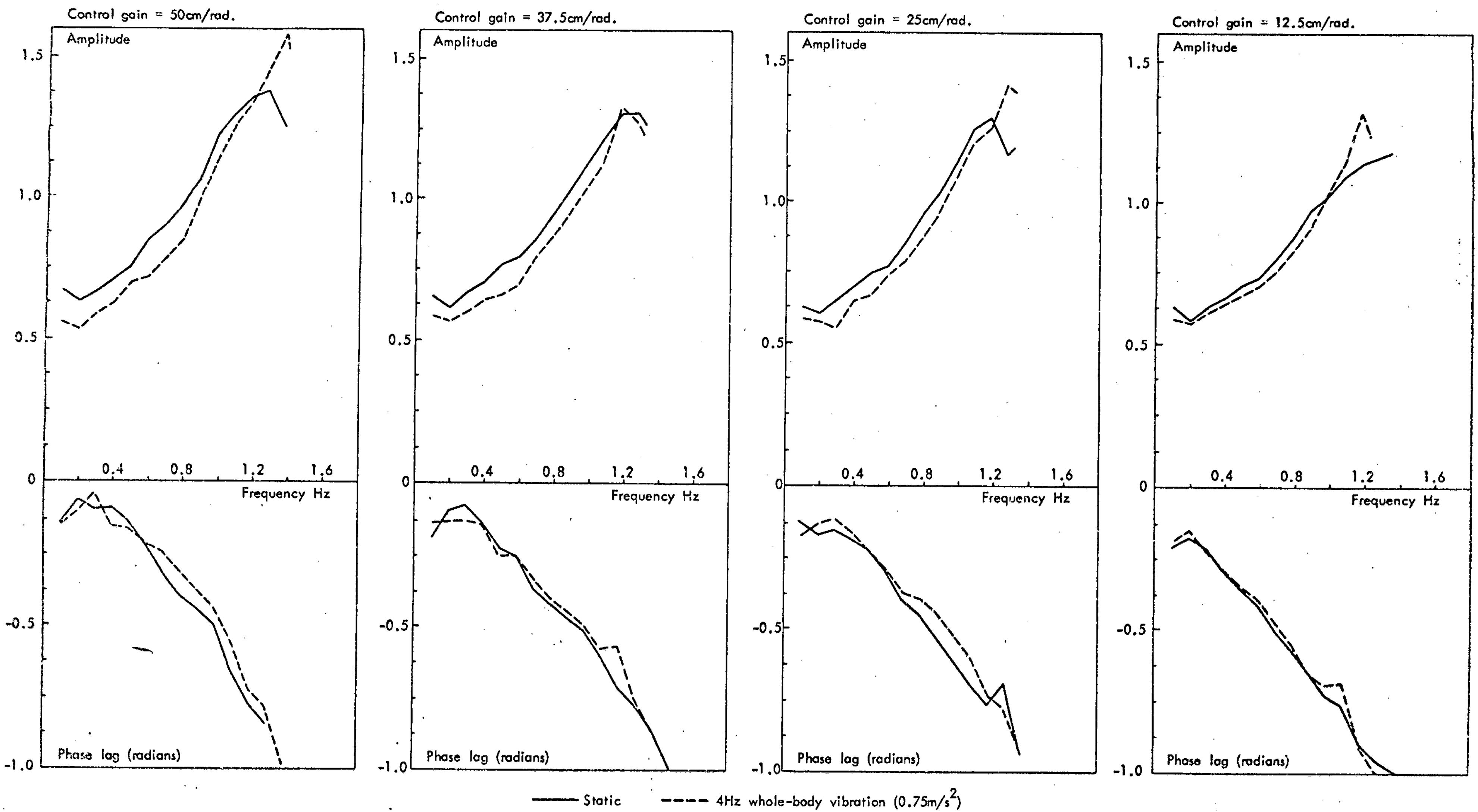


FIG 5.5.1. MEAN CLOSED-LOOP TRANSFER FUNCTIONS OF HUMAN OPERATOR WITH ISOTONIC STICK

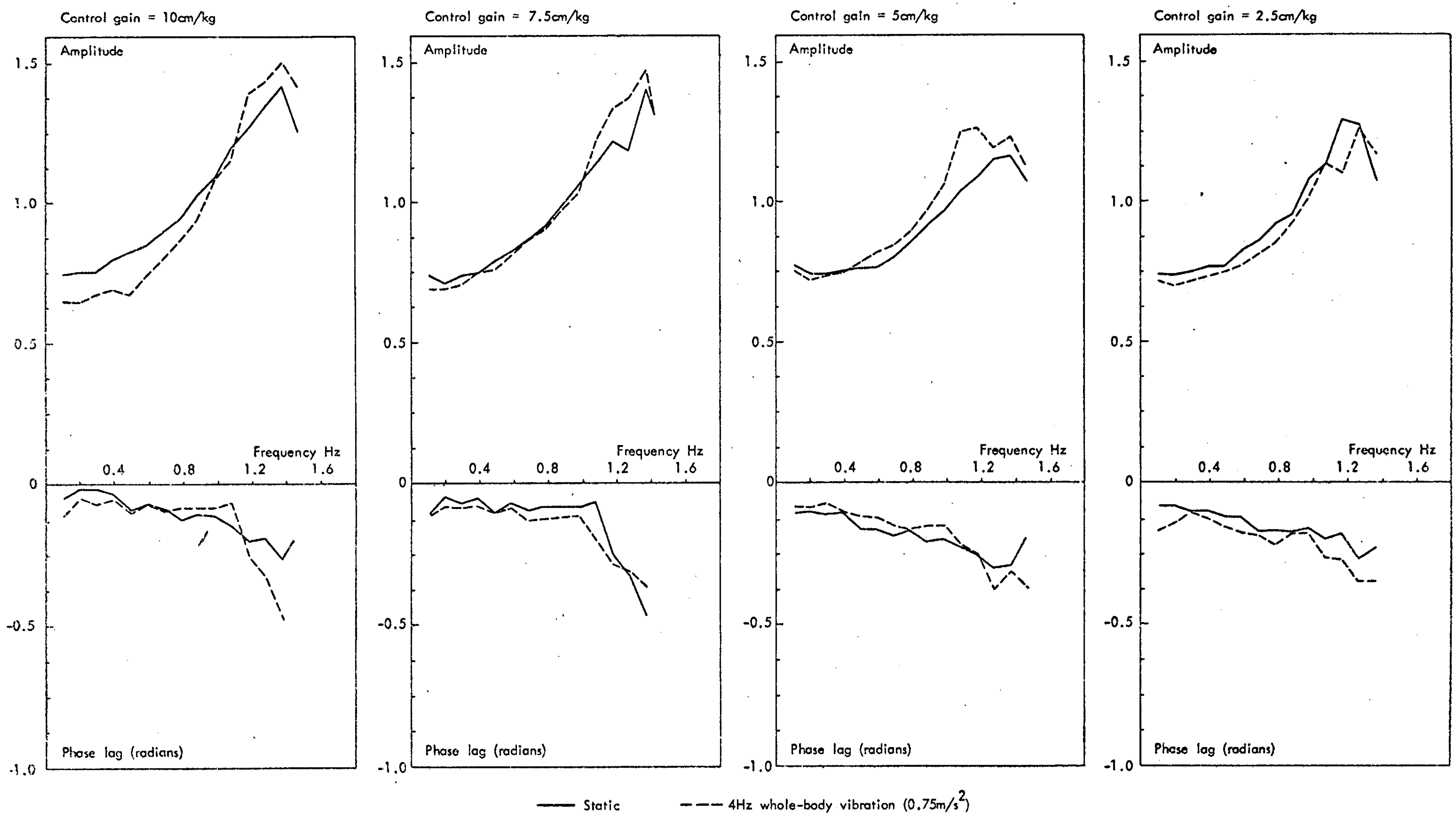


FIG 5.5.2. MEAN CLOSED-LOOP TRANSFER FUNCTIONS OF HUMAN OPERATOR WITH ISOMETRIC STICK

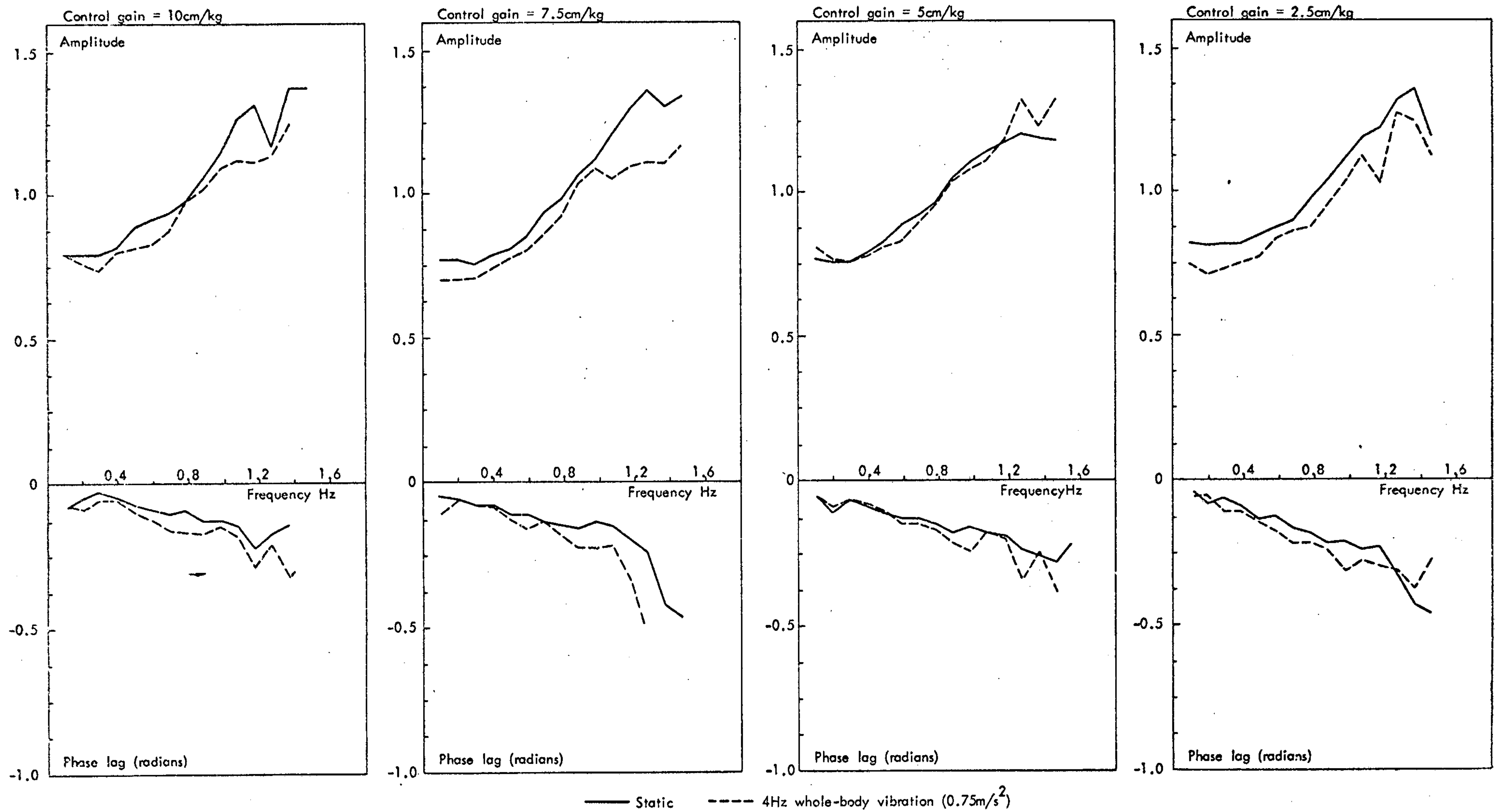
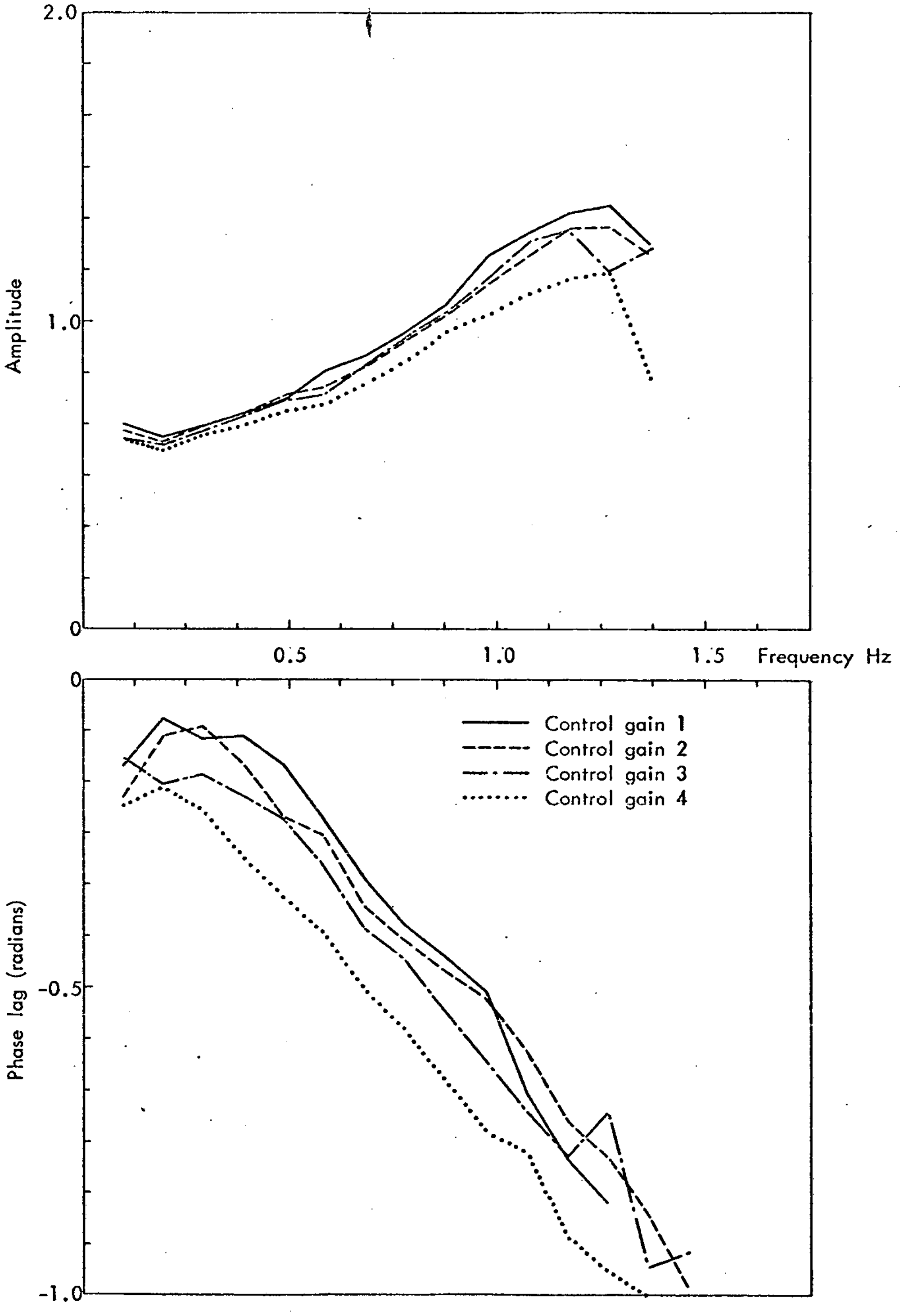


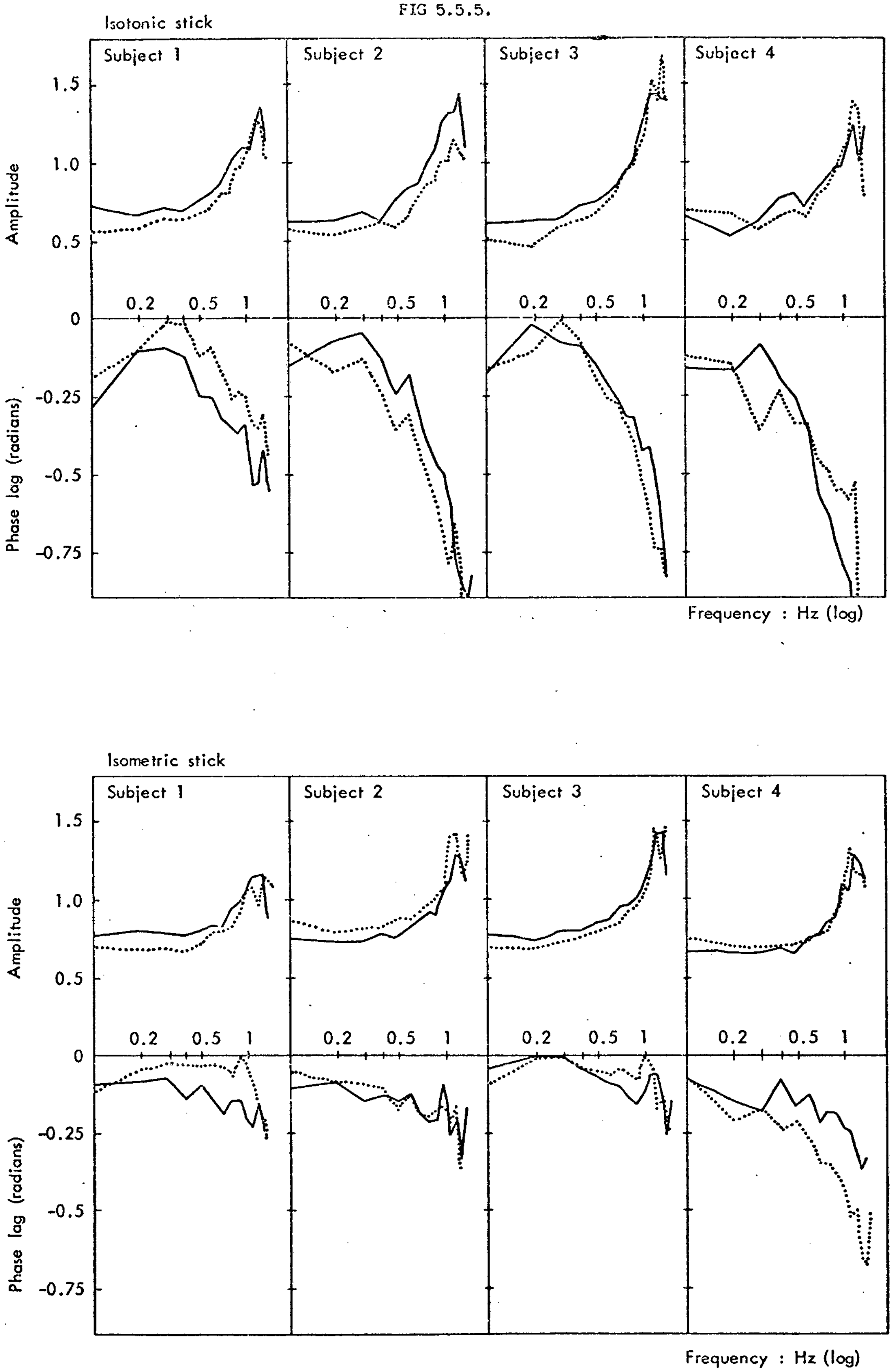
FIG 5.5.3. MEAN CLOSED-LOOP TRANSFER FUNCTIONS OF HUMAN OPERATOR WITH ISOMETRIC KNOB

FIG 5.5.4.



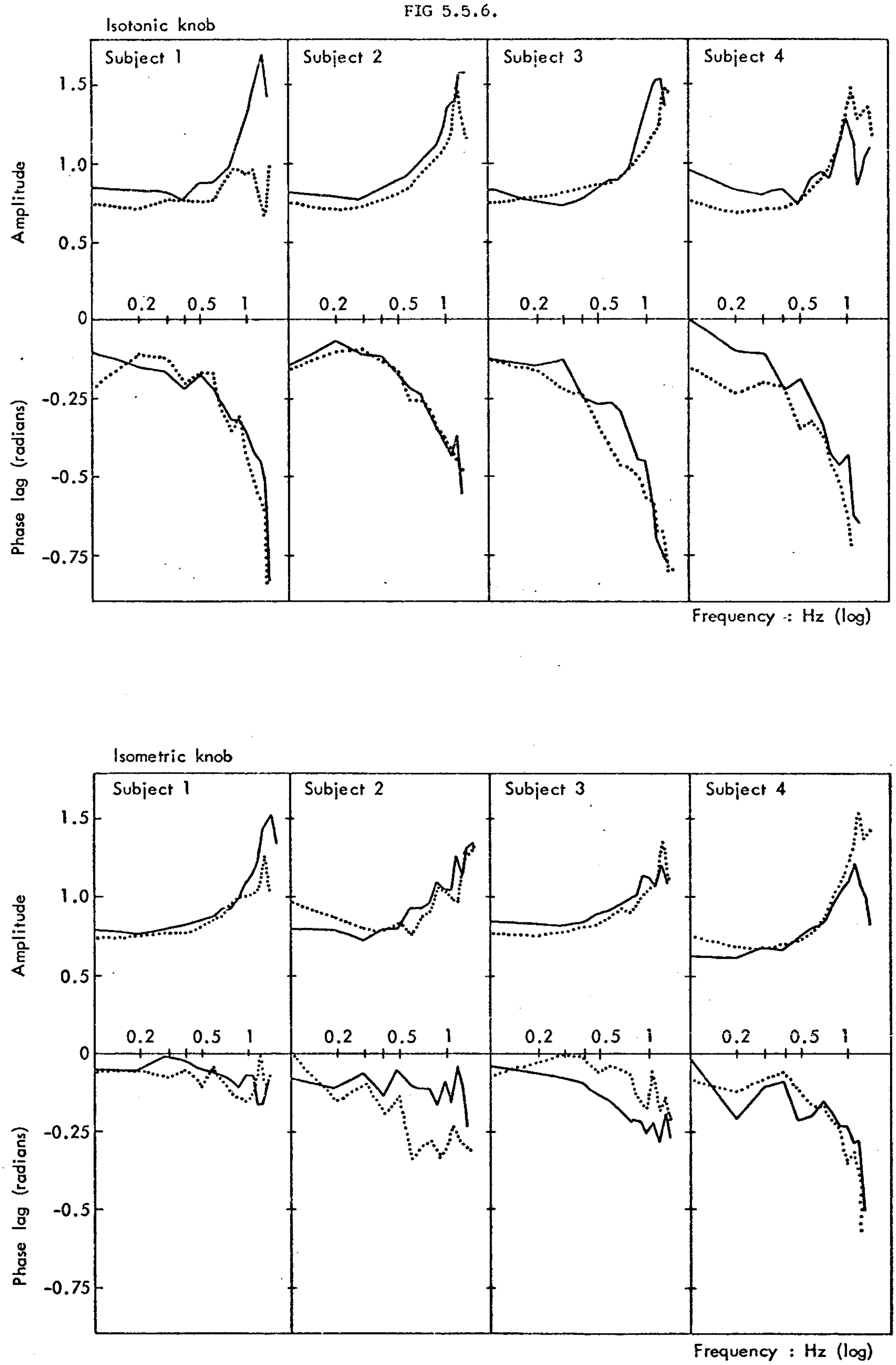
MEAN CLOSED-LOOP TRANSFER FUNCTIONS OF HUMAN OPERATOR WITH ISOTONIC STICK : STATIC CONDITIONS.

FIG 5.5.5.



CLOSED-LOOP TRANSFER FUNCTIONS OF INDIVIDUAL SUBJECTS, WITH JOYSTICK CONTROLS AT OPTIMUM GAINS.
——— STATIC CONDITIONS ·········· 4Hz WHOLE-BODY VIBRATION AT 0.75 m/s^2 RMS.

FIG 5.5.6.



CLOSED LOOP TRANSFER FUNCTIONS OF INDIVIDUAL SUBJECTS, WITH ROTARY CONTROLS AT OPTIMUM GAINS. ——— STATIC CONDITIONS ········· 4Hz WHOLE-BODY VIBRATION AT 0.75m/s^2 RMS.

1954: see appendix B) that the relative inefficiency of isotonic kinaesthetic feedback, compared to isometric feedback, may contribute to the larger delays in making correction with the isotonic controls. These phenomena account for the significant effect of gain on input-correlated error with the isotonic controls. The increase in gain at higher transfer function frequencies in all the transfer functions is evidence of lead generation by the operator. Lead generation is the tendency for the operator to respond to the rate of the input as well as displacement and may be an adaptive strategy to partially compensate for the effect of delays in the control response.

Individual subjects' transfer functions for all four controls at optimum gain conditions (from the mean data) are shown in figures 5.5.5. and 5.5.6. Again, it can be seen that the trends are consistent and reflect the mean data.

5.6. CONCLUSIONS.

It is evident from the results of the above experiment that there is likely to be a considerable interaction between the effects of vibration and control gain in some manual tracking systems. The optimum control gain for minimizing tracking error under a given vibration condition is likely to be lower than that for minimizing error under static conditions, due to increases in vibration-correlated error and non-linear response which both tend to depend upon control gain.

Different controls may not be affected in the same way by vibration. For instance, it was noted in the introduction that isometric controls may be more sensitive than isotonic controls to vibration-induced stick activity at frequencies greater than 5Hz. Hence the form of the interaction between vibration and control gain is likely to be different under different vibration conditions. When setting up control gains for use in real control systems it is therefore apparent that they should be optimized, possibly by experimentation, for the real operational motions.

The results suggest that the observed increase in non-linear response or remnant during vibration conditions is entirely comprised of an increase in motor remnant. This supports the hypothesis proposed by Lewis (1974) that interference with the kinaesthetic feedback mechanisms involved in neuromuscular control loops is a principal means by which vibration degrades manual control performance. However the hypothesis that with translational whole-body vibration rotary controls will be less sensitive to vibration-induced control activity, compared to joystick controls, is not supported by the data.

6. EXPERIMENT TWO: THE EFFECT OF FREQUENCY OF VIBRATION AT THE MAN-CONTROL INTERFACE.

6.1. INTRODUCTION

Experiment two was performed in order to further investigate the sources of increased tracking error variance observed during vibration conditions, and to investigate the dependence of these effects on vibration frequency and control dynamics.

In static conditions the remnant portion of the operator's response has typically been shown to have a continuous and reasonably smooth spectrum, indicating no spectral lines which might be associated with periodic sampling or strongly non-linear behaviour (McRuer & Krendel, 1974, Jex & Magdaleno, 1969). However during high levels of vertical, whole-body vibration, Lewis (1974) measured peaks of fairly periodic activity in the tracking error spectra of some subjects. These peaks occurred mainly between 1 and 2Hz, frequencies higher than those contained in the forcing function. The results of the last experiment show that vibration can result in large increases in remnant activity which is apparently due to motor sources. It was felt that the frequency content of these increases in remnant due to vibration may give more clues to its source so in the present experiment the remnant appearing at frequencies less than 1Hz was analysed separately from that appearing in the 1 to 3Hz band.

The neuromuscular output processes of the operator will be primarily affected by vibration transmitted to the hand-control interface. If the vibration is applied through the seat, the amount of vibration transmitted to the limb-control interface will be dependent on body transmission phenomena. However, if the vibration is applied through the control, the amount of vibration at the interface can be specified exactly. Vibrating the control will also reduce perceptual effects due to visual blurring and any central or non-specific stress effects of vibration due to discomfort, and help to further isolate effects of vibration on the motor system.

6.2. SUBJECTS.

Four, right-handed male subjects were used. Two of the subjects had previously taken part in experiment one. Further details of subjects are given in appendix D. The new subjects both had no previous experience of manual tracking or human vibration experiments. These two subjects attended two practice sessions before the three experimental sessions, while the experienced subjects attended only one practice session. Payment was made to subjects at the rate of £1.00 for attendance at each practice or experimental session.

6.3. PROCEDURE

Six frequencies of vertical, sinusoidal vibration were applied to each of three controls. The vibration frequencies were 0, 4, 8, 16, 32 and 64 Hz. The vibration levels were chosen to correspond to the fatigue-decreased proficiency limits proposed for vertical seat vibration by the International Standards Organisation (ISO 1974). These are listed in table 6.3.1. The controls were single axis isotonic, isometric and spring-centred joysticks. Details of these and of the single-axis, zero order, pursuit tracking task are given in section 4.2. The gains of the

TABLE 6.3.1. VIBRATION CONDITIONS - EXPERIMENT TWO.

CONDITIONS	FREQUENCY	ACCELERATION AMPLITUDE
F0	0	0
F1	4 Hz	1.2 ms^{-2} rms
F2	8 Hz	1.2 ms^{-2} rms
F3	16 Hz	2.4 ms^{-2} rms
F4	32 Hz	4.8 ms^{-2} rms
F5	64 Hz	9.6 ms^{-2} rms

isotonic and isometric sticks were 375 mm/radian and 50 mm/kg respectively - corresponding to the optimum static gains measured in experiment one. The gain of the spring stick was set up as a combination of the above, so that an applied force of 1 kg displaced the stick by 0.13 radians and moved the controlled element by 50 mm on the display.

Each practice session was comprised of nine 5 minute tracking runs, with 2 minute rest periods between runs. The first three runs were always performed with the isotonic stick, the second three with the spring stick and the last three with the isometric (in order to achieve maximum transfer of training between controls).

No integrated absolute error scores were taken during practice or experimental runs, but the forcing function and control output were digitised on-line during the experimental runs, and stored on magnetic disc. There were six tracking runs within each session, one for each vibration condition. Runs were 330 seconds long with 300 seconds rest between runs. Data was acquired only for the last 300 seconds of each run. The subjects performed with a different control at each of the three sessions. Hence the experiment consisted of a balanced 3 by 6 factorial design.

The sampling rate of the analogue to digital conversion was 20 samples per second per channel and the resolution of the spectral analysis was 0.078 Hz, giving 88 degrees of freedom.

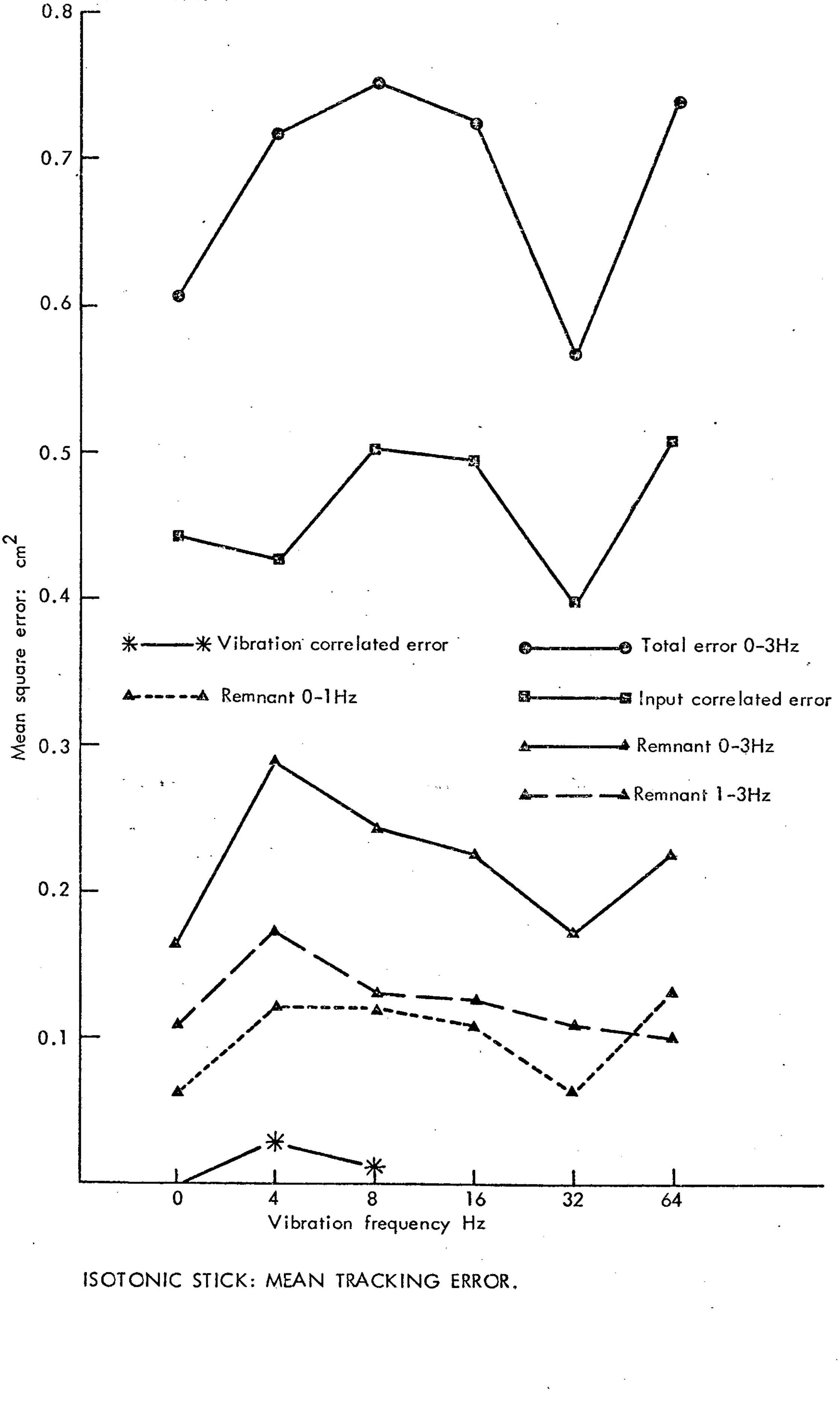
6.4. RESULTS OF TRACKING ERROR MEASURES.

The mean variance of the various tracking error components, for each control, are shown in figures 6.4.1, 6.4.2 and 6.4.3. The remnant, or operator generated noise, is divided up into the variance appearing within two separate frequency bands. It was necessary to limit the data sampling rate to 20 samples/second, thus limiting the bandwidth of the analysis to 10 Hz: consequently estimates of vibration correlated breakthrough could only be obtained for vibration frequencies of 4 and 8 Hz. Vibration breakthrough characteristics have been measured separately for a number of subjects and some data is presented later in this chapter.

Data for each of the components of error variance were collected in the form of a separate, two factor, mixed effects analysis of variance with subjects as randomnized blocks. ANOVA Summary tables are given in tables 6.4.1a to 6.4.1e.

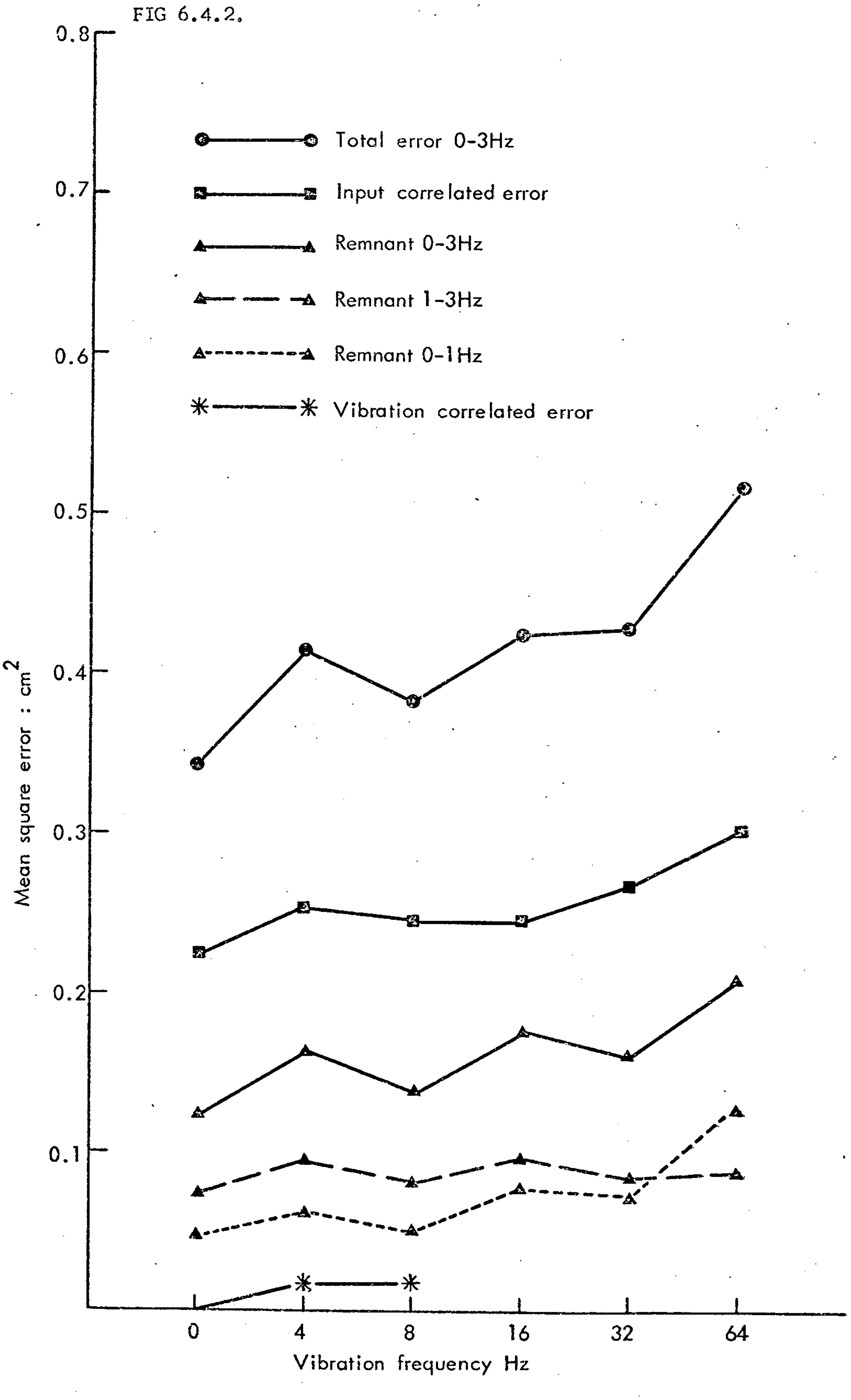
There were significant differences ($p < 0.05$) between performance with the three controls for all the error components except 1 - 3 Hz remnant. The effect of vibration frequency on the

FIG 6.4.1.



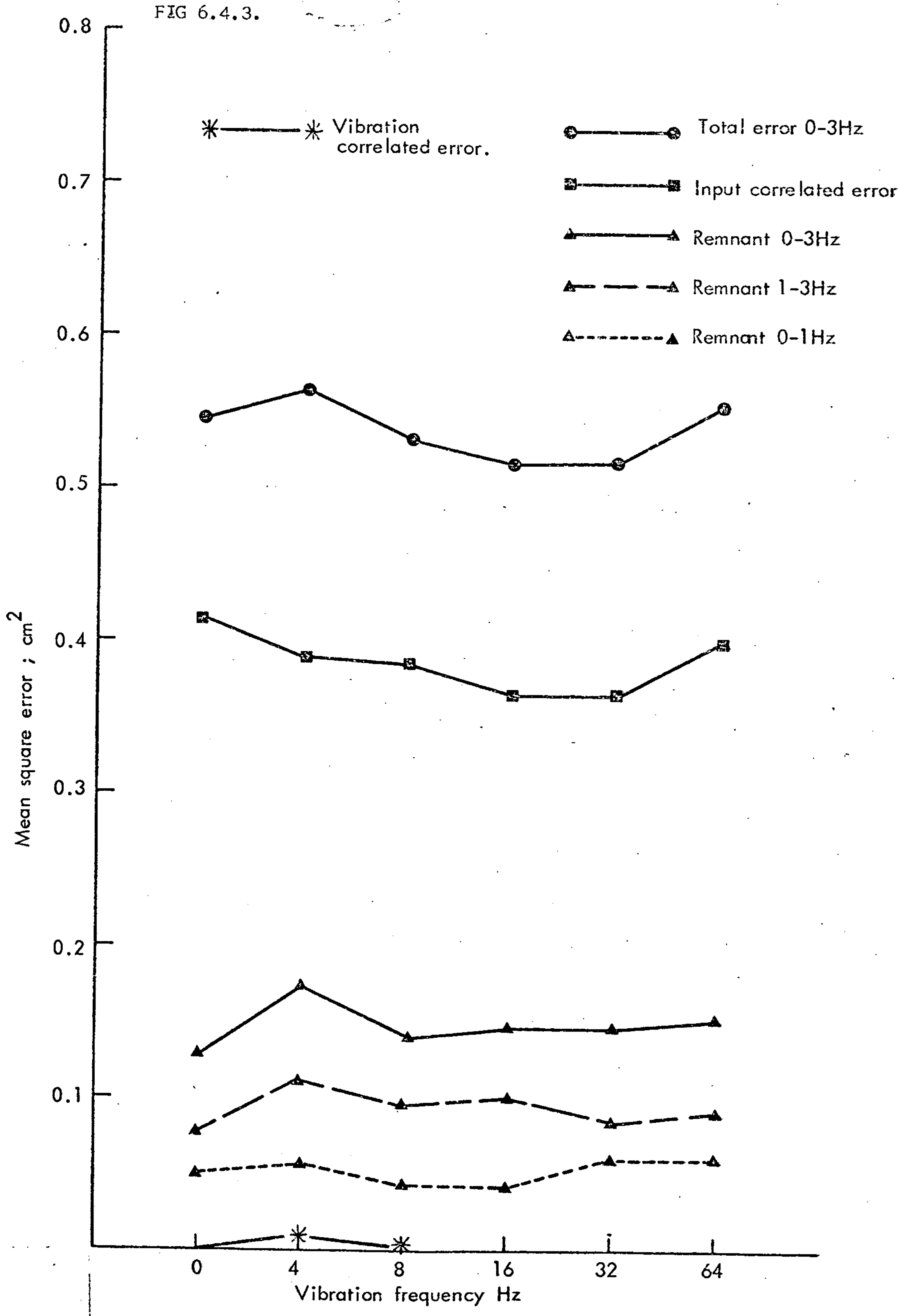
ISOTONIC STICK: MEAN TRACKING ERROR.

FIG 6.4.2.



ISOMETRIC STICK : MEAN TRACKING ERROR.

FIG 6.4.3.



SPRING STICK : MEAN TRACKING ERROR.

TABLE 6.4.1. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 2
MEAN SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, F = Vibration Frequency, C = Control.

(a) TOTAL MEAN SQUARE TRACKING ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.73467E 7	3	0.24489E 7	34.68	0.01
F	0.56894E 6	5	0.11379E 6	1.40	ns
C	0.53243E 7	2	0.26622E 7	15.61	0.01
F x C	0.61643E 6	10	61643.2003	1.35	ns
RESIDUAL	0.36009E 7	51	70606.1194		
F x S	0.12176E 7	15	81174.4006		
C x S	0.10232E 7	6	0.17054E 6		
F x C x S	0.13600E 7	30	45334.3994		

(b) MEAN SQUARE INPUT-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.14408E	3	0.48027E 6	11.76	0.01
F	0.17321E 6	5	34642.3995	0.69	ns
C	0.32327E 7	2	0.16164E 7	16.55	0.01
F x C	0.25020E 6	10	25020.0005	1.00	ns
RESIDUAL	0.20828E 7	51	40838.3526		
F x S	0.75038E 6	15	50025.0675		
C x S	0.58571E 6	6	97618.0021		
F x C x S	0.74667E 6	30	24888.9341		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.24803E 7	3	0.82678E 6	69.48	0.01
F	0.22611E 6	5	45222.3995	2.96	0.05
C	0.45618E 6	2	0.22809E 6	12.32	0.01
F x C	0.18258E 6	10	18258.1001	2.04	0.1
RESIDUAL	0.60687E 6	51	11899.3723		
F x S	0.22846E 6	15	15230.5334		
C x S	0.11103E 6	6	18504.8345		
F x C x S	0.26733E 6	30	8912.7004		
Simple Main Effects					
F at C1	268840.0	5	53768.0	3.53	0.05
F at C2	114819.0	5	22964.0	1.50	ns
F at C3	24358.0	5	4872.0	0.31	ns

(d) MEAN SQUARE REMNANT, 0-1Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.53671E 6	3	0.17890E 6	34.32	0.01
F	84205.7522	5	16841.1509	2.40	0.1
C	0.17888E 6	2	89442.0021	12.10	0.01
F x C	95956.2522	10	9595.6252	2.47	0.05
RESIDUAL	0.26583E 6	51	5212.4415		
F x S	0.10510E 6	15	7006.9000		
C x S	44320.7511	6	7386.7916		
F x C x S	0.11641E 6	30	3880.3333		
Simple Main Effects					
F at C1	107632.0	5	21526.0	3.07	0.05
F at C2	67132.0	5	13427.0	1.91	ns
F at C3	5375.0	5	1075.0	0.15	ns

(e) MEAN SQUARE REMNANT, 0-3 Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.74616E 6	3	0.24872E 6	77.60	
F	71548.0022	5	14309.5998	4.46	
C	76050.5022	2	38025.2510	11.86	
F x C	30914.0005	10	3091.3999	0.96	
RESIDUAL	0.16346E 6	51	3205.1372		
F x S	49915.0011	15	3327.6668		
C x S	56271.0011	6	9378.5002		
F x C x S	57276.0010	30	1909.1999		
Simple Main Effects					
F at C1	70047.0	5	14009.0	4.21	0.05
F at C2	12208.0	5	2442.0	0.73	ns
F at C3	18933.0	5	3787.0	1.13	ns

*note: the multiplier 'E n' signifies x 10^n.
*note: C1 = isotonic stick, C2 = isometric stick, C3 = spring stick.

various error components was significant only for total remnant and 1 - 3 Hz remnant, but there was a significant vibration by control interaction for 0 - 1 Hz remnant. Simple main effects indicated that the effect of vibration frequency was significant for all the remnant measures with the isotonic stick, but insignificant for the other two controls. In order to localise the effects of vibration further a one tailed Dunnett's 't' test was carried out on the three remnant measures for each control to determine whether the error under each vibration condition was greater than in the control condition. The null hypothesis was rejected for the following conditions:

Total remnant: Isotonic stick at 4 Hz and Isometric stick at 64 Hz.

1 - 3 Hz remnant: Isotonic stick at 4 Hz.

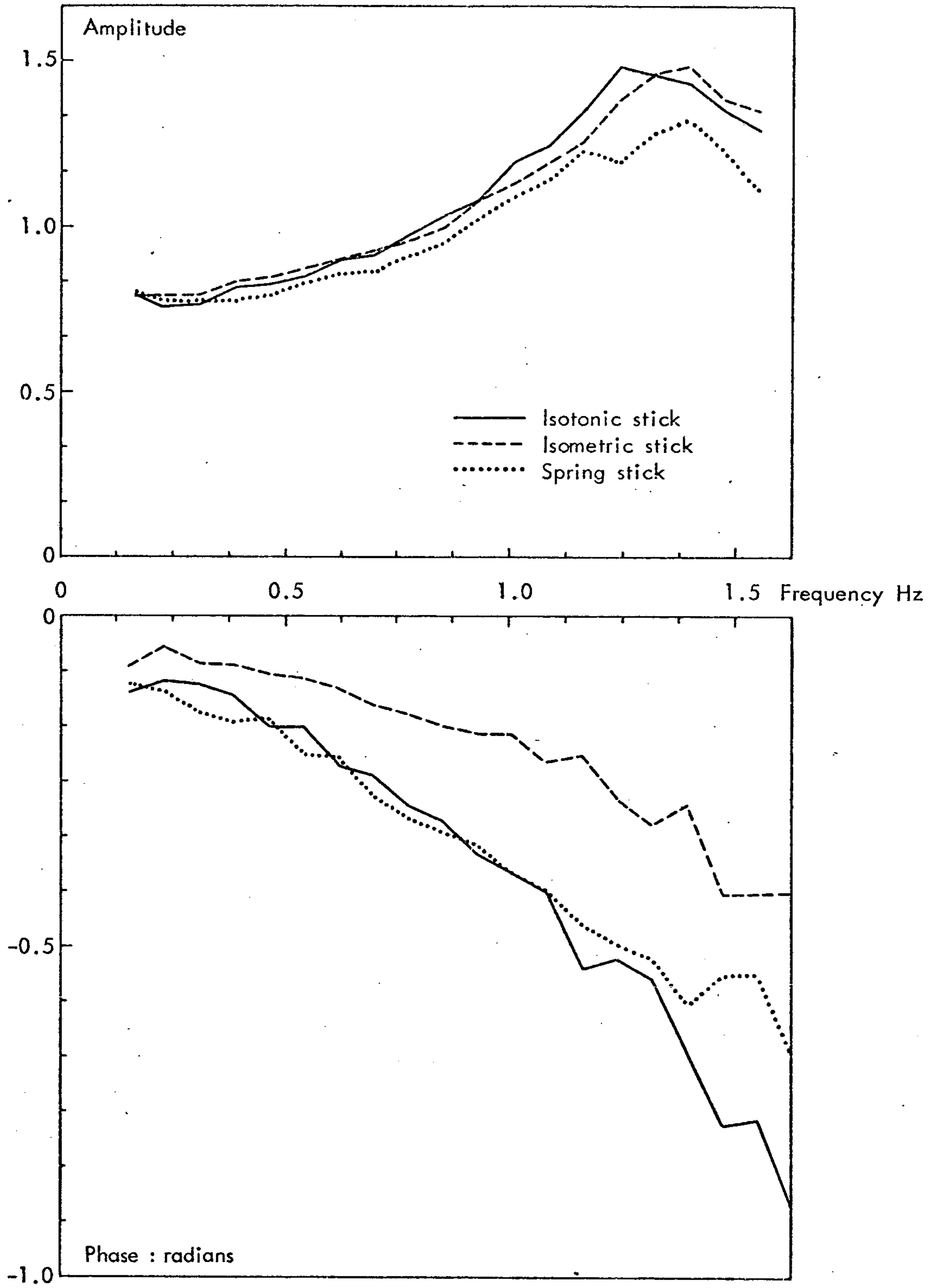
0 - 1 Hz remnant: Isotonic stick at 4, 8 and 64 Hz, and Isometric stick at 64 Hz.

6.5. TRANSFER FUNCTION RESULTS.

Mean human operator transfer functions for each of the three controls are illustrated in figure 6.5.1. The large phase lags with the isotonic and spring sticks, compared to the isometric stick, are immediately obvious, as in experiment one. These can be accounted for by inertia and friction in the moving controls, which tend to delay the initiation and halting of control actions. These phenomena account for the larger input-correlated errors with the isotonic and spring-centred controls.

The gain and phase data from the transfer function measures were subjected to separate, three factor, mixed effects analyses of variance, with subjects as randomnized blocks. ANOVA Summary tables are given in tables 6.5.1a and 6.5.1b. The effects of transfer function frequency were significant for both gain and phase. There was a significant overall difference between controls and a significant frequency by control interaction for phase but not for gain. There was also a significant effect of vibration on phase and a significant vibration by frequency interaction with gain and phase. Analysis of simple main effects showed that the effects of vibration were only significant for transfer function frequencies greater than 1 Hz, and then only for the isotonic

FIG 6.5.1.



MEAN CLOSED-LOOP TRANSFER FUNCTIONS (4SUBJECTS; STATIC CONDITIONS) FOR ISOTONIC, ISOMETRIC AND SPRING STICK DYNAMICS.

TABLE 6.5.1. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 2 TRANSFER FUNCTION MEASURES.

Treatments: S = Subjects, T = Transfer Function Frequency, F = Frequency, C = Control.

(a) MODULUS OF TRANSFER FUNCTION.

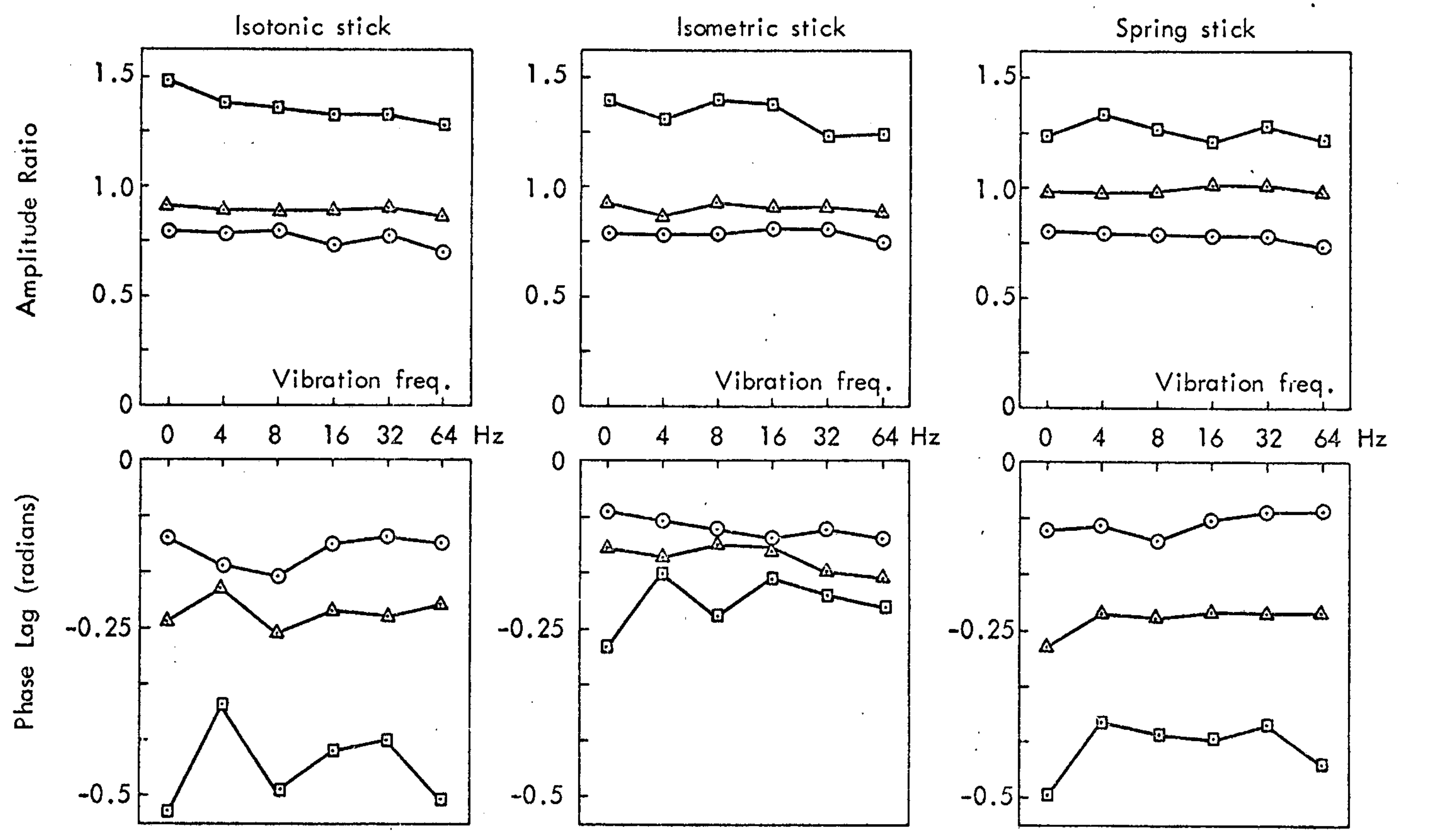
SOURCE	SS	DF	MS	F RATIO	p
S	0.60907	3	0.20302	42.88	0.01
T	35.32391	14	2.52313	83.02	0.01
F	0.19181	5	0.03836	2.14	ns
C	0.15727	2	0.07864	1.32	ns
T x F	0.11329	70	0.00162	0.63	ns
T x C	0.28363	28	0.01013	5.21	0.01
F x C	0.11471	10	0.01147	0.89	ns
T x F x C	0.41607	140	0.00297	1.48	0.1
RESIDUAL	3.82056	807	0.00473		
T x S	1.27643	42	0.03039		
F x S	0.26779	15	0.01785		
C x S	0.35613	6	0.05935		
T x F x S	0.53138	210	0.00253		
T x C x S	0.16313	84	0.00194		
F x C x S	0.38453	30	0.01282		
T x F x C x S	0.84117	420	0.00200		

(b) PHASE LAG OF TRANSFER FUNCTION

SOURCE	SS	DF	MS	F RATIO	p
S	0.21919	3	0.07306	23.82	0.01
T	8.34702	14	0.59622	65.50	0.01
F	0.18984	5	0.03797	3.40	0.05
C	2.89237	2	1.46619	31.83	0.01
T x F	0.32666	70	0.00467	2.08	0.01
T x C	1.15985	28	0.04142	16.19	0.01
F x C	0.12219	10	0.01222	1.17	ns
T x F x C	0.18557	140	0.00133	0.84	ns
RESIDUAL	2.47438	807	0.00307		
T x S	0.38227	42	0.00910		
F x S	0.16734	15	0.01116		
C x S	0.27254	6	0.04542		
T x F x S	0.46982	210	0.00224		
T x C x S	0.21481	84	0.00256		
F x C x S	0.31103	30	0.01037		
T x F x C x S	0.65657	420	0.00156		
Simple Main Effects					
F at T1,C1	0.05148	5	0.01029	0.92	ns
F at T8,C1	0.04234	5	0.00846	0.75	ns
F at T15,C1	0.30828	5	0.06165	5.52	0.01
F at T1,C2	0.01811	5	0.00362	0.32	ns
F at T8,C2	0.04749	5	0.00949	0.85	ns
F at T15,C2	0.13159	5	0.02631	2.35	0.1
F at T1,C3	0.01859	5	0.00371	0.33	ns
F at T8,C3	0.03349	5	0.00669	0.60	ns
F at T15,C3	0.14178	5	0.02835	2.54	0.1

*note: T1 = 0.08 Hz, T8 = 0.64 Hz, T15 = 1.20 Hz.

