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Transmission of vibration through the human body to the head

By

Gurmail Singh Paddan

A thesis presented for the degree of Doctor of Philosophy, 1991

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF ENGINEERING AND APPLIED SCIENCE

INSTITUTE OF SOUND AND VIBRATION RESEARCH

Doctor of Philosophy

TRANSMISSION OF VIBRATION THROUGH THE HUMAN BODY TO THE HEAD

by Gurmail Singh Paddan

This thesis concerns the transmission of vibration through the human body and the effects of various sitting and standing postures on vibration at the head. Knowledge of the transmission of vertical vibration for seated subjects is well advanced, however, this is not the case for horizontal seat motion. Only a few previous studies have dealt with the transmission of translational (mainly vertical) vibration to the heads of standing subjects. Six axes of head motion have been measured for all experiments reported in this thesis.

Experiments conducted with seated subjects involved the investigation of intra-subject variability (repeatability) and inter-subject variability in the transmission of vibration from seat to head. The effect of contact between the subject's back and seat backrest on transmissibility has also been determined. Inter-subject variability was much larger than intra-subject variability and, in some cases, transmissibility between subjects varied by as much as 20:1. Both x- and z-axis seat vibration resulted in head motion occurring mostly in the mid-sagittal plane (i.e. x-, z- and pitch axes). Head motion occurred principally in the y-axis during exposure to y-axis seat vibration. Contact with the seat backrest resulted in more head motion than a posture involving no backrest contact during x- and z-axis seat vibration. The effect of backrest contact on head motion during lateral seat vibration was small.

Laboratory experiments conducted with standing subjects determined intra-subject variability and inter-subject variability in floor-to-head transmissibility and the effect of different body postures on head motion. Head motion occurred mainly in the mid-sagittal plane during exposure to both x- and z-axis floor vibration; lateral floor vibration resulted in mainly lateral head motion. Holding a handrail or standing with legs locked at the knees generally resulted in more head motion than with no hand grips and legs bent postures.

Measurements of head motion of a subject seated in an off-road vehicle traversing rough terrain showed that vibration in both x- and z-axes mostly caused head motion in the x-, z- and pitch axes. Lateral seat vibration mainly affected lateral axis head motion. Roll and pitch motion at the seat had only a small effect on head motion.

This research has explained the transmission of translational motion to the heads of sitting and standing subjects. The data can be used for developing biodynamic models of the human body.

DEDICATION

I dedicate this work to my parents
Mr S.S. Paddan (deceased) and Mrs G.K. Paddan
and my wife, Mrs K.K. Paddan

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Finally, to all the subjects who took part in the experiments reported in this thesis of which 1 subject endured many hours of vibration.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

The extent to which vibration is transmitted through the body will influence the effects of vibration on comfort, performance and health. Vibration of the head may impair vision and difficulties can be encountered in controlling a vehicle or performing some other task. Improved knowledge of the transmission of vibration and how it varies is likely to assist the understanding of various human responses to vibration. For example, the interpretation of previous human whole-body vibration research requires assumptions on how the vibration was transmitted through the body to the different parts.

There is a need to know about vibration which affects body movements in relation to vehicle design. If the vibration is very severe, for example, in an off-road vehicle traversing over rough ground, impacts between the occupants and the confines of the vehicle may become a problem. In such a case, a 'space envelope' within which the head would normally move would be required. If any part of the vehicle was to protrude this envelope, then the likelihood of an impact would be increased. Space envelopes could be used in the design of size of helmets and aid in the selection of impact absorbing materials.

Large movements of the head can be produced by vibration in the horizontal axes resulting in impacts with the surrounding environment. It would be useful to know, from the design point of view, which part of the body or the head is most likely to impact with the vehicle and where on the vehicle the impact would occur. A knowledge of factors which influence such motions will assist in their prevention.

Most of the previous studies concerned with the transmission of vibration through the body to the head have involved the measurement of vertical head motion during exposure to vertical vibration of a seat. However, motion at the head is induced in more than one axis during exposure to vertical seat vibration (e.g. Griffin, 1975; Johnston, 1978). Non-vertical motions at the head can be just as important as vertical motion in some situations. For example, greater displacements of the head are likely to occur in the horizontal axes than in the vertical axis during a rough cross-country ride. The distinct lack of experimental data dealing with vibration in the horizontal axes could explain the reason why most of the biodynamic models proposed by other researchers deal with vertical motions at the seat and the head, and are mostly concerned with seated subjects.

Many biodynamic models exist which attempt to simulate responses of the human body exposed to mechanical vibration. It is necessary to know the effect of various experimental details since many variables, such as subject posture, are known to affect the transmission of vibration through the body to the head. Indications of variations in responses both within an individual and between individuals are required. These could be used to the obtain an estimate of the range of values for the elements to be used in models. Information relating to variation could be used to 'tune' the various model parameters so that the model could be altered to simulate changes in, for example, subject sitting posture. Experimental data are required to assist in the development of models in which the input motion is in a single axis and the output occurs in many axes. This could take the form of either a combination of many single axis models or one complex model with many axes of motion. This applies equally to the biodynamic responses of seated and standing persons. Comprehensive experimental data required for such modelling is not available. With the availability of computer-based modelling packages, the need for experimental data is greater than before.