FIG 6.5.2.



Transfer function frequencies : ⊙ = 0.08 Hz, △ = 0.64 Hz, ⊡ = 1.20 Hz.

THE EFFECT OF VIBRATION FREQUENCY ON PARAMETERS OF HUMAN OPERATOR TRANSFER FUNCTIONS.

control. Figure 6.5.2. shows the effects of vibration on gain and phase at three transfer function frequencies. The effects of vibration on gain are manifested as a slight suppression of high frequency activity, especially at the higher vibration frequencies, but the effect on phase response is more interesting. Vibration has brought about a reduction in high frequency phase lags, especially by 4 Hz vibration with the isotonic stick, implying some facilitation of performance. These transfer function effects are, however, fairly small and result in no overall significant effect on input-correlated error.

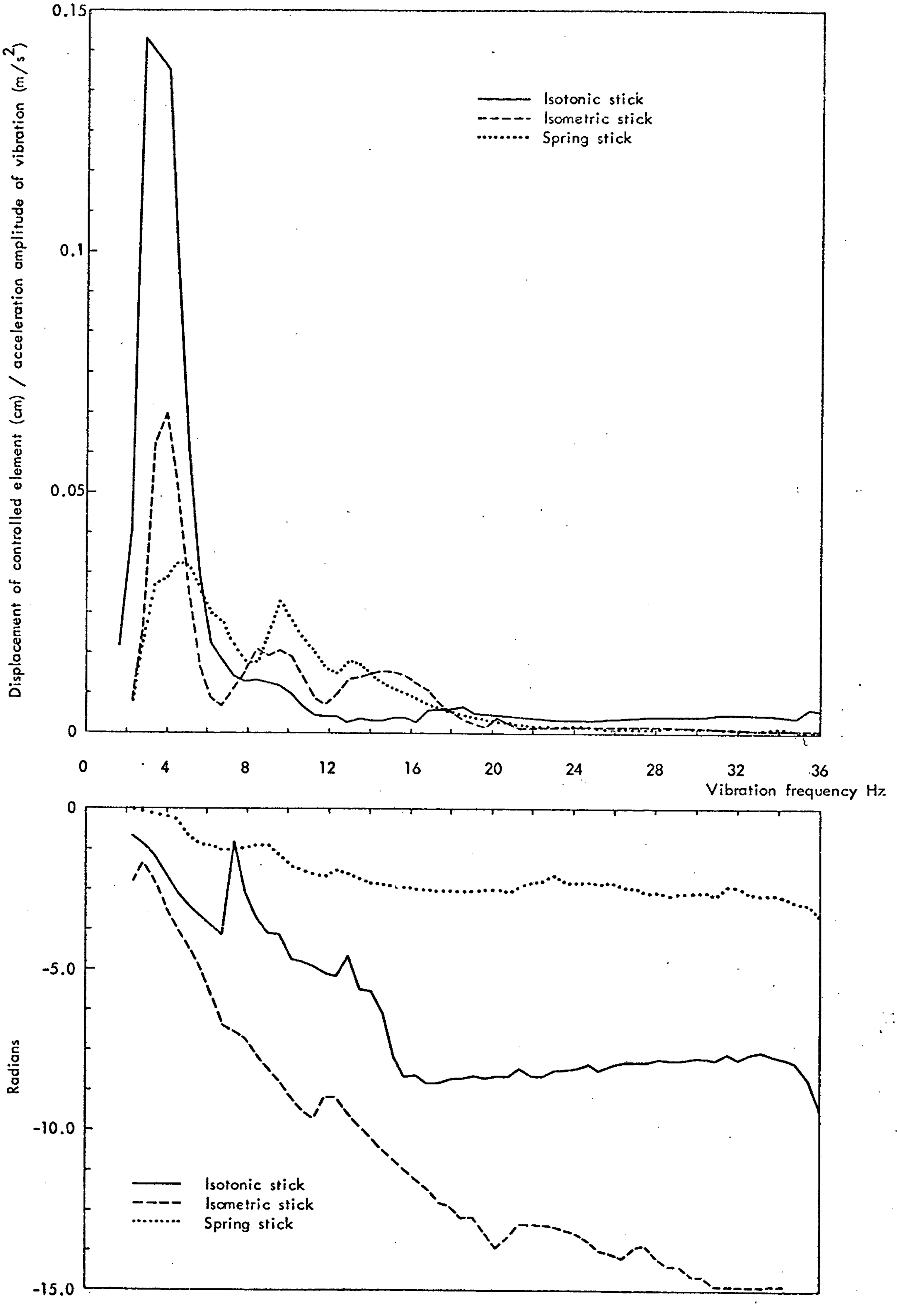
6.6. THE VARIATION OF VIBRATION-INDUCED CONTROL ACTIVITY WITH VIBRATION FREQUENCY.

Figure 6.6.1. shows how vibration-induced control activity varies with vibration frequency for vertical control vibration and the three controls employed in experiment one. For clarity the curves only cover the frequency range up to 36 Hz as the vibration-induced activity was found to be effectively zero at higher frequencies. These curves were obtained by exciting the control with constant velocity, swept sinusoidal vibration over the frequency range and dividing the cross spectrum of the vibration and the control output by the power spectrum of the vibration.* Each curve is the average transmission of vibration to the control over six, 100 second sweeps with a vibration velocity of ± 0.05 m/sec, corresponding to the ISO 25 minute fatigue decreased proficiency limit above 8 Hz. The response is dominated by interaction between the hand and the control and not by the response of the control in isolation. Note that these data apply to one subject only. The difference in magnitude of breakthrough between controls depends, of course, entirely on control gain.

Figure 6.6.2. compares vibration-induced control activity with similar levels of seat and control vibration for two different subjects and isotonic and isometric controls. It can be seen that there is a considerable variability between subjects. Variations can also be expected to occur within subjects with variations in posture and grip, as shown in figures 6.6.3. and 6.6.4.

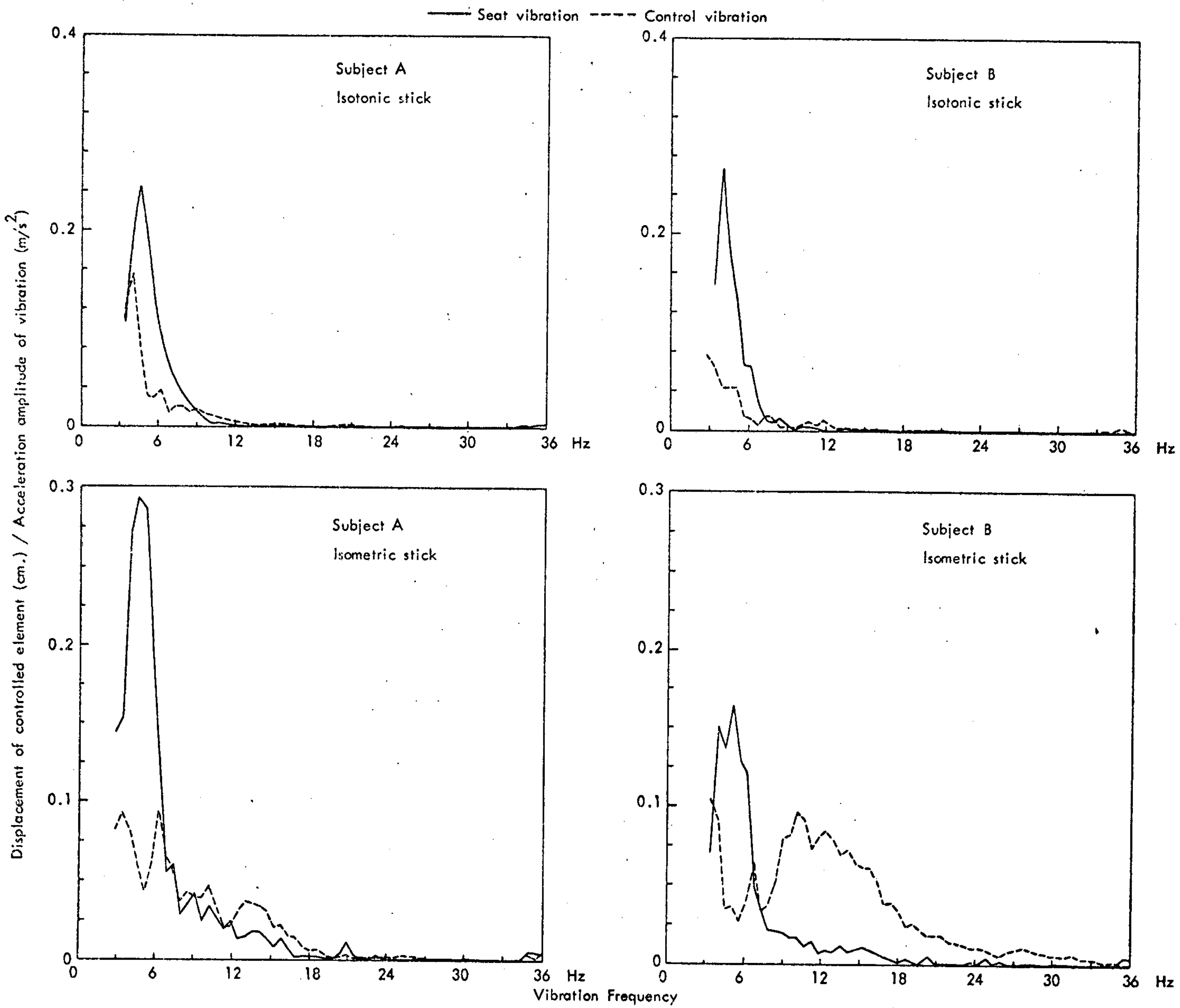
* Subjects were asked to keep the controlled element marker centred on the stationary forcing function marker.

FIG 6.6.1.



VIBRATION BREAKTHROUGH WITH CONTROL VIBRATION.

FIG 6.6.2. VIBRATION BREAKTHROUGH WITH SEAT AND CONTROL VIBRATION FOR TWO SUBJECTS



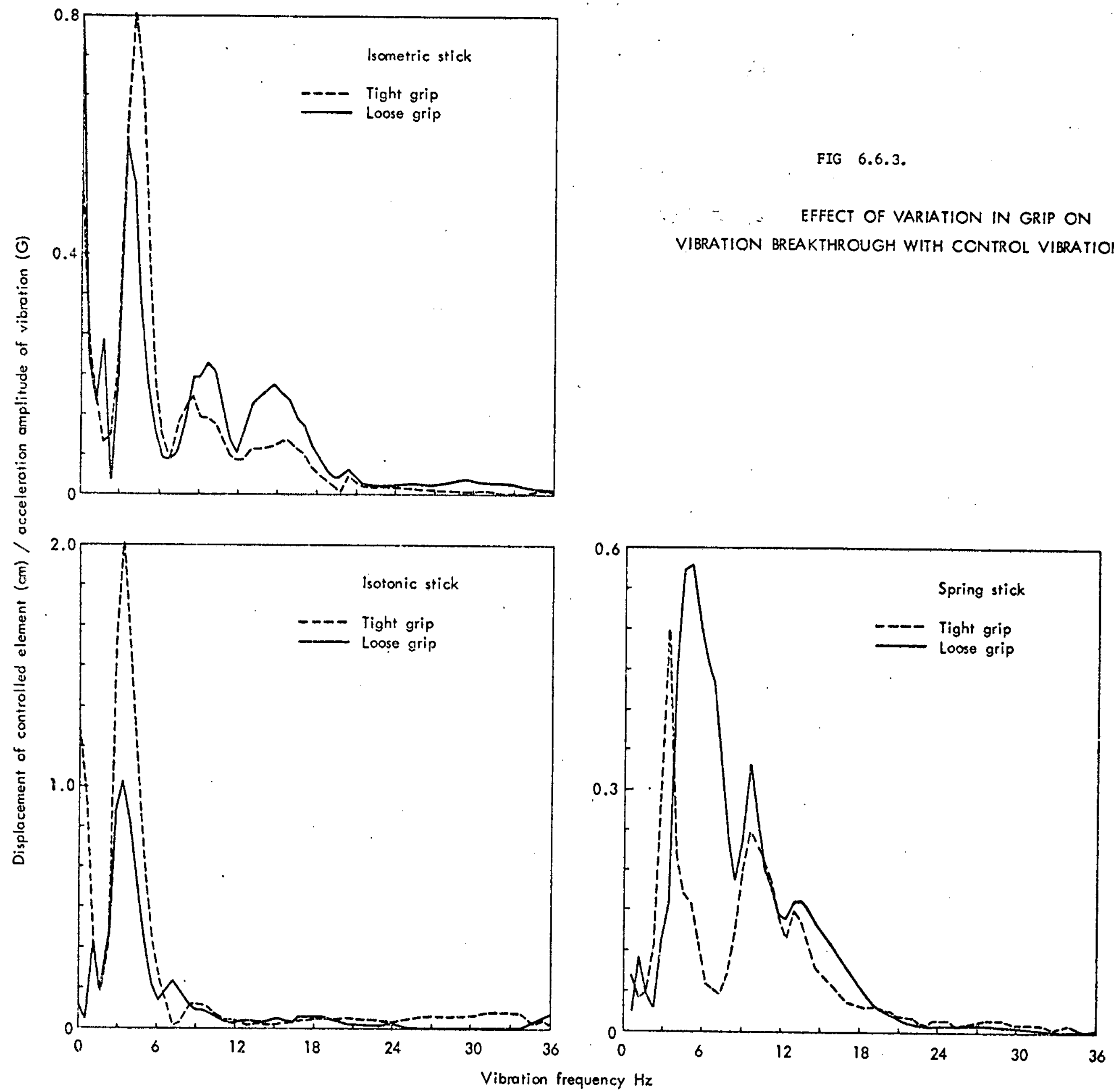
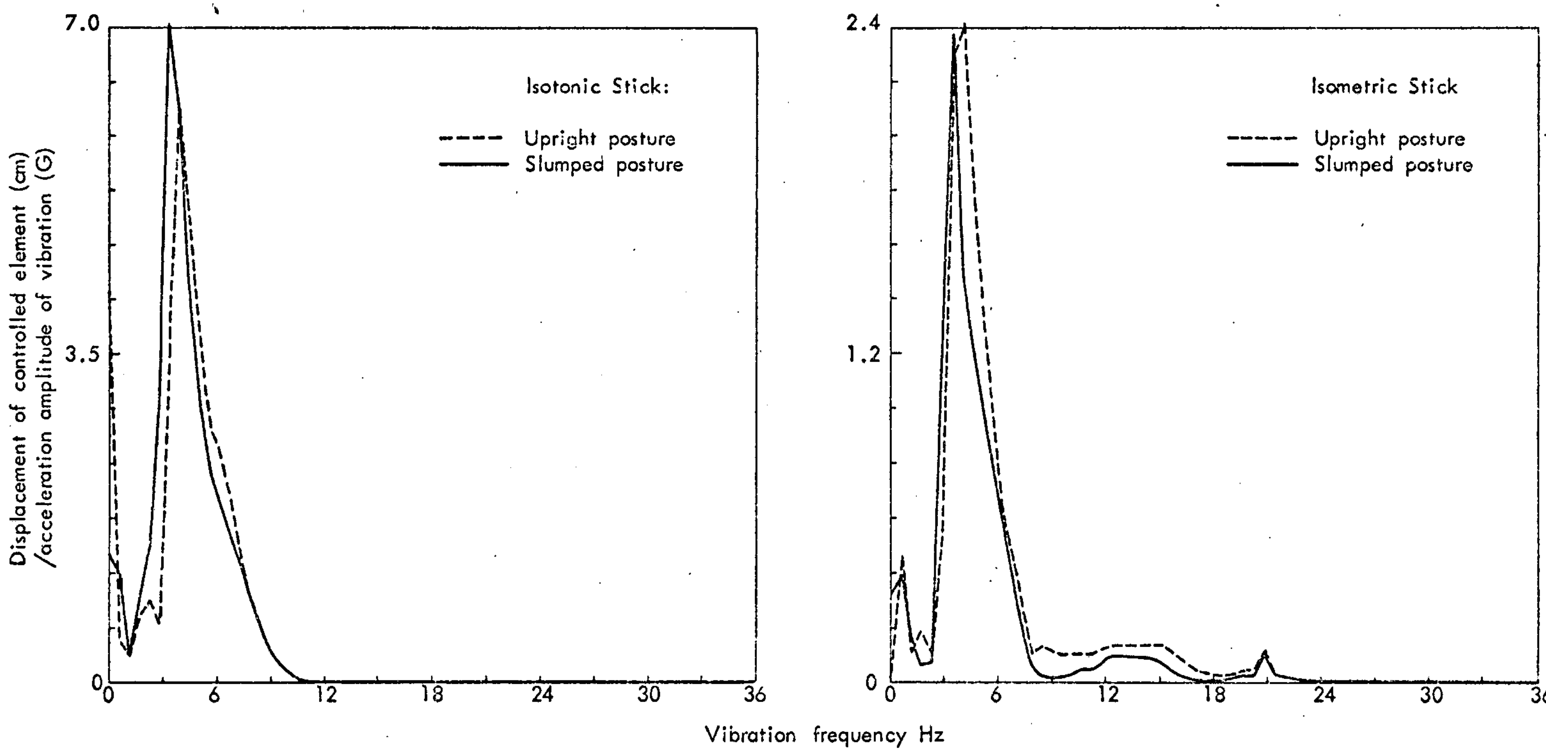


FIG 6.6.3.

EFFECT OF VARIATION IN GRIP ON VIBRATION BREAKTHROUGH WITH CONTROL VIBRATION.

FIG 6.6.4.



EFFECT OF VARIATION IN POSTURE ON VIBRATION BREAKTHROUGH WITH SEAT VIBRATION.

6.7. DISCUSSION.

Low frequency vibration of the isotonic control resulted in significant increases in remnant, consistent with the effects of whole-body vibration on a similar task as shown by Lewis (1974) results of experiment 1. Vibration of the control confines the effects of vibration to the interface between the control and the controlling limbs, ruling out visual blurring due to differential motion between eyes and display as a possible mechanism for the observed increase in remnant. The results therefore appear to confirm that the increase in operator-generated noise due to low frequency vibration is made up primarily of motor remnant, lending support to the hypothesis of Lewis (1974). However further examination of the results, and discussions with subjects after they had completed the experiment, suggests that an alternative explanation is possible.

The results of Lewis (1974) showed that a combination of 3, 5 and 8 Hz vibration tended to induce peaks of remnant error power between 1 and 2 Hz in a zero-order pursuit tracking task with an isotonic control. This tendency was reduced when spring centering was added to the control, consistent with the present results, and the effect was attributed to neuromuscular instability as a consequence of delays in the kinaesthetic feedback mechanisms involved in the neuromuscular actuation processes. Such delays might be expected to result in increases in neuromuscular lags and in a reduction in the amount of coherent motor behaviour. There is some evidence of suppression of gains at higher transfer function frequencies, but this is accompanied by reductions in higher frequency phase lags under 4 Hz vibration. These reductions in response lags may be due to voluntary, adaptive changes in tracking strategy, in order to compensate for disturbances by the vibration. They may also be partially due to increased arousal by the presence of the vibration, coupled with resultant increases in task difficulty.

The discussions with subjects after the experiment indicated that their main problem during the 4 Hz vibration condition was in attempting to control oscillations of the controlled element induced by vibration. Where this vibration breakthrough is significant the subject is essentially presented with a compensatory tracking task, with breakthrough as a forcing function, in addition to the regular pursuit task. The best strategy for the operator in this case would be to ignore the breakthrough and to concentrate on controlling the medial point of the controlled element on the screen. However, the results of Huddleston (1970) suggest that subjects may not be able to make efficient use of medial or nodal images of objects vibrating at 6 Hz or less. Howell and Briggs (1959) reported an experiment in which subjects were required to perform a pursuit tracking task with a low frequency disturbance (0.25-1 Hz) added to the movements of the controlled element. The subjects were instructed to attempt to ignore the disturbance and track only the sinusoidal forcing function, but average tracking error was found to be proportional to the magnitude of the disturbance.

In the experiment by Howell and Briggs the disturbances occurred in the same frequency range as the forcing function. However Robinson (1967) showed that when the noise occurred at a higher frequency than the forcing function, the mean square tracking error was still proportional to the signal to noise ratio. The relative disturbance was slightly decreased as the frequency gap between signal and noise was increased, the operator's performance being similar to a low-pass filter: however the operator could not perform as well as an optimum filter.

Human operators can be shown to employ a combination of several different tracking strategies. Continuous pursuit tracking by trained operators is most consistently characterised by predictive rate tracking based on the input information, combined with intermittent (input-synchronised) error corrections (Young and Stark, 1965). When the forcing function is well within the tracking bandwidth of the operator the intermittent error corrections appear as a relatively low amplitude, broadband spectrum of perceptual remnant activity extending from very low frequencies up to about 2 Hz. If the forcing function frequencies are increased, or become less predictable, there will be a corresponding increase in the necessary rate of intermittent error corrections in order to maintain deviations from the track within required tolerances. However, visual reaction time tends to limit the maximum rate of these error corrections to about 2 per second. Moreover the inevitable reaction time lag involved in making these intermittent corrections makes them less efficient as the unpredictable changes in velocity and direction of the track become more rapid. Hence attempts to track forcing functions with significant power beyond about 1 Hz tends to result in peaks of incoherent activity in the operator's response at around 2 Hz (Young and Stark, 1965). This suggests that the increase in remnant observed with the isotonic control under 4 Hz vibration, which contained significant power in the 1-3 Hz frequency range, could be due to subjects' attempts to control out disturbances of the controlled elememt on the display due to vibration-induced control activity and to perceptual confusion due to masking of voluntary movements of the controlled element by vibration-induced oscillations. This is consistent with the results of experiment one, since increases in control gain will result in corresponding increases in the amplitude of the vibration-induced disturbance in the display. The curves in figure 6.6.2 indicate that a given level of 4 Hz seat vibration is likely to result in considerably more vibration-induced control activity than the same level of control vibration and is therefore likely to cause larger increases in perceptual remnant.

A significant increase in remnant was also observed with the isotonic stick under 8 Hz vibration, but the increases in remnant were largely confined to frequencies below 1 Hz. As the frequency of the vibration-induced disturbance of the controlled element is increased, the subjects will be less able to perceive individual oscillations and the disturbance will appear as a blur of the displayed image of the controlled element, with well defined modal images at the extremes of the oscillation. Subjects should be able to track the forcing function efficiently using the centre of the blurred controlled element image as the response marker. However, the subjects' ability to locate the exact centre of the blur and use it as a response marker will be dependent on the amplitude of the blurred image and a certain amount of perceptual noise will result from uncertainty concerning the medial point of the controlled element.

No significant increases in remnant were observed with either the isometric or spring-centred controls during low frequency vibration. This can be attributed to the smaller amounts of vibration-induced control activity observed with these controls. Vibration-induced disturbances of display information are likely to result in a greater reliance on kinaesthetic cues of limb position and movement. Vibration-induced control activity will also appear in the kinaesthetic sense information but there is evidence to suggest that force cues are more meaningfully related to control output and more resistant to perturbation than displacement cues (e.g., Gibbs, 1954). Hence it is possible that the extra kinaesthetic sense information available to subjects when tracking with isometric and spring-centred controls can also help them to more accurately perceive changes in the medial position of the controlled element, enabling them to make more accurate control responses and reducing the need for intermittent error correction.

The significant increases in low frequency (0 - 1 Hz) remnant observed with the isotonic and isometric controls during 64 Hz vibration cannot be attributed to perceptual confusion because vibration-induced control activity was negligible at this frequency. Physiological studies (see appendix B) have shown that vibration of a muscle or its tendons at frequencies above 20 Hz can produce pronounced illusions of movement and position in the associated limb. These effects can be traced to the muscle-spindle receptors, which interpret the vibration as steady state stretch and initiate reflex contraction of their extrafusal muscles via the spinal stretch reflex arc. The effects have been shown to increase with increases in the amplitude and frequency of the vibration (Goodwin et al., 1972). Normal spinal reflexes have also been shown to be depressed by vibration, the effect increasing with vibration frequency above 10 Hz (Loeckle, 1947, Goldman, 1948). Symptoms consistent with these effects were reported by subjects in the present experiment.

Two subjects reported numbness in their right arms during the 64 Hz condition, which persisted for a short time after the cessation of vibration. Another subject reported a noticeable sluggishness in muscular action while tracking during 64 Hz vibration. The spinal reflex arc constitutes an important servo-control loop, involved in the control of fine muscular contraction and any interference with its operation is likely to lead to increasingly inappropriate movements or motor remnant. The observed effects of 64 Hz control vibration can therefore be attributed to direct interference with neuromuscular actuation mechanisms, as suggested by Lewis (1974).

6.8. CONCLUSIONS.

The primary effect of vertical vibration of the control stick on the simple pursuit tracking task in this study was an increase in remnant, or operator generated noise. The effects of 64 Hz vibration can be attributed to direct vibration interference with kinaesthetic feedback processes in neuromuscular actuation, consistent with the initial hypothesis. The effect of low frequency vibration could also be attributed to motor noise processes due to interference with kinaesthetic feedback, but the results are more consistent with perceptual noise due to confusion introduced into the display by vibration-induced oscillations of the controlled element. The relative resistance of the isotonic and isometric controls to these effects could be interpreted in terms of the more meaningful force feedback available from these controls or, if the main effect of the low frequency vibration is perceptual confusion, the smaller amount of vibration-induced control activity compared with the isotonic control. These hypotheses were further investigated in experiment three.

7. EXPERIMENT THREE: THE EFFECT OF VIBRATION LEVEL.

7.1. INTRODUCTION

Experiment three was performed in order to determine the relative changes in the various tracking error components and in transfer function parameters with increasing levels of 4 Hz and 16 Hz whole-body and control stick vibration. The 4 Hz vibration frequency was used in order to further investigate the hypothesis that the observed effects of low frequency vibration on the simple pursuit tracking task are due to perceptual noise arising from vibration-induced activity of the controlled element on the display, and because of its relatively large effect on performance as shown by the results of experiments one and two. The 16 Hz vibration conditions were also included in order to compare the effects of 4 Hz vibration, which is well within the frequency range of whole-body resonances, with those of vibration in the important frequency range just above the whole-body resonance range. Vibration frequencies around 16 Hz occur at fairly high levels in some vehicles, notably helicopters, and 16 Hz whole-body vibration may result in significant degradation in visual acuity as indicated by its effect on reading tasks (e.g. Lewis, 1977). Resonances of the human eye, in the skull, in the range 16 to 20 Hz have been measured by Ohlbaum (1976). Vibration in the region of 16 Hz has also been shown to have significant effects on neuromuscular processes (see appendix B) and although significant motor effects were only evident during 64 Hz vibration in the results from experiment two, they may occur at higher levels of 16 Hz vibration.

7.2 SUBJECTS.

As in the previous two experiments, there were four, right-handed male subjects. One subject had previously taken part in both experiments one and two and another had taken part in experiment two only. These two experienced subjects did not attend any practice sessions before the experiment, but the two inexperienced subjects both attended two practice sessions. Both the inexperienced subjects had previously taken part in human vibration experiments, but not manual tracking experiments. Further details of subjects are given in appendix D. The subjects were paid £1.00 for attendance at each practice or experimental session.

7.3 PROCEDURE.

Each of the practice sessions for the inexperienced subjects consisted of nine, 300 second tracking runs, with 180 second rests between consecutive runs. Both subjects used the isotonic stick in the first session and the isometric stick in the second.

This study was run as five separate sub-experiments. In experiments 3A to 3D subjects performed the task with each combination of isotonic or isometric control sticks and control or whole-body, sinusoidal vibration at 4 Hz and 16 Hz (see table 7.3.1). There was no vibration in experiment 3E, but subjects performed the task with both isotonic and isometric controls, with a 4 Hz disturbance added to the controlled element on the display. This was intended to simulate the effect on the display of vibration-induced control activity. The vibration levels in each experiment are given in table 7.3.1. At 4 Hz the level of the control vibration was limited by the power available from the vibrator. The levels of whole-body vibration were limited by safety criteria.

The task was the same single-axis, zero-order, pursuit tracking task as in the previous two experiments (details are given in section 4.2). The control gains were as in experiment two.

Each sub-experiment consisted of a balanced, mixed-effects factorial design with subjects as randomized blocks. Each tracking run was $3\frac{1}{2}$ minutes long, with 3 minutes rest between runs. Each of the five experiments was performed on separate days. All the subjects were presented with experimental sessions in the same order. The first experimental session was experiment 3A (isotonic stick and control vibration); the second was experiment 3B (isometric stick and control vibration); the third was experiment 3C (isotonic stick and whole-body vibration); the fourth was experiment 3D (isometric stick and whole-body vibration); and the fifth was experiment 3E (both controls and "artificial vibration breakthrough"). The forcing function and control output were digitised on-line and transferred to magnetic disc for later analysis. The sampling rate of the analogue to digital conversion was 20 samples per second and the resolution of the spectral analysis was 0.078 Hz, giving 62 degrees of freedom.

TABLE 7.3.1.

VIBRATION CONDITIONS - EXPERIMENT THREE

EXPERIMENTS 3A & 3B (VIBRATION OF CONTROL STICK)

	ACCELERATION	AMPLITUDE
FREQUENCY	4 Hz	16 Hz
V0	0	0
V1	0.35 ms^{-2} rms	1.4 ms^{-2} rms
V2	0.70 ms^{-2} rms	2.8 ms^{-2} rms
V3	1.05 ms^{-2} rms	4.2 ms^{-2} rms
V4	1.40 ms^{-2} rms	5.6 ms^{-2} rms
V5	1.75 ms^{-2} rms	7.0 ms^{-2} rms

EXPERIMENTS 3C & 3D (VIBRATION OF SEAT)

	ACCELERATION	AMPLITUDE
FREQUENCY	4 Hz	16 Hz
V0	0	0
V1	0.4 ms^{-2} rms	0.8 ms^{-2} rms
V2	0.8 ms^{-2} rms	1.6 ms^{-2} rms
V3	1.2 ms^{-2} rms	2.4 ms^{-2} rms
V4	1.6 ms^{-2} rms	3.2 ms^{-2} rms
V5	2.0 ms^{-2} rms	4.0 ms^{-2} rms

EXPERIMENT 3E ('APPARENT' VIBRATION OF CONTROLLED ELEMENT ONLY)

	AMPLITUDE OF 4 Hz DISTURBANCE ON DISPLAY
V0	0
V1	2 mm rms
V2	4 mm rms
V3	6 mm rms

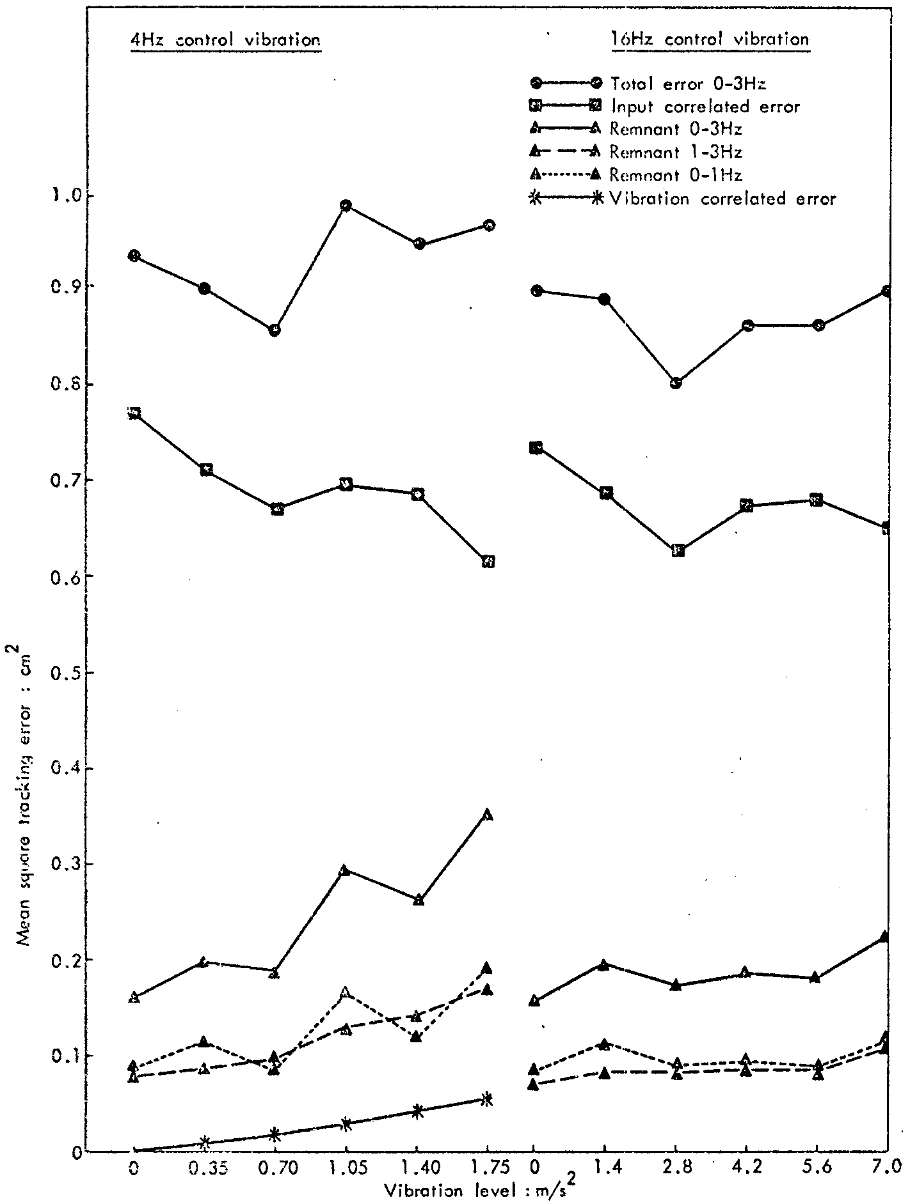
7.4. RESULTS OF TRACKING ERROR MEASURES

The mean variance of the various tracking error components (which were defined in section 4.3) for experiments 3A to 3D are shown in figures 7.4.1 to 7.4.4 respectively. Vibration-correlated error is only available for the 4 Hz vibration conditions as it was necessary to limit the data sampling rate to 20 samples per second (limiting the spectral analysis to a 10 Hz bandwidth). As in the previous experiment remnant was divided into two frequency bands: 0 to 1 Hz and 1 to 3 Hz.

Separate 6 x 2 mixed effects analyses of variance with randomized blocks were performed for each of the components of error variance (mean square error) from each of the sub-experiments. ANOVA summary tables for experiments 3A to 3D are given in tables 7.4.1 to 7.4.4 respectively. Note that ANOVA tables are only given where at least one treatment effect was significant. Tests of simple main effects and trend analyses, using orthogonal contrasts, for the effect of vibration level at each frequency, were performed for each case where the main or interaction effects were significant. Details of these tests are given in the respective ANOVA summary tables. There were significant overall increases in both total remnant and in 1 - 3 Hz remnant with the isotonic stick control during 4 Hz vibration of both the control and the seat, and with the isometric control during 4 Hz vibration of the seat only. There were also significant linear trends in all of these measures with increasing levels of vibration and also in 1 - 3 Hz remnant with 4 Hz vibration of the isometric control stick. 16 Hz control vibration resulted in significant increases and linear trends in total remnant and 1 - 3 Hz remnant with the isometric stick (although Dunnett's t tests showed that the increase was only significant at the highest vibration level) and a significant linear trend in 1 - 3 Hz remnant with the isotonic stick. No significant effects of 16 Hz whole-body vibration were observed with either control. Input-correlated error was not significantly affected by any of the vibration conditions with either control. The overall effect of vibration on total error (excluding vibration-correlated error) was significant only for the isotonic stick with 4 Hz whole-body vibration, however there were significant linear trends with increasing levels of 4 Hz whole-body vibration with both controls.

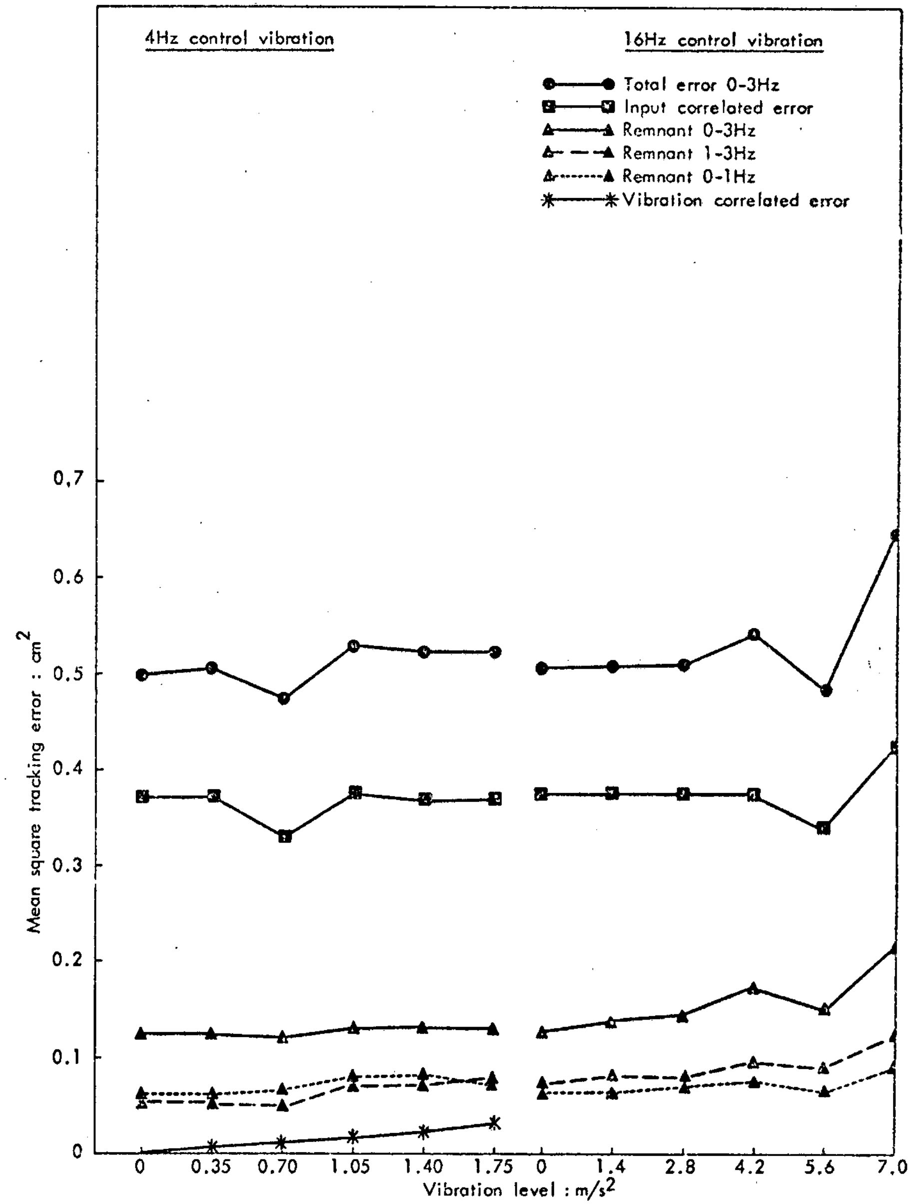
As in experiment two, 4 Hz vibration was observed to result in significant increases in remnant in the 1 - 3 Hz frequency band but not

FIG 7.4.1.



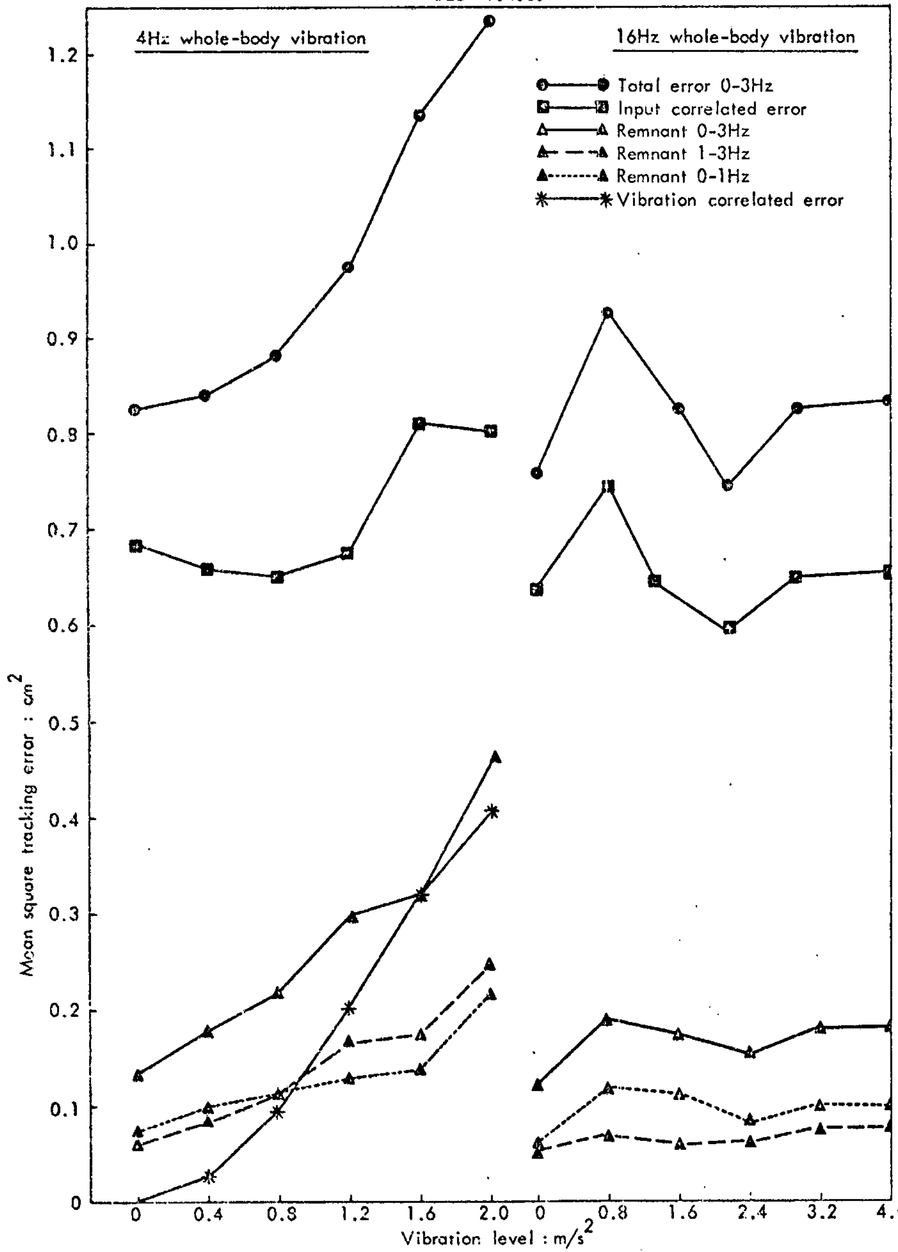
ISOTONIC STICK : MEAN PERFORMANCE AS A FUNCTION OF VIBRATION LEVEL.

FIG 7.4.2.



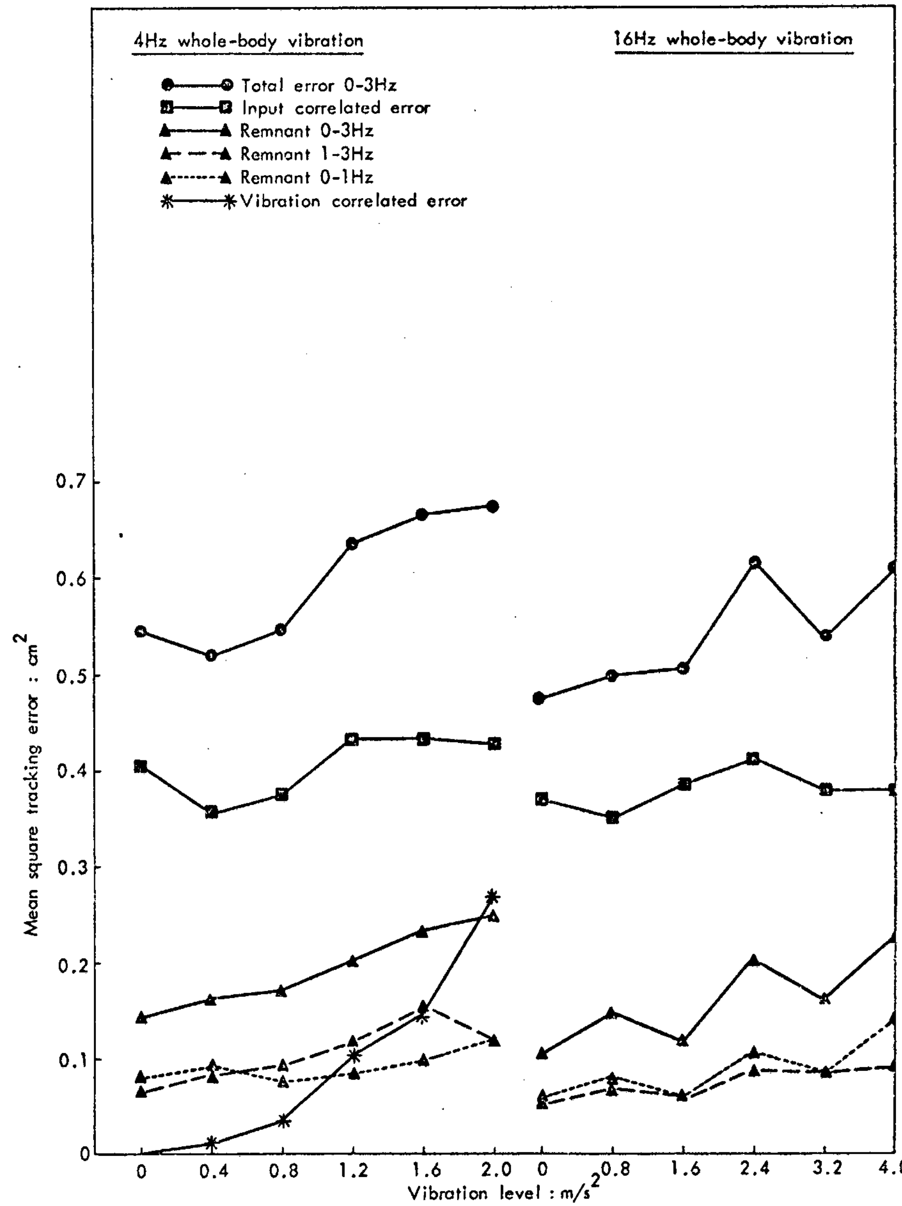
ISOMETRIC STICK : MEAN PERFORMANCE AS A FUNCTION OF VIBRATION LEVEL.

FIG 7.4.3.



ISOTONIC STICK : MEAN PERFORMANCE AS A FUNCTION OF VIBRATION LEVEL.

FIG 7.4.4.



ISOMETRIC STICK : MEAN PERFORMANCE AS A FUNCTION OF VIBRATION LEVEL.

TABLE 7.4.1. ANALYSIS OF VARIANCE TABLES - EXPERIMENT 3A SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, V = Vibration levels, F = Vibration frequency.

(a) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.13158E 7	3	0.43859E 6	19.47	0.01
V	0.54347E 6	5	0.10869E 6	3.38	0.05
F	0.22318E 6	1	0.22318E 6	11.73	0.05
V x F	0.20126E 6	5	40251.2003	2.95	0.05
RESIDUAL	0.74312E 6	33	22518.6978		
V x S	0.48150E 6	15	32099.9341		
F x S	57076.0011	3	19025.3345		
V x F x S	0.20454E 6	15	13636.1344		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	0.67735E 6	5	0.13547E 6	4.22	0.05
LINEAR REG.	0.55545E 6	1	0.55545E 6	17.30	0.01
QUADRATIC	10800.6702	1	10800.6702	0.33	ns
NONLINEAR	0.12190E 6	4	30475.39113	0.94	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 82.00					
V at F2	67378.5021	5	13475.7004	0.41	ns
LINEAR REG.	33704.2315	1	33704.2315	1.04	ns
QUADRATIC	2010.9642	1	2010.9642	0.06	ns
NONLINEAR	33674.2706	4	8418.5676	0.26	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 50.02					

(b) MEAN SQUARE REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.21401E 6	3	71335.6662	44.20	0.01
V	0.12110E 6	5	24219.5005	17.97	0.01
F	52602.5011	1	52602.5010	8.88	0.1
V x F	32780.2511	5	6556.0499	6.44	0.01
RESIDUAL	53253.7510	33	1613.7500		
V x S	20214.0005	15	1347.6000		
F x S	17770.2505	3	5923.4166		
V x F x S	15269.5002	15	1017.9666		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	0.13716E 6	5	27432.0512	20.35	0.01
LINEAR REG.	0.13302E 6	1	0.13302E 6	98.71	0.01
QUADRATIC	1384.2976	1	1384.2976	1.02	ns
NONLINEAR	4136.6563	4	1034.1640	0.76	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 96.98407					
V at F2	16717.5005	5	3343.5000	2.48	0.1
LINEAR REG.	14257.1574	1	14257.1574	10.57	0.01
QUADRATIC	330.0268	1	330.0268	0.24	ns
NONLINEAR	2460.3428	4	615.0857	0.45	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 85.28283					

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.2. ANALYSIS OF VARIANCE TABLES - EXPERIMENT 3B
MEAN SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, V = Vibration level,
F = Vibration frequency.

(a) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	55859.5011	3	18619.8345	3.93	0.05
V	0.11495E 6	5	22989.5005	3.73	0.05
F	21168.0005	1	21168.0005	9.71	0.05
V x F	34556.0011	5	6911.2003	1.80	ns
RESIDUAL	0.15619E 6	33	4733.0758		
V x S	92240.5021	15	6149.3668		
F x S	6539.5001	3	2179.8333		
V x F x S	57411.0010	15	3827.3999		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	35576.7510	5	7115.3502	1.15	ns
LINEAR REG.	23552.2290	1	23552.2290	3.83	0.1
QUADRATIC	324.1071	1	324.1071	0.05	ns
NONLINEAR	12024.5217	4	3006.1304	0.48	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 66.20118					
V at F2	0.11393E 6	5	22785.3501	3.70	0.05
LINEAR REG.	73159.5568	1	73159.5568	11.89	0.01
QUADRATIC	7609.5269	1	7609.5269	1.23	ns
NONLINEAR	40767.1964	4	10191.7990	1.65	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 64.21631					

(b) MEAN SQUARE REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	77455.1271	3	25818.3755	24.46	0.01
V	20600.6255	5	4120.1251	5.07	0.01
F	99.2500	1	99.2500	0.07	ns
V x F	6014.3751	5	1202.8750	0.95	ns
RESIDUAL	34829.1260	33	1055.4280		
V x S	12170.2502	15	811.3499		
F x S	3746.3750	3	1248.7916		
V x F x S	18912.5005	15	1260.8334		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	8167.1876	5	1633.4375	2.01	ns
LINEAR REG.	5661.0035	1	5661.0035	6.97	0.05
QUADRATIC	38.0029	1	38.0029	0.04	ns
NONLINEAR	2506.1841	4	626.5460	0.77	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 69.31399					
V at F2	18447.8130	5	3689.5625	4.54	0.05
LINEAR REG.	13804.1291	1	13804.1291	17.01	0.01
QUADRATIC	269.6458	1	269.6458	0.33	ns
NONLINEAR	4643.6837	4	1160.9209	1.43	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 74.82800					

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.3. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 3C MEAN SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, V = Vibration level, F = Vibration frequency.

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.15288E 8	3	0.50961E 7	37.27	0.01
V	0.22017E 7	5	0.44033E 6	2.39	0.1
F	0.20164E 7	1	0.20164E 7	12.44	0.05
V x F	0.22600E 7	5	0.45201E 6	5.35	0.01
RESIDUAL	0.45114E 7	33	0.13671E 6		
V x S	0.27586E 7	15	0.18390E 6		
F x S	0.48600E 6	3	0.16200E 6		
V x F x S	0.12668E 7	15	84456.5333		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	0.38728E 7	5	0.77455E 6	4.21	0.05
LINEAR REG.	0.35568E 7	1	0.35568E 7	19.34	0.01
QUADRATIC	0.28970E 6	1	0.28970E 6	1.57	ns
NONLINEAR	0.31594E 6	4	78985.0020	0.42	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 91.84198					
V at F2	0.58894E 6	5	0.11779E 6	0.64	ns
LINEAR REG.	35.7142	1	35.7142	0.00	ns
QUADRATIC	3114.6697	1	3114.6697	0.01	ns
NONLINEAR	0.58891E 6	4	0.14723E 6	0.80	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 0.00606					

(b) MEAN SQUARE REMNANT, 0-3Hz

SOURCE	SS	DF	MS	F RATIO	p
S	0.64786E 6	3	0.21595E 6	5.33	0.01
V	0.10364E 7	5	0.20727E 6	4.97	0.01
F	0.77343E 6	1	0.77343E 6	8.91	0.1
V x F	0.69626E 6	5	0.13925E 6	4.64	0.01
RESIDUAL	0.13350E 7	33	40453.6065		
V x S	0.62514E 6	15	41675.9347		
F x S	0.26017E 6	3	86723.6662		
V x F x S	0.44966E 6	15	29977.1997		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	0.16444E 7	5	0.32889E 6	7.89	0.01
LINEAR REG.	0.15404E 7	1	0.15404E 7	36.96	0.01
QUADRATIC	42908.3604	1	42908.3604	1.02	ns
NONLINEAR	0.10405E 6	4	26012.9380	0.62	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 93.67253					
V at F2	88173.0021	5	17634.6001	0.42	ns
LINEAR REG.	23828.1763	1	23828.1763	0.57	ns
QUARDATIC	10407.4407	1	10407.4407	0.24	ns
NONLINEAR	64344.8253	4	16086.2063	0.38	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 27.02434					

(c) MEAN SQUARE REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	92493.7522	3	30831.2505	5.29	0.01
V	0.32774E 6	5	65548.6038	12.06	0.01
F	0.35260E 6	1	0.35260E 6	26.27	0.05
V x F	0.20731E 6	5	41462.6026	8.81	0.01
RESIDUAL	0.19231E 6	33	5827.4620		
V x S	81485.2522	15	5432.3502		
F x S	40258.7511	3	13419.5832		
V x F x S	70562.2521	15	4704.1500		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	0.52472E 6	5	0.10494E 6	19.31	0.01
LINEAR REG.	0.50312E 6	1	0.50312E 6	92.61	0.01
QUADRATIC	5900.1905	1	5900.1905	1.08	ns
NONLINEAR	21603.2817	4	5400.8204	0.99	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 95.88291					
V at F2	10334.1877	5	2066.8374	0.38	ns
LINEAR REG.	7854.6036	1	7854.6036	1.44	ns
QUADRATIC	80.0476	1	80.0476	0.01	ns
NONLINEAR	2479.5840	4	619.8960	0.11	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 76.00601					

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.4. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 3D
MEAN SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, V = Vibration level, F = Vibration frequency

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.38075E 7	3	0.12692E 7	15.87	0.01
V	0.92390E 6	5	0.18478E 6	2.55	0.01
F	0.24169E 6	1	0.24169E 6	1.60	ns
V x F	93920.0022	5	18784.0005	0.25	ns
RESIDUAL	0.26388E 7	33	79964.8537		
V x S	0.10834E 7	15	72224.0022		
F x S	0.45062E 6	3	0.15021E 6		
V x F x S	0.11049E 7	15	73657.6035		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	0.56097E 6	5	0.11219E 6	1.55	ns
LINEAR REG.	0.46528E 6	1	0.46528E 6	6.44	0.05
QUADRATIC	10329.6702	1	10329.6702	0.14	ns
NONLINEAR	95688.4396	4	23922.1098	0.33	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 82.94238					

SOURCE	SS	DF	MS	F RATIO	p
V at F2	0.45685E 6	5	91370.4004	1.26	ns
LINEAR REG.	0.29940E 6	1	0.29940E 6	4.14	0.1
QUADRATIC	4364.6461	1	4364.6461	0.06	ns
NONLINEAR	0.15745E 6	4	39362.7041	0.54	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 65.53571

(b) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.34941E 6	3	0.11647E 6	4.98	0.01
V	0.44306E 6	5	88612.6037	3.51	0.05
F	75203.0022	1	75208.0021	3.62	ns
V x F	44072.0011	5	8814.4006	0.40	ns
RESIDUAL	0.77039E 6	33	23345.0610		
V x S	0.37765E 6	15	25176.8013		
F x S	62202.0011	3	20734.0005		
V x F x S	0.33053E 6	15	22035.4673		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	0.19880E 6	5	39759.6025	1.57	ns
LINEAR REG.	0.19173E 6	1	0.19173E 6	7.61	0.05
QUADRATIC	804.7619	1	804.7619	0.03	ns
NONLINEAR	7066.1095	4	1766.5273	0.07	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 96.44559

V at F2	0.28834E 6	5	57667.2002	2.29	0.1
LINEAR REG.	0.19615E 6	1	0.19615E 6	7.79	0.05
QUADRATIC	1025.5029	1	1025.5029	0.04	ns
NONLINEAR	92182.7209	4	23045.6801	0.91	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 68.02941

(c) MEAN SQUARE REMNANT, 1-3Hz.

SOURCE	SS DF	DF	MS	F RATIO	p
S	0.13466E 6	3	44885.0010	19.78	0.01
V	98023.0022	5	19604.6001	5.41	0.01
F	54270.7510	1	54270.7510	28.88	0.05
V x F	10345.5002	5	2069.1001	2.07	ns
RESIDUAL	74870.5022	33	2268.8030		
V x S	54297.7510	15	3619.8501		
F x S	5637.0001	3	1879.0000		
V x F x S	14935.7502	15	995.7166		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	77571.7521	5	15514.3498	4.28	0.05
LINEAR REG.	65209.0362	1	65209.0362	18.01	0.01
QUADRATIC	5783.4405	1	5783.4405	1.59	ns
NONLINEAR	12362.7151	4	3090.6787	0.85	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 84.06287

V at F2	30796.6880	5	6159.3375	1.70	ns
LINEAR REG.	21620.4321	1	21630.4321	5.97	0.05
QUADRATIC	933.3333	1	933.3333	0.25	ns
NONLINEAR	9166.2561	4	2291.5640	0.63	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 70.23623

*note: F1 = 4Hz, F2 = 16Hz.

in the 0-1Hz band. However inspection of figures 7.4.1 to 7.4.4 reveals that although the increases in 0-1Hz remnant were less consistent, and not statistically significant, the mean increase was of the same order as the increase in 1-3Hz remnant. Mean power spectra of the tracking error components during the six levels of 4Hz whole-body vibration are shown in figure 7.4.5 for the isotonic stick and in figure 7.4.6 for the isometric stick. Mean power spectra for the isometric stick are also shown in figure 7.4.7, during two levels of 16Hz control vibration. It can be seen from these spectra that the remnant, during each of the vibration conditions, was a broadband process, having a relatively flat spectrum extending from very low frequencies up to about 1.6Hz, followed by a gradual attenuation. However the largest increase in remnant activity during the 4Hz vibration conditions appears to occur in the 1-2Hz range, consistent with the observations in section 6.7.

The mean error variance components from experiment 3E are shown in the profile in figure 7.4.8. Separate 4 x 2, mixed effects analyses of variance with randomnized blocks were performed on each component, and ANOVA summary tables are given in tables 7.4.5a to 7.4.5d. The results indicate that artificially induced 4Hz breakthrough to the controlled element in the display resulted in significant increases in remnant and, unlike previous results, in input-correlated error. Also the effect on remnant was significant for both 0-1Hz and 1-3Hz frequency bands. There were no significant differences between controls in any of the remnant measures. The input-correlated error variance was greater with the isotonic control, as was observed in experiment two (due to larger response lags in the transfer function), however this difference only approached statistical significance with $p < 0.1$. There were significant linear trends in all of the remnant measures and in total error (excluding breakthrough), but there were also significant higher-order trends in total error due to the less consistent effects of breakthrough on input-correlated error. Power spectra of the error components for the four levels of 4Hz breakthrough are shown in figure 7.4.9 for the isotonic stick and in figure 7.4.10 for the isometric stick. It can be seen that, for a given level of breakthrough, the mean spectra are very consistent with those in figures 7.4.5 and 7.4.6, for whole-body vibration conditions.

The significant linear trends (and absence from departures from linearity) in the remnant data indicate a high linear correlation between mean square remnant and the r.m.s. level of both 4Hz vibration and breakthrough. It seems more reasonable to expect a

TABLE 7.4.5. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 3E MEAN SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, B = Level of artificial breakthrough, C = Control.

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.16826E 7	3	0.56086E 6	12.78	0.01
B	0.23799E 7	3	0.79331E 6	107.63	0.01
C	0.28662E 7	1	0.28662E 7	14.86	0.05
B x C	38096.0011	3	12698.6672	0.41	ns
RESIDUAL	0.92105E 6	21	43859.4307		
B x S	66336.0022	9	7370.6666		
C x S	0.57834E 6	3	0.19278E 6		
B x C x S	0.27638E 6	9	30708.4458		
Simple Main Effects and Orthogonal Trend Analyses:					
B at C1	0.10939E 7	3	0.36462E 6	49.46	0.01
LINEAR REG.	0.93075E 6	1	0.93075E 6	126.27	0.01
QUADRATIC	0.12338E 6	1	0.12338E 6	16.73	0.01
NONLINEAR	0.16312E 6	2	81559.2520	11.06	0.01
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 85.08787					
B at C2	0.13242E 7	3	0.44139E 6	59.88	0.01
LINEAR REG.	0.12025E 7	1	0.12025E 7	163.14	0.01
QUADRATIC	19740.2505	1	19740.2505	2.67	ns
NONLINEAR	0.12170E 6	2	60849.6260	8.25	0.01
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 90.80932					

(b) MEAN SQUARE INPUT-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.15927E 7	3	0.53089E 6	9.32	0.01
B	0.41717E 6	3	0.13906E 6	7.79	0.01
C	0.21935E 7	1	0.21935E 7	7.19	0.1
B x C	69996.0022	3	23332.0005	1.72	ns
RESIDUAL	0.11961E 7	21	56957.1456		
B x S	0.16059E 6	9	17843.1118		
C x S	0.91410E 6	3	0.30470E 6		
B x C x S	0.12141E 6	9	13490.2229		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	57292.0011	3	19097.3345	0.94	ns
B	0.10965E 7	3	0.36549E 6	20.92	0.01
C	48050.0011	1	48050.0010	3.49	ns
B x C	55573.0011	3	18524.3345	0.74	ns
RESIDUAL	0.42341E 6	21	20162.2857		
B x S	0.15720E 6	9	17466.8892		
C x S	41251.0011	3	13750.3332		
B x C x S	0.22495E 6	9	24994.8891		

Simple Main Effects and Orthogonal Trend Analyses:

SOURCE	SS	DF	MS	F RATIO	p
B at C1	0.73549E 6	3	0.24516E 6	14.03	0.01
LINEAR REG.	0.66485E 6	1	0.66485E 6	38.06	0.01
QUADRATIC	30189.0630	1	30189.0630	1.72	ns
NONLINEAR	70644.3772	2	35322.1885	2.02	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 90.39496					
B at C2	0.41656E 6	3	0.13885E 6	7.94	0.01
LINEAR REG.	0.39974E 6	1	0.39974E 6	22.88	0.01
QUADRATIC	11935.5627	1	11935.5627	0.68	ns
NONLINEAR	16818.6880	2	8409.3440	0.48	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 95.96245					

(d) MEAN SQUARE REMNANT, 0-1Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	89758.5022	3	29919.5005	5.80	0.01
B	0.26563E 6	3	88542.5881	35.70	0.01
C	11819.5002	1	11819.5002	2.88	ns
B x C	16594.2505	3	5531.4166	0.67	ns
RESIDUAL	0.10823E 6	21	5153.7979		
B x S	22319.0005	9	2479.8889		
C x S	12307.0002	3	4102.3336		
B x C x S	73603.7521	9	8178.1944		

Simple Main Effects and Orthogonal Trend Analyses:

SOURCE	SS	DF	MS	F RATIO	p
B at C1	0.14447E 6	3	48157.7510	19.41	0.01
LINEAR REG.	0.13497E 6	1	0.13497E 6	54.42	0.01
QUADRATIC	8464.0002	1	8464.0002	3.41	ns
NONLINEAR	9500.7971	2	4750.3985	1.91	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 93.4238					
B at C2	0.13775E 6	3	45916.2314	18.51	0.01
LINEAR REG.	0.11943E 6	1	0.11943E 6	48.15	0.01
QUADRATIC	410.0625	1	410.0625	0.16	ns
NONLINEAR	18320.1724	2	9160.0861	3.69	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 86.70029					

(e) MEAN SQUARE REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	87390.7522	3	29130.2505	3.21	0.05
B	0.30380E 6	3	0.10127E 6	8.14	0.01
C	10878.0002	1	10878.0002	1.31	ns
B x C	16698.5005	3	5566.1666	0.94	ns
RESIDUAL	0.19005E 6	21	9050.2024		
B x S	0.11193E 6	9	12437.0832		
C x S	24841.5005	3	8280.5002		
B x C x S	53279.0010	9	5919.8888		

Simple Main Effects and Orthogonal Trend Analyses:

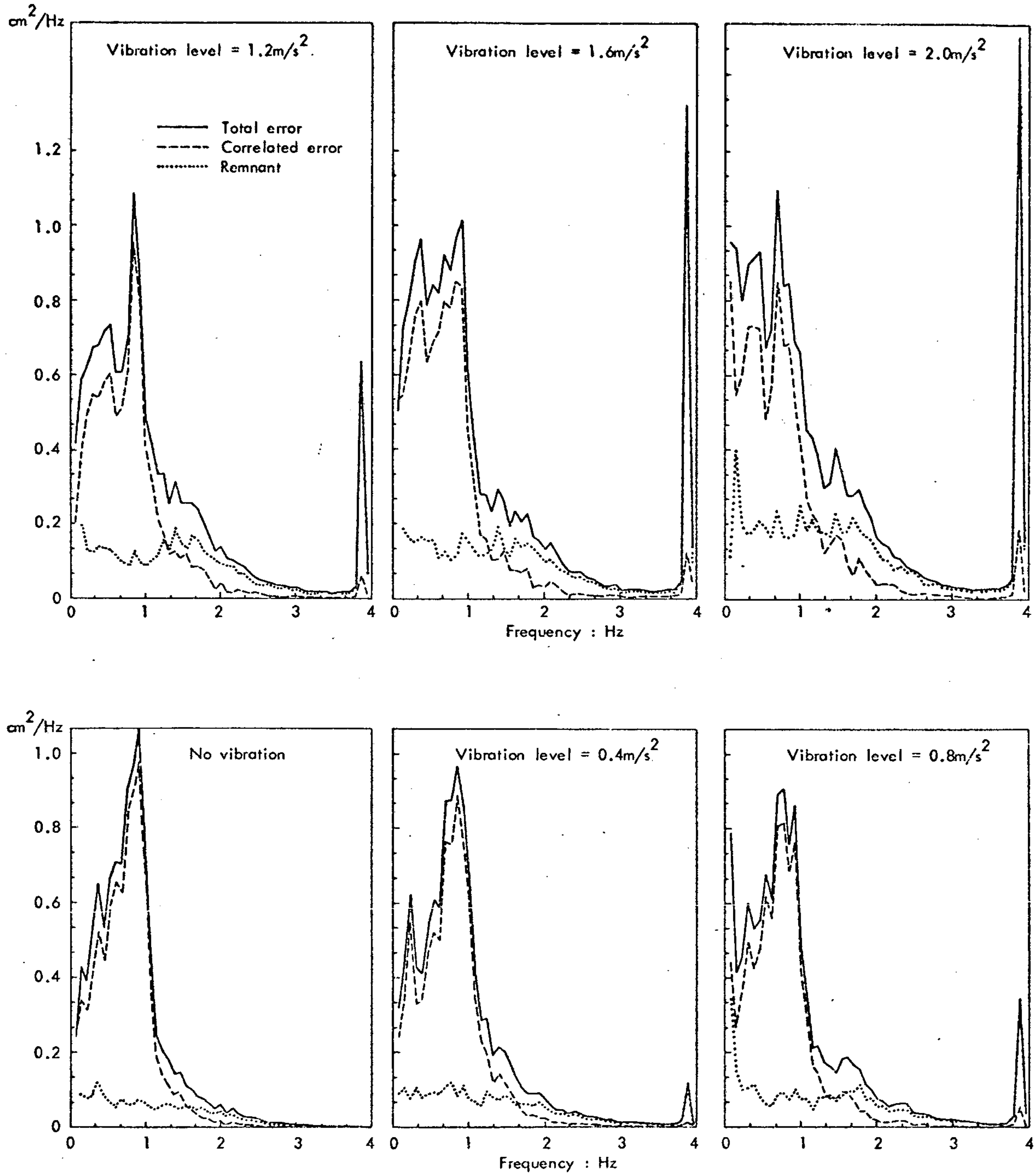
SOURCE	SS	DF	MS	F RATIO	p
B at C1	0.22624E 6	3	75414.1660	6.06	0.01
LINEAR REG.	0.19642E 6	1	0.19642E 6	15.79	0.01
QUADRATIC	5256.2501	1	5256.2501	0.42	ns
NONLINEAR	29826.2974	2	14913.1486	1.19	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 86.81667					

SOURCE	SS	DF	MS	F RATIO	p
B at C2	94258.2521	3	31419.4165	2.52	0.1
LINEAR REG.	82304.4552	1	82304.4552	6.61	0.05
QUADRATIC	7921.0001	1	7921.0001	0.63	ns
NONLINEAR	11953.7971	2	5976.8985	0.48	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 87.31804

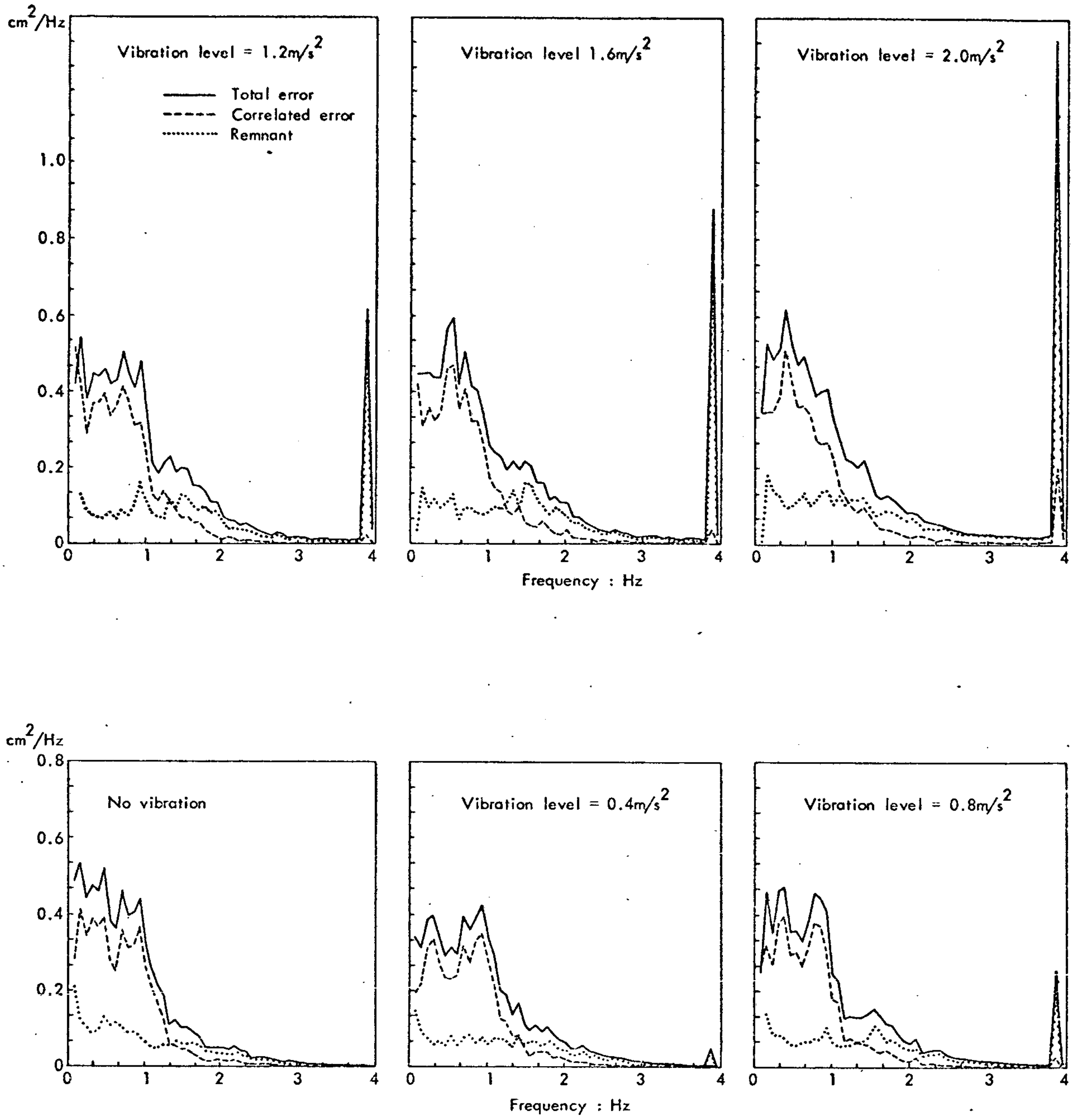
*note: C1 = isotonic stick, C2 = isometric stick.

FIG 7.4.5.



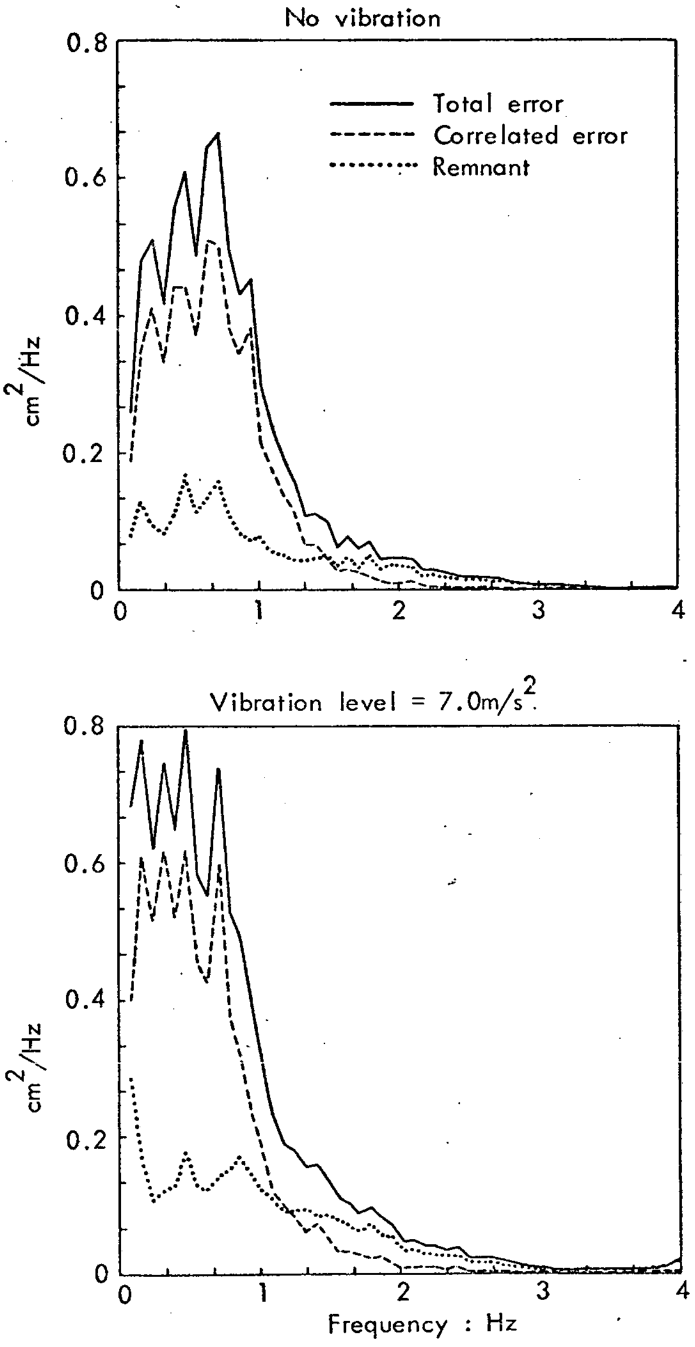
MEAN POWER SPECTRA OF TRACKING ERROR FROM EXPERIMENT 4C : ISOTONIC STICK
4Hz WHOLE - BODY VIBRATION.

FIG 7.4.6.



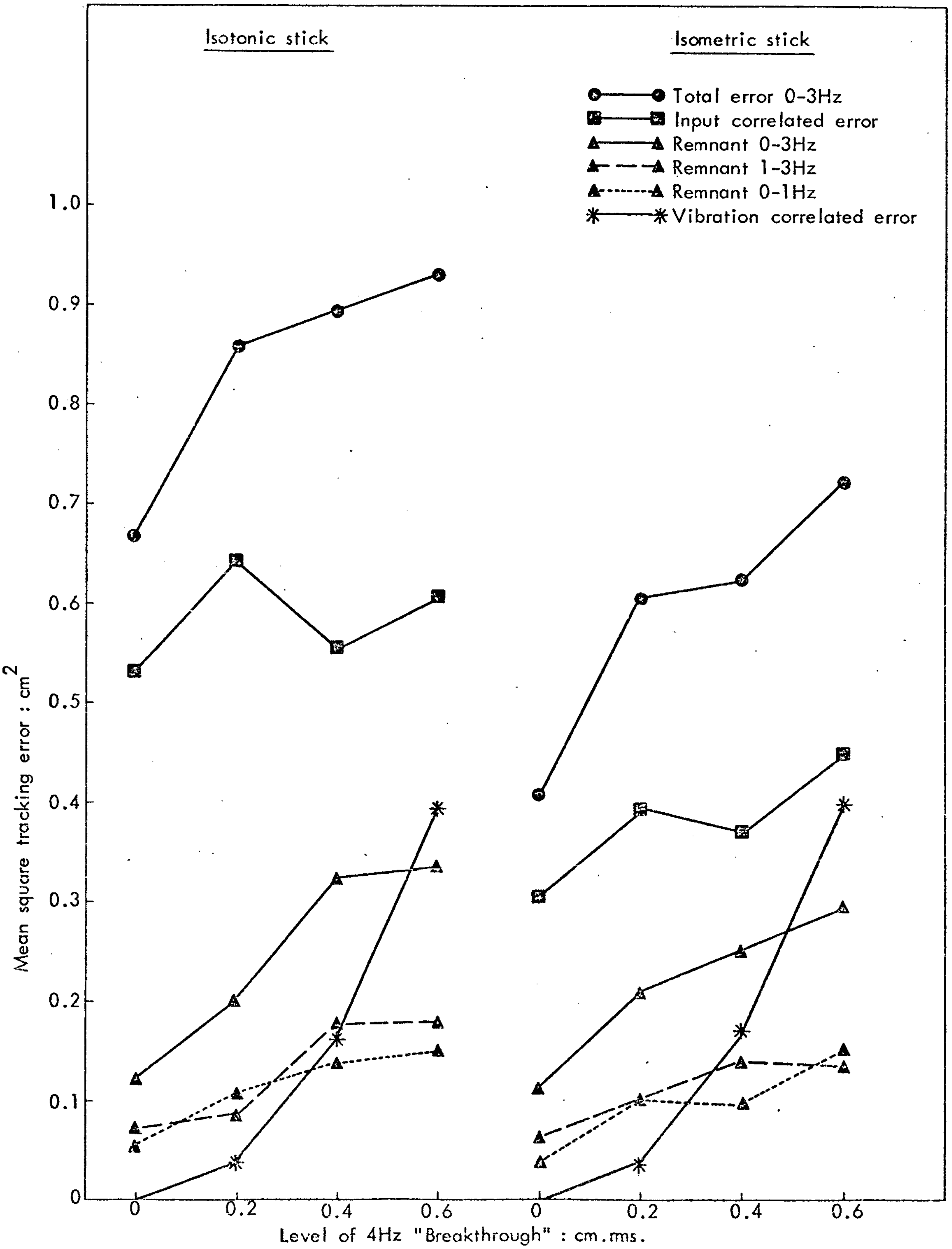
MEAN POWER SPECTRA OF TRACKING ERROR : ISOMETRIC STICK WITH 4Hz WHOLE-BODY VIBRATION.

FIG 7.4.7.



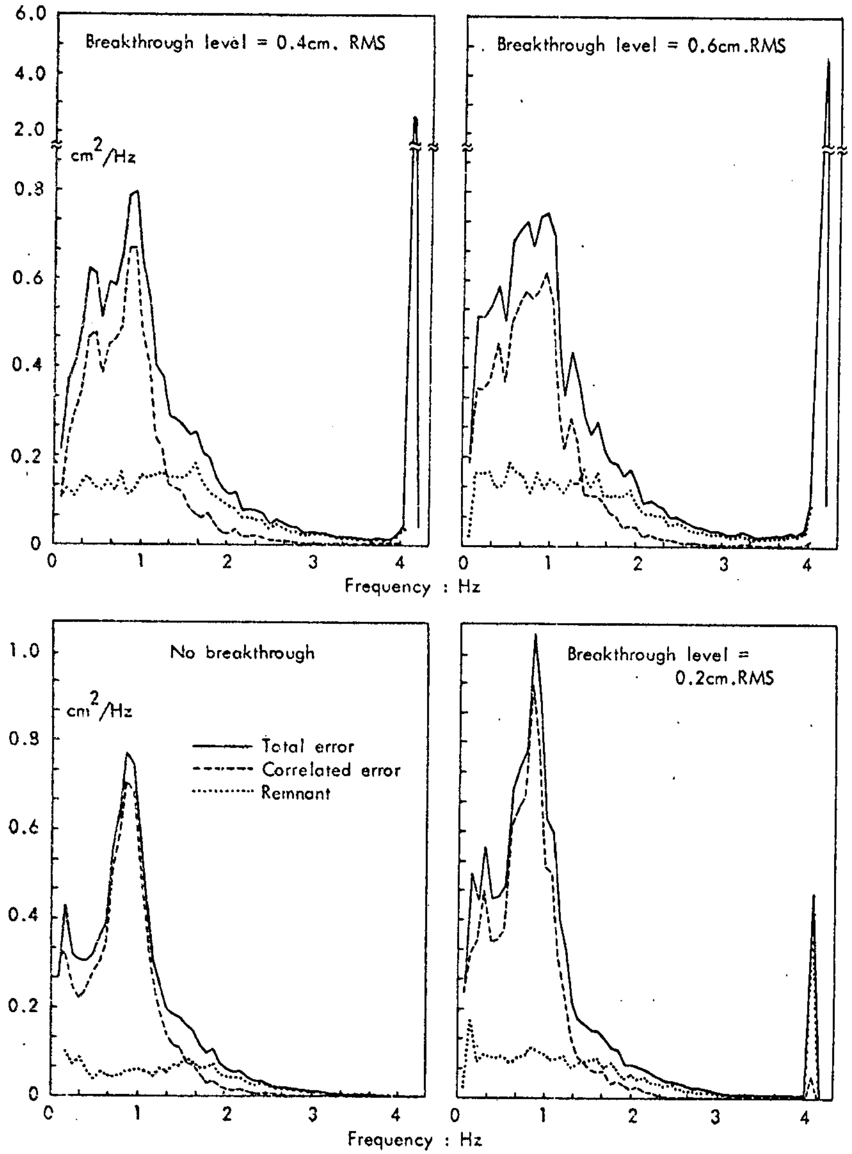
MEAN POWER SPECTRA OF TRACKING ERROR :
ISOMETRIC STICK WITH 16Hz CONTROL VIBRATION

FIG 7.4.8.



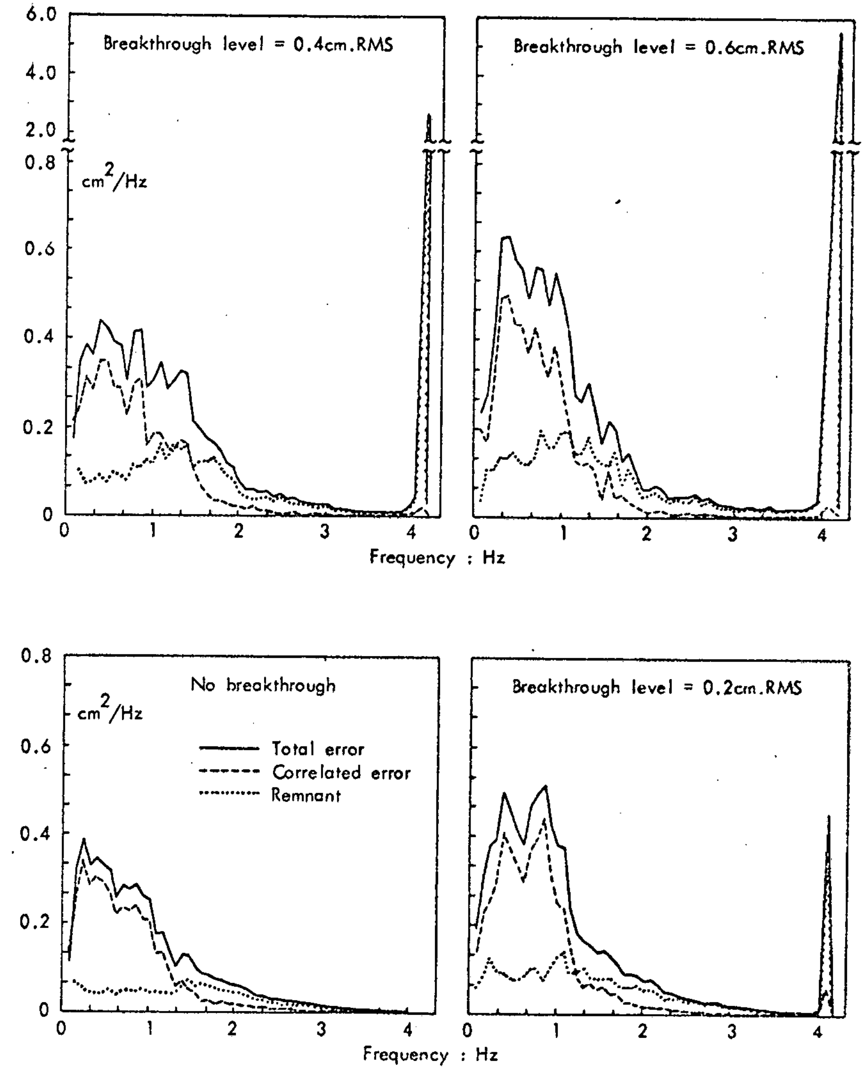
TRACKING IN STATIC CONDITIONS WITH APPARENT 4Hz BREAKTHROUGH TO CONTROLLED ELEMENT.

FIG 7.4.9.



MEAN POWER SPECTRA OF TRACKING ERROR : ISOTONIC STICK IN STATIC CONDITIONS, WITH 4Hz DISTURBANCE OF CONTROLLED ELEMENT.

FIG 7.4.10.



MEAN POWER SPECTRA OF TRACKING ERROR : ISOMETRIC STICK IN STATIC CONDITIONS, WITH 4Hz DISTURBANCE OF CONTROLLED ELEMENT.

linear relationship between r.m.s. vibration level and r.m.s. error rather than mean square error. Kelley (1969) has suggested that the most reliable estimate of error dispersion is r.m.s. error. Providing the time-history of the tracking error has a distribution which is Gaussian, the r.m.s. error has the least relative sampling error compared with other measures of dispersion and itself has a distribution which is approximately Gaussian. Up to this point all of the error measures we have used have been based on the variance or mean square value of the error distributions. Although this procedure has the advantage that the variances of the various error components are additive, squaring the error will increase the length of the tail of the distribution. Therefore the danger exists that mean square error measures may be less compatible with parametric statistical tests than r.m.s. error. To determine whether the interpretation of the results was biased by the choice of scoring method, the analyses of variance were repeated on square-root transforms of the error components. It can be seen from a comparison of the ANOVA summary tables in tables 7.4.6 to 7.4.10 with those based on mean square error scores in tables 7.4.1 to 7.4.5 that the significance levels of the main effects are hardly affected and in no case would lead to different interpretation. Trend analyses were also repeated on the square-root transformations of the mean-square errors. Again, only linear trend components were evident, but there was a general increase in the proportion of the variance which could be accounted for by the linear trends (in most cases this exceeded 90%).

If the increase in remnant is dependent entirely on the level of vibration-correlated activity of the controlled element on the display, as was hypothesized earlier, there should be a constant relationship between remnant and vibration-correlated error across vibration conditions and controls. Linear regression equations and correlation coefficients describing the relationship between r.m.s. remnant (in two frequency bands) and r.m.s. vibration-correlated error are shown in table 7.4.11. None of the regression slopes (for a given remnant bandwidth) are significantly different from the others, apart from the 0 - 3 Hz remnant in experiment 3B (isometric stick and control vibration).

TABLE 7.4.6. ANALYSIS OF VARIANCE TABLES - EXPERIMENT 3A
R.M.S. TRACKING ERROR MEASURES.

Treatments: S = Subjects, V = Vibration levels,
F = Vibration frequency.

(a) R.M.S. REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	674.9179	3	224.9726	28.78	0.01
V	217.8066	5	43.5613	3.61	0.05
F	81.5546	1	81.5546	19.58	0.05
V x F	67.9746	5	13.5949	3.16	0.05
RESIDUAL	257.9531	33	7.8167		
V x S	180.9550	15	12.0636		
F x S	12.4921	3	4.1640		
V x F x S	64.5058	15	4.3003		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	249.7812	5	49.9562	4.14	0.05
LINEAR REG.	211.8217	1	211.8217	17.55	0.01
QUADRATIC	1.7428	1	1.7428	0.14	ns
NONLINEAR	37.9595	4	9.4898	0.78	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 84.80289

V at F2	36.0019	5	7.2003	0.59	ns
LINEAR REG.	18.8949	1	18.8949	1.56	ns
QUADRATIC	1.0853	1	1.0853	0.08	ns
NONLINEAR	17.1070	4	4.2767	0.35	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 52.48300

(b) R.M.S. REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	207.2089	3	69.0696	57.01	0.01
V	109.7597	5	21.9519	19.66	0.05
F	45.7744	1	45.7744	10.38	0.05
V x F	24.5537	5	4.9107	7.36	0.05
RESIDUAL	39.9765	33	1.2114		
V x S	16.7421	15	1.1161		
F x S	13.2294	3	4.4098		
V x F x S	10.0048	15	0.6669		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	115.7900	5	23.1580	20.74	0.01
LINEAR REG.	112.8552	1	112.8552	101.11	0.01
QUADRATIC	0.3783	1	0.3783	0.33	ns
NONLINEAR	2.9348	4	0.7337	0.65	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 97.46539

V at F2	18.3877	5	3.6775	3.29	0.05
LINEAR REG.	16.1306	1	16.1306	14.45	0.01
QUADRATIC	0.3009	1	0.3009	0.26	ns
NONLINEAR	2.2571	4	0.5642	0.50	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 87.72498

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.7. ANALYSIS OF VARIANCE TABLES - EXPERIMENT 3B
R.M.S. TRACKING ERROR MEASURES.

Treatment: S = Subjects, V = Vibration level,
F = Vibration frequency.

(a) R.M.S. REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	35.8339	3	11.9446	4.11	0.05
V	70.0371	5	14.0074	4.82	0.05
F	12.7207	1	12.7207	4.38	0.1
V x F	19.3457	5	3.8691	1.33	ns
RESIDUAL	95.8242	33	2.9037		
V x S	55.2714	15	3.6847		
F x S	4.9882	3	1.6627		
V x F x S	35.5644	15	2.3709		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	25.2714	5	5.0543	1.37	ns
LINEAR REG.	16.2683	1	16.2683	4.41	0.1
QUADRATIC	0.2556	1	0.2556	0.06	ns
NONLINEAR	9.0030	4	2.2507	0.61	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 64.37450					
V at F2	64.1064	5	12.8212	3.47	0.05
LINEAR REG.	39.6725	1	39.6725	10.76	0.01
QUADRATIC	3.3304	1	3.3304	0.90	ns
NONLINEAR	24.4339	4	6.1084	1.65	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 61.88536					

(b) R.M.S. REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	109.1757	3	36.3919	27.20	0.01
V	28.7041	5	5.7408	4.29	0.01
F	0.3525	1	0.3525	0.26	ns
V x F	6.8750	5	1.3750	1.02	ns
RESIDUAL	44.1474	33	1.3378		
V x S	14.5009	15	0.9667		
F x S	4.9638	3	1.6546		
V x F x S	24.6816	15	1.6454		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	12.3667	5	2.4733	2.55	0.1
LINEAR REG.	9.2075	1	9.2075	9.52	0.05
QUADRATIC	0.0837	1	0.0837	0.08	ns
NONLINEAR	3.1591	4	0.7898	0.81	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 74.45412					
V at F2	23.2124	5	4.6424	4.80	0.01
LINEAR REG.	17.4851	1	17.4851	18.08	0.01
QUADRATIC	0.1290	1	0.1290	0.13	ns
NONLINEAR	5.7272	4	1.4318	1.48	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 75.32688					

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.8. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 3C R.M.S. TRACKING ERROR MEASURES.

Treatment: S = Subjects, V = Vibration level, F = Vibration frequency

(a) TOTAL R.M.S. TRACKING ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	1625.5937	3	541.8645	36.68	0.01
V	235.9062	5	47.1812	2.20	ns
F	231.6796	1	231.6796	11.72	0.05
V x F	230.9843	5	46.1968	6.50	0.01
RESIDUAL	487.3984	33	14.7696		
V x S	321.6484	15	21.4432		
F x S	59.2578	3	19.7526		
V x F x S	106.4921	15	7.0994		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	403.8007	5	80.7601	3.76	0.05
LINEAR REG.	377.1970	1	377.1970	17.59	0.01
QUADRATIC	20.9171	1	20.9171	0.97	ns
NONLINEAR	26.6037	4	6.6509	0.31	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 93.41167					
V at F2	71.2070	5	14.2414	0.66	ns
LINEAR REG.	0.0185	1	0.0185	0.01	ns
QUADRATIC	1.5633	1	1.5633	0.07	ns
NONLINEAR	71.1884	4	17.7971	0.82	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 0.02611					

(b) R.M.S. REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	266.8535	3	88.9511	7.39	0.01
V	397.2207	5	79.4441	5.55	0.01
F	291.9902	1	291.9902	11.67	0.05
V x F	220.0390	5	44.0078	6.16	0.01
RESIDUAL	396.6757	33	12.0204		
V x S	214.6484	15	14.3099		
F x S	75.0039	3	25.0013		
V x F x S	107.0214	15	7.1347		
Simple Main Effects and Orthogonal Trend Analyses:					
V at F1	562.5107	5	112.5021	7.86	0.01
LINEAR REG.	546.9016	1	546.9016	38.21	0.01
QUADRATIC	2.8905	1	2.8905	0.20	ns
NONLINEAR	15.6090	4	3.9022	0.27	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 97.22511					
V at F2	54.7500	5	10.9500	0.76	ns
LINEAR REG.	16.2999	1	16.2999	1.13	ns
QUADRATIC	6.2182	1	6.2182	0.43	ns
NONLINEAR	38.4500	4	9.6125	0.67	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 29.77160					

(c) R.M.S. REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	89.5908	3	29.8636	8.98	0.01
V	249.7402	5	49.9480	15.03	0.01
F	295.8759	1	295.8759	89.04	0.05
V x F	133.3203	5	26.6640	8.02	0.01
RESIDUAL	109.6543	33	3.3228		
V x S	41.6484	15	2.7765		
F x S	36.2275	3	12.0758		
V x F x S	31.7773	15	2.1184		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	369.5590	5	73.9118	26.61	0.01
LINEAR REG.	360.5965	1	360.5965	129.87	0.01
QUADRATIC	0.0965	1	0.0965	0.03	ns
NONLINEAR	8.9625	4	2.2406	0.80	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 97.57480

V at F2	12.1479	5	2.4295	0.87	ns
LINEAR REG.	9.1159	1	9.1159	3.28	0.1
QUADRATIC	0.2248	1	0.2248	0.08	ns
NONLINEAR	3.0320	4	0.7580	0.27	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 75.04073

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.9. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 3D R.M.S. TRACKING ERROR MEASURES.

Treatments: S = Subjects, V = Vibration level, F = Vibration frequency

(a) TOTAL R.M.S. ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	691.5156	3	230.5052	17.91	0.01
V	157.2421	5	31.4484	2.89	0.05
F	58.4375	1	58.4375	1.96	ns
V x F	14.3203	5	2.8640	0.24	ns
RESIDUAL	424.6250	33	12.8674		
V x S	162.8828	15	10.8588		
F x S	89.3593	3	29.7864		
V x F x S	172.3828	15	11.4921		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	96.7929	5	19.3585	1.78	ns
LINEAR REG.	80.5281	1	80.5281	7.41	0.05
QUADRATIC	2.2304	1	2.2304	0.20	ns
NONLINEAR	16.2647	4	4.0662	0.37	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 83.19630

SOURCE	SS	DF	MS	F RATIO	p
V at F2	74.7636	5	14.9527	1.37	ns
LINEAR REG.	51.6237	1	51.6237	4.75	0.05
QUADRATIC	0.7404	1	0.7404	0.06	ns
NONLINEAR	23.1398	4	5.7849	0.53	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 69.04929

(b) R.M.S. REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	213.4628	3	71.1543	7.10	0.01
V	219.6582	5	43.9316	4.38	0.05
F	64.4511	1	64.4511	6.43	ns
V x F	21.8378	5	4.3675	0.43	ns
RESIDUAL	330.4004	33	10.0121		
V x S	161.1601	15	10.7440		
F x S	36.3828	3	12.1276		
V x F x S	132.8574	15	8.8571		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	100.0595	5	20.0119	1.86	ns
LINEAR REG.	96.8553	1	96.8553	9.01	0.01
QUADRATIC	0.0524	1	0.0524	0.01	ns
NONLINEAR	3.2042	4	0.8010	0.07	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 96.79769

V at F2	141.3603	5	28.2720	2.63	0.1
LINEAR REG.	95.1689	1	95.1689	8.85	0.01
QUADRATIC	0.0001	1	0.0001	0.01	ns
NONLINEAR	46.1914	4	11.5478	1.07	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 67.32362

(c) R.M.S. REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	140.4433	3	46.8144	24.42	0.01
V	101.7646	5	20.3529	6.85	0.01
F	61.4873	1	61.4873	36.15	0.01
V x F	8.8681	5	1.7736	1.95	ns
RESIDUAL	63.2382	33	1.9163		
V x S	44.5605	15	2.9707		
F x S	5.1025	3	1.7008		
V x F x S	13.57422	15	0.9049		

Simple Main Effects and Orthogonal Trend Analyses:

V at F1	74.2285	5	14.8457	4.99	0.01
LINEAR REG.	63.4126	1	63.4126	21.34	0.01
QUADRATIC	6.1967	1	6.1967	2.08	ns
NONLINEAR	10.8158	4	2.7039	0.91	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 85.42899

V at F2	36.4189	5	7.2837	2.45	0.1
LINEAR REG.	25.9190	1	25.9190	8.72	0.01
QUADRATIC	0.8897	1	0.8897	0.29	ns
NONLINEAR	10.4999	4	2.6249	0.88	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 71.16911

*note: F1 = 4Hz, F2 = 16Hz.

TABLE 7.4.10. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 3E R.M.S. TRACKING ERROR MEASURES.

Treatments: S = Subjects, B = Level of artificial breakthrough, C = Control.

(a) TOTAL R.M.S. ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	205.24610	3	68.41537	13.21	0.01
B	364.30860	3	121.43620	125.40	0.01
C	395.50391	1	395.50391	19.56	0.05
B x C	9.05078	3	3.01693	0.69	ns
RESIDUAL	108.69531	21	5.17597		
B x S	8.71484	9	0.96832		
C x S	60.63672	3	20.21224		
B x C x S	39.33984	9	4.37109		
Simple Main Effects and Orthogonal Trend Analyses:					
B at C1	122.42578	3	40.80859	42.14	0.01
LINEAR REG.	105.93762	1	105.93762	109.40	0.01
QUADRATIC	12.59464	1	12.59464	13.00	0.05
NONLINEAR	16.48816	2	8.24408	8.51	0.05
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 86.53212					
B at C2	232.00391	3	77.33463	79.86	0.01
LINEAR REG.	209.02816	1	209.02816	215.86	0.01
QUADRATIC	6.32647	1	6.32647	6.53	0.05
NONLINEAR	22.97575	2	11.48788	11.86	0.01
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 90.09682					

(b) R.M.S. INPUY-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	258.94532	3	86.31510	9.87	0.01
B	88.05469	3	29.35156	9.68	0.01
C	421.26563	1	421.26563	9.56	0.1
B x C	19.03906	3	6.34635	2.35	ns
RESIDUAL	183.62110	21	8.74386		
B x S	27.27344	9	3.03038		
C x S	132.09766	3	44.03255		
B x C x S	24.25000	9	2.69444		

(c) R.M.S. REMNANT, 0-3Hz

SOURCE	SS	DF	MS	F RATIO	p
S	25.62500	3	8.54167	1.05	ns
B	528.34572	3	176.11524	20.25	0.01
C	16.30859	1	16.30859	3.72	ns
B x C	18.85547	3	6.28516	0.71	ns
RESIDUAL	170.37110	21	8.11291		
B x S	78.26172	9	8.69575		
C x S	13.14844	3	4.38281		
B x C x S	78.95899	9	8.77322		

Simple Main Effects and Orthogonal Trend Analyses:

SOURCE	SS	DF	MS	F RATIO	p
B at C1	325.14063	3	108.38021	12.46	0.01
LINEAR REG.	290.17451	1	290.17451	33.36	0.01
QUADRATIC	21.84793	1	21.84793	2.51	ns
NONLINEAR	34.96613	2	17.48306	2.01	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 89.24584					
B at C2	222.05957	3	74.01986	8.51	0.01
LINEAR REG.	206.82088	1	206.82088	23.78	0.01
QUADRATIC	12.05260	1	12.05260	1.38	ns
NONLINEAR	15.23869	2	7.61935	0.87	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 93.13757					

(d) R.M.S. REMNANT, 0-1Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	87.90821	3	29.30273	6.00	0.01
B	308.79591	3	102.93197	25.80	0.01
C	12.23730	1	12.23730	3.65	ns
B x C	14.29492	3	4.76497	0.75	ns
RESIDUAL	102.54688	21	4.88318		
B x S	35.89356	9	3.98817		
C x S	10.05371	3	3.35124		
B x C x S	56.59961	9	6.28885		

Simple Main Effects and Orthogonal Trend Analyses:

SOURCE	SS	DF	MS	F RATIO	p
B at C1	167.11622	3	55.70540	13.96	0.01
LINEAR REG.	148.46946	1	148.46946	37.22	0.01
QUADRATIC	18.05838	1	18.05838	4.52	0.1
NONLINEAR	18.64676	2	9.32338	2.33	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 88.84204					
B at C2	155.96997	3	51.98999	13.03	0.01
LINEAR REG.	134.53357	1	134.53357	33.73	0.01
QUADRATIC	4.55433	1	4.55433	1.14	ns
NONLINEAR	21.43640	2	10.71820	2.68	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 86.25607					

(e) R.M.S. REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	54.89844	3	18.29948	2.91	0.05
B	240.59766	3	80.19922	8.96	0.01
C	4.41992	1	4.41992	0.82	ns
B x C	8.61523	3	2.87174	0.73	ns
RESIDUAL	131.80860	21	6.27660		
B x S	80.48535	9	8.94282		
C x S	16.16113	3	5.38704		
B x C x S	35.16211	9	3.90690		

Simple Main Effects and Orthogonal Trend Analyses:

SOURCE	SS	DF	MS	F RATIO	p
B at C1	163.83301	3	54.61100	6.10	0.05
LINEAR REG.	139.96172	1	139.96172	15.65	0.01
QUADRATIC	7.54239	1	7.54239	0.84	ns
NONLINEAR	23.87129	2	11.93565	1.33	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 85.42950					

SOURCE	SS	DF	MS	F RATIO	p
B at C1	85.38135	3	28.46045	3.18	0.1
LINEAR REG.	75.83684	1	75.83684	8.48	0.05
QUADRATIC	7.84310	1	7.84310	0.87	ns
NONLINEAR	9.54451	2	4.77226	0.53	ns

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 88.82131

*note: C1 = isotonic stick, C2 = isometric stick.

TABLE 7.4.11.

COEFFICIENTS OF THE REGRESSION EQUATION $Sr = a_0 + a_1 . Sv$, WHERE Sr = r.m.s. REMNANT, AND Sv = r.m.s. VIBRATION CORRELATED ERROR.

CONTROL:	ISOTONIC STICK		ISOMETRIC STICK	
REMNANT BANDWIDTH:	0-3 Hz	1-3 Hz	0-3 Hz	1-3 Hz
EXPERIMENT:	3A	3A	3B	3B
CORRELATION COEFFICIENT:	0.90	0.93	0.68	0.85
INTERCEPT, a_0 (cm):	0.37	0.26	0.35	0.21
SLOPE, a_1:	0.79	0.58	0.09	0.35
5% CONFIDENCE LIMIT OF a_1:	0.52	0.31	0.13	0.31
EXPERIMENT:	3C	3C	3D	3D
CORRELATION COEFFICIENT:	0.97	0.98	0.99	0.85
INTERCEPT, a_0 (cm):	0.35	0.23	0.37	0.26
SLOPE, a_1 :	0.45	0.38	0.25	0.22
5% CONFIDENCE LIMIT OF a_1:	0.17	0.10	0.06	0.19
EXPERIMENT:	3E	3E	3E	3E
CORRELATION COEFFICIENT:	0.95	0.94	0.95	0.92
INTERCEPT, a_0 (cm):	0.37	0.26	0.36	0.26
SLOPE, a_1:	0.39	0.29	0.32	0.21
5% CONFIDENCE LIMIT OF a_1:	0.37	0.33	0.31	0.27

7.5. TRANSFER FUNCTION RESULTS:

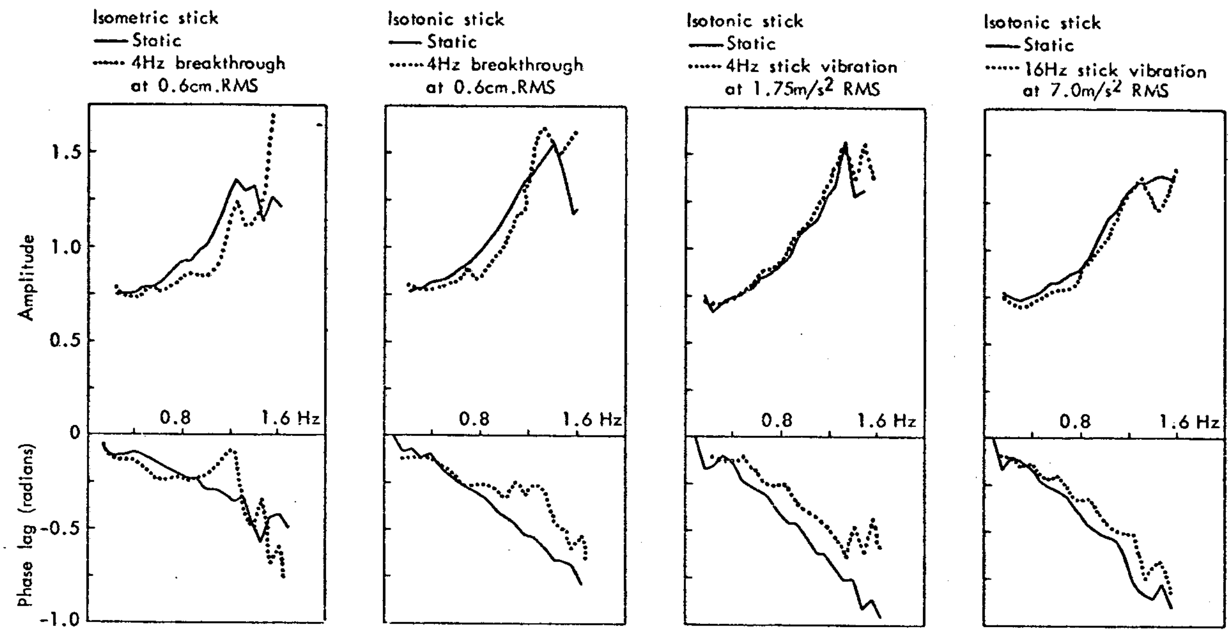
Transfer function data from experiments 3A and 3E are shown in figure 7.5.1. and from experiments 3C and 3D in figure 7.5.2. Transfer function data from experiment 3B was lost due to a computer malfunction. The modulus and phase components of the transfer functions were subjected to separate 2 factor analyses of variance (transfer function frequency and vibration level). Two analyses of variance were performed on the results of each sub-experiment; one for each vibration frequency or, in the case of experiment 3E, control type.

The analyses of variance indicated that significant reductions in phase lags occurred at higher transfer function frequencies during 4 Hz and 16 Hz control vibration and with 4 Hz artificial breakthrough for both controls. These reductions were especially large with the highest levels of artificial breakthrough at transfer function frequencies around 1.2 Hz, which accounts for the significant effect of breakthrough level on input-correlated error. The modulus of the transfer function with the isometric stick was also significantly reduced at frequencies less than 1.5 Hz. There is also evidence of small reductions in phase lags during whole-body vibration in figure 7.5.2., but none of the effects of whole-body vibration were statistically significant.

7.6. DISCUSSION

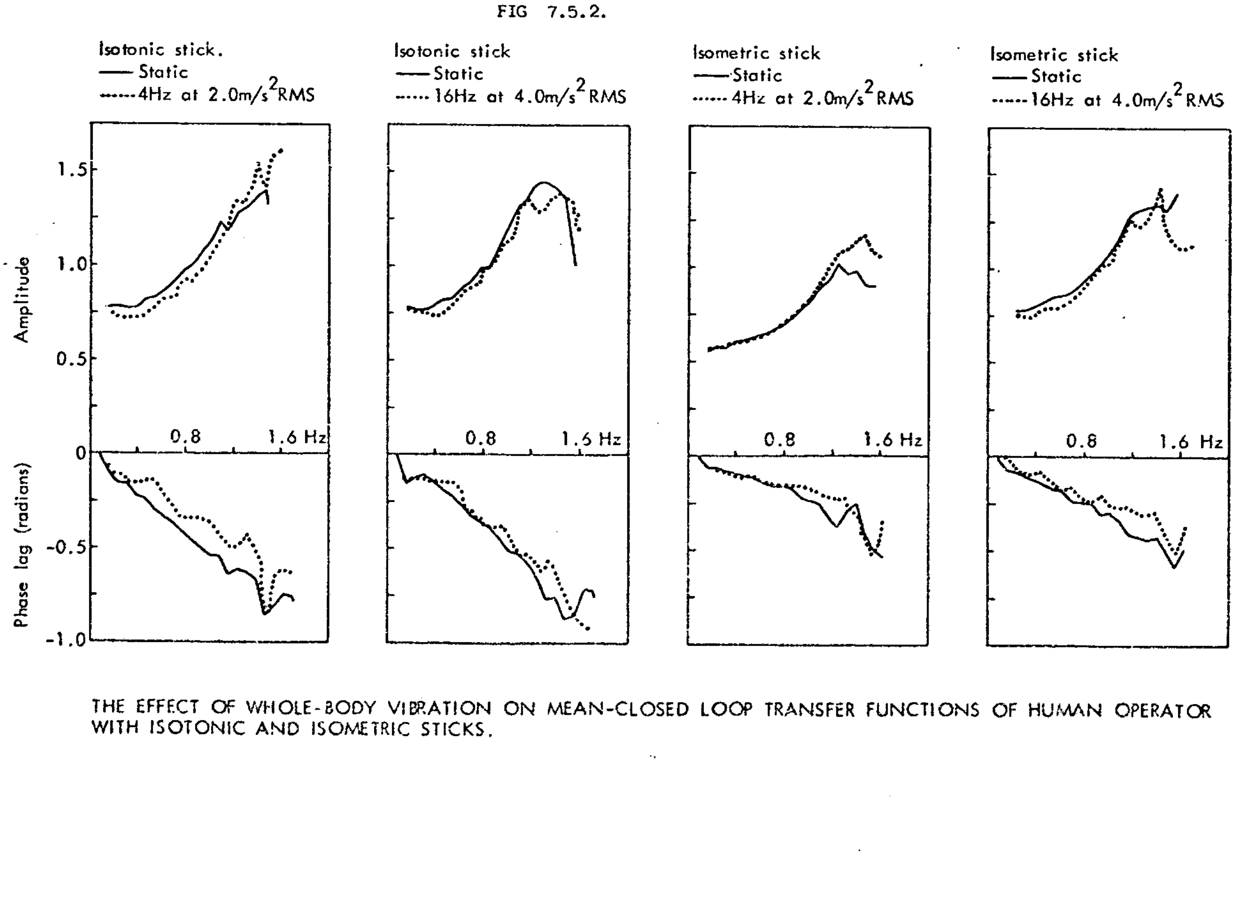
Consistent with previous results, the observed increases in tracking error in the simple pursuit tracking task due to 4 Hz whole-body and control stick vibration are comprised of both vibration-correlated activity and operator-generated noise, or remnant. Also consistent with the results of the previous experiment, the increases in remnant due to 4 Hz vibration include significant amounts of activity beyond the power bandwidth of the forcing function, in the frequency range 1-3 Hz. Inspection of the data suggests that these increases in remnant activity are highly correlated with the amount of vibration-induced activity in the tracking error. It can be seen from table 7.4.11 that artificially inducing similar levels of 4 Hz disturbance in the controlled element to those produced by actual vibration results in similar increases in remnant activity. This leads to the conclusion that the observed increases in remnant due to 4 Hz

FIG 7.5.1.



THE EFFECT OF 'ARTIFICIAL' VIBRATION BREAKTHROUGH AND VIBRATION OF THE CONTROL STICK ON MEAN CLOSED-LOOP TRANSFER FUNCTIONS OF HUMAN OPERATOR.

FIG 7.5.2.



THE EFFECT OF WHOLE-BODY VIBRATION ON MEAN-CLOSED LOOP TRANSFER FUNCTIONS OF HUMAN OPERATOR WITH ISOTONIC AND ISOMETRIC STICKS.

TABLE 7.5.1. EXPERIMENT 3A - TRANSFER FUNCTION MEASURES.

Treatments: S = Subjects, T = Transfer function frequency,
V = Vibration level.

(a) TRANSFER FUNCTION MODULUS WITH 4Hz VIBRATION.