A review of the literature concerned with the transmission of translational seat and floor vibration to the heads of subjects showed some inadequacies in the data available. These ranged from the limitation in the number of active axes at the head to the absence of data for subjects exposed to some axes of vibration (e.g. standing subjects exposed to side-to-side floor vibration). Apparatus was developed for this research which enabled measurements to be made of six axes of motion at the head. This equipment was used to monitor head motion for both seated and standing subjects during exposure to three translational axes of vibration (i.e. fore-and-aft, lateral and vertical). Repeatability and inter-subject variability in the transmission of vibration has been measured for male subjects sitting and standing in different body postures. Measurements of seat and head motions made during field studies have been used to study 'cause and effect' for the transmission of vibration through the human body. It is hoped that the work presented in this thesis will further the knowledge of the transmission of vibration through the human body.

1.2 ORGANISATION AND CONTENT OF THE THESIS

The different chapters and the main content of these are briefly described below.

Chapter 1 - Introduction

This chapter introduces the topic of human response to vibration and briefly describes the content of the thesis. Conventions adopted and terminology used in the thesis are also explained.

Chapter 2 - Literature review

Most previous studies concerned with the transmission of vibration through the body to the head are reviewed in Chapter 2. The effect of various parameters such as posture, head angle, seating condition, backrest angle and harness are discussed; this includes studies with both seated and standing subjects. A large proportion of the studies are concerned with the transmission of vertical vibration to the head (for both seated and standing subjects), the few reportings in which subjects are exposed to vibration in other axes are also reviewed. Some of the deficiencies present in the previous reportings are identified.

Chapter 3 - Equipment

Equipment common to laboratory experiments is described in detail in Chapter 3. Some of the equipment was also used in the measurement of seat and head motion during cross-country vehicle rides.

Chapter 4 - Analyses

This chapter explains the different types of analyses used on vibration data, including the calculation of transmissibilities, coherencies and the determination of various spectra for a multi-input single-output system.

Chapter 5 - Seated subjects

Laboratory experiments conducted to determine the transmission of seat vibration to the head for seated subjects are reported in Chapter 5. These studies were carried out with single-axis translational vibration, this included fore-and-aft, lateral and vertical vibration. For each axis of vibration, intra- and inter-subject variability were determined (i.e. variability in transmissibility within one subject and between individuals). Head motion was measured in all of the six axes using an instrumented bite-bar held between the subjects teeth. The effect of two seating postures on transmissibility is discussed; these postures being 'back-on' (subject's back in contact with the seat backrest) and 'back-off' (no backrest).

Chapter 6 - Standing subjects

The transmission of translational floor vibration to the heads of standing subjects is investigated in Chapter 6. This study includes the determination of both intra- and inter-subject variability and the effect of different postures of the body. The postures were two hand grips on the handrail during fore-and-aft; three foot separations during lateral vibration and three leg-postures during vertical floor vibration.

Chapter 7 - Field experiments

Seat and head motion was measured for a subject seated in a military vehicle traversing over rough cross-country terrain. Three sets of measurements were made; the data collected and the various analyses conducted are explained in Chapter 7. These data are used to determine the 'cause and effect' relations between various axes of seat and head motion.

Chapter 8 - Biodynamic modelling

Some of the literature available concerned with biodynamic models is reviewed in Chapter 8. Possible ways are suggested in which data determined from different experiments reported in this thesis could be used for the development of models.

Chapter 9 - Conclusions and recommendations

This final chapter summarises the experiments conducted and the findings of the investigations. Recommendations are made for future work based on the conclusions.

References and Appendices

Most of the entries included in the reference section are reviewed in the literature review (Chapter 2) and others are used for comparison purposes. Appendices contain subject instructions, physical characteristics of subjects, coherencies and other less relevant information.

1.3 CONVENTIONS

There are both theoretical and typographical conventions used in this thesis. The theoretical convention is the axes used during the measurement of motion and the directions of these axes. Figure 1.1 shows the translational axes of the body defined in ISO 2631 (1985); the directions of these axes will be used in this thesis. The three translational axes are:

- x- axis: back-to-chest (also known as fore-and-aft, shunt, etc.)
- y- axis: right side to left side (also known as lateral, sway, etc.)
- z- axis: foot- (or buttocks-) to-head (also known as vertical, heave, etc.)