SOURCE	SS	DF	MS	F RATIO	p
S	0.73358	3	0.24453	45.40	0.01
T	15.32361	14	1.09454	104.45	0.01
V	0.05206	5	0.01041	0.92	ns
T x V	0.22180	70	0.00316	0.80	ns
RESIDUAL	1.43790	267	0.00538		
T x S	0.44009	42	0.01047		
V x S	0.16940	15	0.01129		
T x V x S	0.82837	210	0.00394		

(b) TRANSFER FUNCTION MODULUS WITH 16Hz VIBRATION.

SOURCE	SS	DF	MS	F RATIO	p
S	0.88690	3	0.29563	58.80	0.01
T	15.26358	14	1.09026	138.76	0.01
V	0.05093	5	0.01018	0.59	ns
T x V	0.19122	70	0.00273	0.75	ns
RESIDUAL	1.34241	267	0.00502		
T x S	0.32999	42	0.00785		
V x S	0.25510	15	0.01700		
T x V x S	0.75732	210	0.00360		

(c) TRANSFER FUNCTION PHASE LAG WITH 4Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	3.54708	3	1.18236	149.75	0.01
T	9.71880	14	0.69420	22.79	0.01
V	0.25254	5	0.05050	5.48	0.01
T x V	0.27546	70	0.00393	1.19	0.1
RESIDUAL	2.10800	267	0.00789		
T x S	1.27907	42	0.03045		
V x S	0.13815	15	0.00920		
T x V x S	0.69078	210	0.00328		

(d) TRANSFER FUNCTION PHASE LAG WITH 16Hz VIBRATION.

SOURCE	SS	DF	MS	F RATIO	p
S	4.84444	3	1.61481	166.94	0.01
T	9.66549	14	0.69039	16.79	0.01
V	0.19265	5	0.03852	3.77	0.05
T x V	0.29416	70	0.00420	1.25	0.05
RESIDUAL	2.58258	267	0.00967		
T x S	1.72606	42	0.04109		
V x S	0.15318	15	0.01021		
T x V x S	0.70334	210	0.00334		

TABLE 7.5.2. EXPERIMENT 3C - TRANSFER FUNCTION MEASURES

Treatments: S = Subjects, T = Transfer function frequency,
V = Vibration level

(a) TRANSFER FUNCTION MODULUS WITH 4Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	3.15900	3	1.05300	101.29	0.01
T	9.91788	14	0.70842	40.67	0.01
V	0.58673	5	0.11735	1.54	ns
T x V	0.37418	70	0.00534	1.24	0.1
RESIDUAL	2.77570	267	0.01039		
T x S	0.73151	42	0.01741		
V x S	1.14099	15	0.07606		
T x V x S	0.90317	210	0.00430		

(b) TRANSFER FUNCTION MODULUS WITH 16Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	1.40341	3	0.46780	69.81	0.01
T	18.51352	14	1.32239	114.56	0.01
V	0.12607	5	0.02521	0.81	ns
T x V	0.16614	70	0.00237	0.59	ns
RESIDUAL	1.78918	267	0.00670		
T x S	0.48480	42	0.01154		
V x S	0.46429	15	0.03095		
T x V x S	0.84006	210	0.00400		

(c) TRANSFER FUNCTION PHASE LAG WITH 4Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	2.66524	3	0.88841	124.02	0.01
T	7.74779	14	0.55341	49.75	0.01
V	0.39054	5	0.07810	2.07	ns
T x V	0.28789	70	0.00411	0.98	ns
RESIDUAL	1.91253	267	0.00716		
T x S	0.46718	42	0.01112		
V x S	0.56556	15	0.03770		
T x V x S	0.87978	210	0.00418		

(d) TRANSFER FUNCTION PHASE LAG WITH 16Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	3.31295	3	1.10432	176.92	0.01
T	9.60229	14	0.68588	29.68	0.01
V	0.11536	5	0.02307	2.21	ns
T x V	0.17197	70	0.00245	0.95	ns
RESIDUAL	1.66653	267	0.00624		
T x S	0.97048	42	0.02310		
V x S	0.15591	15	0.01039		
T x V x S	0.54013	210	0.00257		

TABLE 7.5.3. EXPERIMENT 3D - TRANSFER FUNCTION MEASURES

Treatments: S = Subjects, T = Transfer function frequency,
V = Vibration level

(a) TRANSFER FUNCTION MODULUS WITH 4Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	57.56819	3	19.18940	1248.66	0.01
T	7.05786	14	0.50413	6.25	0.01
V	0.04715	5	0.00942	0.74	ns
T x V	0.24074	70	0.00343	1.36	0.05
RESIDUAL	4.10323	267	0.01536		
T x S	3.38541	42	0.08060		
V x S	0.18930	15	0.01262		
T x V x S	0.52852	210	0.00251		

(b) TRANSFER FUNCTION MODULUS WITH 16Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	1.97867	3	0.65956	137.13	0.01
T	10.68314	14	0.76308	98.99	0.01
V	0.09820	5	0.01964	1.05	ns
T x V	0.18463	70	0.00263	0.81	ns
RESIDUAL	1.28415	267	0.00480		
T x S	0.32376	42	0.00770		
V x S	0.27847	15	0.01856		
T x V x S	0.68188	210	0.00324		

(c) TRANSFER FUNCTION PHASE LAG WITH 4Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	3.70415	3	1.23472	285.17	
T	1.68758	14	0.12054	7.47	0.01
V	0.04563	5	0.00912	1.06	ns
T x V	0.17327	70	0.00247	1.48	0.05
RESIDUAL	1.15604	267	0.00432		
T x S	0.67735	42	0.01612		
V x S	0.12838	15	0.00855		
T x V x S	0.35031	210	0.00166		

(d) TRANSFER FUNCTION PHASE LAG WITH 16Hz VIBRATION

SOURCE	SS	DF	MS	F RATIO	p
S	0.96740	3	0.32247	76.54	0.01
T	3.17989	14	0.22714	21.09	0.01
V	0.10860	5	0.02172	1.23	ns
T x V	0.15095	70	0.00215	1.10	ns
RESIDUAL	1.12485	267	0.00421		
T x S	0.45229	42	0.01076		
V x S	0.26342	15	0.01756		
T x V x S	0.40914	210	0.00194		

TABLE 7.5.4. EXPERIMENT 3E - TRANSFER FUNCTION MEASURES

Treatments: S = Subjects, T = Transfer function frequency, B = Level of 4Hz artificial breakthrough.

(a) TRANSFER FUNCTION MODULUS, ISOTONIC STICK.

SOURCE	SS	DF	MS	F RATIO	p
S	0.24838	3	0.08279	17.04	0.01
T	8.99695	14	0.64264	209.93	0.01
B	0.08271	3	0.02757	2.07	ns
T x B	0.48091	42	0.01145	2.35	0.01
RESIDUAL	0.85995	177	0.00485		
T x S	0.12857	42	0.00306		
B x S	0.11942	9	0.01326		
T x B x S	0.61195	126	0.00485		

(b) TRANSFER FUNCTION MODULUS, ISOMETRIC STICK.

SOURCE	SS	DF	MS	F RATIO	p
S	0.05867	3	0.01955	9.34	
T	6.66147	14	0.47582	128.71	0.01
B	0.16199	3	0.05399	7.00	0.01
T x B	0.30949	42	0.00736	6.36	0.01
RESIDUAL	0.37047	177	0.00209		
T x S	0.15526	42	0.00369		
B x S	0.06933	9	0.00770		
T x B x S	0.14586	126	0.00115		

(c) TRANSFER FUNCTION PHASE LAG, ISOTONIC STICK.

SOURCE	SS	DF	MS	F RATIO	p
S	0.07651	3	0.02550	10.33	0.01
T	3.27513	14	0.23394	271.69	0.01
B	0.35046	3	0.11682	11.65	0.01
T x B	0.57779	42	0.01375	5.58	0.01
RESIDUAL	0.43672	177	0.00246		
T x S	0.03616	42	0.00086		
B x S	0.09022	9	0.01002		
T x B x S	0.31033	126	0.00246		

(d) TRANSFER FUNCTION PHASE LAG, ISOMETRIC STICK.

SOURCE	SS	DF	MS	F RATIO	p
S	0.00098	3	0.00032	0.09	ns
T	0.72754	14	0.05196	13.58	0.01
B	0.13224	3	0.04408	4.26	0.05
T x B	0.42149	42	0.01003	3.20	0.01
RESIDUAL	0.64856	177	0.00366		
T x S	0.16065	42	0.00382		
B x S	0.09306	9	0.01034		
T x B x S	0.39484	126	0.00313		

vibration may be completely accounted for by perceptual noise due to vibration-induced activity of the controlled element appearing in the display.

The increase in remnant for a given level of vibration was greater with the isotonic control than with the isometric control, but the amount of vibration-induced activity in the isometric control was proportionally smaller. The same levels of artificially induced 4 Hz disturbance of the controlled element marker resulted in similar increases in remnant with both controls, showing that the kinaesthetic force information available to subjects with the isometric control does not enable them to reduce the effects of the disturbance. The amount of vibration-induced activity appearing in the control output is of course proportional to the gain of the control, and it was shown in experiment one that increasing the control gain results in a corresponding increase in remnant during 4 Hz vibration.

There were also significant increases in 1-3 Hz remnant with both controls during 16 Hz vibration of the control stick, although only at the very high levels of 7.0 m/s^2. After exposure to higher levels of 16 Hz control vibration all four subjects reported numbness in the controlling limb, similar to that experienced during 64 Hz vibration in experiment two. This suggests that the effect of these high levels of 16 Hz control vibration may be primarily due to direct interference with neuromuscular actuation systems. It can be seen from figure 7.4.7. that the increase in remnant is a fairly broadband process; however it is interesting to note that the most consistent or statistically significant increase in remnant with 16 Hz control vibration occurred in the 1-3 Hz frequency band, whereas the increase due to 64 Hz vibration in the last experiment was significant only in the 0-1 Hz band.

There were no significant effects on input-correlated error during any of the real vibration exposures, as in the last experiment. However the transfer function data revealed that control stick vibration at 4 Hz and 16 Hz resulted in significant reductions in response lags, particularly at higher transfer function frequencies. This effect was even more marked with artificially induced 4 Hz breakthrough in the display, and the overall effect of vibration on input-correlated error was significant in this case. Such an effect could be brought about by adaptive-voluntary changes in the subjects' strategy in order to compensate for disturbances by the vibration. However, no significant effects were observed with whole-body vibration despite increases in vibration-correlated activity and remnant as great or greater than those in the latter two cases. A possible alternative explanation is that the effect is due to increased arousal; however one would intuitively expect whole-body vibration to be a more arousing stimulus than either hand-arm vibration or apparent display vibration. It may be, however, that the arousal mechanism is selective; control vibration and apparent display vibration serving to focus the subject's attention on either control or display.

7.7. CONCLUSIONS

As in the previous two experiments the primary effect of both control stick vibration and whole-body vibration on a single axis, zero order, pursuit tracking task was an increase in remnant, or operator-generated noise. The results obtained during 4 Hz vibration conditions support the hypothesis presented in the introduction to this experiment, showing that the increased remnant can be completely accounted for by perceptual noise due to vibration-induced activity of the controlled element appearing in the display. Very high levels of 16 Hz vibration at the man/control interface also induced increases in remnant which are consistent with direct interference with neuromuscular mechanisms.

The results also confirm the finding from experiment two that control stick vibration can result in significant decreases in response lags. This apparent facilitation of this aspect of the operator's performance is most consistent with increased arousal due to the presence of vibration. However the mechanism appears to be very selective because the effect is not significant with whole-body vibration, despite much greater effects on overall levels of performance.

8. EXPERIMENT FOUR: THE EFFECT OF DURATION OF VIBRATION.

8.1. INTRODUCTION.

The discussion in section 3.5 indicates that marked changes can occur in the sensitivity to vibration of certain tracking tasks during prolonged vibration exposure.

The discovery of time dependent or cumulative effects of vibration would have serious implications on the interpretation of past research since results would be very dependent on order of presentation of stimuli, the length of experimental sessions and other facets of the experimental design. For instance, Khalil and Ayoub (1970) and Dudek et al. (1973) have shown that in certain circumstances the length of tracking runs and rest periods during long vibration exposures could significantly affect conclusions. Experiment four was performed in order to determine the stability of the observed effects of vibration and their underlying mechanisms with prolonged vibration exposures. Subjects were exposed to vertical (z-axis) whole-body vibration at 4 Hz continuously for 60 minutes, whilst engaged in continuous performance of the tracking task using either the isotonic or the isometric control.

8.2. SUBJECTS.

Eight subjects took part in this experiment, four of whom had experience of previous experiments in this series. Further details of the subjects are given in appendix D. Each subject attended two practice sessions before the main experiment. Payment of £1.00 was made for each practice session and each experimental session attended plus an incentive bonus payment. Bonus payments of £3.00, £2.00 and £1.00 were made to the three subjects returning the lowest overall integrated-absolute error scores over the two experimental sessions.

8.3. PROCEDURE.

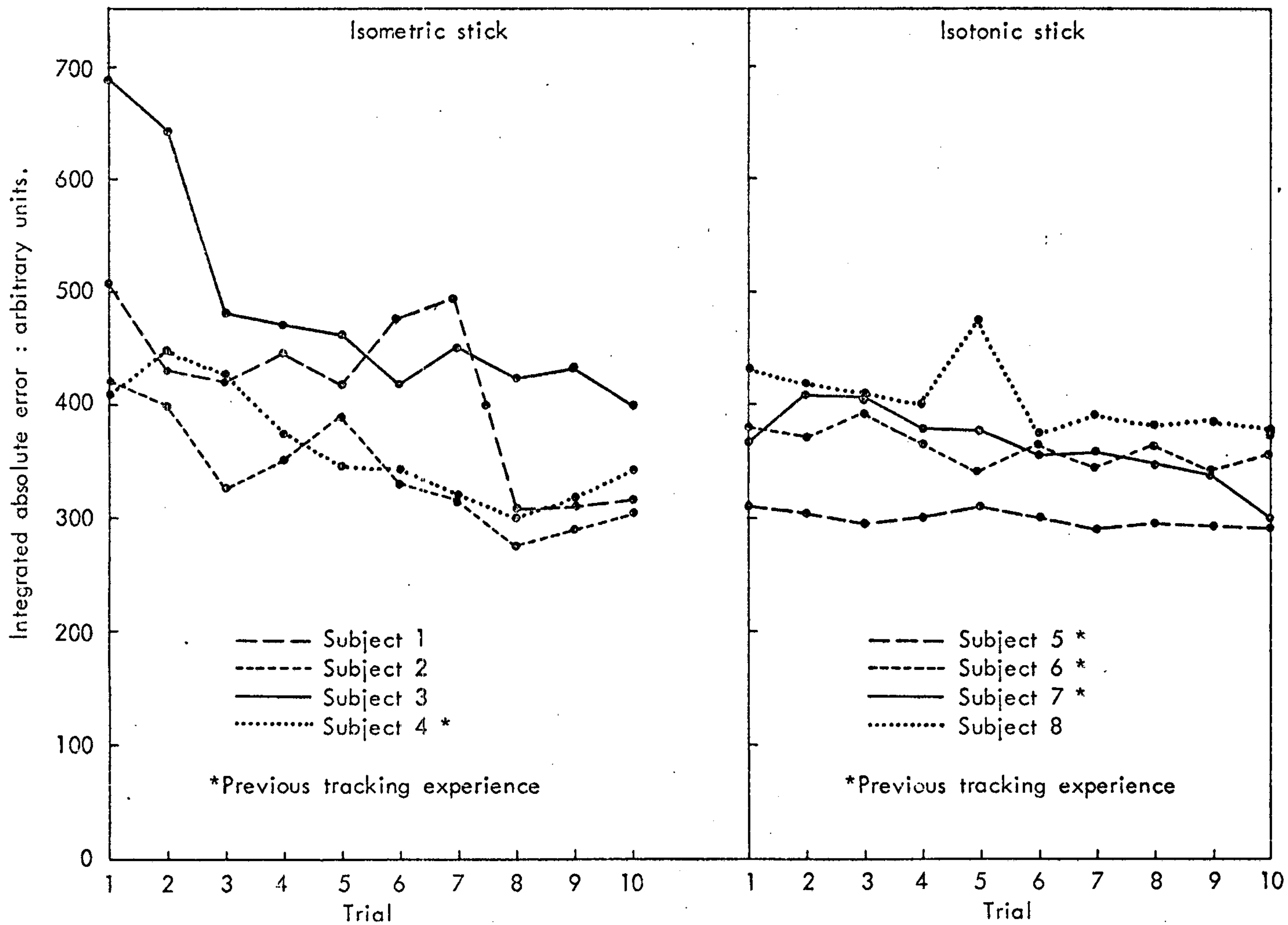
The subjects were divided into two groups of four. One group used the isometric stick control throughout the experiment and the other group used the isotonic control. During the practice sessions the subjects performed 5, ten minute tracking runs, separated by five minute rest periods. Performance was monitored by integrated-absolute error, which was measured by a new, low-drift integrator circuit. The integrated-absolute error score was also measured for the entire length of the experimental runs as a continuous monitor of each subject's performance.

The subjects were given full details of the task and vibration exposures at the beginning of each session. However, they were not allowed to take their watches into the experimental area and were given no clues to the passage of time during experimental runs. Subjects were required to perform the tracking task <u>continuously</u> for 75 minutes. Each subject performed two tracking runs, on consecutive days. One run was performed under static conditions throughout and the other with 4 Hz sinusoidal, whole-body vibration at 1.2 m/s^2 rms for the first 60 minutes and the last 15 minutes under static conditions. The forcing function and control output were recorded continuously for the entire tracking run on an E.M.I. SE84 FM tape recorder, and were later digitised for computer analysis. Data was analysed over each consecutive five minute period throughout each run. Vibration conditions were balanced within each group of subjects. The experiment was analysed as a split plot design with one between subject treatment (control type) and two within subject treatment (period and vibration conditions).

8.4. RESULTS OF TRACKING ERROR MEASURES.

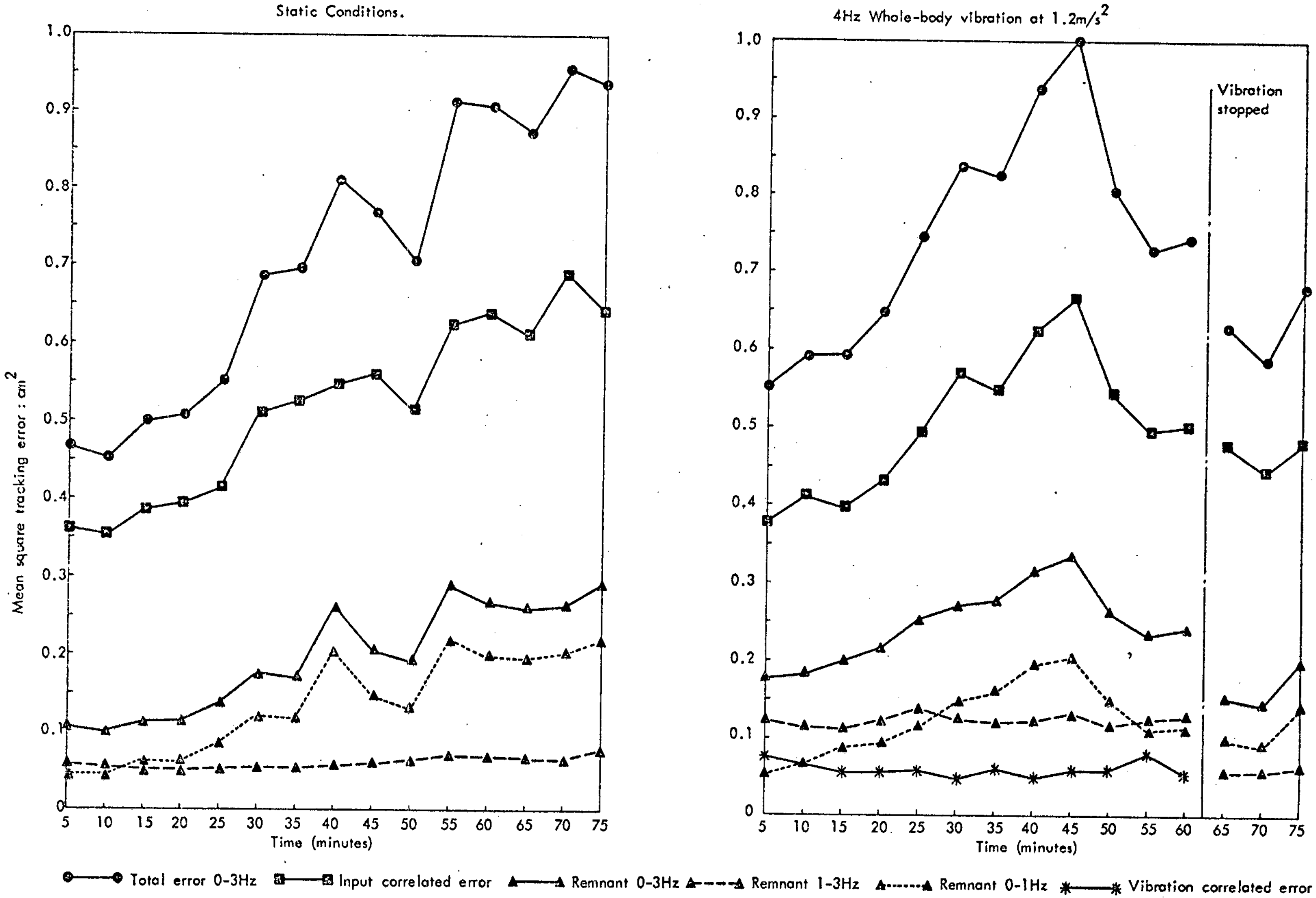
Integrated-absolute error scores for the practice sessions are shown in figure 8.4.1. Separate analyses of variance were performed for each of the mean square error components, as in the previous experiments. Average results for each group of subjects are shown in figures 8.4.2. and 8.4.3. ANOVA summary tables are given in tables 8.4.1a to 8.4.1d. The four sets of error terms in each ANOVA were tested for homogeneity with an F_{max} ratio test. Where the error terms for the two different groups of subjects were found to be significantly different, the significance levels of the F ratios involving that particular error term are based upon a modified number of degrees of freedom, according to the Geisser-Greenhouse conservative F test. None of the treatment effects were significant on either total error (excluding vibration-correlated error) or on input-correlated error, however, there were significant differences between periods in total remnant, 0-1 Hz remnant and 1-3 Hz remnant. There were also significant effects of vibration and significant vibration x control, vibration x control x period and vibration x period

FIG 8.4.1.



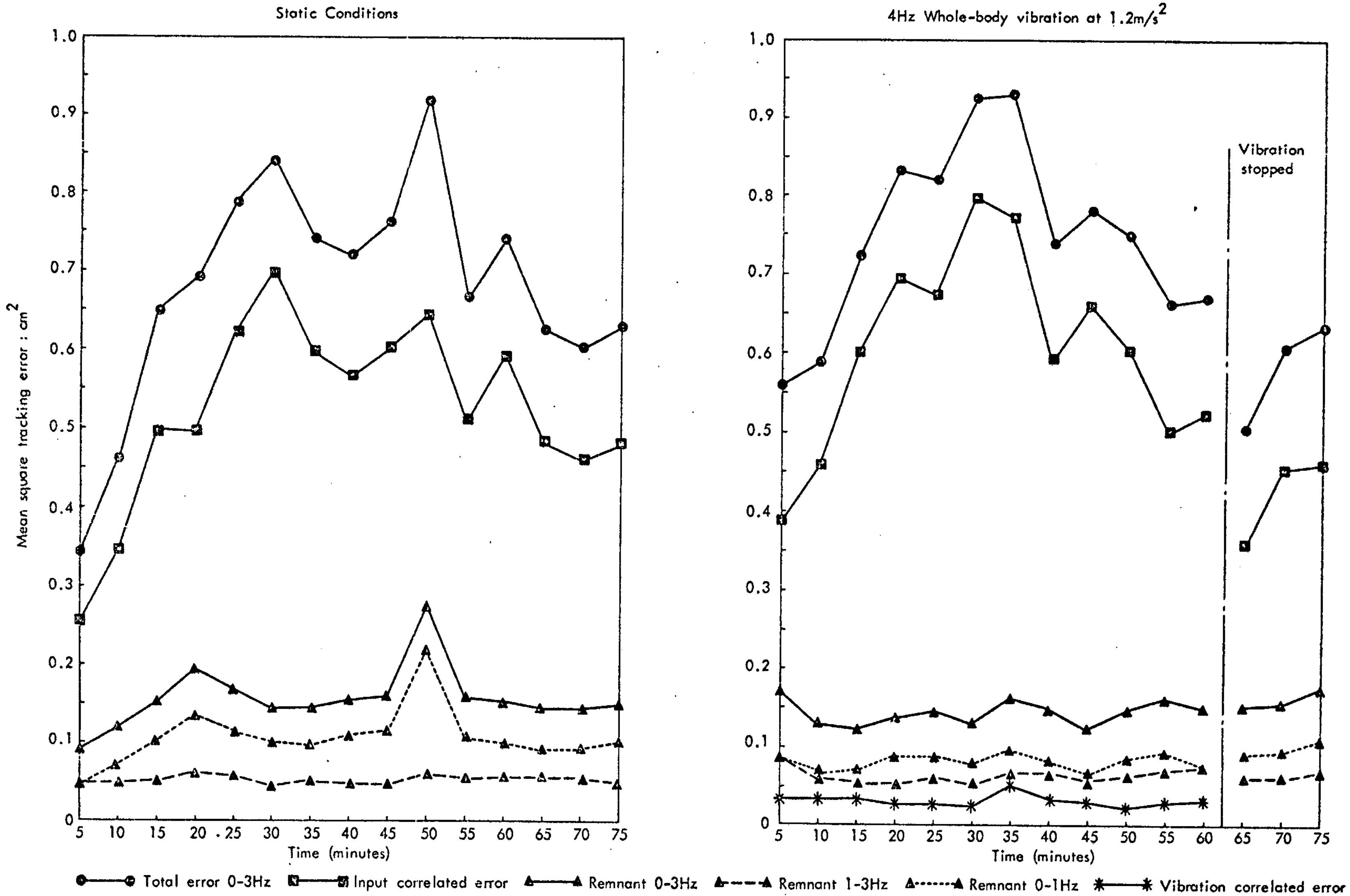
TRACKING ERRORS DURING PRACTICE FOR EXPERIMENT FIVE

FIG 8.4.2.



ISOTONIC STICK : MEAN PERFORMANCE AS A FUNCTION OF DURATION OF A CONTINUOUS TASK.

FIG 8.4.3.



ISOMETRIC STICK : MEAN PERFORMANCE AS A FUNCTION OF DURATION OF A CONTINUOUS TASK.

TABLE 8.4.1. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 4 MEAN SQUARE TRACKING ERROR MEASURES.

Treatments: S = Subjects, C = Control, V = Vibration, P = Period

(a) TOTAL MEAN SQUARE ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
BETWEEN SUBJECTS	0.43870E 9	7	0.62671E 8		
C	0.99994E 6	1	0.99994E 6	0.01	ns
S WITHIN GROUPS	0.43770E 9	6	0.72950E 8		
WITHIN SUBJECTS	0.40440E 9	232	0.17431E 7		
V	0.99994E 6	1	0.99994E 6	0.54	ns
C x V	0.40013E 6	1	0.40013E 6	0.21	ns
V x S	0.11100E 8	6	0.18500E 7		
P	0.73100E 8	1*	0.52214E 7	3.09	ns
C x P	0.31200E 8	1*	0.22286E 7	1.31	ns
P x S	0.14190E 9	6*	0.16893E 7		
V x P	0.28200E 8	1*	0.20143E 7	1.61	ns
C x V x P	0.12700E 8	1*	0.90712E 6	0.72	ns
V x P x S	0.10480E 9	6*	0.12476E 7		

* denotes modified no. of degrees of freedom (Geisser-Greenhouse conservative F-test)

TEST FOR HOMOGENEITY OF ERROR TERMS

SOURCE	SS	DF	MS	F RATIO	p
SUBJECTS AT C1	0.28070E 9	3	0.93567E 8	1.78	ns
SUBJECTS AT C2	0.15700E 9	3	0.52333E 8		
V x S AT C1	0.23000E 7	3	0.76668E 6	3.78	ns
V x S AT C2	0.87000E 7	3	0.29000E 7		
P x S AT C1	0.97700E 8	42	0.23262E 7	2.21	0.05
P x S AT C2	0.44200E 8	42	0.10524E 7		
Vx P x S AT C1	0.24900E 8	42	0.59285E 6	3.21	0.01
Vx P x S AT C2	0.80000E 8	42	0.19048E 7		

(b) MEAN SQUARE INPUT-CORRELATED ERROR, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
BETWEEN SUBJECTS	0.20990E 9	7	0.29986E 8		
C	0.25600E 7	1	0.25600E 7	0.07	ns
S WITHIN GROUPS	0.20734E 9	6	0.34557E 8		
WITHIN SUBJECTS	0.23740E 9	232	0.10233E 7		
V	0.29990E 6	1	0.29990E 6	0.42	ns
C x V	0.19100E 7	1	0.19100E 7	2.73	ns
V x S	0.41901E 7	6	0.69835E 6		
P	0.44500E 8	1*	0.31786E 7	2.63	ns
C x P	0.22500E 8	1*	0.16071E 7	1.33	ns
P x S	0.10130E 9	6*	0.12060E 7		
V x P	0.13400E 8	1*	0.95715E 6	1.76	ns
C x V x P	0.36200E 7	1*	0.25857E 6	0.47	ns
V x P x S	0.45680E 8	6*	0.54381E 6		

* denotes modified no. of degrees of freedom (Geisser-Greenhouse conservative F-test)

TEST FOR HOMOGENEITY OF ERROR TERMS

SOURCE	SS	DF	MS	F RATIO	p
SUBJECTS AT C1	0.15230E 9	3	0.50767E 8	2.76	ns
SUBJECTS AT C2	0.55050E 8	3	0.18350E 8		
V x S AT C1	0.50003E 6	3	0.16668E 6	7.27	ns
V x S AT C2	0.36401E 7	3	0.12134E 7		
P x S AT C1	0.84600E 8	42	0.20143E 7	5.05	0.01
P x S AT C2	0.16720E 8	42	0.39810E 6		
V x P x S AT C1	0.12500E 8	42	0.29761E 6	2.65	0.01
V x P x S AT C2	0.33200E 8	42	0.79047E 6		

(c) MEAN SQUARE REMNANT, 0-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
BETWEEN SUBJECTS	0.52610E 8	7	0.75157E 7		
C	0.67170E 7	1	0.67170E 7	0.87	ns
S WITHIN GROUPS	0.45893E 8	6	0.76488E 7		
WITHIN SUBJECTS	0.54320E 8	232	0.23414E 6		
V	0.25000E 6	1	0.25000E 6	0.29	ns
C x V	0.75600E 6	1	0.75600E 6	0.89	ns
V x S	0.50840E 7	6	0.84734E 6		
P	0.53700E 7	14	0.38357E 6	2.45	0.05
C x P	0.33430E 7	14	0.23879E 6	1.53	ns
P x S	0.13107E 8	84	0.15604E 6		
V x P	0.30900E 7	14	0.22071E 6	1.01	ns
C x V x P	0.51220E 7	14	0.36586E 6	1.68	0.1
V x P x S	0.18198E 8	84	0.21664E 6		

TEST FOR HOMOGENEITY OF ERROR TERMS

SOURCE	SS	DF	MS	F RATIO	p
SUBJECTS AT C1	0.19619E 8	3	0.65397E 7	1.33	ns
SUBJECTS AT C2	0.26270E 8	3	0.87567E 7		
V x S AT C1	0.39180E 7	3	0.13060E 7	3.37	ns
V x S AT C2	0.11600E 7	3	0.38667E 6		
P x S AT C1	0.46210E 7	42	0.11002E 6	1.83	ns
P x S AT C2	0.84900E 7	42	0.20214E 6		
V x P x S AT C1	0.64240E 7	42	0.15295E 6	1.83	ns
V x P x S AT C2	0.11780E 8	42	0.28048E 6		

(d) MEAN SQUARE REMNANT, 0-1Hz.

SOURCE	SS	DF	MS	F RATIO	p
BETWEEN SUBJECTS	0.27524E 8	7	0.39320E 7		
C	0.20610E 7	1	0.20610E 7	0.48	ns
S WITHIN GROUPS	0.25463E 8	6	0.42438E 7		
WITHIN SUBJECTS	0.42410E 8	232	0.18280E 6		
V	0.60500E 6	1	0.60500E 6	0.68	ns
C x V	12000.0002	1	12000.0002	0.01	ns
V x S	0.52730E 7	6	0.87883E 6		
P	0.53080E 7	14	0.37914E 6	3.09	0.01
C x P	0.31400E 7	14	0.22429E 6	1.82	0.1
P x S	0.10302E 8	84	0.12264E 6		
V x P	0.15090E 7	1*	0.10779E 6	0.67	ns
C x V x P	0.28140E 7	1*	0.20100E 6	1.25	ns
V x P x S	0.13447E 8	6*	0.16008E 6		

* denotes modified no. of degrees of freedom (Geisser - Greenhouse conservative F-test)

SOURCE	SS	DF	MS	F RATIO	p
SUBJECTS AT C1	0.11181E 8	3	0.37270E 7	1.27	ns
SUBJECTS AT C2	0.14279E 8	3	0.47597E 7		
V x S AT C1	0.25680E 7	3	0.85600E 6	1.05	ns
V x S AT C2	0.27060E 7	3	0.90200E 6		
P x S AT C1	0.37560E 7	42	89428.5725	1.74	ns
P x S AT C2	0.65450E 7	42	0.15583E 6		
V x P x S AT C1	0.41910E 7	42	99785.7131	2.21	0.05
V x P x S AT C2	0.92640E 7	42	0.22057E 6		

(e) MEAN SQUARE REMNANT, 1-3Hz.

SOURCE	SS	DF	MS	F RATIO	p
BETWEEN SUBJECTS	0.48920E 7	7	0.69886E 6		
C	0.13370E 7	1	0.13370E 7	2.25	ns
S WITHIN GROUPS	0.35550E 7	6	0.59250E 6		
WITHIN SUBJECTS	0.58780E 7	232	25336.2076		
V	0.16430E 7	1	0.16430E 7	19.25	0.01
C x V	0.57000E 6	1	0.57000E 6	6.67	0.05
V x S	0.51200E 6	6	85333.3381		
P	0.29700E 6	14	21214.2857	2.06	0.05
C x P	0.25600E 6	14	18285.7153	1.77	0.1
P x S	0.86500E 6	84	10297.6194		
V x P	0.48900E 6	14	34928.5714	3.86	0.01
C x V x P	0.48700E 6	14	34785.7159	3.84	0.01
V x P x S	0.75900E 6	84	9035.7141		

TEST FOR HOMOGENEITY OF ERROR TERMS

SOURCE	SS	DF	MS	F RATIO	p
SUBJECTS AT C1	0.13990E 7	3	0.46633E 6	1.54	ns
SUBJECTS AT C2	0.21560E 7	3	0.71867E 6		
V x S AT C1	0.18100E 6	3	60333.3331	1.82	ns
V x S AT C2	0.33100E 6	3	0.11033E 6		
P x S AT C1	0.28100E 6	42	6690.4762	2.07	ns
P x S AT C2	0.58300E 6	42	13880.9524		
V x P x S AT C1	0.37200E 6	42	8857.1428	1.04	ns
V x P x S AT C2	0.38800E 6	42	9238.0959		

NOTE: the multiplier 'E n' signifies x 10^n.
NOTE: C1 = isometric stick, C2 = isotonic stick.

interactions on 1-3 Hz remnant.

It can be seen from figures 8.4.2 and 8.4.3 that the variations in total tracking error variance were very large and that the major proportion of this between periods variation is accounted for by variations in input-correlated error. However differences between periods were not always in the direction of increases with time (see also the results of Holland 1967). The statistical nonsignificance of these effects is almost certainly due to very marked differences in the variations in error with time between subjects, which make the average trends unrepresentative of individuals. Total error, input-correlated error and total remnant trends for individual subjects are shown in figures 8.4.4. and 8.4.5. From the results of experiment two we would expect the major effect of vibration to be an increase in 1-3 Hz remnant and it can be seen from figures 8.4.2 and 8.4.3 that the increase during vibration conditions is relatively constant throughout the vibration period. The increase in 1-3 Hz remnant during vibration is larger with the isotonic stick, consistent with earlier results, accounting for the significant vibration by controls interaction. The 1-3 Hz remnant is also immediately reduced to its static level after the cessation of vibration, accounting for the vibration by period interaction and indicating that there were no after-effects of vibration on this aspect of the operator's performance. It can also be seen from figures 8.4.2 and 8.4.3 that the vibration-correlated error is also fairly constant during the vibration, indicating no consistent changes in bio-dynamic response over a 60 minute period.

Although the total mean square error during the first five minute period was always greater under vibration conditions, in most cases the total error under static conditions soon became as bad, or worse, than that under vibration. A nonparametric test for trends based on the number of reverse arrangements in a series (Bendat and Piersol, 1966) was carried out on the first twelve periods (60 minutes) of total error, correlated error, and remnant measures from each individual subject. For every measure except 1-3 Hz remnant, there are significant trends for error to increase with time over the first sixty minutes under static conditions for seven subjects and under vibration for only three subjects. Details of this test are given in table 8.4.2.

Every subject but subject seven showed an immediate recovery after the cessation of vibration, all of the error measures returning to levels

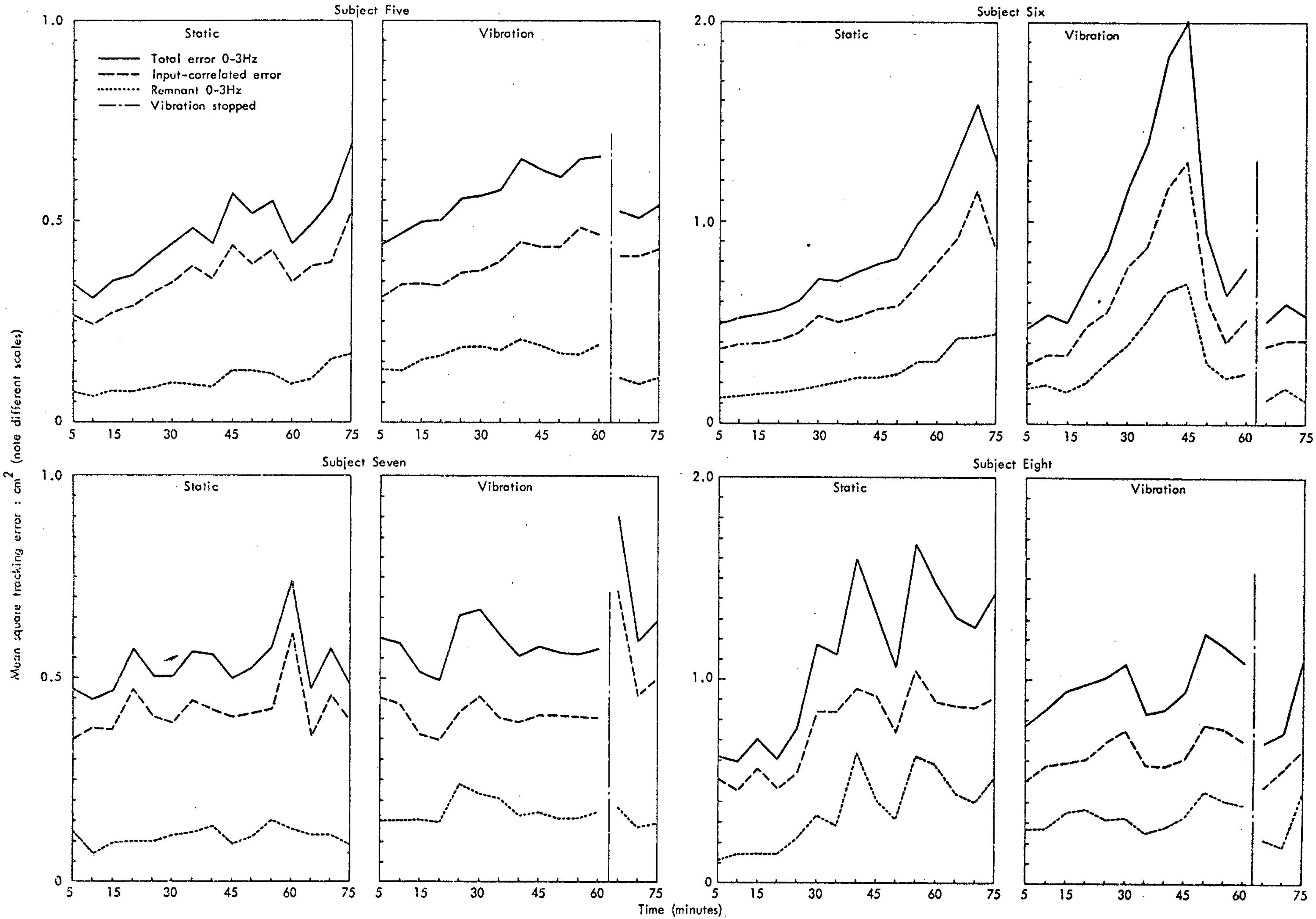


FIG 8.4.4. ISOTONIC STICK : PERFORMANCE OF INDIVIDUAL SUBJECTS AS A FUNCTION OF TASK DURATION.

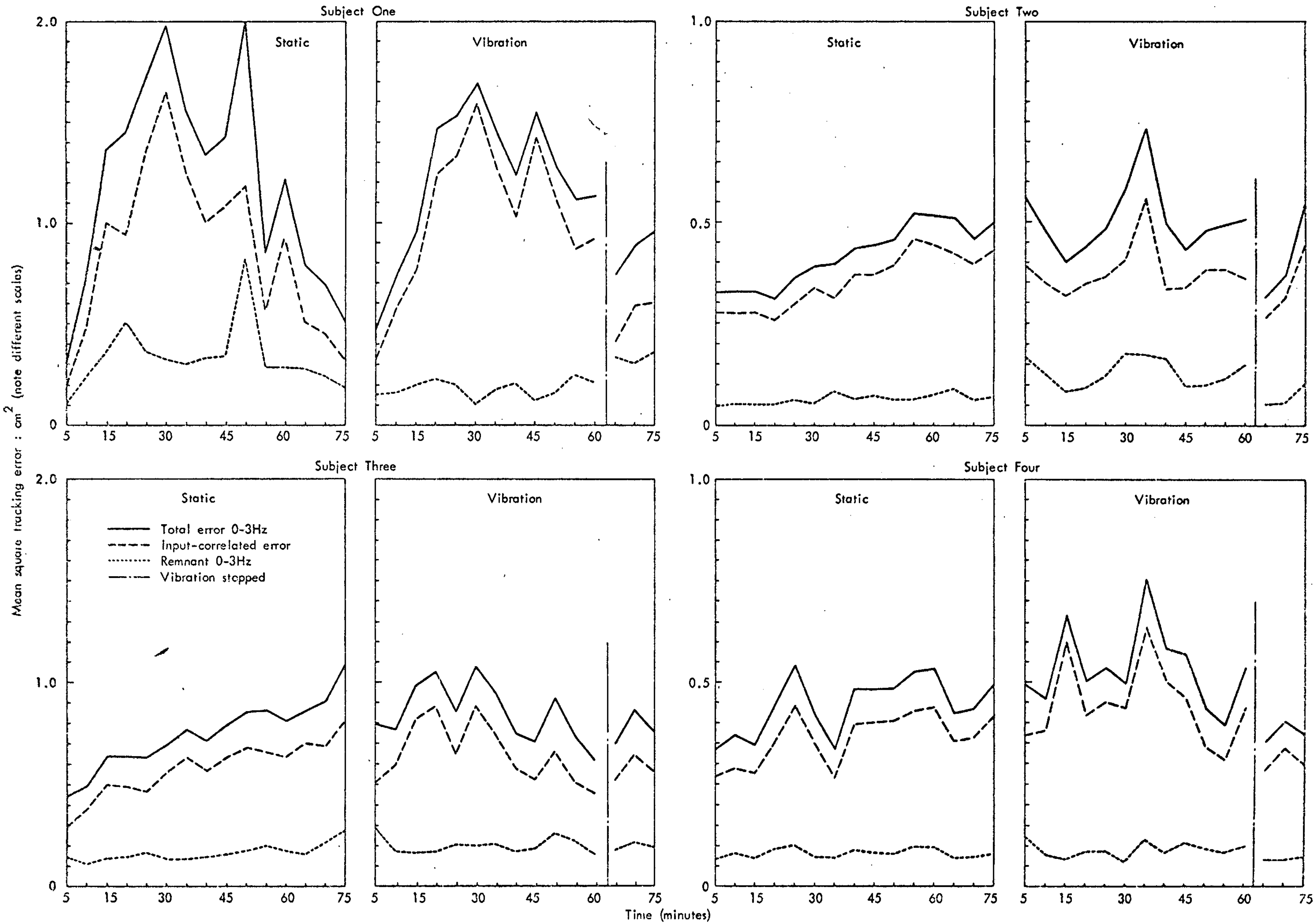


FIG 8.4.5. ISOMETRIC STICK : PERFORMANCE OF INDIVIDUAL SUBJECTS AS A FUNCTION OF TASK DURATION.

TABLE 8.4.2.

NUMBER OF REVERSE ARRANGEMENTS IN INDIVIDUAL ERROR TRENDS
(First 12 periods only: significance levels in brackets).

		TOTAL ERROR 0-3 Hz	CORRELATED ERROR	REMNANT 0-3 Hz	REMNANT 0-1 Hz	REMNANT 1-3 Hz
ISOMETRIC STICK						
SUB. 1	STATIC	27(NS)	29(NS)	31(NS)	32(NS)	24(NS)
SUB. 1	VIBRATION	27(NS)	26(NS)	25(NS)	24(NS)	35(NS)
SUB. 2	STATIC	4(.01)	7(.01)	13(.01)	8(.01)	41(NS)
SUB. 2	VIBRATION	28(NS)	31(NS)	33(NS)	32(NS)	38(NS)
SUB. 3	STATIC	6(.01)	8(.01)	17(.05)	6(.01)	36(NS)
SUB. 3	VIBRATION	45(NS)	43(NS)	33(NS)	38(NS)	25(NS)
SUB. 4	STATIC	15(.01)	14(.01)	21(0.1)	18(.05)	39(NS)
SUB. 4	VIBRATION	35(NS)	33(NS)	28(NS)	26(NS)	32(NS)
ISOTONIC STICK						
SUB. 5	STATIC	11(.01)	9(.01)	11(.01)	6(.01)	40(NS)
SUB. 5	VIBRATION	3(.01)	5(.01)	16(.01)	15(.01)	30(NS)
SUB. 6	STATIC	1(.01)	2(.01)	0(.01)	4(.01)	13(.01)
SUB. 6	VIBRATION	18(.05)	18(.05)	18(.05)	17(.05)	26(NS)
SUB. 7	STATIC	16(.01)	16(.01)	20(0.1)	14(.01)	28(NS)
SUB. 7	VIBRATION	37(NS)	39(NS)	25(NS)	27(NS)	41(NS)
SUB. 8	STATIC	11(.01)	13(.01)	9(.01)	9(.01)	22(NS)
SUB. 8	VIBRATION	16(.01)	16(.01)	19(0.1)	18(.05)	35(NS)

near those at the beginning of the static period, followed by a tendency for error to increase once more.

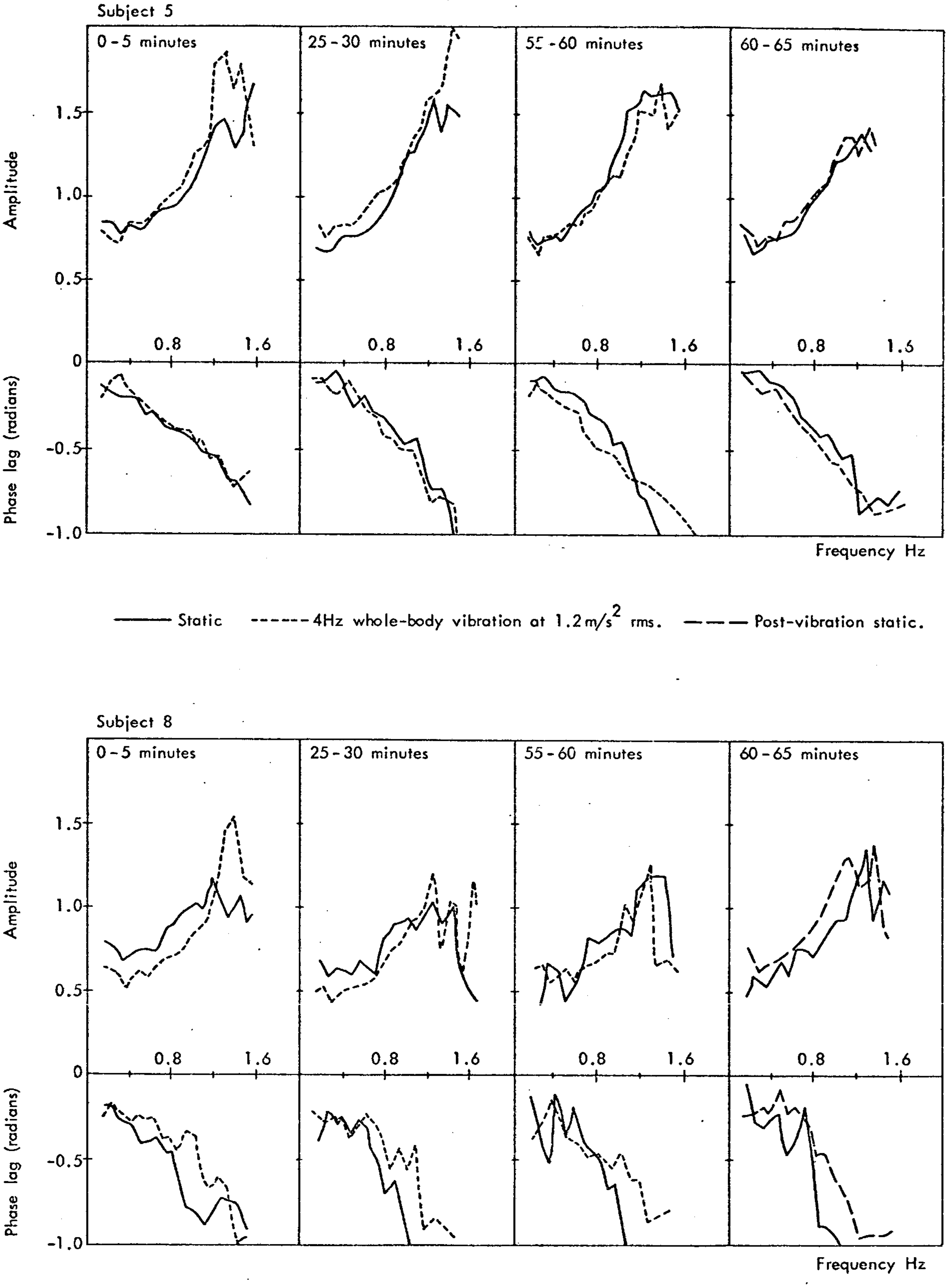
8.5. TRANSFER FUNCTION RESULTS.

As with the error measures there were very large variations between individuals in the transfer function data. Because of the inhomogeneous nature of the data, no statistical comparison was made between periods. Individual transfer functions, measured over 5 minute periods at the beginning, middle and end of the tracking runs, for two subjects from each group are shown in figures 8.5.1 and 8.5.2. The large increase in high frequency phase lags after 30 minutes tracking is immediately obvious, accounting for the large increases observed in input-correlated error. There is also clear evidence of suppression of gain at some frequencies in most of the later periods. This is however unlikely to represent a consistent decrease in the amplitude of the subjects' responses but rather a failure to respond at all for short periods of time, decreasing the average response amplitude of the whole five minute period. The most severe case is subject one, who appeared to make very few coherent responses during the 25-30 minute periods under both static and vibration conditions, especially at low frequencies. It can also be seen from the error data in figures 8.4.2. and 8.4.3. that this suppression of coherent responses was often accompanied by an increase in incoherent or inappropriate responses, as reflected in increases in 0-1 Hz remnant.

8.6. DISCUSSION

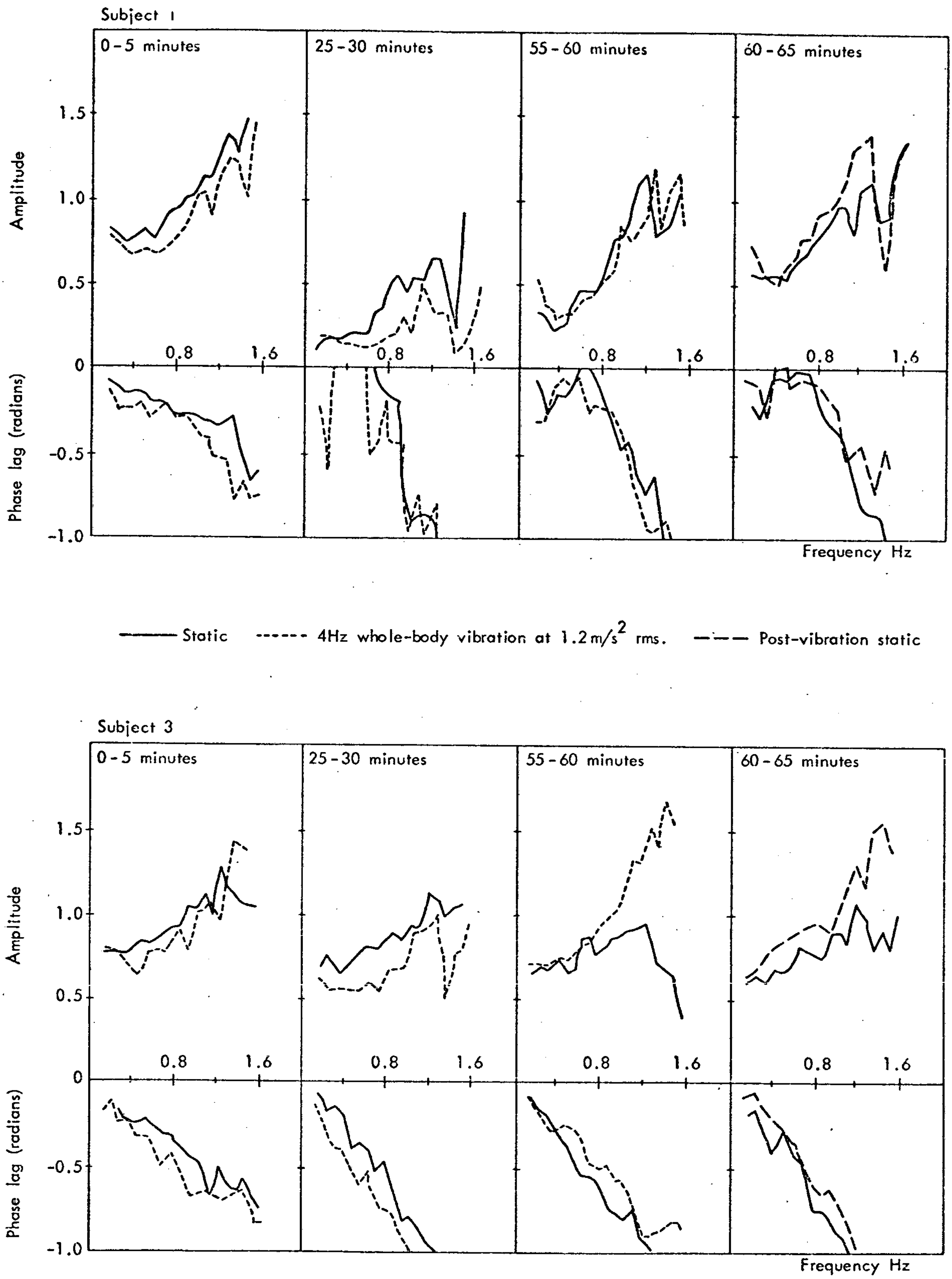
The results of experiment 4 show similar increases in vibration-correlated error and 1-3 Hz remnant during 4 Hz vibration to those observed in the previous two experiments. These effects were constant throughout 60 minute exposures to vibration, and 1-3 Hz remnant immediately returned to the same level as in the static runs after the cessation of vibration. Both the vibration-correlated error and the increase in 1-3 Hz remnant were found to be larger with the isotonic control than with the isometric control, consistent with the results of experiment 3. However there were less consistent and very large changes in input correlated error, and remnant at forcing function frequencies, after extended periods of continuous tracking in both static and vibration conditions. These completely masked the much smaller effects of vibration

FIG 8.5.1.



INDIVIDUAL HUMAN OPERATOR TRANSFER FUNCTIONS WITH THE ISOTONIC STICK DURING A CONTINUOUS, 75 MINUTE TASK.

FIG 8.5.2.



INDIVIDUAL HUMAN-OPERATOR TRANSFER FUNCTIONS WITH THE ISOMETRIC STICK DURING A CONTINUOUS, 75 MINUTE TASK.

on the overall tracking error variance. During the first five minutes of the 75 minute tracking runs lower overall mean tracking errors were returned by the group using the isometric control, due to lower input-correlated errors and smaller effects of vibration. However, after a short period the difference in overall mean tracking errors between the two controls was reversed, although this was largely due to the very rapid rise in input-correlated error with time by one subject in the isometric control group. However, following the cessation of vibration, performance levels effectively returned to normal. The transfer function data indicated that the large changes in correlated error were due to large increases in higher frequency response lags and suppression of average gain as a consequence of subjects' failure to respond to some movements of the controlled element. Increases in 0-1 Hz remnant can also be observed, which mirror the increases in input-correlated error. These increases are probably perceptual remnant due to observation noise, consistent with decreased or wandering attention.

Observations of the subjects whilst they performed the task and discussions with them after the experiment revealed that they had considerable difficulty maintaining an aroused and attentive state after extended periods of tracking. The observed increases in response lags and failure to respond to some of the stimulus is consistent with diminishing levels of arousal with time. Simple laboratory tasks such as the single axis, zero order tracking task employed here may not be particularly demanding to a well practised subject, and laboratory tasks in general are likely to be less motivating than real situations such as in vehicle guidance. Consequently, subjects have difficulty maintaining arousal and attention to the task for more than about 15 minutes. However the effect is likely to be less marked with tracking tasks which demand more of the subjects' information channel capacity or when the subjects are required to perform secondary tasks such as choice reaction time tasks which provide intermittent and novel stimuli.

The sudden recovery of performance levels observed after the cessation of vibration can be seen to be due to increased arousal as a response to novel and sudden stimulation. The non-parametric test for increasing trends carried out on the tracking error data suggested that the increases in error with time were generally smaller or less consistent during vibration conditions: a similar finding to that reported by Wilkinson and Gray (1974). There is confirmation of the arousing nature of motion stimuli in a report by Jackson (1956), who investigated records of altitude and heading of aircraft during a series of 15 hour flights by ten pilots. During the first half of the flights, pilots tended to fly more consistently and accurately in rough air than in calm air. However in the latter parts of the flights they were adversely affected by turbulent conditions, which seems to indicate that some interaction between fatigue and vibration can occur, but only after very long exposures. In simulated low altitude, high speed flight, Hornick and Lefritz (1966) found that pilots were able to maintain their performance levels for four hours whilst subject to random vibration (1-12 Hz) at levels up to 0.2g (z) rms.

8.7 CONCLUSIONS.

Large increases in overall error variance were observed during the 75 minute tracking runs, in both static and vibration conditions, due to large increases in response lags and suppression of coherent responses which appeared to be related to diminished levels of arousal. However differences between periods were not always in the direction of increases with time and there were large individual differences between individual subjects. Tests for trends in individual data indicated that significant tendencies for error variance to increase with time were much more prevalent in static than in vibration conditions, emphasising the arousing nature of the vibration stimulus.

Specific effects of vibration were confined to the remnant and vibration-correlated portions of error variance, consistent with the results of the previous experiments. These effects were slightly greater with the isotonic control stick, but were constant throughout the 60 minute vibration exposures. There was therefore no evidence in the results of any time dependent or cumulative effect of vibration on the performance of the task.

9. EXPERIMENT FIVE: PREDICTING THE EFFECT OF DUAL FREQUENCY VIBRATION ON CONTINUOUS MANUAL CONTROL PERFORMANCE.

9.1. INTRODUCTION.

Man is most frequently exposed to vibration in vehicles. The vibration is generated by out of balance forces in moving parts within the vehicle and external forces acting on it from the atmosphere, terrain, etc. These vibrations are modified by the dynamics of the vehicle, which usually contains a number of resonant structures. Vehicle vibrations therefore tend to be complex, multiple frequency or broad-band processes and vary greatly between vehicles and situations.

It would be impossible to rigorously investigate the effects of each of the many possible vehicle vibration spectra on tracking performance so most laboratory studies have concentrated on single sinusoidal motions. However in order to be able to predict the effects of multiple frequency vibration on performance we need to have a knowledge of the way in which the effects of single sinusoidal components combine.

In the experiment described below, the effect of dual frequency, vertical (z-axis), whole-body vibration on manual control was measured and compared with that predicted from the measured effects of each of the separate vibration components. Three prediction methods were investigated: (a) the rms sum of the weighted components, (b) the most severe weighted component alone, and (c) the arithmetic sum of the weighted components. Method (a) is equivalent to the use of a weighting filter and (b) is equivalent to evaluating the r.m.s. acceleration separately within each third-octave frequency band with reference to the appropriate weighting function: these two procedures are recommended by the International Standards Organisation (1974) for the evaluation of complex vibration spectra.

A second objective of the experiment was to investigate whether the effects of low frequency vibration on a more complex, and in some respects more realistic, task could be accounted for by the same mechanisms as in the single axis task used in all the previous experiments in this series.

9.2. SUBJECTS.

Eight subjects took part in experiment five, six of whom had previously taken part in experiments in this series. Further details of the subjects are given in appendix D. Each subject attended two practice sessions in addition to the two experimental sessions. Payment of £1.00 was made for each session attended.

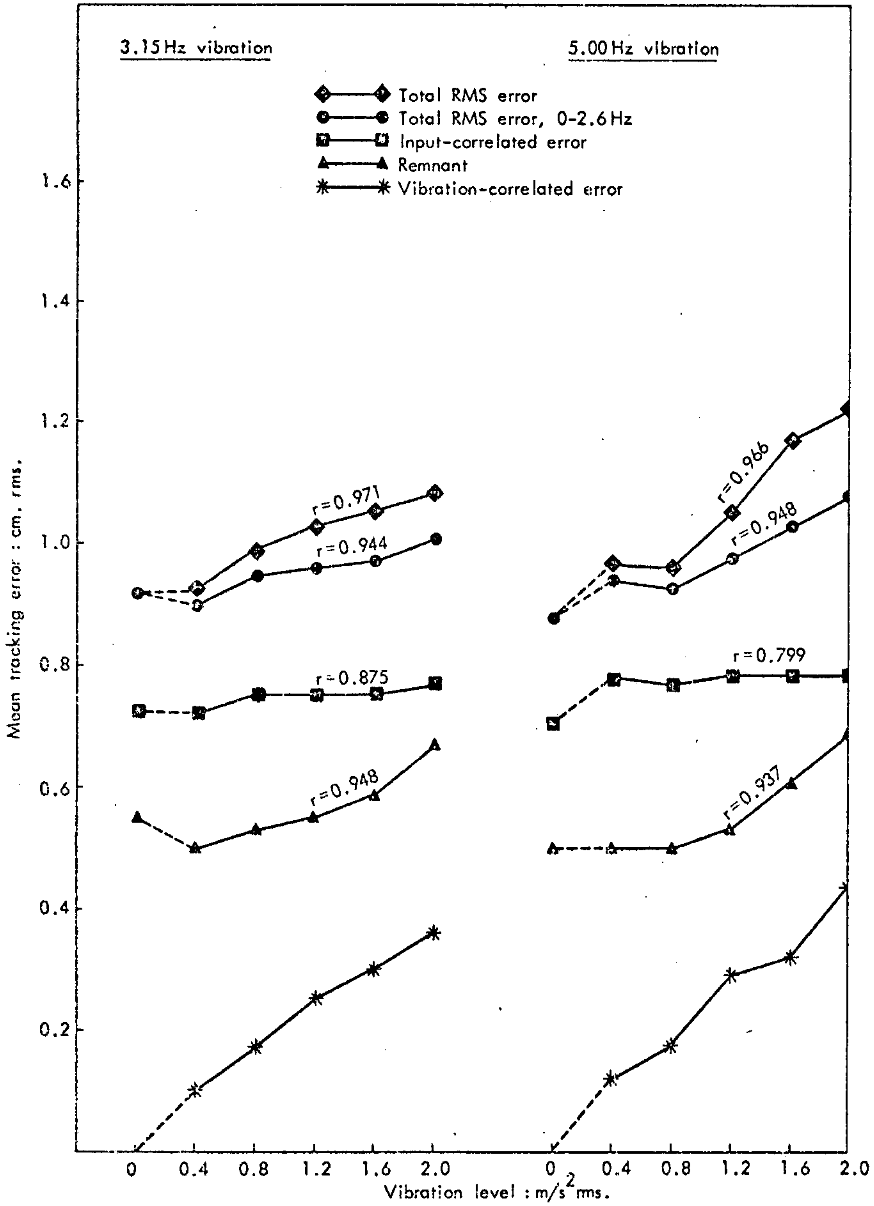
9.3. PROCEDURE.

The task set for the subjects in this experiment was a new, two axis, zero-order, pursuit tracking task; details of which are given in section 4.2. All the subjects used an isotonic joystick control and sat in a simulated helicopter seat with hard seat and back cushion. The subjects were restrained by a tight, five-point harness. The control mechanism was bolted to the seat frame, so that vibration was simultaneously applied through the seat and control.

The first practice session consisted of sixteen, 2-minute tracking runs, with four different control gains presented in balanced order. The four gains corresponded to display/control ratios of 125, 250, 375 and 500 mm displacement of controlled element per radian of control stick deflection. During the first practice session performance was monitored by the integrated modulus of vector error. The gain resulting in the lowest mean error for the eight subjects was 375 mm/rad. and the control gain was set at this level for the second practice session and the experiment. This is the same gain as used in the single-axis task in previous experiments for the isotonic control stick.

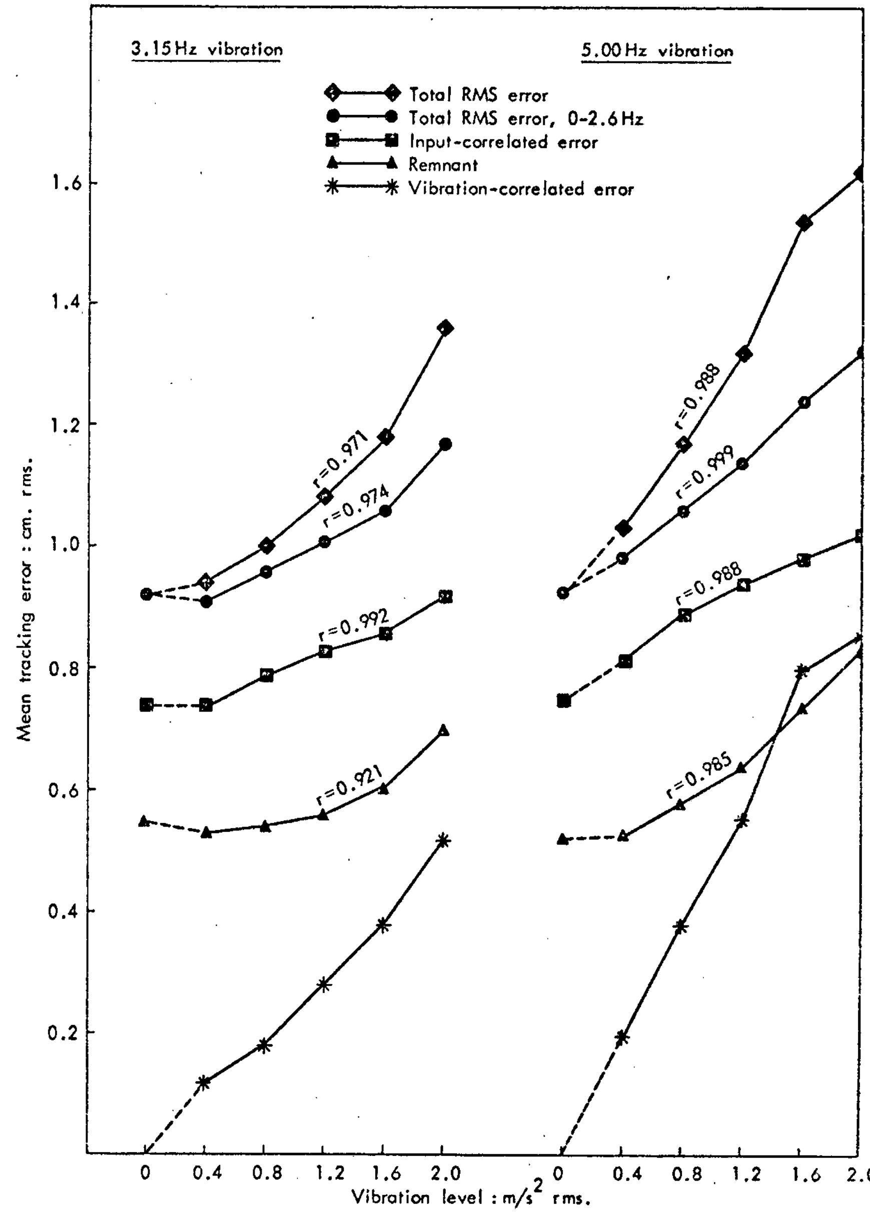
There were two experimental sessions, one in which vertical (z-axis) sinusoidal vibration at 3.15 and 5.00 Hz was presented at six acceleration levels and the other in which ten dual frequency combinations of 3.15 and 5.00 Hz were presented. The six sinusoidal vibration levels at each frequency were 0, 0.4, 0.8, 1.2, 1.6 and 2.0 m/s^2 rms. The ten dual frequency combinations are shown at the top of Tables 9.6.2. and 9.6.3. Sessions and presentation of levels within sessions were balanced between subjects. The two vibration frequencies were chosen to cover a range where the effects of vibration on the tracking task were relatively severe.

FIG 9.4.1a.



MEAN TRACKING ERROR IN HORIZONTAL AXIS WITH SINUSOIDAL VIBRATION.

FIG 9.4.1b.



MEAN TRACKING ERROR IN VERTICAL AXIS WITH SINUSCIDAL VIBRATION.

FIG 9.4.2a.

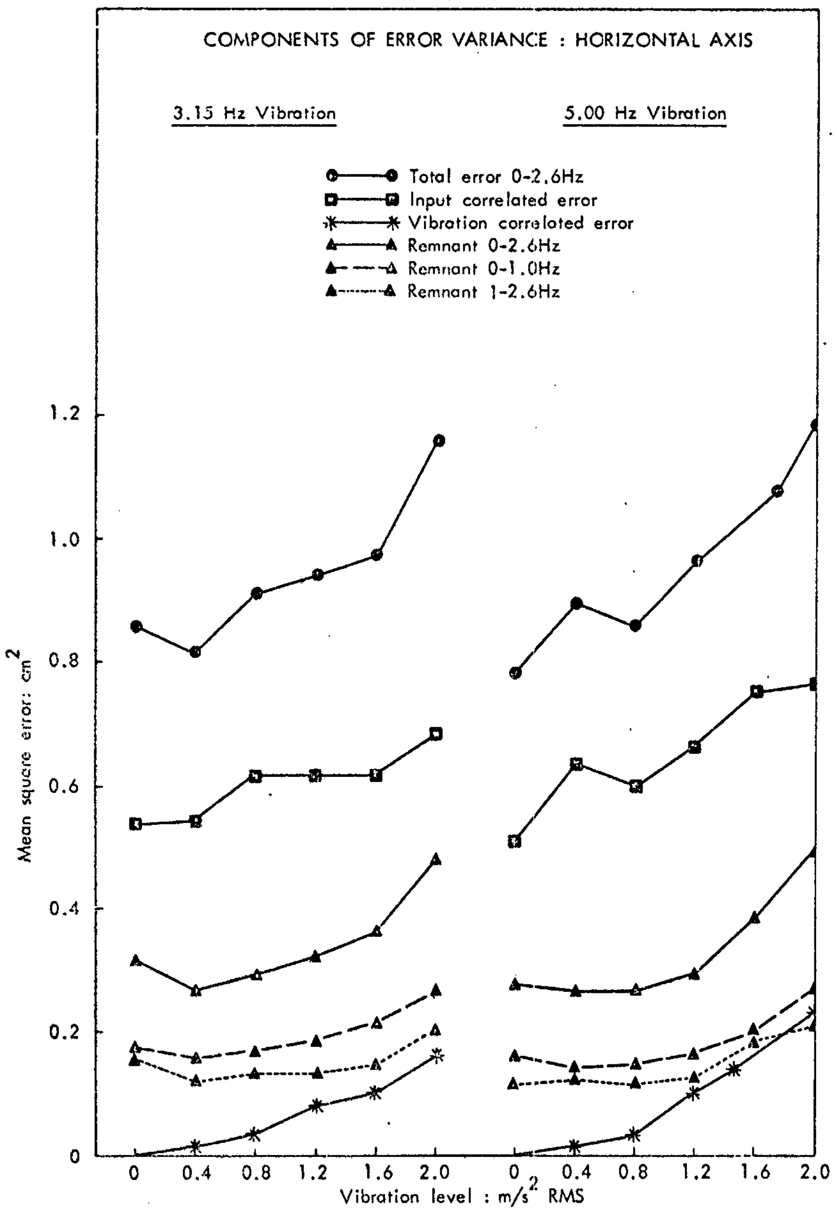


FIG 9.4.2b.

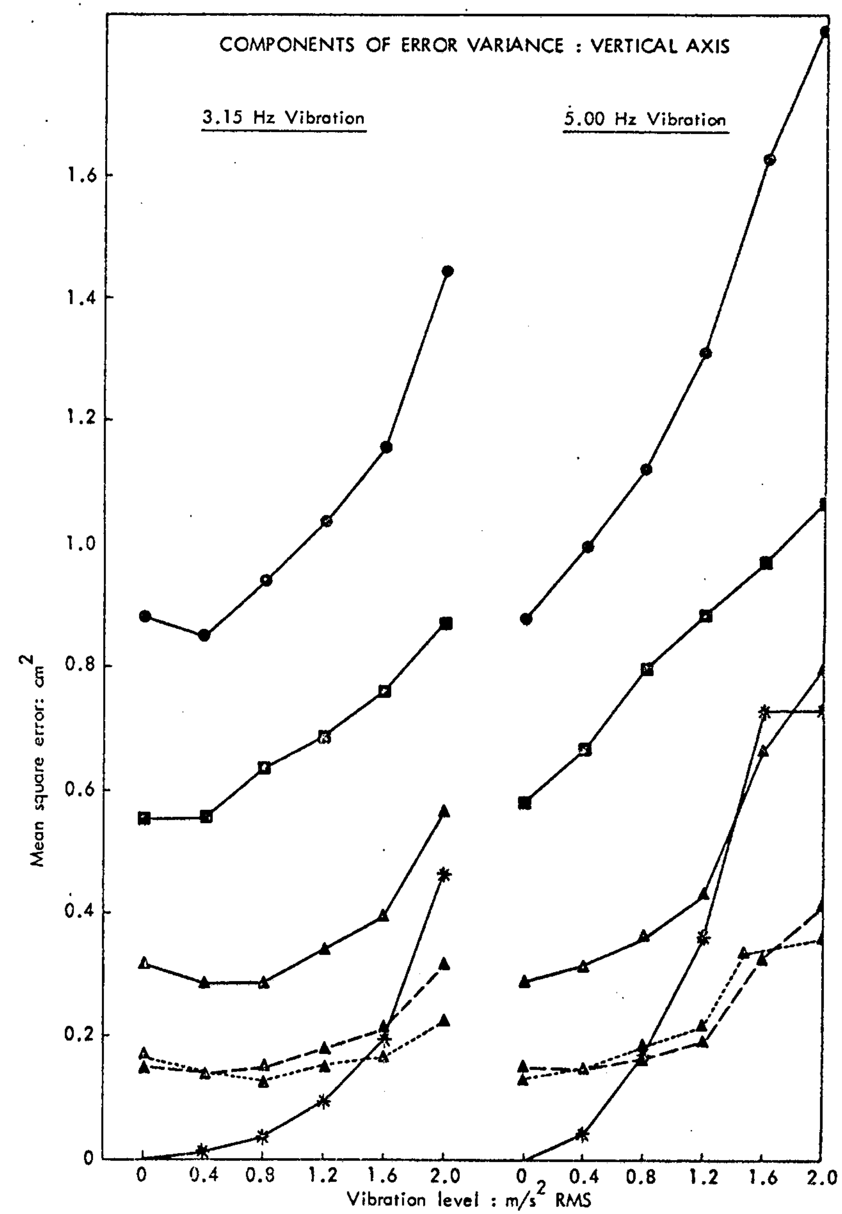


TABLE 9.4.1. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 5
R.M.S. TRACKING ERROR IN HORIZONTAL AXIS.

Treatments: S = Subjects, V = Vibration level, F = Vibration frequency

(a) TOTAL R.M.S. ERROR, 0-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.50694	7	0.07242	39.12	0.01
V	0.10077	5	0.02015	13.56	0.01
F	0.00081	1	0.00081	0.28	ns
V x F	0.00924	5	0.00184	0.92	ns
RESIDUAL	0.14252	77	0.00185		
V x S	0.05199	35	0.00148		
F x S	0.02032	7	0.00290		
V x F x S	0.07020	35	0.00200		
Orthogonal Trend Analyses:					
V at F1	0.04221	5	0.00844	5.70	0.01
LINEAR REG.	0.03333	1	0.03333	22.52	0.01
QUADRATIC	0.00503	1	0.00503	3.40	0.1
NONLINEAR	0.00888	4	0.00222	1.50	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 78.96270					
V at F2	0.06780	5	0.01356	9.16	0.01
LINEAR REG.	0.06359	1	0.06359	42.97	0.01
QUADRATIC	0.00122	1	0.00122	0.82	ns
NONLINEAR	0.00420	4	0.00105	0.71	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 93.79897					

(b) R.M.S. CORRELATED ERROR, 0-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.39987	7	0.05712	27.40	0.01
V	0.03317	5	0.00663	6.54	0.01
F	0.00348	1	0.00348	0.48	ns
V x F	0.00700	5	0.00140	0.65	ns
RESIDUAL	0.16050	77	0.00208		
V x S	0.03546	35	0.00101		
F x S	0.04999	7	0.00714		
V x F x S	0.07503	35	0.00214		
Orthogonal Trend Analyses:					
V at F1	0.02912	5	0.00582	5.76737	0.01
LINEAR REG.	0.02427	1	0.02427	24.03031	0.01
QUADRATIC	0.00000	1	0.00000	0.00244	ns
NONLINEAR	0.00485	4	0.00121	1.20164	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 83.33194					
V at F2	0.05122	5	0.01024	10.14332	0.01
LINEAR REG.	0.03828	1	0.03828	37.90819	0.01
QUADRATIC	0.00535	1	0.00535	5.30442	0.05
NONLINEAR	0.01293	4	0.00323	3.20210	0.05
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 74.74512					

(c) R.M.S. REMNANT, 0-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.32912	7	0.04701	34.97	0.01
V	0.11011	5	0.02202	15.92	0.01
F	0.00038	1	0.00038	0.17	ns
V x F	0.00504	5	0.00100	0.88	ns
RESIDUAL	0.10350	77	0.00134		
V x S	0.04840	35	0.00138		
F x S	0.01522	7	0.00217		
V x F x S	0.03986	35	0.00113		

Orthogonal Trend Analyses:

SOURCE	SS	DF	MS	F RATIO	p
V at F1	0.04018	5	0.00803	5.82	0.01
LINEAR REG.	0.02508	1	0.02508	18.17	0.01
QUADRATIC	0.01387	1	0.01387	10.05	0.01
NONLINEAR	0.01510	4	0.00377	2.73	0.05

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 62.41469

SOURCE	SS	DF	MS	F RATIO	p
V at F2	0.07497	5	0.01499	10.86	0.01
LINEAR REG.	0.05923	1	0.05923	42.92	0.01
QUADRATIC	0.01534	1	0.01534	11.11	0.01
NONLINEAR	0.01574	4	0.00393	2.85	0.05

PERCENTAGE LINEARITY OF TREATMENT EFFECT = 79.00310

(d) R.M.S. REMNANT, 0-1Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.21489	7	0.03069	26.76	0.01
V	0.04647	5	0.00929	6.85	0.01
F	0.00000	1	0.00000	0.01	ns
V x F	0.00668	5	0.00133	1.24	ns
RESIDUAL	0.08832	77	0.00114		
V x S	0.04744	35	0.00135		
F x S	0.00331	7	0.00047		
V x F x S	0.03755	35	0.00107		

(e) R.M.S. REMNANT, 1-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.14547	7	0.02078	29.48	0.01
V	0.06256	5	0.01251	21.51	0.01
F	0.00079	1	0.00079	0.32	ns
V x F	0.00079	5	0.00015	0.32	ns
RESIDUAL	0.05426	77	0.00070		
V x S	0.02035	35	0.00058		
F x S	0.01687	7	0.00241		
V x F x S	0.01702	35	0.00048		

*note: F1 = 3.15Hz, F2 = 5.00Hz.

TABLE 9.4.2. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 5
R.M.S. TRACKING ERROR MEASURES IN VERTICAL AXIS.

Treatments: S = Subjects, V = Vibration level, F = Vibration frequency

(a) TOTAL R.M.S. ERROR, 0-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.99138	7	0.14163	29.59	0.01
V	0.38476	5	0.07695	18.37	0.01
F	0.08432	1	0.08432	6.52	0.05
V x F	0.02618	5	0.00523	1.39	ns
RESIDUAL	0.36853	77	0.00478		
V x S	0.14656	35	0.00418		
F x S	0.09047	7	0.01292		
V x F x S	0.13148	35	0.00375		
Orthogonal Trend Analyses:					
V at F1	0.12321	5	0.02464	5.89	0.01
LINEAR REG.	0.10820	1	0.10820	25.88	0.01
QUADRATIC	0.01348	1	0.01348	3.22	0.1
NONLINEAR	0.01500	4	0.00375	0.89	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 87.81824					
V at F2	0.28774	5	0.05754	13.76	0.01
LINEAR REG.	0.28653	1	0.28653	68.54	0.01
QUADRATIC	0.00078	1	0.00078	0.18	ns
NONLINEAR	0.00121	4	0.00030	0.07	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 99.57938					

(b) R.M.S. INPUT-CORRELATED ERROR, 0-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.44168	7	0.06309	19.69	0.01
V	0.17926	5	0.03585	18.22	0.01
F	0.05949	1	0.05949	5.19	0.05
V x F	0.01011	5	0.00202	0.72	ns
RESIDUAL	0.24671	77	0.00320		
V x S	0.06885	35	0.00196		
F x S	0.08010	7	0.01144		
V x F x S	0.09774	35	0.00279		
Orthogonal Trend Analyses:					
V at F1	0.06260	5	0.01252	6.38	0.01
LINEAR REG.	0.05940	1	0.05940	30.30	0.01
QUADRATIC	0.00188	1	0.00188	0.96	ns
NONLINEAR	0.00319	4	0.00079	0.40	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 94.88895					
V at F2	0.12677	5	0.02535	12.93	0.01
LINEAR REG.	0.12417	1	0.12417	63.35	0.01
QUADRATIC	0.00208	1	0.00208	1.06	ns
NONLINEAR	0.00259	4	0.00064	0.33	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 97.94999					

(c) R.M.S. REMNANT, 0-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.85137	7	0.12162	33.71	0.01
V	0.22278	5	0.04455	9.82	0.01
F	0.02622	1	0.02622	5.51	0.05
V x F	0.02481	5	0.00496	2.02	0.01
RESIDUAL	0.27775	77	0.00360		
V x S	0.15866	35	0.00453		
F x S	0.03326	7	0.00475		
V x F x S	0.08583	35	0.00245		
Orthogonal Trend Analyses:					
V at F1	0.06076	5	0.01215	2.68	0.05
LINEAR REG.	0.04229	1	0.04229	9.33	0.01
QUADRATIC	0.01783	1	0.01783	3.93	0.1
NONLINEAR	0.01846	4	0.00461	1.01	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 69.61099					
V at F2	0.18683	5	0.03736	8.24	0.01
LINEAR REG.	0.17493	1	0.17493	38.61	0.01
QUADRATIC	0.01060	1	0.01060	2.34	ns
NONLINEAR	0.01189	4	0.00297	0.65	ns
PERCENTAGE LINEARITY OF TREATMENT EFFECT = 93.63245					

(d) R.M.S. REMNANT, 0-1Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.41753	7	0.05964	27.03	0.01
V	0.08114	5	0.01622	6.42	0.01
F	0.02045	1	0.02045	6.50	0.05
V x F	0.02191	5	0.00438	2.57	0.05
RESIDUAL	0.16987	77	0.00220		
V x S	0.08840	35	0.00252		
F x S	0.02199	7	0.00314		
V x F x S	0.05946	35	0.00169		

(e) R.M.S. REMNANT, 1-2.6Hz.

SOURCE	SS	DF	MS	F RATIO	p
S	0.47227	7	0.06746	37.30	0.01
V	0.14654	5	0.02930	12.32	0.01
F	0.00733	1	0.00733	3.43	ns
V x F	0.00626	5	0.00125	1.06	ns
RESIDUAL	0.13927	77	0.00180		
V x S	0.03320	35	0.00237		
F x S	0.01495	7	0.00213		
V x F x S	0.04111	35	0.00117		

*note: F1 = 3.15Hz, F2 = 5.00Hz.

Tracking runs were three minutes long, with two minutes rest between runs. The forcing function and control output in both axes of the task were recorded on a four channel F.M. tape recorder for later analysis by digital computer. The sampling rate of the analogue to digital conversion was 12.8 samples/second and the resolution of the frequency analysis was 0.20 Hz, giving 176 degrees of freedom.

9.4. RESULTS OF TRACKING ERROR MEASURES DURING SINUSOIDAL VIBRATION CONDITIONS.

The same components of error variance were evaluated as in previous experiments, however as the first vibration frequency was 3.15 Hz, the bandwidth of the remnant, input correlated error and total error excluding vibration-correlated error was restricted to 2.6 Hz rather than 3 Hz. Also evaluated was the total overall error variance (including the vibration-correlated error component). Each of these mean square error components was evaluated separately for each axis of the two dimensional task. Analyses of variance and prediction procedures for the effects of complex motions were based on square root transformations of these data, or r.m.s. error, as the results of experiment 3 indicate that the r.m.s. error components can be expected to have the most linear relationship to the r.m.s. vibration level. The average r.m.s. error components in each axis of the task, during the sinusoidal vibration conditions, are shown in figures 9.4.1a and 9.4.1b. The average mean square error components, before transformation, are also shown in figures 9.4.2a and 9.4.2b for comparison with the results of experiment 3. Separate 6 x 2, mixed effects analyses of variance, with subjects as randomnized blocks, were carried out for each error component in each axis. ANOVA summary tables for the horizontal error components are given in tables 9.4.1a to 9.4.1e and for vertical error components in tables 9.4.2a to 9.4.2e. The analyses of variance indicate that there were highly significant effects of vibration level on all the error components in both horizontal and vertical axes. There were no significant differences between the effects of the two vibration frequencies on any of the horizontal axis error components, but the 5.00 Hz vibration conditions had a significantly greater effect than the 3.15 Hz vibration conditions on all the vertical error components except 1-2.6 Hz remnant.

It can be seen from figure 9.4.2. that the increases in mean square remnant with increasing vibration level are positively correlated with the levels of vibration-correlated error, as shown in the results of experiment 3 with 4Hz vibration of the seat or control. However, unlike the whole-body vibration conditions in experiment 3, there were consistent and significant increases in input-correlated error in both horizontal and vertical tracking axes with both vibration frequencies. There are also significant increases in remnant in both 0-1Hz and 1-2.6Hz bandwidths in the present results, whereas only the increase in 1-3Hz remnant was significant during the 4Hz whole-body vibration conditions in experiment 3. Larger amounts of vibration-correlated error are present in the vertical tracking axis and, as may be expected from the conclusions of experiment 3, these are accompanied by larger increases in the other error components.

Tests for linear trends in the r.m.s. error components, with increasing r.m.s. vibration levels, were carried out for each axis and vibration frequency using orthogonal contrasts. There were significant linear trends in all the data but there were also significant departures from linearity (indicating the presence of higher order trends also) for input-correlated error in the horizontal axis with 5.00Hz vibration, and for total remnant in the horizontal axis with both 3.15 and 5.00Hz vibration.

9.5. RESULTS OF TRANSFER FUNCTION MEASURES.

The modulus and phase of the closed-loop transfer functions in each axis during sinusoidal vibration conditions, were subjected to 3 factor (transfer function frequency, vibration level and vibration frequency), mixed affects analyses of variance with subjects as randomnized blocks. ANOVA summary tables for the horizontal transfer function are given in tables 9.5.1a and 9.5.1b and for the vertical transfer function in tables 9.5.2a and 9.5.2b. Transfer function data is illustrated graphically in figures 9.5.1 to 9.5.3. Sinusoidal vibration can be seen to result in slight decreases in phase lags in the horizontal axis, although these are not statistically significant. Similar slight decreases in phase lags were observed in the results of experiment 3. The more severe complex motions do not, however, produce

TABLE 9.5.1. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 5
TRANSFER FUNCTION MEASURES, HORIZONTAL AXIS.

Treatments: S = Subjects, T = Transfer function frequency,
V = Vibration level, F = Vibration frequency.

(a) TRANSFER FUNCTION MODULUS.

SOURCE	SS	DF	MS	F RATIO	p
S	2.51797	7	0.35971	58.83	0.01
T	4.67407	5	0.93481	70.86	0.01
V	0.28525	5	0.05705	3.54	0.05
F	0.07882	1	0.07882	1.65	ns
T x V	0.24124	25	0.00964	3.57	0.01
T x F	0.03179	5	0.00635	1.57	ns
V x F	0.03576	5	0.00715	0.44	ns
T x V x F	0.06658	25	0.00266	0.92	ns
RESIDUAL	3.03848	497	0.00611		
T x S	0.46170	35	0.01319		
V x S	0.56284	35	0.01608		
F x S	0.33304	7	0.04757		
T x V x S	0.47284	175	0.00270		
T x F x S	0.14111	35	0.00403		
V x F x S	0.56094	35	0.01602		
T x V x F x S	0.50601	175	0.00289		

(b) TRANSFER FUNCTION PHASE LAG.

SOURCE	SS	DF	MS	F RATIO	p
S	4.33699	7	0.61957	74.68	0.01
T	2.50232	5	0.50046	21.48	0.01
V	0.17381	5	0.03476	2.15	0.1
F	0.00107	1	0.00107	0.01	ns
T x V	0.10481	25	0.00419	1.31	ns
T x F	0.07924	5	0.01584	3.10	0.05
V x F	0.07282	5	0.01456	0.69	ns
T x V x F	0.13993	25	0.00559	1.31	ns
RESIDUAL	4.12297	497	0.00829		
T x S	0.81522	35	0.02329		
V x S	0.56457	35	0.01613		
F x S	0.53221	7	0.07603		
T x V x S	0.55819	175	0.00318		
T x F x S	0.17858	35	0.00510		
V x F x S	0.73117	35	0.02089		
T x V x F x S	0.74304	175	0.00424		

TABLE 9.5.2. ANALYSIS OF VARIANCE SUMMARY TABLES - EXPERIMENT 5
TRANSFER FUNCTION MEASURES, VERTICAL AXIS.

Treatments: S = Subjects, T = Transfer function frequency,
V = Vibration level, F = Vibration frequency.

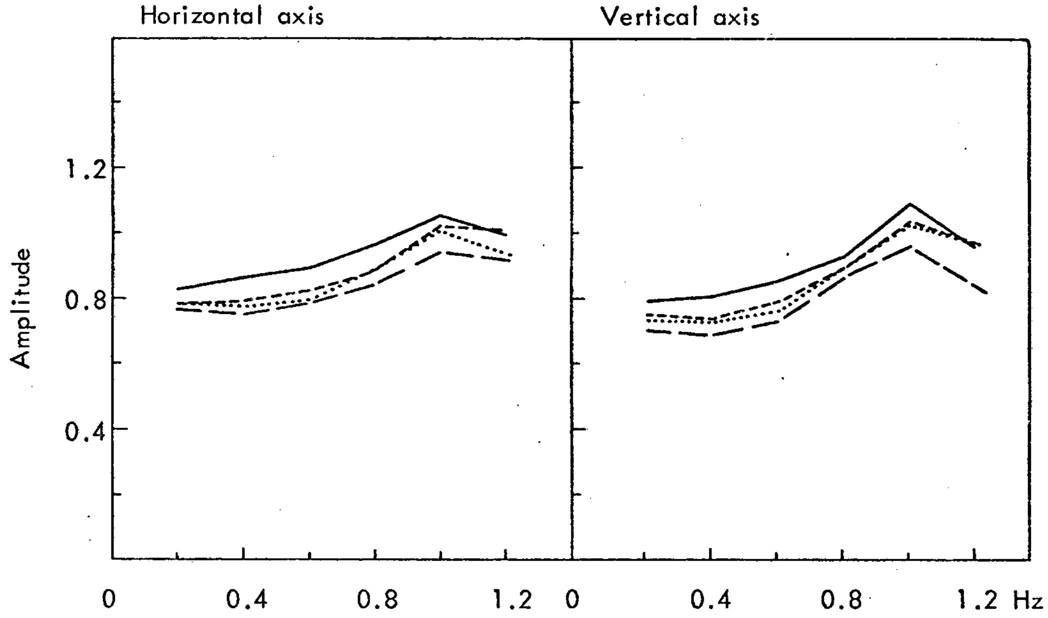
(a) TRANSFER FUNCTION MODULUS.

SOURCE	SS	DF	MS	F RATIO	p
S	5.13889	7	0.73413	51.50	0.01
T	6.67581	5	1.33516	31.69	0.01
V	0.55930	5	0.11186	3.65	0.05
F	0.08612	1	0.08612	0.66	ns
T x V	0.11646	25	0.00465	0.65	ns
T x F	0.00280	5	0.00056	0.09	ns
V x F	0.19049	5	0.03809	1.18	ns
T x V x F	0.19958	25	0.00798	1.35	ns
RESIDUAL	7.08411	497	0.01425		
T x S	1.47458	35	0.04213		
V x S	1.07205	35	0.03063		
F x S	0.90985	7	0.12998		
T x V x S	1.25400	175	0.00716		
T x F x S	0.21454	35	0.00612		
V x F x S	1.12927	35	0.03226		
T x V x F x S	1.02982	175	0.00588		

(b) TRANSFER FUNCTION PHASE LAG.

SOURCE	SS	DF	MS	F RATIO	p
S	4.60400	7	0.65771	44.37	0.01
T	13.67226	5	2.73445	79.84	0.01
V	1.05573	5	0.21115	7.36	0.01
F	0.40927	1	0.40927	3.40	ns
T x V	0.50247	25	0.02009	2.83	0.01
T x F	0.10751	5	0.02150	2.10	ns
V x F	0.22461	5	0.04492	1.26	ns
T x V x F	0.19295	25	0.00771	0.91	ns
RESIDUAL	7.36638	497	0.01482		
T x S	1.19859	35	0.03424		
V x S	1.00406	35	0.02868		
F x S	0.84171	7	0.12024		
T x V x S	1.23994	175	0.00708		
T x F x S	0.35701	35	0.01020		
V x F x S	1.24142	35	0.03546		
T x V x F x S	1.48364	175	0.00847		

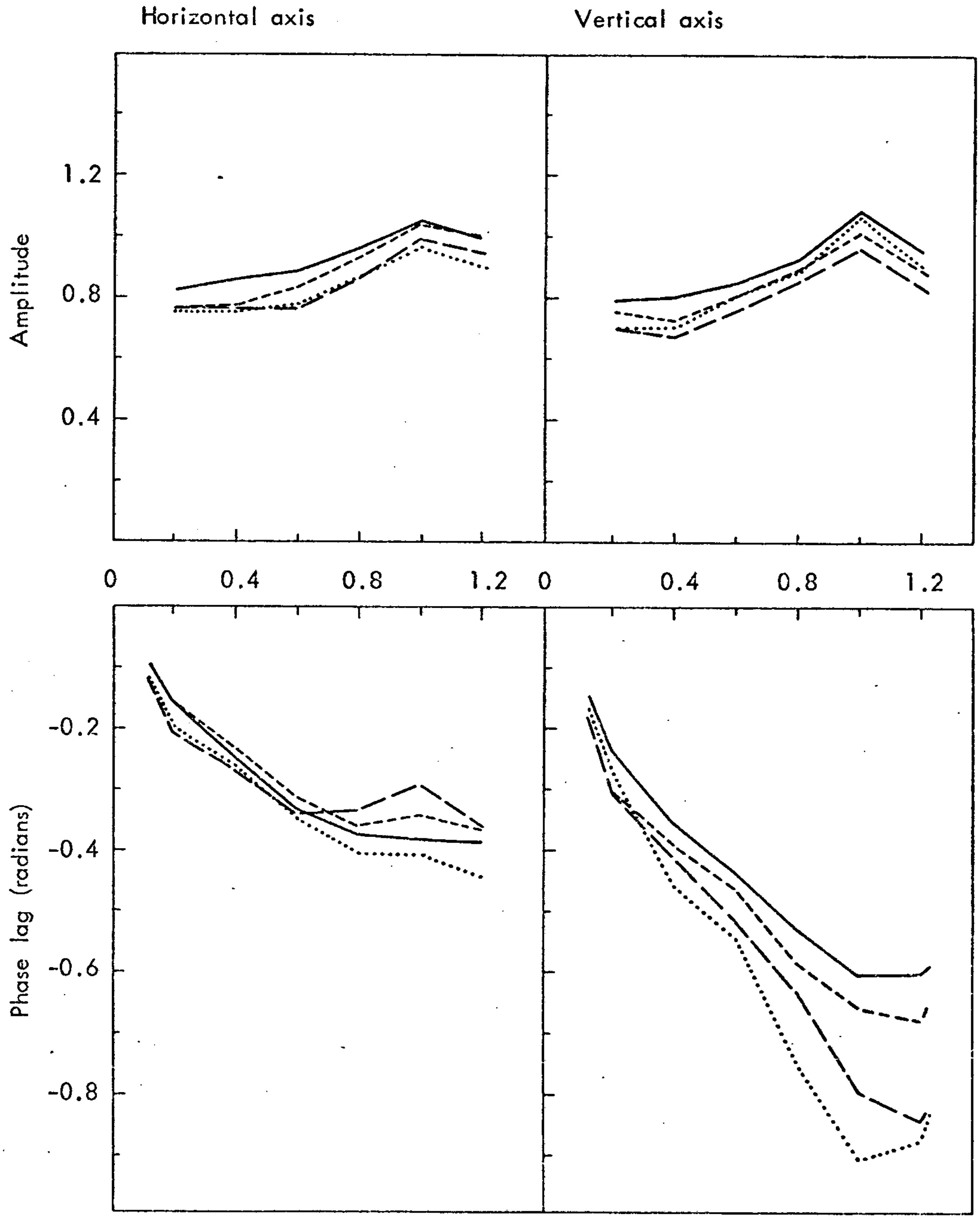
FIG 9.5.1.



- ——— Static
- - - - - 3.15 Hz at 1.2 m/s^2 RMS
- — — 5.00 Hz at 1.2 m/s^2 RMS
- ········ Combination of 3.15 Hz at 1.2 m/s^2 RMS and 5.00 Hz at 1.2 m/s^2 RMS (1.7 m/s^2 RMS).

MEAN CLOSED-LOOP HUMAN OPERATOR TRANSFER FUNCTIONS IN EACH AXIS OF A DUAL AXIS PURSUIT TRACKING TASK DURING SINUSOIDAL AND DUAL-FREQUENCY WHOLE-BODY VIBRATION.

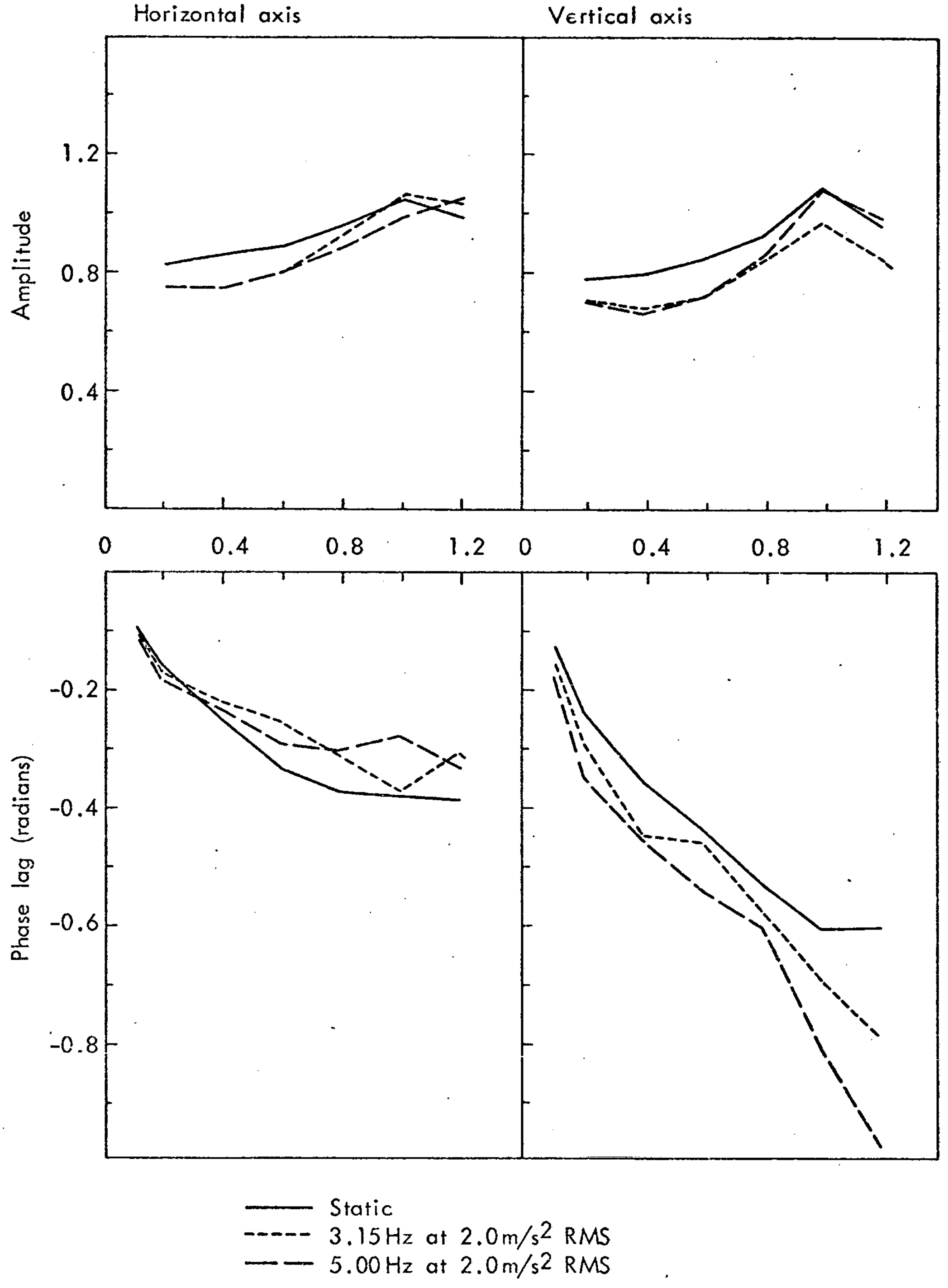
FIG 9.5.2.



Static
3.15 Hz at 1.6 m/s² RMS
5.00 Hz at 1.6 m/s² RMS
Combination of 3.15 Hz at 1.6 m/s² RMS and 5.00 Hz at 1.6 m/s² RMS (2.26 m/s² RMS)

MEAN CLOSED-LOOP HUMAN OPERATOR TRANSFER FUNCTIONS IN EACH AXIS OF A DUAL AXIS PURSUIT TRACKING TASK DURING SINUSOIDAL AND DUAL-FREQUENCY WHOLE-BODY VIBRATION.

FIG 9.5.3.



MEAN CLOSED-LOOP HUMAN OPERATOR TRANSFER FUNCTIONS IN EACH AXIS OF A DUAL-AXIS PURSUIT TRACKING TASK DURING SINUSOIDAL WHOLE-BODY VIBRATION.

this tendency. There are however significant decreases in gain in the horizontal transfer functions with increasing vibration level which appear to be most consistent at lower transfer function frequencies, accounting for the significant vibration level x transfer function frequency interaction. In the vertical axis however, there are highly significant increases in phase lags with increasing vibration levels. A significant vibration level x transfer function frequency interaction reflects the increasing effect at higher transfer function frequencies. The effects of vibration on the vertical modulus are similar to those on the horizontal modulus, decreases in gain occuring with increasing vibration level. The suppression of gain and increases in phase lags account for the signfiicant effects of vibration on input-correlated error.

9.6. PREDICTION OF THE EFFECTS OF COMPLEX MOTION.

The three prediction procedures defined in the introduction to this experiment were evaluated for total overall r.m.s. error, total error excluding vibration-correlated error, vertical input-correlated error and vertical total remnant. Horizontal input-correlated error and remnant were excluded because of the significant nonlinearities indicated by the trend tests.

The regression equations

$$E = A_o + A_1.V_{3.15}$$

and

$$E = B_o + B_1.V_{5.00}$$

were calculated, where E is the mean r.m.s. error, $V_{3.15}$ is the acceleration level of 3.15Hz, sinusoidal vibration and $V_{5.00}$ is the acceleration level of 5.00Hz, sinusoidal vibration. Note that the prediction calculations were based only on the mean data for the eight subjects. Individual linear correlation coefficients were generally much lower than those for the mean data due to order effects and short term perturbations which are partially balanced out when the data are pooled. Individual regression equations and correlation coefficients for total r.m.s. error data are compared in table 9.6.1. Static conditions were excluded from the regression calculations as inspection of the data suggested that there may be some threshold nonlinearities, especially in the horizontal error data. The level $V_{5.00}$ of 5.00Hz vibration equivalent in effect to each 3.15Hz level (i.e. the weighted level of 3.15Hz vibration) was then calculated from

$$V_{5.00} = V_{3.15_w} = \frac{A_o - B_o + A_1.V_{3.15}}{B_1}$$

The level V_p of 5.00Hz vibration equivalent in effect to each of the dual-frequency vibration conditions was calculated according to three different prediction models. These were

$$\text{(a)}\quad V_p = (V^2_{3.15_w} + V^2_{5.00})^{\frac{1}{2}}$$

or the root mean square sum of weighted components.

$$\text{(b)}\quad \text{if } V_{3.15_w} > V_{5.00},\ V_p = V_{3.15_w}$$

$$\text{otherwise,}\qquad V_p = V_{5.00}$$

or the most severe, weighted component alone, and

$$\text{(c)}\quad V_p = V_{3.15_w} + V_{5.00}$$

or the arithmetic sum of weighted components. The equivalent predicted error, E_p, was then calculated from

$$E_p = B_o + B_1.V_p$$

We can obtain 95% confidence limits for error predicted from the above

Table 9.6.1 Regression equations and linear correlation coefficients (r) for total rms tracking error (ε cm) with vibration level (V m/s^2), for individual and mean data.

	3.15 Hz Vibration		5.00 Hz Vibration	
Horizontal Tracking	Regression Equation	r	Regression Equation	r
Subject 1	.878 + .047v	.609	.744 + .175v	.907
Subject 2	.636 + .371v	.938	.992 + .054v	.564
Subject 3	.932 + .216v	.799	.976 + .272v	.939
Subject 4	1.096 + .049v	.602	.968 + .236v	.887
Subject 5	.628 + .212v	.712	.624 + .210v	.957
Subject 6	.932 + .092v	.661	1.032 + .012v	.127
Subject 7	.762 + .064v	.783	.601 + .329v	.936
Subject 8	.932 + .329v	.973	.940 + .231v	.839
Mean Data	.850 + .148v	.971	.864 + .165v	.966
Vertical Tracking				
Subject 1	.848 + .102v	.672	.672 + .259v	.827
Subject 2	.488 + .792v	.925	.892 + 276v	.935
Subject 3	.976 + .285v	.853	1.088 + .736v	.899
Subject 4	1.048 + .164v	.825	.812 + .548v	.930
Subject 5	.744 + .068v	.794	.748 + .200v	.954
Subject 6	.740 + .444v	.994	.832 + .580v	.956
Subject 7	.716 + .128	.953	.728 + .343v	.921
Subject 8	.832 + .120v	.982	.940 + .156v	.853
Mean Data	.801 + .263v	.971	.875 + .387v	.982

equation from

$$\frac{L}{U} = E_p \pm t_{(0.975,\ 3)} \cdot S_{E.V}$$

where $S_{E.V}$ is the standard deviation of the predicted error for a given level of 5.00Hz vibration (Ostle, 1963).

Predicted and measured values of total r.m.s. error are compared in table 9.6.2. for the horizontal axis of the task and in table 9.6.3. for the vertical axis. It can be seen that prediction model (a), the r.m.s. sum of weighted vibration components, resulted in the smallest mean differences and mean absolute differences between measured and predicted values. It can be seen from Figure 9.6.1. that all of the measured values of total r.m.s. error are within the 95% confidence interval for predicted errors at equivalent vibration levels predicted by model (a). However some measured error values were significantly different from predicted values at equivalent vibration levels predicted by models (b) and (c) (see tables 9.6.2. and 9.6.3.). In order to determine whether the mean differences between measured and predicted errors were significantly different from zero, 't' tests were carried out. Mean differences, mean absolute differences and 't' values for all error components, with each prediction model, are given in table 9.6.4. For total r.m.s. error in the horizontal axis the mean differences were significant with prediction models (b) and (c). For total r.m.s. error in the vertical axis the mean difference is significant with all three prediction models, however the mean differences with models (b) and (c) are highly significant ($p<0.01$) and it is evident that the best overall predictions were obtained with model (a).

It is also evident that model (a) gave the best predictions of total r.m.s. error below 2.6Hz, although the mean difference between measured and predicted horizontal error with model (b) was not significant. However it appears that model (a) may not predict input-correlated and remnant error components as well. The best predictions of vertical, input-correlated error were obtained with model (b), the most severe weighted component alone. Inspection of the data reveals that measured error was generally even smaller than that predicted by the most severe component.

Table 9.6.2 Mean levels of rms tracking error in the horizontal axis compared with levels predicted by three procedure.

		Complex Vibration Conditions											
		1	2	3	4	5	6	7	8	9	10	Mean difference of measured & predicted error	Mean absolute difference of measured & predicted error
MEASURED LEVELS	Level of 3.15 Hz component, V1 (m/s^2)	1.200	1.200	1.200	1.200	0.400	0.800	1.600	2.000	1.200	1.600		
	Level of 5.00 Hz component, V2 (m/s^2)	0.400	0.800	1.600	2.000	1.200	1.200	1.200	1.200	1.200	1.600		
	Equivalent 5.00 Hz level of V1 (m/s^2)	0.993	0.993	0.993	0.993	0.273	0.633	1.353	1.713	0.993	1.353		
	Measured rms tracking error (cm)	0.979	1.088	1.188	1.263	1.034	1.038	1.186	1.277	1.087	1.322		
PREDICTED LEVELS: rms sum of Components	Equivalent 5 Hz level of complex vib. (m/s^2)	1.071	1.275	1.883	2.233	1.231	1.357	1.809	2.092	1.558	2.095		
	Predicted rms tracking error (cm)	1.041	1.074	1.175	1.232	1.067	1.088	1.162	1.209	1.121	1.210		
	Difference of measured & predicted error	+.062	-.014	-.013	-.031	+.033	+.050	-.024	-.068	+.034	-.112	-.008	.044
Most severe Components	Equivalent 5 Hz level of complex vib. (m/s^2)	0.993	0.993	1.600	2.00	1.200	1.200	1.353	1.713	1.200	1.600		
	Predicted rms tracking error (cm)	1.028	1.028	1.128	1.194	1.062	1.062	1.087	1.147	1.062	1.128		
	Difference of measured & predicted error	+.049	-.060	-.060	-.069	+.028	+.024	-.099	-.130 *	-.025	-.194 *	-.053	.073
Arithmetic sum of Components	Equivalent 5 Hz level of complex vib. (m/s^2)	1.393	1.793	2.593	2.993	1.473	1.833	2.533	2.913	2.193	2.953		
	Predicted rms tracking error (cm)	1.094	1.160	1.292	1.357	1.107	1.166	1.282	1.344	1.226	1.351		
	Difference of measured & predicted error	+.115 *	+.072	+.104	+.094	+.073	+.128 *	+.096	+.067	+.139 *	+.029	+.092	.092

*Measured value significantly different from prediction at 5% level.

Table 9.6.3. Mean levels of rms tracking error in the vertical axis compared with levels predicted by three procedures

		Complex Vibration Conditions 1	2	3	4	5	6	7	8	9	10	Mean difference of measured & predicted error	Mean absolute difference of measured & predicted error
MEASURED LEVELS	Level of 3.15 Hz components, V1 (m/s)	1.200	1.200	1.200	1.200	0.400	0.800	1.600	2.000	1.200	1.600		
	Level of 5.00 Hz component, V2 (m/s)	0.400	0.800	1.600	2.000	1.200	1.200	1.200	1.200	1.200	1.600		
	Equivalent 5.00 Hz level of V1 (m/s)	0.622	0.622	0.622	0.622	0.078	0.350	0.893	1.165	0.622	0.893		
	Measured rms tracking error (cm)	1.134	1.329	1.601	1.772	1.310	1.333	1.640	1.716	1.421	1.698		
PREDICTED LEVELS: rms sum of Components	Equivalent 5 Hz level of complex vib.(m/s)	0.739	1.013	1.717	2.094	1.203	1.250	1.496	1.673	1.351	1.833		
	Predicted rms tracking error (cm)	1.162	1.268	1.541	1.687	1.341	1.360	1.455	1.524	1.399	1.585		
	Difference of measured & predicted error	+.028	-.061	-.060	-.085	+.031	+.027	-.185	-.192	-.022	-.113	-.063	.080
Most severe Components	Equivalent 5 Hz level of complex vib (m/s)	0.622	0.800	1.600	2.00	1.200	1.200	1.200	1.200	1.200	1.600		
	Predicted rms tracking error (cm)	1.116	1.185	1.495	1.650	1.340	1.340	1.340	1.340	1.340	1.495		
	Difference of measured & predicted error	-.018	-.144	-.106	-.122	+.030	+.007	-.300*	-.376*	-.081	-.203*	-.131	.138
Arithmetic sum of Components	Equivalent 5 Hz level of complex vib.(m/s)	1.022	1.422	2.222	2.622	1.278	1.550	2.093	2.365	1.822	2.493		
	Predicted rms tracking error (cm)	1.271	1.426	1.736	1.891	1.371	1.476	1.686	1.792	1.581	1.841		
	Difference of measured & proedicted error	+.137	+.097	+.135	+.119	+.061	+.143	+.046	+.076	+.160	+.143	+.112	.112

*Measured value significantly different from predicted value at 5% level.

FIG 9.6.1a.

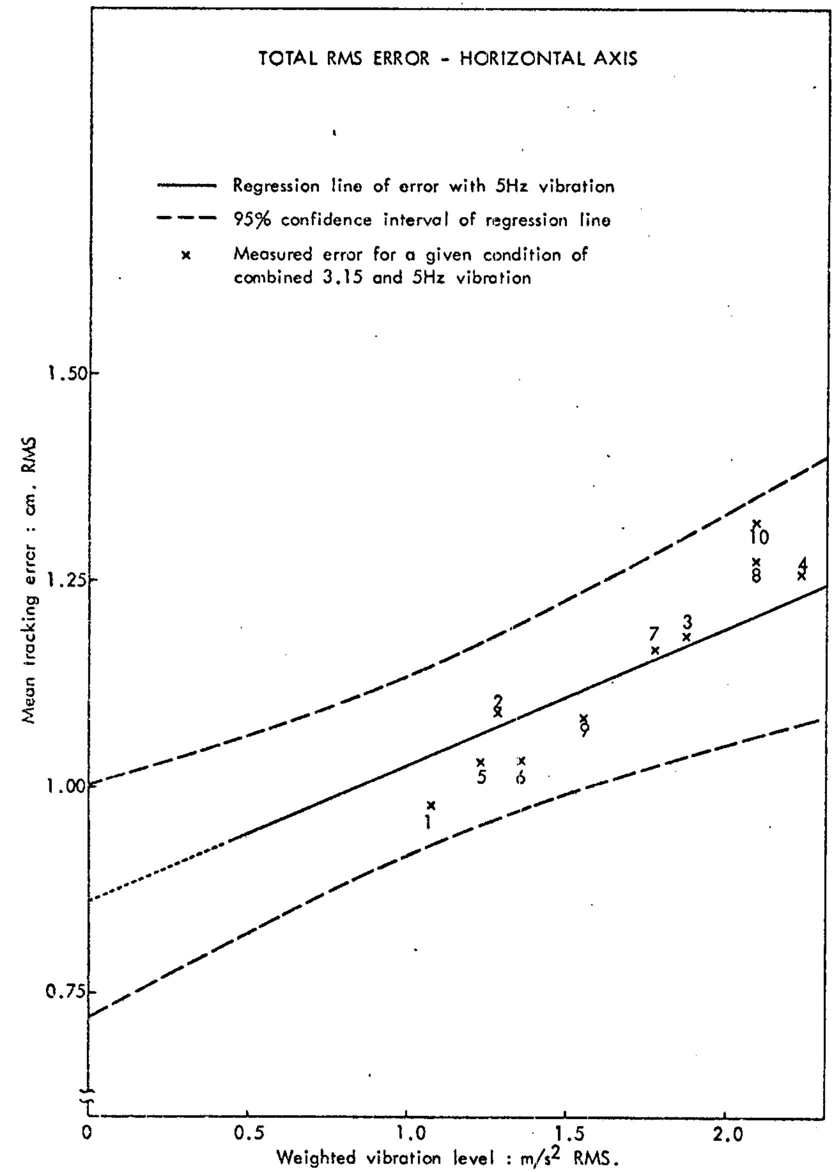


FIG 9.6.1b.

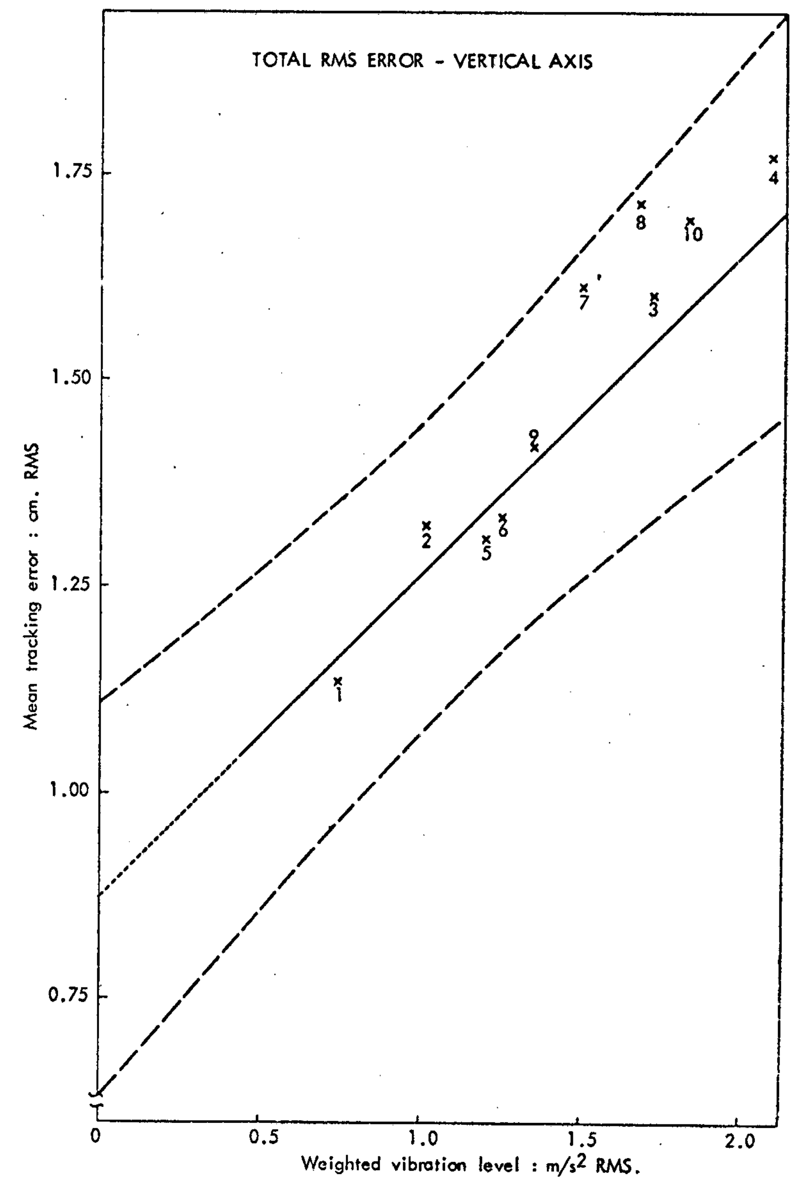


Table 9.6.4. Mean differences of measured and predicted error components with 3 prediction methods

Error components (cm rms)		HORIZONTAL AXIS Total error	Total error 0-2.6 Hz	VERTICAL AXIS Total error	Total error 0-2.6 Hz	Input-correlated error	Remnant
rms sum of components	Mean difference	-.008	+.005	-.063	-.020	+.036	-.059
	Mean absolute difference	.044	.037	.080	.044	.041	.063
	Standard error of difference	.052	.046	.078	.012	.033	.051
	't' statistic	0.48	0.32	2.42*	1.18	3.30**	3.47**
Most severe component	Mean difference	-.053	-.021	-.131	-.057	+.017	-.104
	Mean absolute difference	.073	.052	.138	.073	.050	.105
	Standard error of difference	.072	.059	.124	.080	.050	.074
	't' statistic	2.23*	1.07	3.16**	2.12*	0.98	12.66**
Arithmetic sum of components	Mean difference	+.092	+.062	+.112	+.072	+.071	+.044
	Mean absolute difference	.092	.064	.112	.072	+.071	.048
	Standard error of difference	.032	.031	.037	.028	.034	.026
	't' statistic	8.78**	5.83**	8.99**	7.77**	6.45**	5.14**

*p<.05 **p<.01

The mean difference between measured and predicted values of remnant in the vertical axis were highly significant with all three prediction models. The measured levels of remnant were generally greater than those predicted from the r.m.s. sum of weighted components and less than those predicted from the arithmetic sum of weighted components, although the latter procedure resulted in the lowest mean difference and mean absolute difference between measured and predicted values.

9.7. DISCUSSION.

Consistent with the previous experiments, low frequency whole-body vibration was observed to result in both vibration-correlated error and and increases in remnant, or operator-generated noise. These effects were greater in the vertical axis of the task, indicating that greater amounts of vibration-correlated stick activity are induced in the fore and aft direction than the side to side direction by low frequency vertical vibration of the seat and control. However unlike previous experiments, low frequency, sinusoidal vibration was observed to result in significant increases in input-correlated error. Examination of the transfer function data reveals that these increases are partially due to a significant suppression of gain (i.e. suppression of the amplitude of the operator's response), particularly at low frequencies. Significant increases in response lags, particularly at higher frequencies in the operator's response bandwidth, also contribute to the particularly large increases in input-correlated error in the vertical axis of the tracking task. There is also evidence of a slight reduction in phase lags in the horizontal tracking axis. This phenomenon has been observed in the results of previous experiments, particularly during vibration of the control stick and with artificially-induced low frequency breakthrough to the controlled element, and attributed to increases in the level of arousal of the operator. It is more difficult to explain the present results in terms of a general increase in arousal level, since they were accompanied by a simultaneous and larger increase in response lags in the vertical tracking axis. Nevertheless the mechanism has been shown by previous results to be somewhat selective, being more sensitive to control stick vibration than whole-body vibration, and the phenomenon may be more indicative of the focussing of the operator's attention on certain aspects of the task rather than changes in his arousal state. In this case the subjects appear to have concentrated primarily on the horizontal axis of the task at the expense of performance in the vertical axis. Note that even in static conditions the horizontal phase lags are smaller than the vertical phase lags, and the performance differential between the two axes may be at least partially due to the subjects' previous experiences as six of the subjects had previously taken part in experiments involving tracking in the horizontal axis only. The reduction in transfer function gain cannot easily be explained in terms of attention or arousal states and are more likely to be due to the presence of vibration-correlated activity superimposed upon the movement of the controlled element. This activity is likely to mask the coherent movement of the controlled element and is likely to cause the operator to overestimate the extent of his coherent movements.

The results suggest that the effects of dual-frequency vibration on overall tracking error in a simple manual tracking task, can be successfully predicted from the root mean square sum of weighted frequency components of the vibration. They also suggest that this procedure is more appropriate than predicting from the most severe component alone or from the arithmetic sum of weighted components. However, results of predictions of individual components of error variance show that considerable caution should be exercised in the application of this conclusion. The input-correlated error, or the error due to the linear portion of the operator's response, is over-estimated by the r.m.s. procedure whereas the remnant, or nonlinear portion of the response, is under-estimated. The net result appears to be that the overestimate of input-correlated error and the under-estimate of remnant are balanced out in the task used in this study.

The best prediction of the remnant due to dual-frequency vibration, in terms of the least mean difference and standard error of the difference between predicted and measured values, was given by the arithmetic sum of weighted components procedure. Evidence has been presented in experiments 2 and 3 which suggests that increases in remnant in a zero-order tracking task disturbed by low frequency vibration are due to perceptual confusion of the position of the controlled element on the display caused by vibration-induced activity. The severity of these disturbances is likely to be more dependent on the peak disturbance, which is given by the arithmetic sum of its components rather than its average or root mean square level. The best prediction of input-correlated error were given by the worst component procedure. Input-correlated error reflects the overall strategy and response lags of the operator. As we have already seen, these may be affected by shifts in attention, arousal level and other central factors including adaptive responses by the operator to compensate for the effects of vibration; and because of their complexity the effects of vibration on these processes are not well understood. In some situations, particularly with tasks of long duration, tracking performance has been observed to improve when vibration was present (Catterson et al, 1962, Wilkinson and Gray, 1974). These effects can be best explained in terms of increases in arousal or, as hypothesized earlier in this section, selective focussing of attention on different aspects of the task (the possible mechanisms of such an effect have been discussed at length by Lewis, 1974). It may be that the more irregular nature of the dual-frequency vibration is more arousing than sinusoidal motions, accounting for the overestimate of the effects of complex vibration on input-correlated error by the r.m.s. procedure.

9.8. CONCLUSIONS.

As with the simpler, single-axis tracking task in the earlier experiments, low frequency, z-axis, whole-body vibration was observed to induce increases in remnant or operator-generated noise in both axes of the two axis, zero-order, pursuit tracking task. The extent of these increases in remnant in either axis of the task were correlated with the amount of vibration-correlated error, consistent with the earlier hypothesis that the increases are due to perceptual confusion caused by vibration-correlated activity of the controlled element on the display. More vibration-correlated error was produced in the vertical axis of the tracking task, indicating that z-axis whole-body vibration in the 3 to 5Hz frequency range induces greater amounts of vibration-correlated control activity in the fore and aft horizontal axis than in the side to side axis. The control was also found to be more sensitive to 5.00Hz vibration than 3.15Hz vibration, although the difference is only significant in the vertical tracking axis (i.e. for the fore and aft axis of the control).

The low frequency vibration was also observed to result in significant increases in input-correlated error in the two axis task. Such increases have not been observed in the single-axis task during similar levels of vibration. However significant increases in correlated error have been observed in the single-axis task due to artificially-induced breakthrough on the display and due to diminished arousal during prolongued tracking runs. The increases in input-correlated error observed in this study are largely a result of suppression of gain, or the amplitude of coherent response, by the operator which may be also due to the presence of vibration-correlated activity of the controlled element, causing the operator to over-estimate his coherent control movements. The input-correlated error in the vertical tracking axis was inflated by increased response lags, which were not evident in the horizontal axis, indicating that the subjects attempted to maintain their horizontal tracking performance at the expense of their vertical tracking performance.

The level of sinusoidal vibration equivalent in effect to a given dual-frequency motion was predicted by three methods: (a) the r.m.s. sum of weighted components, (b) the most severe component alone, and (c) the arithmetic sum of weighted components. The best prediction of total r.m.s. error, compared with measured levels, were obtained with method (a) and the worst with method (c). However results of predictions of individual r.m.s. error components indicate that considerable caution should be exercised in the application of this result. The input-correlated error was overestimated by prediction method (a) and remnant was underestimated, the net result being that they balanced out in the prediction of total error. If the increase in total error under vibration had been composed mostly of remnant, as in the previous experiments with a single-axis task, an r.m.s. summation would most likely have underestimated the increase in total error.

10. GENERAL DISCUSSION OF EXPERIMENTAL RESULTS, CONCLUSIONS AND RECOMMENDATIONS.

10.1. GENERAL DISCUSSION.

It can be concluded from the results of experiments two and three that increases in tracking error in a simple one-axis, zero order, pursuit tracking task during low frequency (below 10Hz), sinusoidal, z-axis, whole-body or control vibration can be accounted for by involuntary vibration-induced control activity and operator-generated noise. The increase in operator-generated noise is caused by visual confusion of the position and movements of the controlled element in the display by the vibration-induced control activity. With vibration below 10Hz there is no evidence of any direct interference with neuromuscular actuation in this particular task and the results therefore do not support the hypothesis, proposed by Lewis (1974), that low frequency vibration degrades manual control performance primarily by interference with the kinaesthetic feedback mechanisms involved in the control of motor actions.

The extent to which vibration degrades tracking performance in a system such as has been used in these experiments will therefore be dependent on factors which influence the magnitude of vibration-induced disturbances of the controlled element. These factors include control and system dynamics, the points of application of vibration to the system and biodynamic factors influencing transmission of vibration through the body.

The results of experiment one showed that the effects of low frequency vibration can be considerably lessened by reducing the control gain, thereby reducing the amount of vibration-induced control activity transmitted to the controlled element in the display. Such measures will, however, affect the overall efficiency of the control. Although reductions in the gains of the controls in experiment one resulted in proportional decreases in remnant, and particularly in the increased remnant due to the vibration, reducing the control gain beyond a certain point was also shown to result in a progressive increase in input-correlated error. This increase in input-correlated error was shown to be due to increased response lags on account of the increase in amplitude of control actions necessary to produce a given deflection of the controlled element (this effect may be particularly pronounced with moving controls, in which inertia and friction tend to oppose the initiation and halting of control movements). The optimum control gain will therefore be a compromise between the desirable speed of response and the effects of vibration.

The effect of low frequency vibration may also be reduced if vibration-induced activity in the control can be damped out mechanically or filtered by the control dynamics. In real manual control systems pure zero order control laws are very rare. We would expect the effect of vibration-induced control activity to be considerably diminished in higher order control systems, or systems with higher order lags, due to attenuation by machine dynamics (each integration of the control output represents a 6 dB/octave attenuation of control activity). However low frequency, whole-body vibration has been observed to cause significant increases in remnant in first order, compensatory tracking tasks (e.g., Allen et al, 1973). Howell and Briggs (1959) reported an experiment in which increasing amounts of low-frequency noise were added to either the controlled element or forcing function markers in a pursuit tracking task, or to the error marker in the same task with a compensatory display. It was found that the tracking error was least affected when the controlled element in the pursuit display was disturbed and most affected when the compensatory display was disturbed. This indicates that smaller vibration-induced disturbances may be required to produce similar tracking error increases in a compensatory task. No data concerning the effect of vibration on a first-order pursuit task is known to the author. Also, in a first order task there is no direct relationship between control displacement, or force, and the displacement of the controlled element in the display. In this case the operator may be more dependent on exteroceptive kinaesthetic cues of the state of the controlling limb, and extra confusion may arise due to vibration-induced movements superimposed on voluntary control actions.

There was some evidence in the results of experiments 2 and 3 that vibration frequencies higher than 10Hz can interfere with neuromuscular actuation processes, as suggested by Lewis and Griffin (1976). These effects were also observed to result in increases in operator-generated noise, but the effects were only observed when very high levels of vibration were present at the limb/control interface and, at least for frequencies up to 64Hz, are not likely to often occur in vehicles. However these results may have relevance to situations involving the control of vibrating hand tools.

The results of the first three experiments were measured during vibration exposures of less than five minutes duration. However, human operators in real manual control situations are usually exposed to vibration for much longer periods. It can be concluded from the results of experiment three that vibration-induced stick activity and operator generated noise due to perceptual confusion during low frequency whole-body vibration, are effectively constant throughout a 60 minute vibration exposure and show no trace of any after-effect. However the results also show that after only about 15 minutes continuous performance of the simple tracking task there was a large increase in response lags and suppression of coherent responses by the subjects due to the under-arousing nature of the laboratory task. Operators in real manual control situations are much less likely to be affected in such a way, as their tasks are usually more motivating and they are generally exposed to a wider variety of stimuli than those present in the controlled laboratory environment. The implications of these results for the design of experiments investigating the specific effects of vibration (i.e. those effects due to some kind of mechanical interference) on manual control tasks in the laboratory are that tracking runs should be very short, with as much stimulation as possible between runs, if the results are not to be confounded with problems of arousal and motivation (especially if the performance measures cannot distinguish between specific and non-specific effects of vibration.). This situation is exacerbated by the more arousing nature of vibration runs compared to static control runs.

For instance, Khalil and Ayoub (1970) and Dudek et al (1973) have described experiments in which subjects performed a tracking task for periods of one or two hours under different work/rest schedules, from 5 minutes on and 5 off to 60 minutes on and 60 off, during continuous 5Hz vertical (z axis) vibration. As the length of the work/rest periods increased, the difference in average tracking error between static and vibration conditions became progressively less, until with 60 minute work/rest periods the overall performance was better during vibration than in static conditions.

The results of experiment five emphasise the difficulties in predicting the effects of even short-time vibration exposures when the task is more complex than that in the first few experiments or when the motions are non-sinusoidal. In a two-axis tracking task whole-body vibration was observed to result in significant increases in input-correlated error, due to changes in the operators' closed loop transfer function. These transfer function changes took the form of both suppression of gain and increases in response lags. This suggests that the operator's ability to track through display noise may be diminished with increases in the amount of information he is required to transmit. That the increases in response lags appeared only in the vertical tracking record illustrate that the operator is not able to give his entire attention to the whole task simultaneously: in this case attention appears to have been selectively focussed on the horizontal aspect of the tracking task, at the expense of vertical tracking performance. Regarding the prediction of the effects of complex vibration waveforms, the best predictions of r.m.s. tracking error during dual-frequency whole-body vibration were obtained by an r.m.s. summation procedure. However the results of the predictions of individual components of tracking error indicate that this is not likely to hold true for all tracking tasks. It has already been pointed out that in the dual-axis task in experiment five there were significant increases, due to vibration, in both remnant and input-correlated tracking error. During complex vibration the input-correlated error was overestimated by the r.m.s. prediction procedure and the remnant was underestimated, the net result being that they balanced out in the prediction of total error. However it was shown in the first experiment that variations in control gain can considerably affect the relative amounts of input-correlated error and remnant in the tracking error, and their sensitivity to vibration. The primary effects of vibration on single-axis tracking tasks described in the first four experiments and by Allen et al (1973) and Levison (1976) has been shown to be increases in remnant, with little or no effect on input-correlated error. The present results suggest that an r.m.s. summation procedure would therefore be likely to considerably underestimate the increase in overall error caused by dual-frequency vibration with these tasks.

It does not seem reasonable to expect one simple prediction model to precisely predict the effects of dual frequency vibration on a range of different control tasks, but different models may be appropriate to different situations. A root mean square summation procedure may however provide a reasonable approximation for general purposes such as the evaluation of complex vibration with respect to the International Standard for the evaluation of human response to vibration (1974) or the guide for the evaluation of human exposure to helicopter vibration (Griffin, 1975). Limits set by these procedures are not intended to be precise predictions of any particular aspects of performance, but as indicators of vibration conditions which may have adverse effects on the performance of a range of different tasks and whether there is a need for more detailed consideration of particular cases.

The effectiveness of prediction models such as the r.m.s. summation procedure is dependent on the validity of the frequency weightings and the derived relationship between performance and vibration level for the particular performance measure which is being used. Therefore a better understanding of frequency weightings, and their dependence on various properties of the task, is needed before these methods can be applied in a general case.

10.2. GENERAL CONCLUSIONS.

The major conclusions which may be drawn from the experiments reported in this thesis may be summarised as follows:

(i) The primary effects of vibration on the performance of a single-axis, zero-order pursuit tracking task were found to be increases in tracking error variance due to vibration induced control activity and increased operator-generated noise or remnant.

(ii) Some statistically significant effects were observed in the frequency response and response lags of subjects under certain vibration conditions, however the magnitudes of these effects were minimal.

(iii) The hypothesis proposed by Lewis and Griffin (1976), that interference with the kinaesthetic feedback mechanisms involved in neuromuscular actuation processes is a principal mechanism for the increase in remnant, is supported only for vibration frequencies greater than 10Hz. However, even at high frequencies these effects are only observed when very high levels of vibration are present at the limb-control interface.

(iv) The increase in operator-generated noise during low frequency vibration may be accounted for by increased perceptual noise caused by vibration-induced activity of the controlled element in the display. The magnitude of this effect is dependent on the amount of vibration-induced activity in the control output, which is dependent on biodynamic factors and control gain. The effect is constant during vibration exposures up to one hour and there are no indications of any after-effect of vibration.

(v) Prolonged, continuous performance of the simple single axis pursuit tracking task during both static and vibration conditions resulted in large increases in response lags and suppression of coherent responses which were related to diminished levels of arousal. However, there were indications that the effects of task duration were less severe in vibration conditions due to the arousing nature of the vibration stimulus.

(vi) The effect of a complex vibration waveform on the overall tracking error variance in the simple zero-order pursuit tracking task employed in experiment 5, can be successfully predicted from the root mean square sum of weighted frequency components of the vibration. However the results of predictions of individual components of error indicates that caution should be exercised in the application of this conclusion. The input-correlated error, or the error due to the linear portion of the operator's response, is overestimated by the r.m.s. procedure, whereas the remnant, or nonlinear portion of the response, is underestimated. The net result is that they were balanced out in the prediction of total error variance with this particular task.

10.3. RECOMMENDATIONS.

The results of the experiments reported in this thesis are based on a small number of subjects, with relatively short periods of training. Because of the complexity of the analysis procedures it was necessary to restrict the numbers of subjects, particularly in the earlier experiments, in order to be able to investigate a reasonably large number of experimental conditions. This compromise between the number of subjects (and hence the statistical power of the experiments) and the number of conditions it was possible to investigate was considered to be appropriate as the data were not intended to be used in a strictly quantitative sense (i.e. as parameters for mathematical predictive models). The experiments were performed more as a qualitative investigation to isolate the mechanisms by which vibration may affect the performance of a simple manual control task and indicate their relative importance. It is clear from the experimental results that the behaviour of different subjects was generally consistent however it would have been useful, if data from a large number of subjects had been available, to quantify the intersubject differences which may be expected in the population in the form of statistical distributions.

It must be emphasised at this stage that the results and conclusions of this study can only be generalised to similar tracking tasks, although the conclusions appear to be consistent with the results of other researchers, using different tasks. Further research, along similar lines, is necessary to determine the nature of possible interactions of display mode and control law with the observed effects. Having a knowledge of the mechanisms by which vibration degrades control performance, and of parts of the control process which are most likely to be affected, will enable simpler experiments to be designed, using only the most relevant performance measures and much larger groups of subjects, to provide data for more quantitative models of performance in a form which can be easily applied by design engineers. Initially, the most convenient form for such information would be frequency weighting functions, which could be used to both evaluate existing vibration spectra and to define realistic limits for projected vehicles, etc., in terms of the probability of occurrence of a particular magnitude of error. The limitations of this approach are discussed in section 3.11. If it can be shown that the conclusions of this study can be extended to other tasks, with more complex displays and control laws, such weighting functions could be derived directly from measures of vibration-correlated control activity over the relevant range of frequencies.

The most important practical implication of this research is that considerable attention should be given to the biodynamic aspects of the hand/control combination, as well as the seat and restraint systems, in order to minimise the amount of vibration transmitted to the control. This may be achieved by increasing the spring stiffness and frictional or viscous damping, however it must be appreciated that changing any of these parameters will also affect the dynamic response of the control at tracking frequencies. With the control gains used in this study a pure isometric stick was shown to perform better than a similarly sized and shaped pure isotonic stick both under static and vibration conditions, however this may not have been the case if the control gains had not been optimised, as the amount of vibration-correlated activity appearing in the control output is also proportional to the gain. As the optimum gain under static conditions is likely to be higher than that under vibration a compromise must be reached between the effects of vibration and dynamic response at tracking frequencies. The optimum compromise for both control gain and factors such as damping will depend on individual circumstances, such as consequences of error and the frequency content of the forcing function and of the vibration, and should therefore be determined where possible by experimentation with the same vibration and seating conditions as in the final operational system.

REFERENCES

ALLEN, R.W. & JEX, H.R. (1968) An experimental investigation of compensatory and pursuit tracking displays with rate and acceleration control dynamics and a disturbance input. NASA CR-1082

ALLEN, R.W. & JEX, H.R. (1972) A simple fourier analysis technique for measuring the dynamic response of manual control systems. IEEE Transactions on Systems, Man and Cybernetics, SMC-2, 638-643.

ALLEN, R.W., JEX, H.R. & MAGDALENO, R.E. (1973) Manual control performance and dynamic response during sinusoidal vibration. AMRL-TR-73-78

ANDERSON, G.C., FINNIE, B.W. & ROBERTS, G.T. (1967) Pseudo-random and random test signals. Hewlett - Packard Journal, 19, 2-20.

ASHLEY, C. (1976) Work vehicle suspension seating. Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Shrivenham.

BAHRICK, H.P., FITTS, P.M. & BRIGGS, G.I. (1957) Learning curves - facts or artifacts. Psychological Bulletin, 54, 256-268.

BARNES, J., GUTMANN, J. & HODGSON, R. (1973) Industrial Applications Section E: generation and uses of pseudo-random binary sequences. In Mc Mos Handbook, Motorola inc., semiconductor products div., Pp 11, 29 - 11, 38.

BEKEY, G.A. (1962) The human operator as a sampled-data system. I.R.E. Transactions on Human Factors in Electronics, HFE-3, 43-51.

BENDAT, J.S. & PIERSOL, A.G. (1966) Measurement and Analysis of Random Data. New York: Wiley.

BENNETT, G. (1971) Human performance in the turbulent environment. Paper to International Conference on Atmospheric Turbulence, Royal Aeronautical Society, London.

BENNETT, M.D., COLE, S.H., FARMILO, B., PAGE, S.J., WEBB, R. & WITHEY, W.R. (1976) An investigation into some of the human responses to sinusoidal and random vibration in the upright and semi-reclined seated posture. Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Shrivenham.

BERTHOZ, A. (1972) Striated and smooth muscle activity during low frequency vibration. Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Sheffield.

BESCO, R.O. (1961) The effects of cockpit vertical accelerations on a simple piloted tracking task. Human Factors, 3, 229-236.

BRAY, R.S. & LARSEN (1965) Simulator investigations of the problems of flying a swept-wing transport aircraft in heavy turbulence. NASA SP-83.

BROADBENT, D.E. (1963) Differences and interactions between stresses. Quarterly Journal of Experimental Psychology, 15, 2050211.

BRONZITE, M. (1970) Simple active filters design procedure, Wireless World, 76, 117-119.

BROWN, M.C., ENGBERG, I. & MATTHEWS, P.C.B. (1967) The relative sensitivity to vibration of muscle receptors of the cat. Journal of Physiology, 192, 773-800.

BUCKHOUT, R. (1964) Effects of whole-body vibration on human performance. Human Factors, 6, 157-163.

BURKE, D. & GIBBS, C.B. (1965) A comparison of free-moving levers and pressure levers in a positional control system. Ergonomics, 8, 23-29.

CATTERSON, A.D., HOOVER, G.N. & ASHE, W.F. (1962) Human psychomotor performance during prolonged vertical vibration. Aerospace Medicine. 33, 598-602.

CHERNIKOFF, R. & TAYLOR, F.V. (1952) Reaction time to kinaesthetic stimulation resulting from sudden arm displacement, Journal of Experimental Psychology, 43, 1-8.

CHERRY, E.C. (1957) On the validity of applying communication theory to experimental psychology. British Journal of Psychology, 48, 176-188.

COLLINS, J.K. (1976) Proprioceptive space perception after anaesthetization of the mid-interphalangeal joint of the finger. Perception and Psychophysics, 20, 45-48.

COOPER, I.S. (1966) A cerebellar mechanism in resting tremor. Neurology, 16, 1003-1015.

CRAIK, K.J.W. (1947) Theory of the human operator in control systems: 1. The operator as an engineering system. British Journal of Psychology 38, 56-61.

DAVSON, H. & EGGLETON, M.G. (1962) Principles of Human Physiology, 13th edition, chapter 49. Philadelphia: Lea & Febiger.

DE GAIL, P., LANCE, J.W. & NEILSON, P.D. (1965) Differential effects on tonic and phasic reflex mechanisms produced by vibration of muscles in man. Journal of Neurology, Neurosurgery and Psychiatry, 29, 1-11.

DINNERSTEIN, A.J. & LOWENTHAL, M. (1962) Percertion speed and behaviour: a theoretical note. Perceptual and Motor Skills, 15, 717-718.

DUDEK, R.A., AYOUB, M.M. & EL-NAWAWI, M.A. (1973) Optimal work-rest schedules under prolonged vibration. Ergonomics, 16, 469-479.

DUPUIS, H. (1974) Human exposure to whole-body vibration in military vehicles and evaluation by application of ISO/DIS 2631. AGARD CP-145, paper B2.

EDWARDS, E. (1967) Communication Theory. Ergonomics, 10, 139-153.

EKLUND, G. (1972) Position sense, state of contraction and the effects of vibration. Journal of Neurology, Neurosurgery and Psychiatry 35, 606-611.

EKLUND, G. & HAGBARTH, K.E. (1966) Normal variability of tonic vibration reflexes in man. Experimental Neurology, 16, 80-92.

ELLSON, D.G., HILL, H. & GRAY, F. (1947) Wave length and amplitude characteristics of tracking error curves. USAF Air Material Command, Memo Report TSEAA 694-2D.

FISHBEIN, W.I. & SALTER, L.C. (1950) The relationship between truck and tractor driving and disorders of the spine and supporting structures. Industrial Medicine and Surgery, 19, 444-445.

FORBES, A.R. (1959) Survey of the effect of buffetting and vibration on human behaviour. RAF Institute of Aviation Medicine, FPRC Memo 105

FORBES. A.R. (1960) The effects of whole-body vibration on tracking performance. RAF Institute of Aviation Medicine, Report No. 144

FOTHERGILL, L.C. & GRIFFIN, M.J. (1977) The evaluation of discomfort produced by multiple frequency whole-body vibration. Ergonomics, 20, 263-276.

FRASER, T.M., HOOVER, G.N. & ASHE, W.F. (1961) Tracking performance during low frequency vibration. Aerospace Medicine, 32, 829-835.

FRASER, T.M. (1964) Aspects of the human response to high speed, low level flight. Aerospace Medicine, 35, 365-370.

GARNER, K.C. (1968) Introduction to control systems performance measurements. Oxford: Pergamon.

GARVEY, W.D. & MITNICK, L.L. (1957) An analysis of tracking behaviour in terms of lead-lag errors. Journal of Experimental Psychology, 53, 372-378.

GIBBS, C.B. (1954) The continuous regulation of skilled response by kinaesthetic feedback. British Journal of Psychology, 45, 24-39.

GIBBS, C.B. (1962) Controller design: interaction of controlling limbs, time lags and gains in positional and velocity systems. Ergonomics, 5, 385-402.

GIBBS, C.B. (1965) Probability learning in step-input tracking. British Journal of Psychology, 56, 233-242.

GIBBS, G.B. (1970) Servo-control systems in organisms and the transfer of skill. In Skills, (edited by D. Legge) Penguin modern psychology readings. Pp. 211-226.

von GIERKE, H.E. (1973) Cybernetics and Bionics AMRL-TR-73-23.

GILSON, R.D., BENSON, A.J. & GUEDRY, F.E. (1970) Influence of vestibular stimulation and display luminance in the performance of a compensatory tracking task. Aerospace Medicine, 41, 1231-1237.

GOODWIN, G.M., McCLOSKEY, D.I. & MATTHEWS, P.C.B. (1972) The contribution of muscle spindle afferents to kinaesthesia as shown by vibration induced illusions of movement and by the effects of paralysing joint afferents. Brain, 95, 705-748.

GOTTLIEB, G.L., & AGARWAL, G.C. (1973a) Postural adaptation: the nature of adaptive mechanisms in the human motor system. In Advances in behavioural biology, vol. 7: control of posture and locomotion. (edited by R.B.Stein, K.G.Pearson, R.S.Smith & J.B.Redford) New York: Pilenum, Pp. 197-210.

GOTTLIEB, G.L. & AGARWAL, G.C. (1973b) Modulation of postural reflexes by voluntary movement, 1. Modulation of the active limb. Journal of Neurology, Neurosurgery and Psychiatry, 36, 529-539.

GOTTLIEB, G.L. & AGARWAL, G.C. (1973c) Modulation of postural reflexes by voluntary movement, 2. Modulation at an inactive joint. Journal of Neurology, Neurosurgery and Psychiatry, 36, 540-546.

GOTTLIEB, G.L., AGARWAL, G.C. & STARK, L. (1970) Interaction between voluntary and postural mechanisms of the human motor system. Journal of Neurophysiology, 33, 365-381.

GRETHER, W.F. (1972) Two experiments on the effects of combined heat, noise and vibration stress. AGARD CP-101, paper C3.

GRETHER, W.F., HARRIS, C.S., MOHR, G.C., NIXON, C.W., OHLBAUM, M., SOMMER, H.C., THALER, V.H. & VEGHTE, J.H. (1971) Effects of combined heat, noise and vibration stress on human performance and physiological functions. Aerospace Medicine, 42, 1092-1097.

GRIFFIN, M.J. (1972) The transmission of tri-axial vibration to pilots in the Scout AH Mkl helicopter. University of Southampton, ISVR Technical Report 58.

GRIFFIN, M.J. (1974) Levels of vehicle vibration and the ISO limits. Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Yeovil.

GRIFFIN, M.J. (1975a) Vertical vibration of seated subjects: effects of posture, vibration level and frequency. Aviation, Space and Environmental Medicine, 46, 269-276.

GRIFFIN, M.J. (1975b) Levels of whole-body vibration affecting human vision. Aviation, Space and Environmental Medicine, 46, 1033-1040.

GRIFFIN, M.J. (1975c) The evaluation of human exposure to helicopter vibration, ISVR Technical Report 78, University of Southampton.

GRIFFIN, M.J. (1976) Subjective equivalence of sinusoidal and random whole-body vibration. Journal of the Acoustical Society of America, 60, 1140-1145.

GRIFFIN, M.J. & LEWIS, C.H. (1978) A review of the effects of vibration on visual acuity and continuous manual control. Part 1: Visual Acuity, Journal of Sound and Vibration, 56, 383-413.

GRIFFIN, M.J. & WHITHAM, E.M. (1976) A study of the discomfort produced by dual-axis whole-body vibration. Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Shrivenham.

GRIMSTER, W.F., HOLLIDAY, C.D. & HERRICK, C.S. (1974) Sea King pilot vibration. Westland Helicopters Ltd., Research Paper No. 463, Part 2.

GUIGNARD, J.C. (1965) Vibration, In a Textbook of Aviation Physiology, chapter 29, (edited by J.A.Gillies) Oxford: Pergamon.

GUIGNARD, J.C., LANDRUM, C.J. & REARDON, R.E. (1976) Experimental evaluation of International Standard (ISO 2631) for whole-body vibration exposures. University of Dayton Research Institute, UDRI-TR-76-79.

HAGBARTH, K.E. & EKLUND, G. (1965) Motor effects of vibratory muscle stimuli in man. In Proceedings of the First Nobel Symposium. (edited by R. Granit) Almquist & Wiksell: Stockholm.

HALLIDAY, A.M. & REDFEARN, J.W.T. (1956) An analysis of the frequencies of finger tremor in healthy subjects, Journal of Physiology, 134, 600-611.

HALLIDAY, A.M. & REDFEARN, J.W.T. (1958) Finger tremor in tabetic patients and its bearing on the mechanism producing the rhythm of physiological tremor. Journal of Neurology, Neurosurgery and Psychiatry, 21, 101-108.

HAMMERTON, M. & TICKNER, A.H. (1966) An investigation into the comparative suitability of forearm, hand and thumb controls in aquisition tasks. Ergonomics, 9, 125-130.

HAMMOND, P.H. (1955) Involuntary activity in biceps following the sudden application of velocity to the abducted forearm. Journal of Physiology, 127, 23P-25P.

HAMMOND, P.H., MERTON, P.A. & SUTTON, G.G. (1956) Nervous Gradation of muscular contraction, British Medical Bulletin, 12, 214-218.

HANSSON, J.E. & SUGGS, C.W. (1973) Lagfrekventa vibrationers effekt pa reglagemanovrering: the effect of seat vibration on vehicle operators' lever and pedal control capabilities. Institutionen for Skogstecknik Skogshagiskolon, Stockholm, Nr. 63.

HARRIS, C.S., CHILES, W.D. & TOUCHSTONE, R.M. (1964) Human performance as a function of intensity of vibration at 5 cps. AMRL-TR-64-83.

HARRIS, C.S. & SHOENBERGER, R.W. (1965) The effects of vibration on performance. AGARD Collected Papers No.2. 307-326.

HARRIS, C.S. & SHOENBERGER, R.W. (1966) Effects of vibration on human performance. Journal of Engineering Psychology, 5, 1-15.

HARRIS, C.S. & SHOENBERGER, R.W. (1970) Combined effects of noise and vibration on psychomotor performance. AMRL-TR-70-14.

HARRIS, C.S. & SOMMER, H.C. (1973) Interactive effects of intense noise and low-level vibration on tracking performance and response time. Aerospace Medicine, 44, 1013-1016.

HILTON, D.H. (1970) Design considerations relating to tractor cabin suspension design. Paper to Conference on Agricultural and Allied Industrial Tractors, Institute of Mechanical Engineering, London.

HOLLAND, C.L. (1966) Performance and physiological effects of long-term vibration. AMRL-TR-66-145.

HOLLAND, C.L. (1967) Performance effects of long-term random vibration. Human Factors, 9, 93-104.

HORNICK, R.J. (1962) The effects of whole-body vibration in three directions upon human performance. Journal of Engineering Psychology, 1, 93-101.

HORNICK, R.J., BOETTCHER, C.A. & SIMONS, A.K. (1961) The effect of low frequency, high amplitude, whole-body, longitudinal and transverse vibration on human performance. Bostrom Research Laboratories Report, Project TEI-1000.

HORNICK, R.J. & LEFRITZ, N.L. (1966) Aircrew response to the environment of low-altitude, high-speed flight. Proc. 18th Annual National Aerospace Electronics Conference, Dayton.

HOWELL, W.C. & BRIGGS, G.E. (1959) The effects of visual noise and locus of perturbation on tracking performance. Journal of Experimental Psychology, 58, 166-173.

HUDDLESTON, J.H.F. (1966) Cockpit motion requirements for flight simulation. RAF Institute of Aviation Medicine, Report 363.

HUDDLESTON, J.H.F. (1970) Tracking performance on a visual display apparently vibrating at one to ten Hertz. Journal of Applied Psychology, 54, 401-408.

INTERNATIONAL STANDARDS ORGANISATION (1974) Guide for the evaluation of human exposure to whole-body vibration. ISO 2631-1974(E).

JACKSON, K.F. (1956) Aircrew fatigue in long range maritime reconnaissance. Air Ministry Flying Personnel Research Committee Report FPRC 907.2.

JANSEN, J.K.S. (1966) On fusimotor reflex activity. In Nobel Symposium 1 (edited by R. Granit) New York: Wiley, Pp. 91-105.

JEX, H.R. (1967) Two applications of a critical instability task to secondary work-load research. IEEE Transactions on Human Factors in Electronics, HFE, 8, 279-282.

JEX, H.R. (1974) Evaluating biodynamic interference with operational crews. AGARD CP-145, Paper B24.

JEX, H.R. & MAGDALENO, R.E. (1969) Corroborative data on normalization of human operator remnant. IEEE Transactions on Man-Machine Systems, MMS-10, 137-140.

JEX, H.R., McDONNELL, J.D. & PHATAK, A.V. (1966) A critical tracking task for manual control research. IEEE Transactions on Human Factors in Electronics, HFE-7.

JEX, H.R., McDONNELL, J.D. & PHATAK, A.V. (1966) A critical task for man-machine research related to the operator's effective delay time: Part 1. NASA CR-616.

JOHNSTON, M.E. (1976) Equal performance contours. Paper to Informal Group on Human Response to Vibration, Annual Conference, Shrivenham.

KELLEY, C.R. (1966) Design applications of adaptive (self-adjusting) simulators. NASA SP-128, 379-402.

KELLEY, C.R. (1967) Research applications of adaptive tasks. Paper to 3rd International Congress on Ergonomics, Birmingham.

KELLEY, C.R. (1969) The measurement of tracking proficiency. Human Factors, 11, 43-64.

KERR, T.H., NETHAWAY, J.E. & CHINN, H.W. (1963) Aircraft tests in high speed, low level flight, including impressions of a spring-mounted seat. AGARD report 442.

KHALIL, T.M. (1969) Performance and recovery under prolonged vibration. Unpublished Ph.D. Thesis, Texas Tech. University.

KHALIL, T.M. & AYOUB, M.M. (1970) On prolonged vibration and the work-rest schedule. Paper to Human Factors Society Annual Conference, San Francisco.

KLEINMAN, D.L., BARON, S. & LEVISON, W.H. (1971) A control theoretic approach to manned-vehicle systems analysis. IEEE Transactions on Automatic Control, AC-16.

LEVISON, W.H. (1974) Analysis of vibration-induced pilot remnant. In Proceedings of the 10th Annual Conference on Manual Control, Wright-Patterson Air Force Base, Ohio.

LEVISON, W.H. (1976) Biomechanical response and manual tracking performance in sinusoidal, sum of sine and random vibration environments. AMRL-TR-75-94.

LEVISON, W.H., BARON, S. & KLEINMAN, D.C. (1969) A model for human controller remnant. IEEE Transactions on Man-Machine Systems, MMS-10, 137-140.

LEVISON, W.H. & HOUCK, P.D. (1975) A guide for the design of control sticks in vibration environments. AMRL-TR-74-127.

LEWIS, C.H. (1974) The development of a predictive model of the effects of vibration on human operator performance. Unpublished M.Sc. Thesis, University of Southampton.

LEWIS, C.H. (1977) Frequency of whole-body vibration and reading performance, Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Northampton.

LICKLIDER, J.C.R. (1960) Quasi-linear operator models in the study of manual tracking. In: Developments in Mathematical Psychology, Glencoe: Free Press.

LIPPALD, O.C.J. (1972) Oscillation in the stretch reflex arc and the origin of the rhythmical, 8-12 C/S component of physiological tremor. Journal of Physiology, 206, 359-382.

LOECKLE, W.E. (1947) Effect of vibration on the autonomic nervous system and tendon reflexes. Royal Aircraft Establishment library translation no.183.

LOVESEY, E.J. (1971a) Some effects of dual-axis heave and sway vibration on compensatory tracking. RAE Technical Memo. EP 484.

LOVESEY, E.J. (1971b) An investigation into the effects of dual axis vibration, restraining harness, visual feedback and control force on a manual positioning task. RAE Technical Report TR 71213.

LOVESEY, E.J. (1971c) Some effects of multi-axis vibration upon weapon aiming through a binocular sight. RAE Technical Report TR 71243.

LOVESEY, E.J. (1975) The helicopter - some ergonomic factors. Applied Ergonomics, 6, 139-146.

LOWES, A.L., ELLIS, N.C., NORMAN, D.A. & MATHENY, W.G. (1968) Improving piloting skills in turbulent air using a self-adaptive technique for a digital operational flight trainer. NAVTRADEVCEN-67-C-0034-2.

MARSDEN, C.D., MERTON, P.A. & MORTON, H.B. (1972) Servo action in human voluntary movement. Nature, 238, 140-143.

MATTHEWS, B.H.C. (1933) Nerve endings in mammalian muscles. Journal of Physiology, 18, 1-53.

MATTHEWS, J. (1968) Some measurements of vibration encountered by operators of agricultural machinery. National Institute of Agricultural Engineering, Internal Note no.27.

MATTHEWS, P.B.C. (1962) The differentiation of two types of fusimotor fibres by their effects on the dynamic response of muscle spindle primary endings. Quarterly Journal of Experimental Physiology, 47, 324-333.

MATTHEWS, P.B.C. (1964) Muscle spindles and their motor control. Physiological Review, 44, 219-288.

MATTHEWS, P.B.C. (1966) Reflex activiation of the Soleus muscle of the decerebrate cat by vibration. Nature, 209, 204-205.

McCLOSKEY, D.I. (1973) Differences between the senses of movement position shown by the effects of loading and vibration of muscles in man. Brain Research, 63, 119-131.

McNEILL, W.E., DRINKWATER, F.J. & VAN DYKE, R.D. (1953) A flight study of the effects on tracking performance of changes in the lateral-oscillatory characteristics of a fighter airplane. NACA research memo. RM A53H10.

McRUER, D.T. & GRAHAM, D. (1963) Pilot-vehicle control system analysis, A.I.A.A. Paper 63-31.

McRUER, D.T., GRAHAM, D., KRENDEL, E.S. & REISNER, W. (1965) Human pilot dynamics in compensatory systems. AFFDL-TR-65-15.

McRUER, D.T. & KRENDEL, E.S. (1974) Mathematical models of human pilot behaviour. AGARD-AG-188.

MEHR, M.H. (1973) Two axis positioning and tracking controls, Applied Ergonomics, 4, 154-157.

MERCER, C.A. (1973) Development of data analysis in sound and vibration. Journal of Sound and Vibration, 28, 631-642.

MOSS, F.A. (1929) S.A.E. Journal, 25, 298.

MOSS, F.A. (1931) S.A.E. Journal. 28, 580.

MOZELL, M.M. & WHITE, D.C. (1958) Behavioural effects of whole-body vibration. Aerospace Medicine, 29, 716-724.

NAGASAWA, Y., HAGIHARA, H., ARAMAKI, S. & ITO, T. (1969) The influence of vibration on motor performance (1) - the effect of horizontal transverse vibration on tracking task. Japan Air Self-defence Aeromedical Laboratories Report no. 9, 1-7.

NASHNER, L. (1970) Sensory feedback in human posture control. Unpublished Sc. D. Thesis, M.I.T.

NAVAS, F. & STARK, L. (1968) Sampling or intermittency in hand control system dynamics. Biophysical Journal, 8, 252-302.

OBORNE, D.J. (1977) Vehicle vibration and passenger comfort. Paper to Ergonomics Society Annual Conference, Birmingham.

O'HANLON, J.G. & GRIFFIN, M.J. (1971) Some effects of the vibration of reading material upon visual performance. ISVR Technical Report 49, University of Southampton.

OHLBAUM, M.K. (1976) Mechanical resonant frequency of the human eye in vivo. AMRL-TR-75-113.

OSTLE, B. (1963) Statistics in Research, (Ames, Iowa University Press.) Pp. 171.

PAILLARD, J. (1960) The patterning of skilled movements. In: Handbook of Physiology, Section 1, Vol.3. (edited by J. Field, H.W. Magoun & V.E. Hall), American Physiological Society. Pp. 1679-1708.

PARKS, D.L. (1961) A comparison of sinusoidal and random vibration effects on human performance. The Boeing Company Technical Report D3-3515-2.

PIRANIAN, A.G. (1974a) The effects of sustained acceleration, airframe buffet and aircraft flying qualities on tracking performance. A.I.A.A. Conference on Mechanics and Control of Flight, Anaheim, Cal.

PIRANIAN, A.G. (1974b) The effect of the individual and combined stresses of vibration and sustained G on pilot performance. AGARD CP-145, Paper B6.

POULTON, E.C. (1965) On increasing the sensitivity of measures of performance. Ergonomics, 8, 69-76.

POULTON, E.C. (1974) Tracking Skill and Manual Control, Chapter 7, New York: Academic Press.

RACK, P.M.H. (1973) The stretch reflex response to movement of human elbow joint. In Advances in Behavioural Biology, Vol. 7: Control of Posture and Locomotion. (edited by R.B.Stein, K.G.Pearson, R.S.Smith & J.B.Redford) New York: Plenum, Pp. 245-255.

RADKE, A.O. (1956) The application of human engineering data to vehicular seat design. Bostrom Research Laboratories, Report no.117.

RAGLAND, S., CHAMBERS, R.M., CROSBIE, R.J. & HITCHCOCK, L. (1964) Simulation and effects of severe turbulence on jet airline pilots. U.S. Naval Air Development Centre Report, NADC-ML-6411.

RANCE, B.H. & CHAPPELOW, J.W. (1974) Aircrew assessment of the vibration environment in helicopters. AGARD CP-145, Paper B1.

ROBINSON, G.H. (1967) The human controller as an adaptive, low pass filter. Human Factors, 9, 141-147.

RODRICK, P.T. (1972) Vibration effects on pilot tracking performance using a rigid control stick. Unpublished M.Sc. Thesis, Naval Postgraduate School, Monterey.

ROSENBLUETH, A., WEINER, N. & BIGELOW, J. (1943) Behaviour, purpose and teleology, Philosophy of Science, 10, 18-24.

ROWLANDS, G.F. (1973) Transmission of vibration by aircrew seats. Paper to U.K. Informal Group on Human Response to Vibration, Annual Conference, Salford.

ROWLANDS, G.F. (1975) The transmission of vibration by the human body. Unpublished Ph.D Thesis, Loughborough University.

SHANNON, C.E. (1948) A mathematical theory of communication. Bell System Technical Journal, 27, 379-423 and 623-656.

SCHMITZ, M.A. (1959) The effect of low frequency, high amplitude, whole-body, vertical vibration on human performance. Bostrom Research Laboratories Report No.128.

SCHMITZ, M.A. & SIMONS, A.K. (1959) Man's response to low frequency vibration. ASME Paper 59-A-200.

SHOENBERGER, R.W. (1967) Effects of vibration on complex psychomotor performance. Aerospace Medicine, 38, 1264-1269.

SHOENBERGER, R.W. (1970) Human performance as a function of direction and frequency of whole-body vibration. AMRL-TR-70-7.

SHOENBERGER, R.W. (1972) Human response to whole-body vibration. Perceptual and Motor Skills, 34, 127-160.

SHOENBERGER, R.W. (1974) Mechanisms of vibration effects on aircrew performance. AGARD CP-145, Paper B17.

SHOENBERGER, R.W. & WILBURN, D.L. (1973) Tracking performance during whole-body vibration with side-mounted and centre-mounted control sticks. AMRL-TR-72-120.

SHURMER, C.R. (1967) Effects on tracking performance of each, and in combinations of, the heave, sway and roll axes. British Aircraft Corporation, Guided Weapons Division, Report AD8544316.

SHURMER, C.R. (1969) Tracking performance in single and multi-axis vibration environments. Paper to Ergonomics Research Society Annual Conference.

SIMONS, A.K., RADKE, A.O. & OSWALD, W.C. (1956) A study of 'truck ride' characteristics of standard cushions versus suspension type seats in military vehicles. Human Engineering Project, Contract No. DA-11-022-ORD-1999, Final Report.

SOLIDAY, S.M. & SCHOHAN, B. (1965) Performance and physiological responses of pilots in simulated low-altitude, high-speed flight. Aerospace Medicine, 36, 100-104.

SOMMER, H.C. & HARRIS, C.S. (1972) Combined effects of noise and vibration on cognitive and psychomotor performance. AGARD CP-101 Paper C4.

SOMMER, H.C. & HARRIS, C.S. (1973) Combined effects of noise and vibration on human tracking performance and response time. Aerospace Medicine, 44, 276-280.

STARK, L., IIDA, M. & WILLIS, P.A. (1961) Dynamic characteristics of the motor co-ordination system in man. Biophysical Journal, 1, 279-300.

STAYNER, R.M. (1971) Aspects of the development of a test code for tractor suspension seats. Journal of Sound and Vibration, 20, 247-252.

STRIKELEATHER, L.F. & SUGGS, C.W. (1970) An active suspension seat for off road vehicles. Transactions of the A.S.A.E., 13, 99-106.

SWOPE, A. & BRANDENBURG, G.C. (1931) S.A.E. Journal, 28, 582.

TORLE, G. (1965) Tracking performance under random acceleration: effects of control dynamics. Ergonomics, 8, 481-486.

TUSTIN, A. (1947) The nature of the operator's response in manual control, and its implications for controller design. Journal of the I.E.E., 94, 190-202.

VALLBO, A.B. (1971) Muscle Spindle response at the onset of isometric contractions in man: time differences between fusimotor and skeletomotor effects. Journal of Physiology, 318, 405-431.

WALL, P.D. (1970) Sensory role of impulses travelling in the dorsal columns. I.E.E.E. Transactions on Man-Machine Systems, MMS-11, 39-44.

WASICKO, R.J. (1966) NASA research experience on jet aircraft control problems in severe turbulence. AGARD CP-17, Part 2.

WEISZ, A.Z., GODDARD, C.J. & ALLEN, R.W. (1965) Human performance under random and sinusoidal vibration. AMRL-TR-65-209.

WEISZ, A.Z., ALLEN, R.W. & GODDARD, C.J. (1966) An evaluation of three types of hand controllers under random, vertical vibration. 2nd Annual NASA-University Conference on Manual Control, MIT.

WELFORD, A.T. (1958) Ageing and human skill, Oxford University Press, for the Nuffield Foundation.

WEMPE, T.E. (1965) Effects of gust-induced and manoeuvring acceleration stress on pilot-vehicle performance. Aerospace Medicine, 36, 246-255.

WIENER, N. (1948) Cybernetics, Wiley: New York.

WILKINSON, R.T. (1969) Some factors influencing the effect of environmental stressors on performance. Psychological Bulletin, 72, 260-272.

WILKINSON, R.T. & GRAY, R. (1974) Effects of duration of vertical vibration beyond the ISO fatigue-decreased proficiency time on the performance of various tasks. AGARD CP-145, Paper B19.

WILSON, R.V. (1974) Display collimation under whole-body vibration. Human Factors, 16, 186-195.

WOLF, R.J. & MARTZ, H.F. jr. (1975) Personal characteristics and whole-body vibration. Human Factors, 17, 415-416.

YOUNG, L.R. & STARK, L. (1965) Biological control systems - a critical review and evaluation. NASA CR-190.

ZACH, D.J. (1971) The development of a suspension seat for mobile construction equipment. S.A.E. Paper 710515.

ZIEGLER, P.N. & CHERNIKOFF, R. (1968) A comparison of three types of controls on a third order tracking task. Ergonomics, 11, 369-374.

APPENDIX A.

Most of the laboratory experiments on the effects of vibration on manual tracking which have been described in published research papers are described in the following table. The table lists the important properties of each task and the vibration conditions and summarizes the results. However, the reader is advised to consult the original papers for more complete information. Note that the table does not include studies where vibration has been combined with other environmental stresses (such as heat and noise) as these have been described in detail in section 3. 9.

Reference	Task details	Vibration conditions	Results and conclusions
Allen, Jex and Magdaleno 1973.	Compensatory tracking in a single, vertical (z- and x-axis vibration) or roll (y-axis) axis. Control dynamics were either first order or simulated, short-period response of a large bomber (z- and x-axis vibration) and the simulated roll response of a stability-augmented aircraft (y-axis vibration). Two centre-mounted control sticks were used in the study: an undamped displacement stick with light spring gradient and an isometric stick. The forcing function was the sum of 5 sinusoids (0·08–1·67 Hz). An analogue Fourier analyser was used to measure subjects' describing functions and to partition error variance into that correlated with the tracking input, vibration and remnant. The transmission of vibration from seat to control and shoulder was also measured for each vibration frequency. The length of each tracking run was 100 s (z-axis vibration) or 50 s (x- and y-axis vibration). 3 subjects.	Seat, control and display all vibrated. 15 conditions of sinusoidal vibration, not including static sessions at the beginning and end of each session: 2, 6 and 10 Hz, all at $\pm 0{\cdot}4\,g$ (z). 1·3, 2, 3, 4·5, 7 and 10 Hz, all at $\pm 0{\cdot}4\,g$ (x- and y-axes, presented separately).	Error performance was found to degrade with increasing frequency of vertical (z-axis) vibration. The effect of vibration frequency was more pronounced with the isometric stick than with the spring stick, although there was less error under static conditions with the isometric control. There was more vibration-correlated error with the isometric stick, but this was a very small part of the total tracking error. Increased tracking error with z-axis vibration was largely due to increases in operator-generated noise or remnant: particularly at 10 Hz, when there was evidence of visual blurring. There was also evidence of increased neuromuscular lags with 10 Hz vibration. There were dramatic increases in tracking error with lateral (y-axis) vibration: particularly at the lower frequencies. This was primarily due to increases in operator-generated noise, in response to large, vibration-induced motion in the control stick. These effects were greatest with the spring stick. With fore and aft (x-axis) vibration there was considerable variation in biomechanical response between subjects, which led to large individual performance differences as a function of vibration frequency. The x-axis vibration induced considerable vertical motions of the torso and head, which induced visual blurring and neuromuscular lags at high frequencies. There were large increases in operator-generated noise with the spring stick, although vibration feedthrough to the control was greater with the isometric stick.

Reference	Task details	Vibration conditions	Results and conclusions
Bennett, Cole, Farmilo, Page, Webb and Withey 1976.	Zero order, continuous, compensatory tracking in a single (horizontal) axis, using a spring-biased foot pedal control (depressing and releasing the pedal caused the controlled element to move to the right and left, respectively). The forcing function was pseudo-random noise, filtered at 0·15 Hz. Absolute error was integrated over successive 2½ min intervals during each 30 min, continuous tracking run. A visual, choice reaction time task was run concurrently with the tracking task, and in addition various physiological and transmissibility measures were made. The seat from an AFV was used, which was set in both upright and semi-reclined positions. 12 subjects.	Seat, control and display were all vibrated. 6 conditions of vertical (z-axis) vibration, not including no-vibration control conditions: 6 Hz at 0·21, 0·28 and 0·35 g rms; narrow band random vibration—(0–5 Hz) with superimposed transient shocks, arranged to give a crest factor of 8, at 0·21, 0·28 and 0·35 g rms. The first 10 min of each tracking run was in static conditions, the next 10 min was under one of the vibration conditions and the last 10 min was static.	All the vibration conditions produced decrements in tracking performance. The random vibration produced greater performance decrements than the sinusoidal vibration at the same acceleration level. There was marginally better performance under vibration with the semi-reclined seat position.
Buckhout 1964.	First order, continuous, compensatory tracking in two axes with an aircraft joystick control. The forcing function was narrow band, random noise: no frequency details are given. Integrated absolute error was measured over 5 min runs. Aircraft seat with harness. 15 subjects.	Seat, control and display mounted on vibrator. Experimental sessions consisted of 3 vibration runs followed by one post-vibration control run. A total of 9 conditions of sinusoidal vertical (z-axis) vibration were presented: 5 Hz at $\pm 0{\cdot}26\,g$, $\pm 0{\cdot}31\,g$ and $\pm 0{\cdot}36\,g$; 7 Hz at $\pm 0{\cdot}29\,g$, $\pm 0{\cdot}35\,g$ and $0{\cdot}41\,g$; 11 Hz at $\pm 0{\cdot}55\,g$, $\pm 0{\cdot}66\,g$ and $\pm 0{\cdot}77\,g$.	Performance was degraded by all the vibration conditions. Decrements in vertical tracking performance ranged from 34 to 74% and in horizontal tracking performance from 10 to 48%. Decrements in performance were positively correlated with the amount of vibration transmitted to the subject's sternum, and were greatest with 5 Hz vibration.
Catterson, Hoover and Ashe 1962.	Task identical to that of Fraser, Hoover and Ashe [38]. 5 subjects.	Seat, control and display mounted on vibrator. 12 vibration conditions, not including no-vibration control conditions: 2, 4, 6, 8, 11 and 15 Hz, all at 0·065 and 0·13 inch double amplitude (z). Each vibration exposure lasted 20 min with tracking runs at the middle and end. Two no-vibration runs before each exposure.	Tracking performance was significantly improved at all vibration frequencies at 0·065 in, but was degraded at 0·13 in for all frequencies. Vibration frequency had no significant effect on performance and the authors conclude that performance is a function of vibration displacement only. Some of the higher vibration conditions caused back and chest pains in some subjects.

Reference	Task details	Vibration conditions	Results and conclusions
Dudek, Ayoub and El-Nawawi 1973.	Task identical to that in Khalil and Ayoub [54], except that three alternative work-rest schedules were used, over periods of 2 h. These were 30/30, 40/40 and 60/60 min.	Seat, control and display all vibrated. One condition of vertical (z-axis) sinusoidal vibration, continuous for 2 h, and a no-vibration control condition of similar duration: 5 Hz at 0·2 g peak.	The vibration significantly degraded tracking performance. In static conditions the average error over the 2 h period was smallest for a 30/30 min work-rest schedule and increased significantly as the work and rest periods became longer. However, under vibration the differences in error between work-rest schedules were significant and with the 60/60 min work-rest schedule the average performance was better with vibration than without. The authors conclude that in static conditions the subjects' performances were considerably influenced by the task "boredom component", whereas the vibration stimulus tended to reduce its effect.
Forbes 1960.	Zero order, continuous compensatory tracking in two axes with a miniature, side-arm joystick mounted on a seat armrest. Sinusoidal forcing functions. Error integrated over one minute periods. The seat was equipped with a headrest and 4 in foam cushion. Full harness. 5 subjects.	Seat, control and display all vibrated. 5 conditions of vertical (z-axis) sinusoidal vibration: 1, 2, 3, 4 and 5 Hz at ±0·25 in.	Vertical control was significantly impaired by the 2, 3, 4 and 5 Hz vibration conditions and horizontal (bank) control by 3, 4 and 5 Hz vibration. There was a marked peak in vertical errors with 4 Hz vibration but horizontal errors were similarly increased by 3, 4 and 5 Hz motion. The author concluded that effects of vibration were due to a combination of impairments of visual acuity (particularly in the vertical control axis) and involuntary movement of the hand and arm induced by jolting and shoulder-girdle resonance.
Fraser, Hoover and Ashe 1961.	Zero order, continuous, compensatory tracking in two axes with a centrally mounted, free moving control stick. No forcing function details given. Integrated absolute error measured over 2 min periods within each 5 min run. Contoured, hard wood seat with no restraints. 4 subjects.	48 vibration conditions with seat, control and display mounted on vibrator: 2, 4, 7 and 12 Hz, each at 0·0625, 0·125, 0·1875 and 0·25 in double amplitude (x-, y- and z-axes, presented separately). The 12 highest amplitude conditions were repeated with a static display.	Tracking performance was significantly degraded by vertical (z) and transverse (y) vibration but was little affected by longitudinal (x) vibration. Errors were found to be primarily related to the amplitude of the vibration. Tracking was slightly less accurate with a static display.

Reference	Task details	Vibration conditions	Results and conclusions
Gilson, Benson and Guedry 1970.	Zero order, continuous, compensatory tracking in a single (horizontal) axis with a spring centred joystick. The forcing function was the sum of six sine waves (0·0125 to 0·25 Hz). Performance was measured by integrating absolute error over successive 1 s periods within 250 s tracking runs. The display was a 4 cm diameter cross-pointer indicator instrument. Electro-oculographic records, of lateral eye movements reflexly elicited by the motion, were taken during tracking runs and in total darkness. Additional experimental conditions were 4 levels of display illumination. The subject sat upright with his head supported close to the centre of rotation. 20 subjects.	Subjects' tracking ability was tested at each illumination level under static conditions and during sinusoidal oscillation in yaw (rotation about z-axis) of seat, control and display. The yaw motion was 0·04 Hz at ±159 deg/s.	The very low frequency angular vibration in yaw employed in this experiment brought about substantial decrements in tracking performance. The motion elicited considerable, lateral, reflex eye movement (nystagmus), especially in dark conditions. The nystagmus was partially, but not completely, suppressed when performing the tracking task although display illumination did not effect the extent of the nystagmus. The tracking error reflected the same periodicity as the angular acceleration and the nystagmus, indicating that these involuntary eye movements may have been the main cause of performance degradation.
Guignard, Landrum and Reardon 1976.	Zero order, continuous, compensatory tracking in a single (unspecified) axis, using a footpedal control. Random forcing function. The tracking task was run sequentially with several other tasks, including subjective ratings, visual acuity and auditory vigilance, and repeated at various times during a vibration exposure. Rigid seat with fixed footrest and hand grips. Lap only harness. 8 subjects.	12 conditions of vertical (z-axis) sinusoidal vibration, corresponding to the ISO fatigue decreased proficiency limit for that particular period of exposure: 2 and 4 Hz, each for periods of 8 h, 4 h, 2·5 h, 25 min and 16 min; 8 Hz for periods of 25 and 16 min.	There were no significant differences in performance between vibration exposures and corresponding control conditions. Neither were there any significant differences between pre- and post-vibration performance at any of the tasks.
Hansson and Suggs 1973.	(From English summary) Tracking with either left or right hand control levers or a pedal control, with variable work position and control resistance. 20 subjects: 10 male and 10 female.	Seat and controls only vibrated, display static. Vertical (z-axis), sinusoidal vibration over the range 1·6 to 4·5 Hz at amplitudes up to 20 mm double amplitude.	Control operation began to be affected at frequencies of 2 to 2·5 Hz and double vibration amplitudes of 10 to 20 mm. Work position and control resistance both had a significant effect on performance. The best control resistances were found to be between 0·5 and 2·7 kp for levers and 2·3 kp for the pedal. There were no differences between performance with the left or right hand lever. No significant differences in tracking error were found between pedal and levers in the male group, but in the female group more vibration was transmitted to the pedal than to the levers.

Reference	Task details	Vibration conditions	Results and conclusions
Harris, Chiles and Touchstone 1964.	First order, continuous, compensatory tracking in two axes with a side-arm, displacement joystick. The forcing function was random noise. Tracking runs were 3 min long, with 1 min rest between consecutive runs: five runs in a 20 min period of continuous vibration. Hard, wooden seat with full harness in simulated aircraft cockpit. 10 subjects.	Seat, control and display all mounted on vibrator. Five conditions of vertical (z-axis) vibration, and pre- and post-vibration control conditions: 5 Hz at 0, 0·12, 0·16, 0·20 and 0·26 g peak.	None of the vibration conditions affected horizontal tracking performance, but vertical tracking performance deteriorated with increasing vibration level although performance decrements were significant only at the two highest vibration levels. There were significant decreases in vertical tracking error, at each vibration level, within each 20 min vibration condition but there was no significant difference between performance in pre- and post-vibration trials.
Harris and Shoenberger 1966.	First order, continuous, compensatory tracking in two axes with a joystick mounted on the right armrest of the seat. The forcing function was random noise from 0·02 to 0·27 Hz (5 and 7 Hz vibration conditions) or 0·02 to 0·50 Hz (11 Hz vibration conditions). Absolute error was integrated over 3 min periods. Hard wood seat with full harness. 10 subjects.	Seat, display and control were mounted on vibrator. 15 conditions of vertical (z-axis) sinusoidal vibration: 5 Hz at 0, 0·10, 0·15, 0·20 and 0·26 g peak; 7 Hz at 0, 0·15, 0·20, 0·25 and 0·30 g peak; 11 Hz at 0, 0·25, 0·37, 0·49 and 0·62 g peak.	The primary purpose of this series of experiments was to find the minimum acceleration levels necessary to produce significant decrements in tracking performance. The minimum level which produced a significant decrement at each frequency was 0·20 g peak at 5 Hz; 0·25 g peak at 7 Hz and 0·37 g peak. Note that Shoenberger [69] ran a similar experiment in which the tracking task was replaced by target identification, probability monitoring and warning light monitoring and found little evidence of performance decrements with the same vibration. He concluded that effects of vibration on tracking are biomechanical.
Holland 1966, 1967	First order, continuous, compensatory tracking in two axes with "side-arm" and "centre-stick" isotonic controls. The forcing function was the sum of 15 sine waves (0·075 to 0·75 Hz). Visual and auditory choice reaction time were secondary tasks. The task was run for 45 min in each hour of the vibration exposure: 5 min with the centre stick and 40 min with the side-arm control. Absolute error was integrated over successive 5 min periods and immediate knowledge of results given. Skin temperature, heart rate and respiration rate were also measured. The seat was a standard wood office chair. 12 subjects: 6 were assigned to each of the two vibration spectra.	Seat, control and display were all mounted on the vibrator. There were two triangular shaped, random spectra of vertical (z-axis) vibration, one with the peak at 2 Hz and the other with the peak at 5 Hz. Subjects were exposed continuously during three 6 h sessions to one of three vibration levels: 0· 0·12 and 0·16 g r.m.s.	Both horizontal and vertical tracking were degraded by all the vibration conditions, although the two vibration amplitudes were not significantly different in effect. Average hourly errors were significantly different but not always in the direction of the expected increase with time. The vibration spectrum peaking at 5 Hz was significantly greater in effect than that peaking at 2 Hz. The centre stick was significantly better than the side-arm control, but this result may be confounded by order effects. Horizontal tracking was consistantly better than vertical tracking.

Reference	Task details	Vibration conditions	Results and conclusions
Hornick also Hornick, Boettcher and Simons 1962, 1961.	Task identical to that of Schmitz [29] with the addition of a peripheral vision test. 20 subjects.	Seat and controls mounted on vibrator, display static. The task was run continuously for one hour, including 15 min pre- and post-vibration control trials. 45 vibration conditions, not including no-vibration control conditions: 1·5, 2·5, 3·5, 4·5 and 5·5 Hz, each at 0·15, 0·25 and 0·35 *g* peak (*x*-, *y*- and *z*-axes, presented separately: Hornick *et al.* [87] report on *x*- and *y*-conditions only).	Tracking and pedal performance were significantly degraded by vibration. The worst effects were found to be at 5·5 Hz for vertical (*z*) motion, 2·5 and 3·5 Hz for longitudinal (*x*) motion and 1·5 and 2·5 Hz for transverse (*x*) motion: hence performance decrements appear to be related to body resonances. Decrements in tracking performance increased as a function of time of exposure to vibration and recovery was not complete for some time after the vibration had stopped, but this may have been due to a time linked fatigue effect. The vibration had no effect on choice reaction time, visual acuity or body sway but peripheral vision was slightly affected by transverse (*y*) vibration.
Huddleston 1970.	Zero order, continuous, compensatory tracking in two axes with a short joystick. Sinusoidal forcing functions (0·05 Hz). Performance was measured by "time on target" within four 30 s periods for each experimental condition. The subjects viewed the display (a small zero-reader instrument) through a periscope, the lower mirror of which was controlled by a servo system and moved on an (unspecified) axis in simple harmonic motion. Two experiments were run: in the first, 20 subjects performed the tracking task with an apparently vibrating display. In the second, 6 subjects performed the tracking task then were instructed to fixate on the display while eye movements were measured by electro-oculographic potential.	In the first experiment there were 20 conditions of apparent display vibration (subject and control remained static throughout), caused by vibrating the lower mirror of the display periscope at 1 to 10 Hz in 1 Hz steps, each at 2 and 4 degrees double amplitude. In the second experiment the vibration conditions were 1, 2, 3, 4, 5 and 6 Hz at 4 degrees double amplitude.	Tracking performance was significantly impaired by all the vibration conditions compared to pre- and post-vibration static runs. At 4 Hz and below the higher vibration level degraded performance considerably more than the lower, but at 5 Hz performance was significantly worse with the lower vibration than with the higher. The mean tracking performance was worse at 3 Hz with the higher vibration level and at 5 Hz with the lower level. During the tracking task in second experiment a significant sinusoidal component of eye motion was visible at 1, 2 and 3 Hz with all subjects. At 4 Hz the eye stayed near the centre of the vibration excursion, wandering up and down from time to time. At 5 Hz all subjects tried to fixate at or near the upper excursion limit for most of the time and at 6 Hz, fixation on the upper nodal image was apparently unhindered. It appears that decrements in tracking performance with the apparently vibrating display were due to disturbance of visual acuity. This is especially prevalent with display vibration in the

Reference	Task details	Vibration conditions	Results and conclusions
			range 3 to 6 Hz, where there is a change in viewing strategy: below 3 Hz the eye is able to compensate for oscillation of the visual image by pursuit, however, this becomes more inefficient as the amplitude of the oscillations increases. At 6 Hz and above the eye is able to fixate the upper virtual image.
Khalil and Ayoub also Khalil 1970, 1969.	Zero order, continuous, compensatory tracking in a single (vertical) axis, using a side-arm control lever with hand rest. Complex forcing function. Subjects performed the task according to four alternative work-rest schedules, for periods of 1 h. Work and rest periods were equal in each schedule, the actual durations being 5, 10, 15 and 30 min. Tracking error was integrated over the first 45 s of every minute of work. Vibration transmission to hip and head was also measured. Office-type chair. 7 subjects.	Seat, control and display all vibrated. One condition of vertical (z-azis) sinusoidal vibration, continuous for 1 h, and a no-vibration control condition of similar duration. 5 Hz at 0·2 g peak.	The vibration had a significant effect on tracking performance, and caused increases in vertical tracking error of over 50%. There was no overall significant difference in tracking error due to test period or work-rest schedule under static or vibration conditions, however, there was a significant interaction between vibration and work-rest schedule. Under static conditions the average tracking performance improved as work-rest schedules change from 30/30 tp 5/5, whereas the opposite occurred under vibration conditions, the optimum work-rest schedule under vibration being 30/30. Hence the difference between mean performance levels in static and vibration conditions at this task, over a 60 min period was least for a 30/30 min work-rest schedule and greatest for a 5/5 min work-rest schedule.
Levison and Houck 1975.	First order, continuous, compensatory tracking in a single (vertical) axis. Six hand controls: spring centred displacement sticks with three different gains and isometric sticks with three gains. Two stick locations were investigated for each stick (centre and side-arm). The forcing function was the sum of 5 sinusoids (0·5, 1·25, 3·0, 6·3 and 10·5 rad/s). Aircraft type seat. 10 subjects.	Seat, control and display all vibrated. One vibration condition only, plus no-vibration control runs: sum of 5 sinusoids, at 2, 3·3, 5, 7 and 10 Hz, with equal acceleration amplitudes. The combined acceleration level was 0·3 g (z axis)	There was little difference in overall tracking performance, in vibration conditions, between the six control sticks. Considerably more vibration feed-through was observed with the isometric sticks, but feed-through accounted for less than 10% of the total error variance. The primary effects of vibration in this experiment were increases in operator-generated noise and increased time delays. There was no evidence of visual decrements. Control location had no significant effect on performance, or on head, shoulder or elbow accelerations.

Reference	Task details	Vibration conditions	Results and conclusions
Levison 1976.	First order, continuous, compensatory tracking in a single (vertical) axis using isometric and spring centred, centre-mounted control sticks. The forcing function was the sum of 5 sinusoids (0·5, 1·25, 3·0, 6·3 and 10·5 rad/s). Error variance was partitioned into that correlated with the tracking input and the vibration, and remnant. Transfer functions between the vibrating platform and the shoulder and platform, and stick were also measured. Tracking runs were 2 min long. 7 subjects.	Seat, control and display all vibrated. 15 conditions of vertical (z-axis) vibration including 2, 3·3, 5·7 and 10 Hz sinusoidal vibration at 0·15 and 0·30 g rms. A combination of equal acceleration components at the above frequencies, with combined levels of 0·15 and 0·30 g rms; random vibration, comprising a flat acceleration spectrum over the range 2–10 Hz, at 0·15, 0·20 and 0·30 g rms.	Although static errors were less with the isometric stick, vibration induced a relatively larger increase in error with the isometric compared with the spring stick under all the vibration conditions. Vibration breakthrough generally accounted for a negligible fraction of the error variance but the breakthrough was much larger with the isometric stick than with the spring stick. The important effects of vibration appeared to be an increase in motor-related remnant and time delay—both of which were linearly correlated with shoulder accelerations. The effect of vibration frequency on error variance was not significant, but the largest effects were at 3·3 Hz for the spring stick and 7 Hz for the isometric stick.
Lewis 1974.	Zero order, continuous, pursuit tracking in a single (horizontal) axis. Three side-arm controls: a pure isotonic stick and two spring sticks, with different spring constants. The forcing function was the sum of 4 sinusoids (0·1 to 0·9 Hz). The tracking error from each 3 min run was subjected to Fourier analysis to give estimates of error variance within various frequency bands, and distinguish error due to vibration breakthrough to the control from other sources. Information channel capacity was also estimated from the coherency of forcing function and control output. Subjects sat on a flat, hard seat with no back and no restraints. 12 subjects.	Only the seat was vibrated; control and display were static. 4 conditions of vertical (z-axis) vibration: a combination of 3, 5 and 8 Hz sinusoids with equal acceleration amplitudes, with combined levels of 0, 0·43, 0·87 and 1·73 m/s^2 rms.	Information channel capacity was significantly reduced by all the vibration conditions, although the effect of a given level of vibration is reduced by introducing spring centering in the control stick. The total mean square tracking error was only significantly affected by the highest vibration level, but there were greater effects within some error frequency bands. There were significant increases at all vibration levels in the error variance at forcing function frequencies. Vibration also induced large peaks of operator generated noise around 2 Hz, particularly with the pure isotonic control stick. Vibration directly transmitted to the control formed a very small part of the total error. The authors suggest that these results are evidence of interference with kinaesthetic feedback by vibration.

Reference	Task details	Vibration conditions	Results and conclusions
Lovesey 1971a.	Zero order, continuous, compensatory tracking in two axes with a miniature, side-arm joystick. Forcing functions were the sum of two sine waves (0·05 and 0·18 Hz). Absolute error was integrated over 1 min runs. Hard seat with back rest. 18 subjects. The effect of a full harness was investigated with 3 subjects only.	Seat and control only were vibrated, display static. 12 vibration conditions, including 6 of sinusoidal vibration: 3, 5 and 7 Hz at ±0·2 g (z-axis). 3, 5 and 7 Hz at ±0·1 g (y-axis) and, also 6 dual axis combinations of the above.	Each of the conditions of vertical (z-axis) vibration degraded tracking performance more than any of the transverse (y-axis) vibration conditions. Multi-axis vibration tends to degrade tracking by an amount equal to the product of the decrements produced by each axis alone. Restraining the subjects with a full seat harness tends to improve horizontal tracking and degrade vertical tracking.
Lovesey 1971b.	Zero order, compensatory positioning task using an aircraft type ramshorn control column (dual axis). The control was spring centred and required a significant break-out force. Performance was measured by the sum of maximum deviations (error peaks) either side of the mid position, and by the number of positive deviations greater than 1 mm 40 s runs. The control station was the cockpit of a large transport aircraft. Additional experimental conditions were the addition of a restraining harness; the removal of visual feedback, thus restricting control to kinaesthetic feedback alone; and biasing the position of the control so it was necessary to push forward and to the left to maintain it in the mid position. 3 subjects.	Seat, control and display all vibrated. 6 vibration conditions, including 4 of sinusoidal vibration, 2 and 2·7 Hz at ±0·25 g (z-axis), 2 and 2·7 Hz at ±0·14 g (y-axis), and also 2 dual axis motions of 2 Hz (z or y) and 2·7 Hz (y or z) at the same levels.	Positional control was adversely affected by all the vibration conditions. Generally, y-axis motion produced greater performance decrements than z-axis motion. Dual axis vibration affected control accuracy by an amount greater than the sum of the effects produced by each axis alone. The effects of all the vibration conditions were made worse with the use of a restraining harness, with bias in the control position and in the absence of visual feedback.

Reference	Task details	Vibration conditions	Results and conclusions
Lovesey 1971c.	Second order simulated missile control task in two axes, using a miniature, spring loaded joystick mounted on seat armrest. The control station was the cockpit of a Scout helicopter on a flight simulator. Visual data was presented via a padded binocular sight, against which the subject's head was pressed by an inflatable cushion. Performance was measured by time on target over 30 s runs. The effect of adding a full restraining harness were also investigated. 9 subjects. Only 5 subjects were used with the sinusoidal vibration conditions.	Display, seat and control were all vibrated. Five vibration conditions were as recorded, in vertical (z), pitch (rotation about y-axis) and roll (rotation about x-axis) axes, at the floor of a hovercraft at typical cruise speeds over five combinations of wave heights and directions. 10 sinusoidal vibration conditions were also used: 0·3, 1 and 4 Hz at $\pm 0{\cdot}1\ g$ (z); 0·6, 1 and 4 Hz at $\pm 0{\cdot}2\ g$ (z); 0·6 Hz at $\pm 0{\cdot}1\ g$ (y) singly and in combination with 0·3, 1 and 4 Hz at $\pm 0{\cdot}1$ (z).	With the hovercraft motion there was a progressive decrement in performance with increasing sea state severity. The most severe motion contained predominant vertical (z-axis) accelerations of $\pm 0{\cdot}35\ g$ at 8 Hz and large amplitude roll and pitch components at 10 and 3 degrees/s, respectively. All of the sinusoidal vibration caused some degradation in performance. The low frequency, 0·3, 0·6 and 1 Hz motions in z- and y-axes had the least effect on performance. 4 Hz z-axis vibration at $\pm 0{\cdot}2\ g$ had the greatest effect on performance and on subjective comfort. With dual axis vibration, performance was generally slightly worse than that with either of the motions applied singly.
Mozell and White 1958.	Zero order, continuous, compensatory tracking in two dimensions, with an aircraft joystick control. Forcing functions were 0·4 Hz sinusoids. Performance measured by integrated, absolute error over 2 min runs. Aircraft seat with full harness. 8 subjects: 4 performed at each vibration amplitude.	Seat and control mounted on vibrator; display static. 10 vibration conditions: 0, 8, 13, and 23 Hz, each at $\pm 0{\cdot}05$ inch (z) and $\pm 0{\cdot}1$ inch (z).	None of the vibration conditions were found to significantly degrade tracking performance.
Nagasawa, Hagihara, Aramaki and Ito 1969.	Zero order, continuous, pursuit tracking in a single (horizontal) axis using a joy stick control. Sinusoidal forcing function (0·07 Hz). Performance measured by overall and vibration-correlated tracking error. Seat with back and headrest, and full harness. 5 subjects.	Seat only vibration, control and display static. 5 conditions of horizontal (y-axis) sinusoidal vibration, not including no-vibration control conditions: 1, 3, 5, 7 and 9 Hz, all at displacements of 5 mm double amplitude.	The greatest decrement of tracking performance was observed with 3 Hz vibration, with relatively large increases in vibration-correlated error at 3 and 5 Hz. The authors conclude that vibration-induced oscillations of the control interfered with feedback of tracking performance, and that the effects of y-axis vibration on tracking performance are predominantly related to frequency rather than acceleration.
Parks 1961.	Continuous, compensatory tracking in two axes with an aircraft control column. Sinusoidal forcing functions (0·066 Hz vertically and 0·083 Hz horizontally). Performance measured by integrated	Seat, control and display mounted on vibrator. 10 vibration conditions of vertical (z) vibration, including 4 sinusoidal conditions: 0·75 Hz at 4·52 and 1·57 in double amplitude, 2·5 Hz at 1·08 and 0·26 in	Vertical tracking errors were significantly increased by vibration, but there was little effect on horizontal tracking or reaction time. Performance was most affected by 2·5 Hz sinusoidal vibration at 1·08 in double amplitude

Reference	Task details	Vibration conditions	Results and conclusions
	absolute error over 4 min runs. Aircraft seat with hard cushion and lap only belt. 10 subjects.	double amplitude; 4 conditions of fixed frequency, random amplitude vibration: 0·75 Hz at 4·26 in double amplitude max. and 1·7 in rms, 2·5 Hz at 2·16 in double amplitude max. and 0·09 in rms. 2 levels of real aircraft vibration spectrum from 0·5 to 3 Hz.	and least affected by 0·75 Hz vibration.
Rodrick 1972.	Continuous, compensatory tracking in two axes with a side-arm isometric stick, equipped with an armrest. Control dynamics were simulations of aircraft short-period response (second order instability) in vertical axis and aileron response (first order instability) in horizontal axis. Forcing function was the sum of 4 sinusoids (0·01 to 0·16 Hz). Performance measured by time on target within a 1 min tracking run. No seat details. 5 subjects, all unpracticed at the task when experiment started.	Both vibration of the control stick only with static seat and display, and vibration of seat, control of seat, control and display. 22 conditions of vertical (z-axis), sinusoidal vibration of the control stick, with 2 no-vibration control conditions: 5, 10, 15, 20, 25, 30, 40 and 50 Hz at 0·5 g rms, 10, 15, 20, 25, 30, 40 and 50 Hz at 1·0 g rms and 15, 18, 21, 24, 27, 30 and 40 Hz at 1·5 g rms. 22 conditions of vertical (z-axis), sinusoidal vibration of the seat, with 2 no-vibration control conditions: 5, 10, 15, 20, 25, 30, 40 and 50 Hz at 0·25 g rms, 10, 15, 20, 25, 30, 40 and 50 Hz at 0·40 g rms, and 15, 18, 21, 24, 27, 30 and 40 Hz at 0·60 g rms.	Tracking scores with seat vibration were higher overall, even though the corresponding vibration levels were lower. There was much more variation between subjects with control vibration than with seat vibration, but this may be a practice effect (control vibration was presented first and subjects were not practiced before the experiment). All subjects show a marked degradation in performance with vibration in the 20 to 25 Hz range, but there was little evidence of an expected degradation at 5 Hz. Learning effects were quite marked over the course of the experiment and scores tended to improve between runs independently of vibration conditions. It was the author's hope that the random order of vibration conditions prevented learning from influencing the overall result.
Schmitz also Schmitz and Simons 1959.	Simulated driving task involving: (a) zero order, continuous, compensatory tracking in one (horizontal) axis, with a steering wheel; 0·06 Hz sinusoidal forcing function; (b) constant foot pressure task: the pressure applied to a pedal was indicated on a dial; (c) foot reaction time; the subject was required to move his foot to a brake pedal in response to a red light on the display. In addition were tests of visual acuity, body sway and hand tremor. Tracking and foot pressure measured by integrated absolute error averaged over 15 min periods. Hard wood seat. 18 subjects.	Seat and controls mounted on vibrator; display static. The task was run continuously for 2 h, including 15 min pre- and post-vibration control trials and 1½ h constant vibration. 4 vibration conditions, not including no-vibration control conditions: 2·5 Hz at 0·18 g (z) peak and 0·35 g (z) peak, 3·5 Hz at 0·15 g (z) peak and 0·30 g (z) peak.	Tracking and pedal performance were significantly degraded by all of the vibration conditions. Error increased as a function of both amplitude and frequency of vibration. There were no significant between trials effects within any 1½ h exposure; however tracking performance was significantly worse in post-vibration compared with pre-vibration trials. Foot reaction time was unaffected by the vibration. Body sway and manual tremor were also unaffected but visual acuity was affected by amplitude and frequency of vibration.

Reference	Task details	Vibration conditions	Results and conclusions
Shoenberger 1970.	First order, continuous, compensatory tracking in two axes with a joystick mounted to the right of the subject. The forcing function was the sum of 9 sine waves (0·075 to 0·75 radians/s). Absolute error was integrated over 4 min tracking runs. Subjects performed a visual, choice reaction time task at the same time as tracking. Hard, aircraft type seat with full harness. Separate experiments were run for each of the three vibration axes, with 10 different subjects for each.	Seat, control and display were all mounted on the vibrator. 21 conditions of sinusoidal vibration: 1, 3, 5, 8 and 11 Hz, each at 0·2 and 0·4 *g* peak (*x*-, *y*- and *z*-axes, presented separately).	Both levels of transverse (*y*-axis) vibration produced significant decrements in horizontal and vertical tracking with the greatest interference at 1 and 3 Hz and the least at 11 Hz. Both levels of longitudinal (*x*-axis) vibration significantly degraded horizontal tracking at all frequencies except 11 Hz, with the greatest effect at 5 Hz. There were large decrements in vertical tracking with *x*-axis vibration at 0·4 *g* for all frequencies—particularly 1, 3 and 5 Hz. A level of 0·2 significantly degraded vertical tracking at 1, 5 and 8 Hz. Vertical (*z*-axis) vibration significantly degraded horizontal and vertical tracking at both levels and all frequencies except 11 Hz at 0·2 *g* peak. There was no overall significant difference between the effect of 0·2 and 0·4 *g* peak vibration in the *z*-axis and tracking scores were almost constant over the frequency range. Vibration in the *y*-axis degraded horizontal tracking much more than vibration in the *x*- or *z*-axes—particularly at 1, 3 and 5 Hz. The very large effect of *y*-axis vibration was probably due to lack of support for the swaying body. However, *x*- and *z*-axis vibration had a greater effect on vertical tracking than on horizontal tracking. The author interprets the different effects on horizontal and vertical tracking, of vibration axis and frequency, in terms of biodynamic interference with the manipulative and visual aspects of the tracking task. He concludes that mechanical interference is the primary mechanism responsible for decrements by whole body vibration in tasks of this nature.
Shoenberger and Wilburn 1973.	First order, critically unstable tracking task in a single (vertical) axis, using centre- and side-mounted, isometric joystick controls. Subjects were required to track a dynamically unstable controlled element. The instability of the controlled element was gradually increased until the subject could no longer	Seat, control and display all vibrated. 4 conditions of vertical (*z*-axis), sinusoidal vibration: 0, 2, 6 and 10 Hz, all at ±0·4 *g*.	With both sticks, all three vibration frequencies produced significantly poorer performance than the control condition. The poorest performance occurred at 6 Hz, but was not significantly different from performance at 2 and 10 Hz. There was a significant frequency by sticks interaction, indicating that the effect of stick location was

Reference	Task details	Vibration conditions	Results and conclusions
	maintain control. The highest level of instability for which a subject could maintain control was the performance measure, and is equal to the subject's "effective delay time". Hard aircraft type seat with full harness and padded armrest. 8 subjects.		frequency dependent. The side-stick was better at 2 Hz, but the centre stick was slightly better at 6 Hz and significantly better at 10 Hz. The large performance decrement at 10 Hz with the side-stick may be due to transmission of vibration to the subject's tracking hand via the armrest.
Shurmer 1967, 1969.	Zero order, continuous, compensatory tracking in two axes with two different hand controls: isotonic and isometric, finger-operated joysticks. The forcing function was the sum of two sine waves (3 and 11 Hz). Performance was measured by time on target (target width was 10% of maximum display excursion) over 30 s tracking runs. The subject sat in a Martin Baker Mk 8 ejection seat, in a simulated aircraft cockpit. His right forearm was supported by a padded armrest (the control was operated by the fingers of the right hand). 3 point harness. 6 subjects.	21 vibration conditions including 12 of sinusoidal vibration in one of three axes and 9 unspecified, multi-axis combinations of these. Transverse (y-axis) motion: 2 Hz at 0·1 and 0·2 g peak; 4 Hz at 0·05 and 0·1 g peak. Vertical (z-axis) motion: 2 Hz at 0·3 and 0·5 g peak; 4 Hz at 0·1 and 0·3 g peak. Roll (rotation about an x-axis, with centre of motion 2 ft below seat): 2 Hz at 1·5 and 3·0 degrees/s peak; 4 Hz at 0·25 and 0·5 degrees/s peak.	With transverse (y-axis) vibration, performance was degraded more by a 4 Hz than a 2 Hz motion at a similar acceleration level. This effect was most pronounced for horizontal tracking performance. With vertical (z-axis) vibration, 2 Hz vibration had a greater effect on tracking performance than 4 Hz motion, especially on vertical tracking. These frequency effects were opposite to those expected, considering body resonance phenomena. With roll (rotation about x-axis), tracking decrements are more pronounced at 4 Hz, even though the acceleration levels were lower at 4 Hz than at 2 Hz. For multiaxis motions, the best prediction of overall performance decrement was obtained simply by multiplying together the degradation factors for each axis alone, with appropriate weighting factors. The isometric stick was more sensitive to all the vibration conditions than the isotonic control, although their performances were similar under static conditions.
Torle 1965.	First order, continuous, compensatory tracking in two axes with a displacement stick. Sinusoidal forcing functions (approx. 0·1 Hz). Total rms tracking error was measured over 30 s runs. The trials were carried out in a "G seat" built by SAAB. The seat was inclined backwards at 30 degrees and had a hard leather cushion. Additional experimental conditions were 3 levels of backlash in the task, 3 levels of friction in the control stick and two armrests. 3 subjects.	The vibration spectrum consisted of simulated gust-induced turbulence, over the frequency range 0·2 to 5 Hz, at 4 levels: 0, 0·15, 0·20 and 0·30 g (z) rms. Each session consisted of 24, 30 s tracking runs, divided into 6 blocks. Every second block was performed under static conditions.	The relative effect of the vibration on tracking errors decreased with the introduction of a small amount of backlash, but in absolute terms any backlash caused a deterioration in performance. In the absence of vibration, friction in the control reduced tracking precision but with vibration errors were reduced by a certain amount of friction: however this was not statistically significant. Small and large armrests reduced errors equally under vibration: this effect increased with increased acceleration level.

Reference	Task details	Vibration conditions	Results and conclusions
Weisz, Goddard and Allen 1965.	First order, continuous, compensatory tracking in two axes with a side-mounted, friction damped, displacement stick. 2 forcing functions were used, representing 2 levels of task difficulty: 10 sinusoids (0·075-0·509 rad/s) and 15 sinusoids (0·075-0·750 rad/s). The tracking task was performed both with and without choice reaction time and auditory vigilance secondary tasks. Tracking runs were 20 min, either continuous (first experiment) or with 1 min rest after every 5 min (second experiment). Error was integrated over four 4·5 min periods within each run. Contoured, wooden seat with full harness. 12 subjects for each of two experiments.	Seat, control and display all mounted on vibrator. 12 conditions of vertical (*z*-axis) vibration, 5 Hz sinusoidal, 5 Hz random amplitude and 4·12 Hz random vibration, each at 0, 0·035, 0·106 and 0·177 *g* rms. In the second experiment the 0·177 *g* level was replaced by 0·212 *g* rms.	In general, performance deteriorated with increasing vibration level. There were no significant differences between the effects of the different types of vibration. In the first experiment (continuous tasks) tracking errors significantly increased over the 20 min tracking runs, at all vibration levels, however, in the second experiment (1 min rest after every 5 min) performance was constant over time at all vibration levels. In the first experiment there was significant trials by subjects interaction, the performance of some subjects deteriorating more than others over time. There was a significant interaction between vibration and presence of secondary tasks: performance decrements under vibration were disproportionately greater when subjects were required to perform secondary tasks.
Weisz, Allen and Goddard 1966.	First order, continuous, compensatory tracking in two axes with three different hand controls: a free moving stick, a viscously damped stick and an isometric "torque controller" in which the output was proportional to applied torque about the centroid of the hand grip. The forcing function was the sum of 30 sine waves (0·012 to 1·2 Hz). Absolute error was integrated over 4·5 min periods. The subject's transfer functions and cross covariance of input and output were also calculated. An unpadded school chair was used with a harness. 6 subjects.	Seat, control and display were al' mounted on the vibrator. There were 3 vibration conditions: no-vibration; 5 Hz sinusoidal vibration at 0·248 *g* (*z*) rms and a random vibration spectrum (4 to 12 Hz) also at 0·248 *g* (*z*) rms.	There was no significant effect of vibration on tracking performance, although performance was superior under static and vibration conditions with the isometric control: there was no difference between the free moving and viscously damped controls. The cross covariance and transfer function data suggests that the superiority of the isometric control is due to smaller lags in the response of subjects compared to those with the moving controls.
Wilkinson and Gray 1974.	Zero order, continuous, compensatory tracking in a single (vertical) axis, using a miniature, side-arm control stick. Quasi-random forcing function. Performance was measured by integrating absolute error over 3 min tracking runs. The tracking task was run sequentially with vigilance, visual search and handwriting tasks: there were six	Seat, control and display all vibrated. One vibration condition, with no-vibration control runs: 5 Hz at 1·2 m/s (*z*-axis) rms continuously for 3 h.	Even though the vibration exceeded the ISO 3 h fatigue decreased proficiency limit, there was no consistent increase in its adverse effects, over time, with any of the tasks. Tracking performance was significantly worse with vibration compared to static conditions, but performance improved during each session both with and without vibration. This improvement

Reference	Task details	Vibration conditions	Results and conclusions
	tracking runs within the course of a continuous, 3 h vibration exposure. The seat had a dry-fluid cushion. 8 subjects.		was more marked, though not significantly so, with vibration. The authors suggest that there may have been more support for the ISO time-dependency proposals if the task had been performed continuously throughout the vibration exposure.
Wilson 1974.	Zero order, continuous, compensatory tracking in two axes with a side-arm joystick control. Sinusoidal forcing function (0·1 Hz). Performance was measured by time on target within 5 min runs. The display (a small zero-reader instrument) was viewed either directly or through a collimated lens (producing a virtual image of the display at infinity). The subjects sat in a Martin Baker Mk 4 ejection seat with hard, moulded cushion and wore a flying helmet and full harness. 8 subjects.	Seat and control only vibrated, display static. 5 conditions of vertical (z-axis) sinusoidal vibration, with pre- and post-vibration static runs: 2, 4, 6, 8 and 10 Hz, each at 6·5 mm double amplitude.	There were no significant effects of vibration on horizontal tracking, but with vertical tracking time on target tended to be progressively degraded with increasing vibration frequency (note that the vibration conditions are constant amplitude, resulting in high accelerations at the higher frequencies). However, when the display was viewed directly there were marked peaks in performance decrements with 4 and 6 Hz vibration. The collimated lens improved tracking at all frequencies, but only significantly so at 4 and 6 Hz. For a given linear displacement of either the eye or display the relative angular movement between the two is reduced with increasing distance between them. Therefore, viewing the virtual image of the display at infinity should lead to a stationary retinal image. The improvement in tracking performance with a collimated display is therefore probably due to an improvement in visual acuity.
Wolf and Martz Jr 1975.	Zero order, continuous, compensatory tracking in a single (vertical) axis, with a side-arm control handle. Absolute tracking error was integrated over 50 s runs. There were 30 tracking runs during a 30 min, continuous vibration exposure. The seat was a metal stool. Measures were taken of each subject's age, height, weight, percentage of body fat, chest and waist circumference and self-estimated motivation level and physical condition. The number of subjects was not indicated.	One vibration condition, with no-vibration control conditions: 5 Hz at 0·16 inch double amplitude (z-axis).	The performance decrement induced by the vibration was not significantly, linearly related to any of the measured personal characteristics. However, the performance decrement was significantly correlated with time of day. This observed correlation was greater during the first 15 min of each vibration exposure than during the last 15 min.

APPENDIX B. NEUROMUSCULAR MECHANISMS AND MOTOR CONTROL IN VIBRATION ENVIRONMENTS.

One of the main objectives of the experimental part of this thesis is to investigate more thoroughly the basic mechanisms by which vibration can affect manual control performance. This appendix comprises a discussion of the neuromuscular, or motor processes which contribute to the performance of a tracking task, and what is known about the effects of vibration on these processes in isolation. Information such as this can be used to aid the interpretation of experimental results, and in predicting the parts of a human operator system which are likely to be susceptible to vibration with the aid of models such as that described by Lewis (1974).

B.1. THE ORGANISATION OF THE NEUROMUSCULAR SYSTEM.

The classical concept of sensori-motor behaviour is that of a chain of three separate processes, which leads from stimulation of the sense organs to resulting behaviour. These are respectively perceptual processes which include the reception of incoming signals by the sense organs and their interpretation, central or translation processes which relate perception to action, and motor or effector processes which shape and carry-out the resulting action (Welford 1958). It was assumed that the variability and adaptability in human behaviour is achieved by acquiring, over time, a large number of pre-formed responses which can be put into action as the occasion demands. However the extent of the adaptability which can be observed in human behaviour would require an almost infinite number of pre-formed responses. The alternative possibility is that the human operator is capable of continuously calculating appropriate responses based on sensory data as well as past experience.

Some thirty-five years ago a number of researchers in the then relatively new field of control engineering noted similarities between the motor responses of human operators and those of automatic control systems (Rosenbleuth et al, 1943, Wiener 1948, Tustin 1947, Craik 1947), leading to the acknowledgement of the importance of continuous sensory feedback in the control of all sensory motor actions. Craik (1947) noticed that tracking errors produced in a simple ramp tracking task were periodic in nature, with a predominant frequency of about 2 Hz and smaller clusters of frequencies over the range 1-4 Hz. The mean error in any direction was nearly proportional to the rate of the ramps. Craik likened this behaviour to that of an intermittent correction servo, in which a follow-up motor is intermittently switched into circuit and runs until it has reduced the misalignment to zero. He suggested that about 0.3s after the end of a preceeding corrective movement, subjects triggered off a corrective movement having a pre-determined time course and usually occupying about 0.2s. The 0.3s periods between movements were accounted for by the reaction time of the subject (the time taken for the eye to detect a misalignment, for the nerve impulses to traverse the central nervous system, for the appropriate response to be selected and for the nerve impulses to reach the muscles). Craik also suggested that other sensory modalities could be involved in the control of movement: the visual misalignment could become translated into a kinaesthetic misalignment, which would act as the continuous input to the limb until the joint and muscle receptors registered the correct position. This would result in a similar series of oscillations since, Craik postulated, kinaesthetic control would be subject to the same reaction time delay as visual control. This theory excludes some complex patterns of movement, such as typing or playing a musical instrument, from continuous feedback control since the movements are executed at a rate which would be impossible if they were continuously governed by the detection of misalignments followed by a reaction time lag. Craik suggested that such movements must be triggered off ballistically and that sensory feedback control must take the form of a delayed modification of the amplitude of subsequent movements. Chernikoff and Taylor (1952) confirmed that reaction time for a voluntary response to an unexpected kinaesthetic stimulation was in the same order as that for other sense modalities. The kinaesthetic stimulus was provided by dropping the subject's splinted right arm, which was previously held in position by an electromagnet. The arm was held completely relaxed and limp before its release. The subject responded to the stimulus either by stopping his falling arm or by releasing a telegraph key held in his left hand. The mean arm stop reaction time of six subjects was 0.129s and the mean key release reaction time was 0.149s. Reaction times to auditory and tactile stimuli were also measured by the key release method, the mean results being 0.151 and 0.160s respectively.

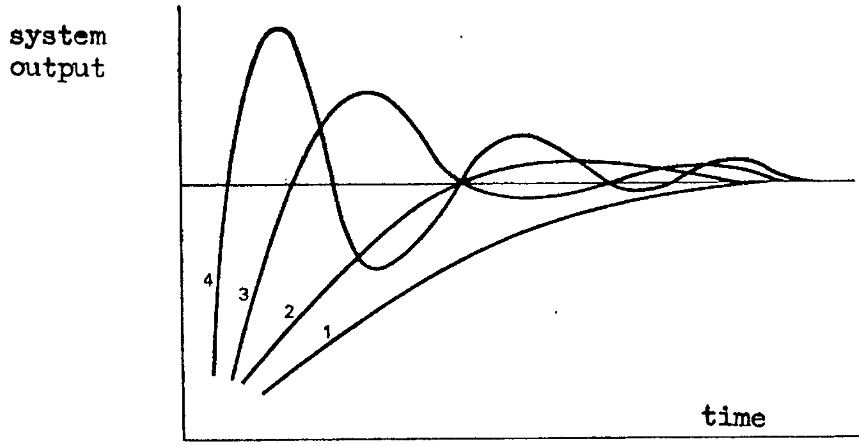
Gibbs (1954) presented experimental evidence to show that controlled changes in proprioceptive stimulation lead to significant changes in psychomotor performance, and that the amount of positive transfer between two skills is determined largely by the relative adequacy of the proprioceptive data in the first and second tasks. Notwithstanding the evidence of Craik (1947) and Chernikoff and Taylor (1952), he suggested that these results can be reconciled only with the theory that skilled responses are continuously regulated by kinaesthetic feedback. Gibbs ran a series of experiments involving first order, compensatory tracking in two axes. Both continuous tracking and target acquisition tasks were performed, using either free-moving (isotonic:output proportional to control displacement) or pressure (isometric:output proportional to control force) joysticks. Before the main experiment the control gains were optimised in a pilot experiment with nine subjects. A further thirty-six subjects were divided into two groups, closely matched in ability. Both groups performed a continuous tracking task for a total of fifteen minutes on three consecutive days; one group with the pressure control and the other with the free-moving control. Each group was then transferred to the other control for the next three consecutive days. The group which used pressure control for the first three days returned consistently lower r.m.s. error scores than the group with the free-moving control. After exchanging controls, on the fourth day, the errors of the group transferring from the pressure control to the more difficult free-moving control significantly increased. However there was no deterioration in the scores of the group transferring from the free-moving to the easier pressure control. After a longer period of training, twenty-four subjects performed further trials to compare free-moving and pressure levers with a more rapidly varying forcing function, and the superiority of the pressure control proved to be highly significant. Trials involving target acquisition also showed that significantly less time was required to operate the pressure control after the instruction to acquire the target, and that significantly less time was taken to complete an acquisition. An analysis of r.m.s. tracking error within consecutive, one second periods during the trials showed that the greatest differences between the two controls occurred in periods following changes in the direction of target motion, requiring corresponding adjustments in the controlling limb. This suggested to Gibbs that a major factor in the superiority of the pressure control was a reduced delay in modifying a previous muscular state and a more rapid settling to a new rate of contraction. Gibbs explained these differences in performance in terms of differences in proprioceptive discharge during isotonic and isometric muscular contraction. He presented physiological evidence which suggests that discharges of the muscle and joint receptors during isometric contraction are more rapidly conducted to the central nervous system and are more meaningfully related to the limb output than those available during isotonic contraction. However Gibbs (1954) does seem to have overlooked the fact that with an isotonic control both the inevitable friction in the mechanism and the inertia of the arm/control combination will oppose changes in velocity and direction, whereas these effects are absent in a pure isometric control. The presence of inertia and friction is bound to play some part, as well as differences in kinaesthetic feedback, in the larger errors after direction changes with the isotonic control compared to the isometric control.

Referring to the above results, Gibbs (1965) put forward the hypothesis that new movements are first controlled by exterceptors (i.e. vision), but that detailed duties of monitoring are delegated to proprioceptors for the longest possible period. He suggested that the degree of dependence on vision depends on the probability and predictability of the outcome of specific responses. This delegation would release exteroceptors and the limited span of attention from detailed duties of monitoring. Implicit in Craik's (1947) theory is the idea that to be of use in controlling movement all sensory feedback must travel around a complete control loop involving centres of higher consciousness. However Gibbs (1965) assumed that proprioceptive monitoring is delegated from a conscious to an automatic level. This would have the effect of reducing the time taken to amend directional errors from the visual reaction time (of the order of 0.25s) to the order of 0.10s, or the latency in the motor-proprioceptor circle of nerves (Gibbs, 1965). Gibbs went on to describe an experiment in which subjects were required to track a step function, with unequal probabilities of step direction, using a control which moved in the opposite direction to that of the controlled element on the display. Subjects frequently started movements in the wrong direction and early in practice the mean time to correct an incorrect response was 0.24s, but later in practice the mean correction time was reduced to 0.11s. It was suggested that the latter time is too fast for visual correction and instead is due to kinaesthetic correction. Marsden et al (1972) reported an experiment in which flexion movements of the top joint of the thumb were made against a constant opposing force, generated by a torque motor. About half-way through some of the movements, perturbations were introduced in the applied force: the force was either greatly reduced (allowing the thumb to accelerate), doubled (driving the thumb back) or caused to simulate a stiff spring (halting the movement). Response measures included the angular displacement of the thumb and the integrated electromyogram of the flexor muscle, indicating the degree of muscle activation at any instant. The electromyogram records showed that after a delay of only 50-60 ms the muscle attempted to compensate for deviations from the desired track by reacting in the opposite sense. Displacement records showed that compensation for the perturbations was more or less complete in less than 0.2s. Marsden et al concluded that the response to muscle stretch on suddenly driving the thumb backward was reflex, and that it was initiated by the same spinal reflex arc as the stretch reflex (Hammond, 1954) and the tendon jerk, since the latencies were similar. They further concluded that since the response to release had the same latency as the response to halting, they were both manifestations of the same mechanism and that the release response is the stretch reflex operating in reverse, showing that the muscle must have been receiving excitation via the stretch reflex arc at the moment of release. These results provide powerful evidence of a follow-up servo action in neuromuscular actuation at the spinal level.

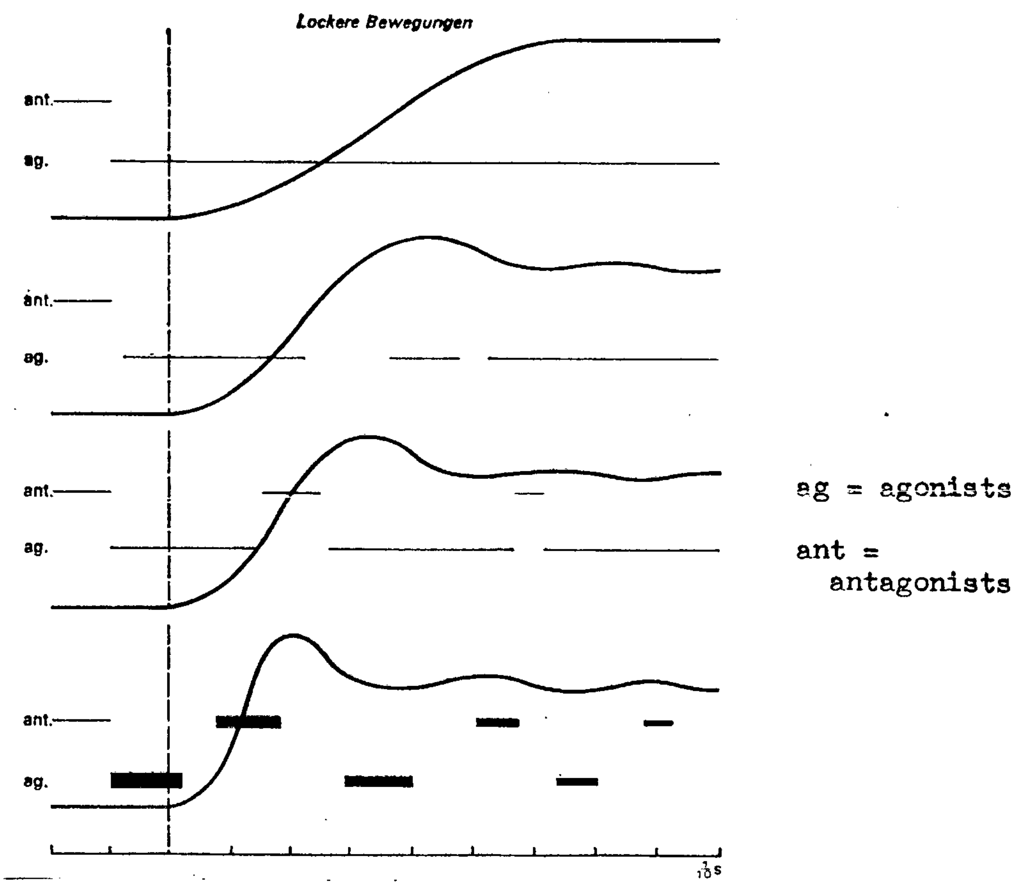
A follow-up servomechanism is a feedback control system in which the motion of an output member is constrained to continuously follow the motion of an input member, usually incorporating power amplification. The essential feature of the servo is a controlling device which is able to continuously detect the error between the output and the input. The error information is then used to control the output in such a way as to correct the detected error. Hence the follow-up servomechanism can be considered to be an automatic, continuous, compensatory tracking system. The performance of such a system is very flexible, as it is capable of attaining a given goal despite unexpected changes in external forces. However the performance of practical servo systems is limited by the inevitable delays in the transmission of feedback information and its translation into action. If the net phase lag in the system becomes such that the detected error is 180° out of phase with the output, fluctuations will not be attenuated at all but will be increased with each cycle by an amount equal to the open-loop gain of the controller, resulting in total instability. Therefore in order to maintain stability the maximum speed of response of the system output must be such that the open-loop gain is reduced to less than unity at frequencies where the phase lag in the system is 180° or more. This is the Nyquist criterion, which was discussed in section 3.1. with reference to manual compensatory tracking systems. The responses of a simple linear servo system, with variations in open-loop gain, to step input are shown in figure B.1.1. It can be seen that as the gain approaches an unstable condition there is an increasing tendency for the output to overshoot, the ensuing oscillations taking longer to damp out as the gain increases.

The phenomenon known as physiological tremor has been shown to be due to underdamped oscillations in the stretch reflex servo-loop (Halliday and Redfearn, 1958, Lippold, 1970). Physiological tremor is a slight oscillation which is superimposed on the normal contractions of all voluntary muscle, having an amplitude about 1 to 2% as large as that of the total movement produced by the contraction. In man the predominant frequency is in the range 8 to 12 Hz, peaking at around 9 Hz, and is independent of mass (Halliday and Redfearn 1956). A reflex loop with a latency of 55 ms would be expected to oscillate at 9 Hz; Lippold (1970) has demonstrated that a brief, stepwise displacement applied to the outstretched finger gives rise to a train of oscillations lasting up to a second, and of the same frequency of the physiological tremor. These oscillations were shown to have a constant phase relationship with the applied displacement, and the frequency could be raised or lowered by warming or cooling the arm (thereby altering the conduction velocity of the servo-loop). Hence these oscillations are consistent with those observed in an underdamped servo-system. This indicates that the stability of the neuromuscular system is normally slightly compromised in favour of speed of response. Of course the dynamic response of such a system is influenced a great deal by the load being driven: a viscous load will tend to increase the damping of the servo whereas an inertial load will increase the tendency to overshoot and oscillate. However unlike most man-made control systems, the stretch reflex servo appears to be able to adjust its dynamic properties to maintain an optimum

FIG B.1.1.



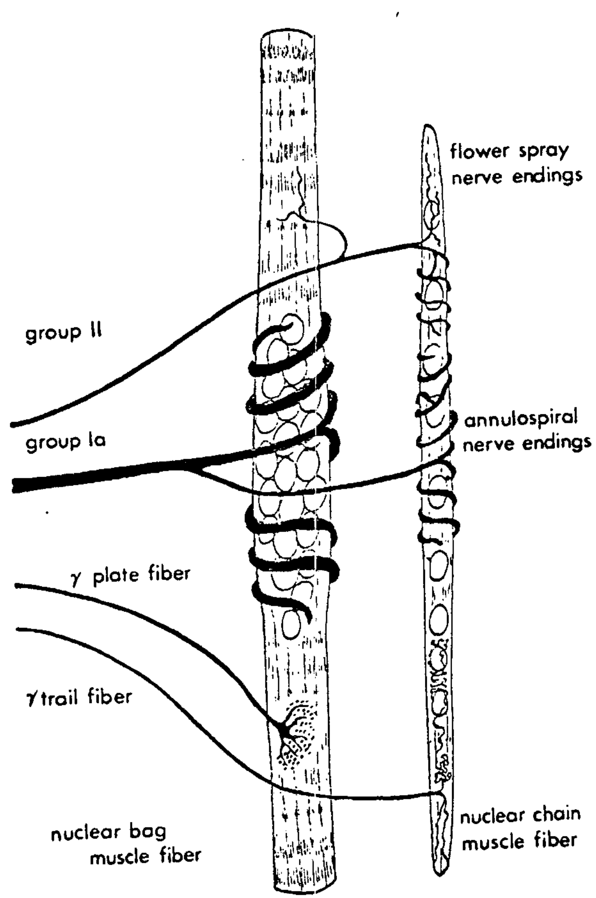
a. The transient stability of a first order servo system with varying degrees of damping. (Curves 2,3 and 4 are progressively underdamped and show increasing signs of oscillatory behaviour; curve 1 is overdamped and shows great stability at the expense of a long response time).



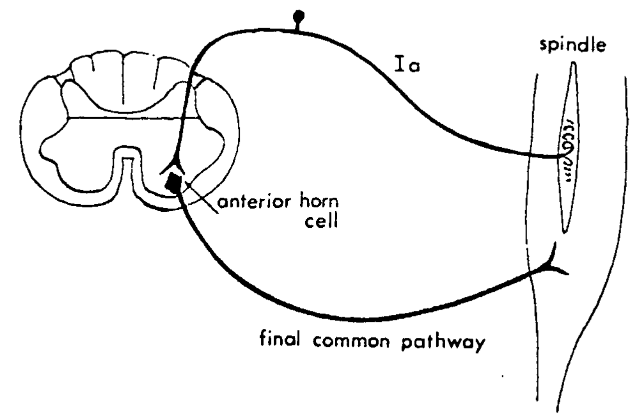
b. The distribution of muscular activity in two antagonizing groups of muscles at four stages of incresing speed of movement. (The electromyographic activity of each group is represented by a line, the thickness of which varies with intensity; The mechanographic record shows incresing tendency to oscillation when the speed of execution is increased). after Paillard (1960).

response speed despite large variations in load. For instance Marsden et al (1972) repeated their earlier reported experiment with a ten-fold increase in the forces acting on the thumb and discovered that the displacement patterns, indicating the extent of the deviations from a constant velocity track, were identical to those observed with lower forces. In order to achieve this the electrical activity in the muscle was considerably increased. Gottleib et al (1970) have also demonstrated that under conditions of active contraction, the gain of the Hoffman reflex in the soleus muscle (in an intact human subject) is approximately double that in the relaxed muscle. The effects of this elevation in loop gain are manifested in an increased speed of system response and a reduction in damping and stability of the affected loops. Studying the dynamics of quiet standing in man, Nashner (1970) determined that the gain of the ankle reflex loop was only about one third of that necessary for postural stability. However the gain was observed to suddenly increase when body sway exceeded a certain threshold.

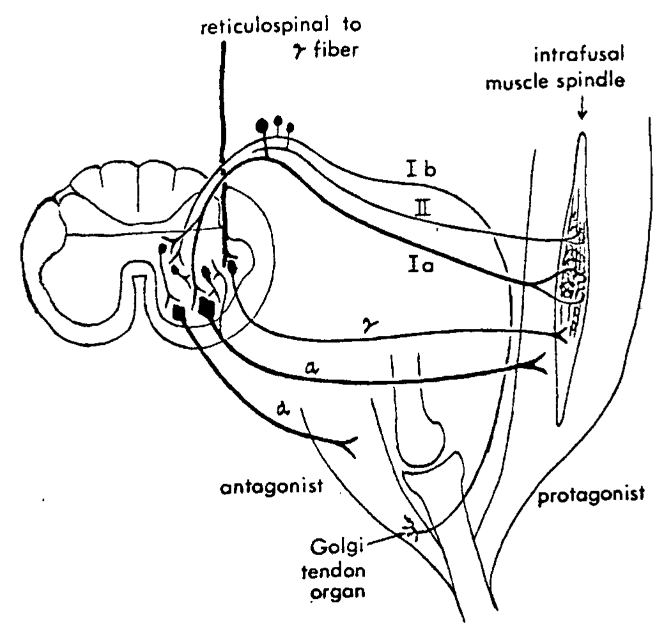
The muscle-spindle, which is the error detector and controller in the stretch-reflex servo-loop (Hammond et al 1956), is a complex organ located in all voluntary muscle. The spindles consist of capsules of connective tissue, about 1mm long, enclosing six or more 'intrafusal' muscle fibres and a number of sensory and motor nerve endings. They are located between the normal, 'extrafusal' muscle fibres and are oriented parallel to them. The ends of the capsules extend into and merge with the connective tissue of the whole muscle, hence the spindles are effectively connected in parallel with the muscle. There are two types of intrafusal muscle fibre (Matthews 1964): one is a large fibre of striated, contractile tissue, with a noncontractile, nonstriated equatorial region in which are concentrated most of the cell nuclei. The other type is a smaller fibre, with striations and nuclei distributed along its entire length. Because of the respective distributions of nuclei within them the former are referred to as nuclear bag fibres and the latter as nuclear chain fibres. The spindles are equipped with two types of sensory receptors (see figure B.1.2). The primary afferent has endings wrapped around the centre of the intrafusal muscle fibres: these are referred to as annulospiral endings. The afferent nerve fibres leading from them are large and fast conducting group Ia types. The secondary, or flower spray endings originate from the ends of the intrafusal fibres and lead to smaller group II afferent nerve fibres. Measurements by Matthews (1933) demonstrated that during dynamic stretch



a. The two types of intrafusal muscle fibre in muscle spindles and their sensory and motor connections.



b. The basic stretch reflex arc.



c. The complete spinal servo-mechanism.

FIG B.1.2. Sensory mechanisms in muscular control at the spinal level.

the discharge in both group Ia and group II afferents was approximately proportional to the rate of stretch. Under static stretch the response was weaker but for small and moderate loads the discharge was proportional to the log of the applied tension. Under active, isometric tension (produced by stimulating the motor nerves supplying the extrafusal muscle mass while maintaining the length of the muscle constant) there was no variation in discharge rate, as would be expected from receptors connected in parallel with the muscle. The primary elements in the stretch reflex arc (Hammond 1954) are the Ia afferent fibre from the muscle spindle and the final common pathway from the anterior horn cell (see figure B.1.2) which is the efferent motor nerve innervating the extrafusal muscle mass (which is composed of large, alpha motor fibres). Hence when the main muscle is stretched the resulting Ia afferent discharge causes the main muscle to respond by contracting.

The reflex arc is also modulated by several other feedback elements in order to prevent over or under contraction and to provide more delicate control of muscle stretch. In addition to the direct stimulation of the alpha efferents serving its own muscle, the Ia afferent acts through an inhibitory interneurone in order to inhibit motor activity in the antagonist muscle. Another inhibitory loop is initiated by the Golgi tendon organ. Golgi tendon organs are located at junctions between muscle fibres and tendons, at both ends of the muscle, and are effectively connected in series with the muscle. They are served by relatively large group Ib afferent nerve fibres, giving a discharge proportional to applied tension above a relatively high threshold (Matthews 1933). If the tendon of the antagonist in figure 4.1.4. is stretched due to excessive contraction, the resulting Ib afferent discharge acts via an inter-neurone to inhibit the contraction of the agonist in order to protect itself against overstretch. Another inhibitory inter-neurone, known as a Renshaw cell, receives feedback fibres from the alpha motor neurone itself in order to prevent its overdischarge.

The stretch reflex mechanisms described above are very efficient for holding a fixed posture but would also make voluntary movement almost impossible were it not for efferent motor fibres serving the intrafusal muscle fibres in the muscle spindles. These efferents are referred to as gamma or fusimotor fibres, distinguishing them from the alpha motor fibres which innervate the extrafusal muscle mass. Matthews

(1962) was able to distinguish two types of gamma motor fibre, which he referred to as gamma I and gamma II fibres, although they are more recently referred to as gamma plate fibres and gamma trail fibres (Jansen 1966) according to the nature of their endings. Histological details of these endings are still a source of contention among physiologists, but the weight of evidence suggests that gamma trail fibres end only on nuclear chains and gamma plate fibres end only on nuclear bags (see figure B.1.2.). The plate endings are also referred to as static gamma motor fibres and the trail endings as dynamic gamma motor fibres, because of their relative effects on the response of the spindle afferents to stretch. The latter increase the sensitivity of the afferent discharge to the rate of muscle stretch and the former increase the sensitivity to the amount of absolute stretch. When stimulated, the gamma fibres produce contraction in the ends of the intrafusal muscle fibres, stretching their central portions and stimulating the Ia afferents as though the extrafusal muscle fibres were being stretched. This will cause the muscle to shorten reflexly until the increased discharge in the spindle afferents is offset (i.e. when the muscle has shortened to the same extent as the spindles). Hence the gamma efferents are the input to the follow-up servo-mechanism: the sensory endings in the spindle detect differences in length between muscle and spindle and control the muscle length so as to follow changes in spindle length.

The system so far described is still not flexible enough to account for the observed variety in neuromuscular response (i.e. changes in dynamic properties to compensate for loading, etc.). The importance of higher centres in the central nervous system in the control of the dynamic properties of the stretch reflex servo-loop can be seen from the effects of locomotor ataxias such as Tabes Dorsalis, which progressively destroys the dorsal columns of the spinal chord (the dorsal columns are the large, fast conducting nervous pathways which carry afferent information from the muscle receptors to the central nervous system). This condition results in complete instability of the normal reflex mechanisms: attempts to perform controlled limb movements result in uncontrollable oscillations as if the gain of the servo system had been turned up well beyond critical limits. Feedback from the muscle receptors is therefore used by the higher centres to control the stability of spinal mechanisms. Afferent information from joint receptors has also been shown to be of importance in the control of the dynamic properties of muscular actions. Marsden et al (1972) found that anaesthesia of the thumb (which could not affect sensory afferents in the muscles controlling the thumb which are located in the forearm) resulted in considerable suppression in the gain of the stretch reflex. Joint receptors are not believed to be able to elicit direct reflex actions in their associated muscles (Marsden et al 1972).

The part of the central nervous system normally implicated in the co-ordination and control of motor actions is the cerebellum. Davson and Eggleton (1962) state that "the cerebellum, by virtue of its anatomical connections with the main motor and sensory systems, operates primarily as a feed-back centre that continuously modifies motor activity in the light of the fluctuating sensory activity from proprioceptive receptors." The basic mechanisms by which muscular actions are achieved are present at the spinal level, but it is necessary to bring these basic mechanisms into operation in a co-ordinated manner and this is achieved by the higher control loops. It is likely that the cerebellum is able to exert control over the dynamic response of the spinal servo-mechanism in two ways. Control of pure gain is possible by selectively inhibiting (or turning-off) a certain proportion of the individual servo units in a particular muscle. Another way of increasing the damping (and stability) of a servo-loop at higher frequencies is to provide additional negative feedback proportional to the rate of change of the output. This can clearly be achieved by changing the balance between static and dynamic fusimotor (gamma) stimulation of the muscle spindles.

It can be seen from the above discussion that sensori-motor behaviour is not, as was originally believed, a simple chain of sensory, central and motor processes connected in series but a complex hierarchy of recirculating information (see, for instance, Gibbs (1970) and Paillard (1960)). Motor processes are therefore as dependent upon the efficiency of a number of sensory processes as on the performance of the effector organs themselves. Evidence is presented in the next section to show that some of these sensory processes are sensitive to vibration and that these effects of vibration can lead to some difficulties in the control of certain motor actions.

B.2. PHYSIOLOGICAL STUDIES OF THE EFFECTS OF VIBRATION ON THE NEUROMUSCULAR SYSTEM.

Because of their high sensitivity to rate of change of length or tension of the muscle spindle, the Ia muscle receptors may be expected to be sensitive to vibratory stimuli applied to the muscle. Brown et al (1967) have confirmed that the Ia afferent of a de-efferented muscle (in this case the soleus muscle of a cat) are extremely sensitive to longitudinal vibration of the muscle, applied to the tendon. When the muscle was under moderate tension (20-200g. wt.) the endings could be 'driven' to discharge one impulse for each cycle of the vibration over the whole range of frequencies investigated (100 to 500 Hz). The vibration amplitude required to produce 'driving' was fairly consistent over the frequency range, and the most sensitive endings could be 'driven' by vibration amplitudes less than 10μ. The sensitivity of the Ia endings was increased by fusimotor (gamma) stimulation but was found to decrease under conditions of active contraction (consistent with the Ia responses to simple muscle stretch). Brown et al (1967) also measured the responses of the Group II muscle spindle afferents and the Ib Golgi tendon organs and found them to be insensitive to vibration compared to the Ia endings. Both endings could be 'driven' by the vibration at lower frequencies in the 100 to 500 Hz range, but only with large vibration amplitudes.

The role of the muscle spindle as an error detector and controller in the spinal servo-loop which controls muscle contraction has been discussed in the previous section. In normal circumstances an increase in discharge of the Ia afferents from a muscle signifies an increase in the error between the desired contractual state of the muscle (signalled by the gamma fusimotor system) and the actual steady state contraction. The Ia discharge would elicit a reflex contraction (the stretch reflex) in the muscle in order to correct the error. It can be seen from the results reported above that the response of the Ia afferent to vibratory stimulation is similar to that due to non-cyclic stretch of the muscle and several researchers have demonstrated a stretch reflex response to vibration of the muscle or its tendons. Matthews (1966) was able to elicit a strong stretch reflex in a decerebrate preparation (soleus muscle of the cat) by vibration the muscle tendon at frequencies in the range 50 to 500 Hz, and found that the reflex lasted for entire period of application of vibration, even when this was of the order of one minute. The strength of the reflex was dependent on the amplitude of the vibration up to an approximately constant maximum tension, and the reflex still occurred after ablation of most of the cerebellum showing that the mechanism is at the spinal level.

Stretch reflexes have also been induced by vibration of the muscles in intact human subjects by De Gail (1966), Eklund (1972), Eklund and Hagbarth (1966), Hagbarth and Eklund (1965), Goodwin et al (1972) and McCloskey (1973). In these studies vibration has usually been applied to the belly of a muscle in the arm or leg, and this usually results in a tonic reflex contraction of the muscle and relaxation of its antagonists. The reflexes are strongest when the muscle is in a state of moderate tension. When the muscle is relaxed the reflex contraction may not begin immediately at the onset of the stimulus, but it usually appears after a variable latency (Hagbarth and Eklund 1965). During isometric contraction, vibration of a muscle has also been shown to result in an increase in tension in itself and a decreased tension in its antagonists (Hagbarth and Eklund 1965). Such increases in force cannot be perceived by the subject, and in some circumstances the subjects feel that the muscle is actually relaxing.

The vibration-induced reflex activity, normally referred to as the Tonic Vibration Reflex, is also accompanied by pronounced illusions of movement and position in the associated limb. Goodwin et al (1972) showed that although the 20 subjects were able perceive the reflex movement of a forearm, about the elbow joint, when the biceps muscle was vibrated, they severely underestimated the rate of the movement and its extent. The blindfolded subjects were required to track the movement of the vibrated arm with their other arm, starting with both arms in the same position at the onset of the vibration. The initial part of the reflex movement was not perceived by the subjects, but when a movement of about 10° (about the elbow) had occurred the subject became aware of the movement and began to move the tracking arm. However the rate of movement of the tracking arm was slower than that of the vibrated arm, so that the misalignment between them increased progressively. After the vibrated arm had moved through about 40° its movement was gently arrested without the subject's knowledge. The subjects then had strong sensations that their arms were being moved in the opposite direction to that in which they had just been moving. Similar results, including pronounced illusions of movement and position during isometric contraction, were observed by Eklund (1972) for movements of the leg about the knee joint.

Eklund and Hagbarth (1966) have found that with peak vibration amplitudes of 0.6 to 1.8 mm the strength of the tonic vibration reflex increases with vibration frequency (both for isotonic and isometric contractions) over the range 20 to 200 Hz (the vibration waveforms were, however, not very pure). McCloskey (1973) found that vibration of the biceps at frequencies of 30 Hz and below did not cause illusions of movement in the arm, even though the peak to peak vibration amplitude was fairly large (about 50 mm) compared to previously described experiments. This lower frequency vibration was, however, shown to produce large illusions of arm position (the order of 10^{o} error in alignment at the elbow) when subjects were asked to match the positions of the fingertips of vibrated and non-vibrated arms. In each case the subjects believed the vibrated muscle to be more extended than it actually was.

The experiments described above show that vibration can, by interference with kinaesthetic feedback mechanisms, considerably affect a subject's ability to make accurate control movements, particularly in the absence of visual cues. The results also show that afferent information from the muscle receptors, particularly the Ia spindle afferents, can play a significant role in the conscious perception of both limb movement and position, a role which has previously been delegated entirely to joint receptors. Eklund (1972) showed that vibration of the knee joint and its surrounding tissue had no effect on the tonic vibration reflex, hence it would be difficult to implicate joint receptors in any way in the production of either the reflex or its associated illusions.

In all of the experiments described so far in this section the vibration has been applied directly to either the muscle or its tendons. To the author's knowledge there have been no reports of tonic vibration reflexes elicited by vibration transmitted from another part of the body, as in whole-body vibration. However Loeckle (1947) has shown that whole-body vibration can affect the normal operation of the stretch reflex loop. Tests were made of the strength of the tendon jerk reflex on Achilles, Patellar and Biceps tendons of subjects sitting on a flat, hard, vibrating seat. The vibration was observed to significantly reduce the activity of all the reflexes: sometimes the reflex disappeared altogether. With 30 Hz vibration at an amplitude of ± 1 mm the reflex activity was reduced quite suddenly (within 2 or 3 seconds of the onset of the stimulus) but with 50 Hz vibration at ± 0.05 mm the effect was seen to build up gradually. The effect often persisted for up to an hour after the cessation of the vibration. The effect was not significantly affected by loading the limb. Depression of normal reflex activity has also been observed at the same time as the tonic vibration reflex, during vibration of the muscle, by De Gail et al (1966). De Gail et al (1966) have also shown the depression of reflex activity by vibration to be due to a mechanism at the spinal level, as it is present below the level of spinal chord transections. It could be that the vibration induced activity in the Ia muscle spindle afferents pre-empts the transmission of other information, the tendon jerk stimulus being below the 'noise' level created by the vibration stimulus. Because of the importance of the stretch reflex loop in the efficient control of motor actions it would not be surprising if the depression of normal reflex activity significantly affected the accuracy with which precise movements can be made.

The major effect of depression of normal reflex activity, and of the tonic vibration reflex and its associated illusions, is likely to be seen as an increased reliance on visual cues of limb position and force. As visual feedback is subject to larger delays than kinaesthetic feedback mechanisms this is likely to result in more delays, and noise, in making accurate adjustments. Although the more obvious effects of the tonic vibration reflex have not been observed during whole-body vibration, they are likely to be elicited by vibration transmitted to the arm from a vibrating control or hand tool. However all of the studies performed on this phenomenon have used vibration frequencies greater than 20 Hz so the extent to which the effects occur at lower frequencies is not known.

It can be seen from the discussion in the previous section that the stretch reflex acts essentially as a stabilizer for limb position, to resist the effects of external force perturbations. The reflex is therefore an active damping influence on vibration-induced oscillation of the controlling-limb, serving to reduce the amount of vibration-correlated activity in the control output. In this context the frequency response of the stretch reflex loop has obvious importance. Rack (1973) performed an experiment on normal human subjects in which the left forearm and hand were fixed in a mould which was mounted on bearings allowing only a flexion-extension movement of the elbow joint. The forearm was then driven through sinusoidally alternating flexion-extension movements by a crank and rotating fly-wheel. Limb position and the force opposing arm movement were measured via force and position transducers at the wrist. The subject flexed his elbow against the crank to maintain a constant mean force: to assist him in this the mean force measured at the wrist was displayed on a meter. At both low and high frequencies the limb exhibited an apparently frictional resistance to movement, the tension on the crank and couplings being greater when the limb was being pulled toward the extended position than when it was flexing back towards the fly-wheel. However in the frequency band from about 7 Hz to about 13 Hz the direction of the force was observed to change so that the limb was doing work on the fly-wheel. This behaviour can be seen to be similar to that observed in an underdamped servo-mechanism driven beyond its critical frequency. This leads to the conclusion that the latencies in the stretch reflex loop are such that when it is driven at frequencies in the 7 to 13 Hz band there is a phase reversal for information transmitted around the loop. For a 180° phase shift the response latency of the loop would be one half period, or 50 ms for a 10 Hz forcing function which is in agreement with results presented in the previous section. The above results were obtained with a mean flexion force of 12 kg. As the mean force was decreased the frequency band in which force reversals occurred was observed to become smaller, until with a mean force of 3.5 kg no force reversals were observed but at frequencies in the region of 10 Hz the resistance to sinusoidal movement of the limb was practically zero. This is a powerful illustration of the capacity of the stretch reflex control loop to change its damping ratio in order to maintain optimum dynamic characteristics over wide variations in load. With a 3.5 kg load the system was approximately critically damped, but as the load was increased the gain of the control loop was proportionally increased in order to maintain the same speed of response. This was achieved at the cost of system stability, however this instability only becomes apparent when rapidly varying forces are applied to the loaded arm. The implication of this result for manual control performance is that the resistance of a controlling limb to vibration-induced activity of a control or tool will decrease as the vibration frequency increases up to 10 Hz, but will then increase once more for vibration frequencies up to at least 20 Hz (which was the highest frequency used in the experiment by Rack (1973)). This tendency will be particularly marked when fairly large control forces are employed, as in isometric control functions, and when the control force exceeds about 3.5 kg the controlling limb may even amplify vibration-induced activity in the region of 10 Hz.

To conclude, it can be seen from the above discussion that in certain circumstances vibration can adversely affect the performance of neuromuscular system. However the importance of such effects in a manual tracking task can only be determined by experimentation using such a task. The extent to which direct effects of vibration on neuromuscular processes degrades manual control performance is likely to be largely dependent on the extent to which other mechanisms, such as conscious correction using feedback, can compensate for errors incurred in the automatic, kinaesthetically regulated mechanisms.

APPENDIX C. COMPUTER PROGRAMS FOR ANALYSES OF VARIANCE AND SIMPLE MAIN EFFECTS.

The programs listed on the following pages are written in FORTRAN IV-PLUS. A number of system subroutines are used for inputting and outputting data: these are listed below.

CALL TYPE
Type a new line to terminal.

CALL TYPE('&**')
Type to terminal character string between ' ', (& indicates a new line).

CALL TYPEI(K)
Type integer to terminal.

CALL TYPER(V)
Type floating point value to terminal.

CALL ASKN(A, '&***')
Read next job parameters as a file name. If the name is not found the message supplied is printed on the terminal and the programs waits for the user to type a file name.

CALL ASKI(K, '&***')
Read next job parameter as an integer. If not supplied print a message and wait for user to type in an integer.

CALL ASKR(B, '&***')
As ASKI except uses a real value.

CALL INPUT(A, CB, M)
Open input file. Read control block to CB. M is a marker used by the IN subroutine to indicate the end of the file.

CALL OUTPUT(B)
Open output file for OUT subroutine.

CALL INS(A, O, O)
Start reading input file at block O number O.

Assign 100 to M - 100 is the label that the program will jump to if you request a value beyond the end of the file.

CALL INEND(A)
Close input file.

CALL OUTEND(B, CB)
Close output file with CB as its control block.

C.1. 2 FACTOR ANALYSIS OF VARIANCE WITH RANDOMIZED BLOCKS.

note: data is input in serial form as a single data file.

********** LISTING OF PDEVLIST **********

```
FORTRAN IV-PLUS V02-04G                   11:18:05    12-MAY-78          PAGE 1
                /RO/TR:ALL/WR

                DIMENSION AA(300),BB(300),CB(128)
                DIMENSION ZABS(1080),ZAB(270)
                CALL TYPE('&ANALYSIS OF VARIANCE')
                CALL ASKI(NS,'&NO. OF SUBJECTS/BLOCKS, S = ')
                CALL ASKI(NA,'&NO. OF LEVELS OF FACTOR A = ')
                CALL ASKI(NB,'&NO. OF LEVELS OF FACTOR B = ')
                CALL ASKN(AA,'&INPUT FILE =  ')
                CALL ASKN(BB,'&OUTPUT FILE = ')
                NABS=NA*NB*NS
                NAB=NA*NB
                NAS=NA*NS
                NBS=NB*NS
                CALL INPUT(AA,CB,M1)
                ASSIGN 999 TO M1
                CALL INS(AA,0,0)
                X=0.0
                ABS=0.0
                S=0.0
                AS=0.0
                AB=0.0
                BS=0.0
                A=0.0
                B=0.0
                I=1
       10       CALL IN(AA,ZABS(I))
                X=X+ZABS(I)
                ABS=ABS+ZABS(I)*ZABS(I)
                I=I+1
                GO TO 10
       999      X=X*X/NABS
                DO 20 I=1,NAB
```

```
20      ZAB(I)=0.0
        DO 40 I=0,NS-1
        T=0.0
        DO 30 J=1,NAB
        K=J+(I*NAB)
        ZAB(J)=ZAB(J)+ZABS(K)
30      T=T+ZABS(K)
40      S=S+T*T/NAB
        CALL OUTPUT(BB)
        CALL PSAVE
        CALL PSCLR
        CALL TYPE('&B X A  COLUMN TOTALS - OVER S SUBJECTS')
        CALL TYPE
        CALL TYPE
        M=0
        DO 600 J=1,NB
        DO 600 I=1,NA
        M=M+1
        CALL TYPE
        CALL TYPEI(J,I)
        CALL TYPER(ZAB(M))
        CALL OUT(BB,ZAB(M))
600     CONTINUE
        CALL TYPE
        CALL TYPE
```



```
        DO 50 I=1,NAB
50      AB=AB+ZAB(I)*ZAB(I)/NS
        DO 70 I=1,NA
        T=0.0
        II=NA*(NB-1)+I
        DO 60 J=I,II,NA
60      T=T+ZAB(J)
70      A=A+T*T/NBS
        DO 90 I=0,NB-1
        T=0.0
        II=I*NA
        DO 80 J=II+1,II+NA
```

```
80    T=T+ZAB(J)
90    B=B+T*T/NAS
      DO 120 I=0,NS-1
      II=I*NAB
      DO 110 J=II+1,II+NA
      T=0.0
      JJ=NA*(NB-1)+J
      DO 100 K=J,JJ,NA
100   T=T+ZABS(K)
110   AS=AS+T*T/NB
120   CONTINUE
      DO 140 I=0,NBS-1
      II=I*NA
      T=0.0
      DO 130 J=II+1,II+NA
130   T=T+ZABS(J)
140   BS=BS+T*T/NA
200   CONTINUE
      DFTOT=NABS-1
      DFSUB=NS-1
      DFTRT=NAB-1
      DFA=NA-1
      DFB=NB-1
      DFAB=DFA*DFB
      DFRES=DFSUB*DFTRT
      DFAS=DFA*DFSUB
      DFBS=DFB*DFSUB
      DFABS=DFA*DFB*DFSUB
      SSTOT=ABS-X
      SSSUB=S-X
      SSTRT=AB-X
      SSA=A-X
      SSB=B-X
      SSAB=AB-A-B+X
      SSRES=ABS-S-AB+X
      SSAS=AS-A-S+X
      SSBS=BS-B-S+X
      SSABS=ABS-AB-AS-BS+A+B+S-X
      SMTOT=SSTOT/DFTOT
      SMSUB=SSSUB/DFSUB
```

```
      SMTRT=SSTRT/DFTRT
      SMA=SSA/DFA
      SMB=SSB/DFB
      SMAB=SSAB/DFAB
```



```
      SMRES=SSRES/DFRES
      SMAS=SSAS/DFAS
      SMBS=SSBS/DFBS
      SMABS=SSABS/DFABS
      FSUB=SMSUB/SMRES
      FTRT=SMTRT/SMRES
      FA=SMA/SMRES
      FB=SMB/SMRES
      FAB=SMAB/SMRES
      FAS=SMA/SMAS
      FBS=SMB/SMBS
      FABS=SMAB/SMABS
      CALL TYPE('&   ABS          AB          A          B          X')
      CALL TYPE
      CALL TYPE
      CALL TYPER(ABS,AB,A,B,X)
      CALL TYPE
      CALL TYPE
      CALL TYPE('&   S            AS          BS     ')
      CALL TYPE
      CALL TYPE
      CALL TYPER(S,AS,BS)
      CALL TYPE
      CALL TYPE
      CALL ASKI(III,'&TYPE 0 FOR ANOVA SUMMARY TABLE ')
      CALL PSCLR
      CALL TYPE('&ANOVA SUMMARY TABLE')
      CALL TYPE
      CALL TYPE
      CALL TYPE('&SOURCE         SS          DF          ')
      CALL TYPE('MS          F   ')
      CALL TYPE
      CALL TYPE
```

```
      CALL TYPE('&SUBJECTS   ')
      CALL TYPER(SSSUB,DFSUB,SMSUB,FSUB)
      CALL TYPE
      CALL TYPE('&TREATMENTS')
      CALL TYPER(SSTRT,DFTRT,SMTRT,FTRT)
      CALL TYPE
      CALL TYPE('&     A      ')
      CALL TYPER(SSA,DFA,SMA,FAS)
      CALL TYPE
      CALL TYPE('&     B      ')
      CALL TYPER(SSB,DFB,SMB,FBS)
      CALL TYPE
      CALL TYPE('&     AB     ')
      CALL TYPER(SSAB,DFAB,SMAB,FABS)
      CALL TYPE
      CALL TYPE('&RESIDUAL   ')
      CALL TYPER(SSRES,DFRES,SMRES)
      CALL TYPE
      CALL TYPE('&     AS     ')
      CALL TYPER(SSAS,DFAS,SMAS)
      CALL TYPE
      CALL TYPE('&     BS     ')
      CALL TYPER(SSBS,DFBS,SMBS)
FORTRAN IV-PLUS V02-04G                11:18:05    12-MAY-78            PAGE 4
XNOVA.FTP       /RO/TR:ALL/WR

      CALL TYPE
      CALL TYPE('&     ABS    ')
      CALL TYPER(SSABS,DFABS,SMABS)
      CALL TYPE
      CALL TYPE
      CALL TYPE('&TOTAL      ')
      CALL TYPER(SSTOT,DFTOT,SMTOT)
      CALL TYPE
      CALL TYPE
      CALL TYPE
      CALL ASKI(III,'&TYPE 0 TO CONTINUE COMPUTATION ')
      CALL PSCLR
      CALL PSRES
      CALL OUTEND(BB,CB)
      CALL INEND(AA)
      END
```

C.2. 3 FACTOR ANALYSIS OF VARIANCE WITH RANDOMIZED BLOCKS.

note: data is input in serial form as a single data file.

********** LISTING OF PDEVLIST **********

```
FORTRAN IV-PLUS V02-04G                11:56:41    12-MAY-78            PAGE 1
XNOVA3.FTP        /RO/TR:ALL/WR

                  DIMENSION AA(300),BB(300),CB(128)
                  DIMENSION ZABCS(15,15,2,10),ZABC(15,15,2)
                  DIMENSION D(17),SS(17)
                  CALL TYPE('&3 FACTOR ANALYSIS OF VARIANCE')
                  CALL ASKI(NS,'&NO. OF SUBJECTS/BLOCKS, S = ')
                  CALL ASKI(NA,'&NO. OF LEVELS OF FACTOR A = ')
                  CALL ASKI(NB,'&NO. OF LEVELS OF FACTOR B = ')
                  CALL ASKI(NC,'&NO. OF LEVELS OF FACTOR C = ')
                  CALL ASKN(AA,'&INPUT FILE =  ')
                  CALL ASKN(BB,'&OUTPUT FILE = ')
                  CALL ASKI(IG,'&TYPE 1 FOR ANOVA ONLY ',0)
                  CALL INPUT(AA,CB,M1)
                  ASSIGN 999 TO M1
                  CALL INS(AA,0,0)
                  X=0.0
                  ABS=0.0
                  S=0.0
                  AS=0.0
                  AB=0.0
                  BS=0.0
                  A=0.0
                  B=0.0
                  ABCS=0.0
                  C=0.0
                  CS=0.0
                  ABC=0.0
                  AC=0.0
                  BC=0.0
                  T=0.0
                  P=0.0
                  I=1
                  J=1
```

```
      K=1
      L=1
10    CALL IN(AA,ZABCS(I,J,K,L))
      IF(L.EQ.1)ZABC(I,J,K)=0.0
      ZABC(I,J,K)=ZABC(I,J,K)+ZABCS(I,J,K,L)
      T=T+ZABCS(I,J,K,L)
      ABCS=ABCS+ZABCS(I,J,K,L)*ZABCS(I,J,K,L)
      I=I+1
      IF(I.LE.NA)GO TO 10
      I=1
      J=J+1
      IF(J.LE.NB)GO TO 10
      J=1
      K=K+1
      IF(K.LE.NC)GO TO 10
      K=1
      L=L+1
      S=S+T*T/(NA*NB*NC)
      X=X+T
      T=0
      GO TO 10
999   X=X*X/(NA*NB*NC*NS)
      D(17)=NA*NB*NC*NS-1
      SS(17)=ABCS-X
FORTRAN IV-PLUS V02-04G                11:56:41    12-MAY-78          PAGE 2
XNOVA3.FTP      /RO/TR:ALL/WR

      D(1)=NS-1
      SS(1)=S-X
      IF(IG.EQ.1)GO TO 20
      CALL TYPE
      CALL TYPE('&A X B X C  COLUMN TOTALS - OVER S SUBJECTS')
      CALL TYPE
      CALL TYPE
20    CONTINUE
      CALL OUTPUT(BB)
      DO 50 K=1,NC
      DO 50 J=1,NB
      DO 50 I=1,NA
```

```
      IF(IG.EQ.1)GO TO 30
      CALL TYPE
      CALL TYPEI(I,J,K)
      CALL TYPER(ZABC(I,J,K))
   30 CONTINUE
      CALL OUT(BB,ZABC(I,J,K))
      ABC=ABC+ZABC(I,J,K)*ZABC(I,J,K)/NS
   50 CONTINUE
      CALL TYPE
      CALL TYPE
      DO 80 I=1,NA
      T=0
      DO 70 L=1,NS
      P=0
      DO 60 K=1,NC
      DO 60 J=1,NB
   60 P=P+ZABCS(I,J,K,L)
      AS=AS+P*P/(NB*NC)
   70 T=T+P
   80 A=A+T*T/(NB*NC*NS)
      D(2)=NA-1
      SS(2)=A-X
      D(10)=(NA-1)*(NS-1)
      SS(10)=AS-A-S+X
      DO 110 J=1,NB
      T=0
      DO 100 L=1,NS
      P=0
      DO 90 K=1,NC
      DO 90 I=1,NA
   90 P=P+ZABCS(I,J,K,L)
      BS=BS+P*P/(NA*NC)
  100 T=T+P
  110 B=B+T*T/(NA*NC*NS)
      D(3)=NB-1
      SS(3)=B-X
      D(11)=(NB-1)*(NS-1)
      SS(11)=BS-B-S+X
      DO 140 K=1,NC
      T=0
      DO 130 L=1,NS
```

```
      P=0
      DO 120 J=1,NB
      DO 120 I=1,NA
FORTRAN IV-PLUS V02-04G                11:56:41    12-MAY-78        PAGE 3
XNOVA3.FTP      /RO/TR:ALL/WR

120   P=P+ZABCS(I,J,K,L)
      CS=CS+P*P/(NA*NB)
130   T=T+P
140   C=C+T*T/(NA*NB*NS)
      D(4)=NC-1
      SS(4)=C-X
      D(12)=(NC-1)*(NS-1)
      SS(12)=CS-C-S+X
      DO 170 I=1,NA
      DO 170 J=1,NB
      T=0
      DO 160 L=1,NS
      P=0
      DO 150 K=1,NC
150   P=P+ZABCS(I,J,K,L)
      ABS=ABS+P*P/NC
160   T=T+P
170   AB=AB+T*T/(NC*NS)
      D(5)=(NA-1)*(NB-1)
      SS(5)=AB-A-B+X
      DO 200 I=1,NA
      DO 200 K=1,NC
      T=0
      DO 190 L=1,NS
      P=0
      DO 180 J=1,NB
180   P=P+ZABCS(I,J,K,L)
      ACS=ACS+P*P/NB
190   T=T+P
200   AC=AC+T*T/(NB*NS)
      D(6)=(NA-1)*(NC-1)
      SS(6)=AC-A-C+X
      DO 230 J=1,NB
      DO 230 K=1,NC
      T=0
```

```
                DO 220 L=1,NS
                P=0
                DO 210 I=1,NA
        210     P=P+ZABCS(I,J,K,L)
                BCS=BCS+P*P/NA
        220     T=T+P
        230     BC=BC+T*T/(NA*NS)
                D(7)=(NB-1)*(NC-1)
                SS(7)=BC-B-C+X
                D(8)=(NA-1)*(NB-1)*(NC-1)
                SS(8)=ABC-AB-AC-BC+A+B+C-X
                D(9)=(NA*NB*NC-1)*(NS-1)
                SS(9)=ABCS-S-ABC+X
                D(13)=(NA-1)*(NB-1)*(NS-1)
                SS(13)=ABS-AB-AS-BS+A+B+S-X
                D(14)=(NA-1)*(NC-1)*(NS-1)
                SS(14)=ACS-AC-AS-CS+A+C+S-X
                D(15)=(NB-1)*(NC-1)*(NS-1)
                SS(15)=BCS-BC-BS-CS+B+C+S-X
                D(16)=(NA-1)*(NB-1)*(NC-1)*(NS-1)
                SS(16)=ABCS-S-ABC+X
```



```
                DO 240 M=10,15
        240     SS(16)=SS(16)-SS(M)
                CALL TYPE
                CALL TYPE('&BASIC QUANTITIES')
                CALL TYPE
                CALL TYPE('&      A             B             C')
                CALL TYPE
                CALL TYPER(A,B,C)
                CALL TYPE
                CALL TYPE('&      AB            AC            BC            ABC')
                CALL TYPE
                CALL TYPER(AB,AC,BC,ABC)
                CALL TYPE
                CALL TYPE('&      AS            BS            CS')
                CALL TYPE
                CALL TYPER(AS,BS,CS)
                CALL TYPE
```

```
      CALL TYPE('&     ABS          ACS          BCS')
      CALL TYPE
      CALL TYPER(ABS,ACS,BCS)
      CALL TYPE
      CALL TYPE('&     ABCS         S            X')
      CALL TYPE
      CALL TYPER(ABCS,S,X)
      CALL TYPE
      CALL ASKI(III,'&TYPE O FOR ANOVA SUMMARY TABLE  ')
      CALL PSAVE
      CALL PSCLR
      CALL TYPE('&               ANOVA SUMMARY TABLE')
      CALL TYPE
      CALL TYPE('&     SOURCE       SS           DF          MS')
      CALL TYPE('           F RATIO')
      CALL TYPE
      DO 250 M=1,17
      SM=SS(M)/D(M)
      XM=M
      CALL TYPE
      CALL TYPER(XM,SS(M),D(M),SM)
      IF(M.GT.8)GO TO 250
      MM=M+8
      F=SM/(SS(MM)/D(MM))
      CALL TYPER(F)
  250 CONTINUE
      CALL TYPE
      CALL TYPE
      CALL TYPE('&               SOURCE KEY')
      CALL TYPE
      CALL TYPE('&1=SUBJECTS   2=A   3=B   4=C   5=AB   6=AC   7=BC')
      CALL TYPE
      CALL TYPE('&8=ABC   9=RESIDUAL   10=AS   11=BS   12=CS   13=ABS')
      CALL TYPE
      CALL TYPE('&14=ACS   15=BCS   16=ABCS   17=TOTAL')
      CALL TYPE
      CALL ASKI(III,'&        TYPE O TO CONTINUE  ')
      CALL INEND(AA)
      CALL OUTEND(BB,CB)
      END
```

C.3. SIMPLE MAIN EFFECTS AND TREND ANALYSES>

note: the input file for this program is the output file from either of the previous 2 analysis of variance programs.

```
          ********** LISTING OF PDEVLIST **********

FORTRAN IV-PLUS V02-04G               12:13:01    12-MAY-78          PAGE 1
XSMF.FTP        /RO/TR:ALL/WR

                DIMENSION YF(300),CB(128),MXL(6),MXQ(6)
                CALL TYPE('&SIMPLE MAIN EFFECTS')
                CALL ASKN(YF,'&INPUT FILE = ')
                CALL ASKI(NP,'&NO. OF TREATMENT LEVELS OF FACTOR A = ')
                CALL ASKI(NS,'&NO. OF SUBJECTS = ')
                CALL ASKR(SMAS,'&A X S INTERACTION MEAN SQUARE = ')
                IF(NP.GT.4)GO TO 4
                MXL(1)=-3
                MXL(2)=-1
                MXL(3)=1
                MXL(4)=3
                MXQ(1)=1
                MXQ(2)=-1
                MXQ(3)=-1
                MXQ(4)=1
                ICL=20
                ICQ=4
                GO TO 6
      4         IF(NP.GT.5)GO TO 5
                MXL(1)=-2
                MXL(2)=-1
                MXL(3)=0
                MXL(4)=1
                MXL(5)=2
                MXQ(1)=2
                MXQ(2)=-1
                MXQ(3)=-2
                MXQ(4)=-1
                MXQ(5)=2
                ICL=10
```

```
      ICL=14
      GO TO 6
5     MXL(1)=-5
      MXL(2)=-3
      MXL(3)=-1
      MXL(4)=1
      MXL(5)=3
      MXL(6)=5
      MXQ(1)=5
      MXQ(2)=-1
      MXQ(3)=-4
      MXQ(4)=-4
      MXQ(5)=-1
      MXQ(6)=5
      ICL=70
      ICQ=84
6     CONTINUE
      CALL INPUT(YF,CB,M)
      ASSIGN 99 TO M
      CALL INS(YF,0,0)
      CALL TYPE
      CALL TYPE('&      SOURCE           SS            DF          ')
      CALL TYPE(' MS              F RATIO')
      NTREAT=1
7     SSA=0
      SA=0
FORTRAN IV-PLUS V02-04G              12:13:01     12-MAY-78            PAGE 2
XSMF.FTP        /RO/TR:ALL/WR

      BL=0
      BQ=0
      DO 10 I=1,NP
      CALL IN(YF,()
      SSA=SSA+Y*Y
      SA=SA+Y
      IF(NP.LT.4.OR.NP.GT.6)GO TO 10
      BL=BL+MXL(I)*Y
      BQ=BQ+MXQ(I)*Y
10    CONTINUE
      DFA=NP-1
```

```
      DFL=1
      DFDEP=NP-2
      SSA=(SSA/NS)-(SA*SA/(NS*NP))
      SMA=SSA/DFA
      FA=SMA/SMAS
      IF(NP.LT.4.OR.NP.GT.6)GO TO 20
      SSL=BL*BL/(ICL*NS)
      SSQ=BQ*BQ/(ICQ*NS)
      SSDEP=SSA-SSL
      SMDEP=SSDEP/DFDEP
      FL=SSL/SMAS
      FQ=SSQ/SMAS
      FDEP=SMDEP/SMAS
20    CONTINUE
      CALL TYPE
      CALL TYPE('&TREATMENT')
      CALL TYPEI(NTREAT)
      CALL TYPER(SSA,DFA,SMA,FA)
      IF(NP.LT.4.OR.NP.GT.6)GO TO 80
      CALL TYPE('&LINEAR REG.')
      CALL TYPER(SSL,DFL,SSL,FL)
      CALL TYPE('&QUADRATIC  ')
      CALL TYPER(SSQ,DFL,SSQ,FQ)
      CALL TYPE('&NONLINEAR  ')
      CALL TYPER(SSDEP,DFDEP,SMDEP,FDEP)
      RCO=100*SSL/SSA
      CALL TYPE('&PERCENTAGE LINEARITY OF TREATMENT EFFECT =')
      CALL TYPER(RCO)
80    NTREAT=NTREAT+1
90    GO TO 7
99    CALL TYPE
      CALL INEND(YF)
      END
```

C.4. SPLIT PLOT ANALYSIS OF VARIANCE.

note: the 2 factor analysis of variance program is run first on the data.. The input file for this program is then formed from the basic quantities output from the 2 factor analysis.

```
          ********** LISTING OF PDEVLIST **********

FORTRAN IV-PLUS V02-04G                12:23:39    12-MAY-78          PAGE 1
XSPLOT.FTP          /RO/TR:ALL/WR

               DIMENSION F(300),CB(128),Q(30)
               CALL TYPE('&SPLIT PLOT ANOVA SUMMARY')
               CALL ASKN(F,'&ANOVA OUTPUT 1, 2 AND COMBINED =')
               CALL ASKI(NB,'&NO. OF LEVELS OF TREATMENT B =')
               CALL ASKI(NC,'&NO. OF LEVELS OF TREATMENT C =')
               CALL ASKI(NS,'&NO. OF SUBJECTS/BLOCKS =')
               CALL INPUT(F,CB,M)
               ASSIGN 999 TO M
               CALL INS(F,0,0)
               I=1
      10       CALL IN(F,Q(I))
               I=I+1
               GO TO 10
      999      CALL INEND(F)
               NS=NS/2
               NA=2
               SSA1=Q(6)-Q(5)
               SSA2=Q(14)-Q(13)
               SSBS1=Q(8)-Q(4)-Q(6)+Q(5)
               SSBS2=Q(16)-Q(12)-Q(14)+Q(13)
               SSCS1=Q(7)-Q(3)-Q(6)+Q(5)
               SSCS2=Q(15)-Q(11)-Q(14)+Q(13)
               SSBCS1=Q(1)-Q(2)-Q(7)-Q(8)+Q(3)+Q(4)+Q(6)-Q(5)
               SSBCS2=Q(9)-Q(10)-Q(15)-Q(16)+Q(11)+Q(12)+Q(14)-Q(13)
               AS=Q(22)
               ABCS=Q(17)
               A=Q(5)+Q(13)
               B=Q(20)
               AB=Q(4)+Q(12)
```

```
      C=Q(19)
      AC=Q(3)+Q(11)
      ABS=Q(24)
      ACS=Q(23)
      BC=Q(18)
      ABC=Q(2)+Q(10)
      X=Q(21)
      SSTOT=ABCS-X
      SSSUB=AS-X
      SSA=A-X
      SSSUBWG=AS-A
      SSWSUB=ABCS-AS
      SSB=B-X
      SSAB=AB-A-B+X
      SSBS=ABS-AB-AS+A
      SSC=C-X
      SSAC=AC-A-C+X
      SSCS=ACS-AC-AS+A
      SSBC=BC-B-C+X
      SSABC=ABC-AB-AC-BC+A+B+C-X
      SSBCS=ABCS-ABC-ABS-ACS+AB+AC+AS-A
      DFSUB=NA*NS-1
```



```
      DFA=NA-1
      DFSUBWG=NA*(NS-1)
      DFWSUB=NS*NA*(NB*NC-1)
      DFB=NB-1
      DFAB=(NA-1)*(NB-1)$SUS
      DFBS=NA*(NS-1)*(NB-1)
      DFC=NC-1
      DFAC=(NA-1)*(NC-1)
      DFCS=NA*(NS-1)*(NC-1)
      DFBC=(NB-1)*(NC-1)
      DFABC=(NA-1)*(NB-1)*(NC-1)
      DFBCS=NA*(NS-1)*(NB-1)*(NC-1)
      DFTOT=NA*NB*NC*NS-1
      CDFB=1
      CDFAB=NA-1
```

```
      CDFBS=NA*(NS-1)
      DFA1=NS-1
      DFBS1=(NS-1)*(NB-1)
      DFCS1=(NS-1)*(NC-1)
      DFBCS1=(NS-1)*(NB-1)*(NC-1)
      PSA1=SSA1/DFA1
      PSA2=SSA2/DFA1
      PSBS1=SSBS1/DFBS1
      PSBS2=SSBS2/DFBS1
      PSCS1=SSCS1/DFCS1
      PSCS2=SSCS2/DFCS1
      PSBCS1=SSBCS1/DFBCS1
      PSBCS2=SSBCS2/DFBCS1
      IF(PSA1.GT.PSA2)FA1=PSA1/PSA2
      IF(PSA1.LE.PSA2)FA1=PSA2/PSA1
      IF(PSBS1.GT.PSBS2)FBS1=PSBS1/PSBS2
      IF(PSBS1.LE.PSBS2)FBS1=PSBS2/PSBS1
      IF(PSCS1.GT.PSCS2)FCS1=PSCS1/PSCS2
      IF(PSCS1.LE.PSCS2)FCS1=PSCS2/PSCS1
      IF(PSBCS1.GT.PSBCS2)FBCS1=PSBCS1/PSBCS2
      IF(PSBCS1.LE.PSBCS2)FBCS1=PSBCS2/PSBCS1
      PSTOT=SSTOT/DFTOT
      PSSUB=SSSUB/DFSUB
      PSA=SSA/DFA
      PSSUBWG=SSSUBWG/DFSUBWG
      PSWSUB=SSWSUB/DFWSUB
      PSB=SSB/DFB
      PSAB=SSAB/DFAB
      PSBS=SSBS/DFBS
      PSC=SSC/DFC
      PSAC=SSAC/DFAC
```



```
      PSCS=SSCS/DFCS
      PSBC=SSBC/DFBC
      PSABC=SSABC/DFABC
      PSBCS=SSBCS/DFBCS
      FA=PSA/PSSUBWG
```

```
      FAC=PSAC/PSCS
      FBC=PSBC/PSBCS
      FABC=PSABC/PSBCS
      CALL PSAVE
      CALL PSCLR
      CALL TYPE
      CALL TYPE
      CALL TYPE('&ANOVA SUMMARY TABLE')
      CALL TYPE
      CALL TYPE
      CALL TYPE
      CALL TYPE('&      SOURCE          SS          DF          ')
      CALL TYPE('MS           F             DF(CONS.)')
      CALL TYPE
      CALL TYPE
      CALL TYPE('&BETWEEN SUBJECTS')
      CALL TYPER(SSSUB,DFSUB,PSSUB)
      CALL TYPE
      CALL TYPE('&           A      ')
      CALL TYPER(SSA,DFA,PSA,FA)
      CALL TYPE
      CALL TYPE('&S  WITHIN GROUPS')
      CALL TYPER(SSSUBWG,DFSUBWG,PSSUBWG)
      CALL TYPE
      CALL TYPE('&WITHIN SUBJECTS ')
      CALL TYPER(SSWSUB,DFWSUB,PSWSUB)
      CALL TYPE
      CALL TYPE('&           B      ')
      CALL TYPER(SSB,DFB,PSB,FB,CDFB)
      CALL TYPE
      CALL TYPE('&           AB     ')
      CALL TYPER(SSAB,DFAB,PSAB,FAB,CDFAB)
      CALL TYPE
      CALL TYPE('&           BS     ')
      CALL TYPER(SSBS,DFBS,PSBS)
      CALL TYPE('                 ')
      CALL TYPER(CDFBS)
      CALL TYPE
      CALL TYPE('&           C      ')
      CALL TYPER(SSC,DFC,PSC,FC,CDFB)
      CALL TYPE
```

```
      CALL TYPE('&          AC      ')
      CALL TYPER(SSAC,DFAC,PSAC,FAC,CDFAB)
      CALL TYPE
      CALL TYPE('&          CS      ')
      CALL TYPER(SSCS,DFCS,PSCS)
      CALL TYPE('                ')
      CALL TYPER(CDFBS)
```



```
      CALL TYPE
      CALL TYPE('&          BC      ')
      CALL TYPER(SSBC,DFBC,PSBC,FBC,CDFB)
      CALL TYPE
      CALL TYPE('&          ABC     ')
      CALL TYPER(SSABC,DFABC,PSABC,FABC,CDFAB)
      CALL TYPE
      CALL TYPE('&          BCS     ')
      CALL TYPER(SSBCS,DFBCS,PSBCS)
      CALL TYPE('                ')
      CALL TYPER(CDFBS)
      CALL TYPE
      CALL TYPE
      CALL TYPE('&      TOTAL       ')
      CALL TYPER(SSTOT,DFTOT,PSTOT)
      CALL TYPE
      CALL TYPE
      CALL TYPE
      CALL ASKI(IFO,'&FINISHED ?')
      CALL TYPE
      CALL TYPE
      CALL TYPE('&TEST FOR HOMOGENEITY OF ERROR TERMS')
      CALL TYPE
      CALL TYPE
      CALL TYPE('&      SOURCE          SS          DF          ')
      CALL TYPE('MS            F MAX.')
      CALL TYPE
```

```
      CALL TYPE
      CALL TYPE('&SUBJECTS AT A1   ')
      CALL TYPER(SSA1,DFA1,PSA1,FA1)
      CALL TYPE
      CALL TYPE('&SUBJECTS AT A2   ')
      CALL TYPER(SSA2,DFA1,PSA2)
      CALL TYPE
      CALL TYPE('&        BS AT A1   ')
      CALL TYPER(SSBS1,DFBS1,PSBS1,FBS1)
      CALL TYPE
      CALL TYPE('&        BS AT A2   ')
      CALL TYPER(SSBS2,DFBS1,PSBS2)
      CALL TYPE
      CALL TYPE('&        CS AT A1   ')
      CALL TYPER(SSCS1,DFCS1,PSCS1,FCS1)
      CALL TYPE
      CALL TYPE('&        CS AT A2   ')
      CALL TYPER(SSCS2,DFCS1,PSCS2)
      CALL TYPE
      CALL TYPE('&       BCS AT A1   ')
      CALL TYPER(SSBCS1,DFBCS1,PSBCS1,FBCS1)
      CALL TYPE
      CALL TYPE('&       BCS ST A2   ')
      CALL TYPER(SSBCS2,DFBCS1,PSBCS2)
      CALL TYPE
      CALL TYPE

      CALL ASKI(IFO,'&FINISHED ?')
      CALL PSCLR
      CALL PSRES
```



```
      END
```

APPENDIX D. CHARACTERISTICS OF THE SUBJECTS.

SUBJECTS	DATE OF BIRTH	EXPERIMENTS PARTICIPATED IN	PREVIOUS EXPERIENCE OF VIBRATION EXPERIMENTS	PREVIOUS EXPERIENCE OF TRACKING EXPERIMENTS	HEIGHT (metres)	WEIGHT (kg.)
a	16/08/48	1,2	YES	YES	1.85	76.2
b	14/04/49	1	NO	NO	1.88	101.6
c	28/05/51	1	YES	YES	1.63	55.0
d	23/12/56	1,2,3	NO	NO	1.73	57.2
e	3/10/51	2,3,4,5	YES	NO	1.61	60.3
f	19/12/49	2,4	YES	YES	1.78	66.2
g	24/03/52	3,4	YES	NO	1.60	50.0
h	5/07/52	3,4	YES	NO	1.75	61.3
i	1/09/52	4,5	YES	NO	1.66	66.7
j	31/12/56	4,5	NO	NO	1.80	60.3
k	12/06/47	4,5	YES	YES	1.76	69.0
l	3/10/45	4	YES	YES	1.74	76.2
m	2/07/55	5	NO	NO	1.90	81.3
n	16/06/53	5	YES	NO	1.78	59.7
o	30/01/53	5	YES	NO	1.81	60.3
p	6/03/52	5	NO	NO	1.80	66.7