Rotational motion is not so well defined in ISO 2631 (1985), however, the convention adhered to will be the right-hand cork screw rule. This is illustrated in Figure 1.2 and the three rotational axes are:

roll (r_x) - rotation about the x-axis
pitch (r_y) - rotation about the y-axis
yaw (r_z) - rotation about the z-axis

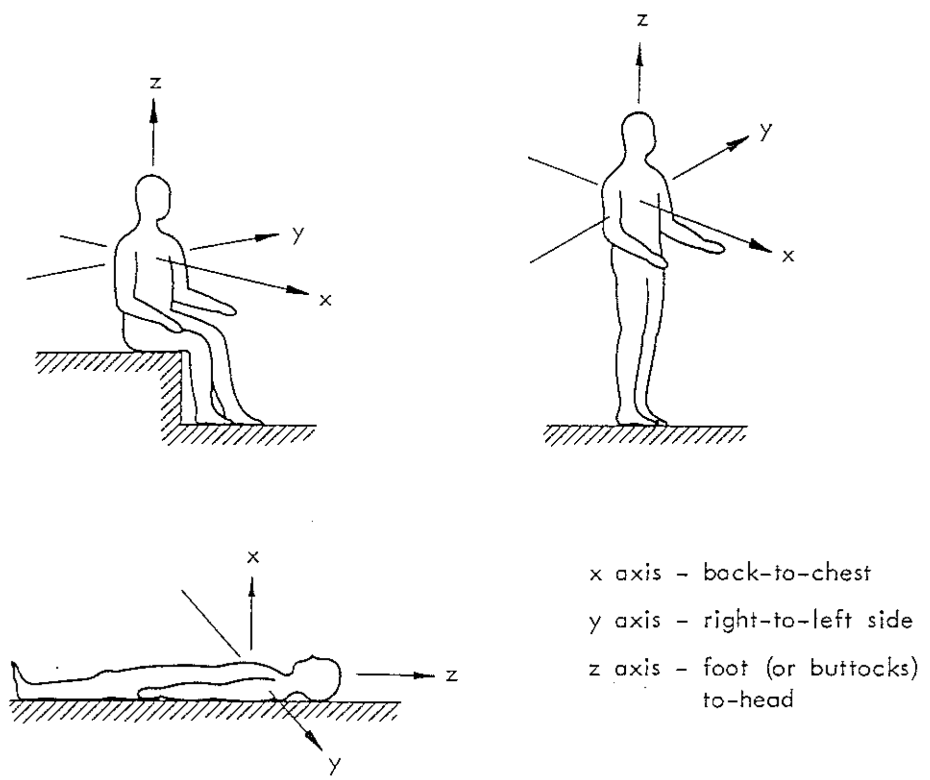


Figure 1.1 Body coordinate system defined in ISO 2631 (1985).

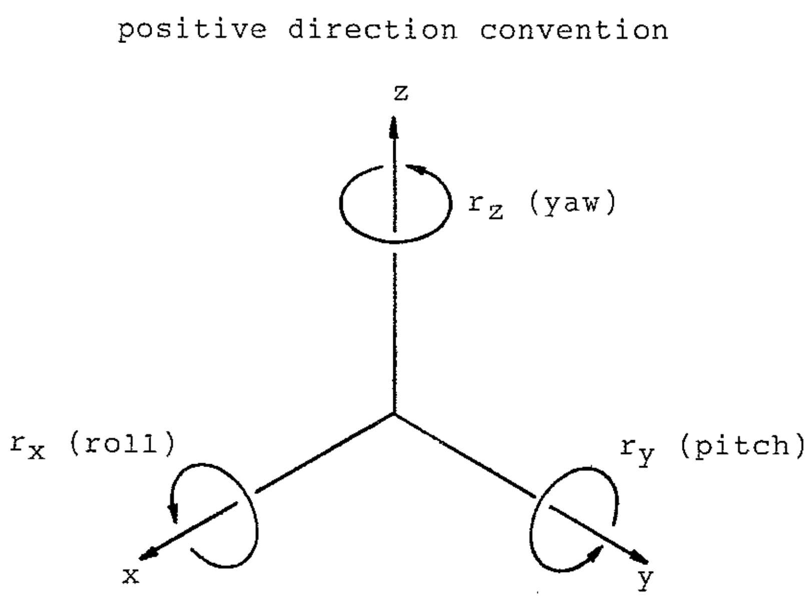


Figure 1.2 Convention adopted in this thesis for translational and rotational axes.

There are three biodynamic planes that will be referred to in this thesis, these are mutually perpendicular planes each containing three of the six axes mentioned above. The three planes and the included axes are:

mid-sagittal plane:	x-axis, z-axis, pitch (also known as median plane)
mid-coronal plane:	y-axis, z-axis, roll (also known as frontal plane)
horizontal plane:	x-axis, y-axis, yaw (also known as transverse plane)

The mid-sagittal plane divides the human body into two halves (left and right). The mid-coronal plane divides the body into posterior and anterior halves. The horizontal plane divides the body into top and bottom; a specific horizontal plane that can be used at the head is a Frankfort plane which is at the height of the two auditory meati and touches the lowest point of the orbits (eye sockets).

Typographical conventions used are that, in addition to x-axis, terms such as x-head and x-seat are also used in the thesis, these refer to the directions (x-axis in this case) and the location (head and seat respectively). This convention also applies to the other axes. Translational acceleration is measured in metres per second per second and will be written as ms^{-2} and rotational accelerations are measured in radians per second per second and will be written as $rads^{-2}$. Transmissibility (modulus of the ratio of the response of a system to the excitation) is dimensionless if both input and output motions are either translational or rotational. However, if excitation motion is translational and the output is rotational, then the units of transmissibility are $(rads^{-2})/(ms^{-2})$. Conversely, if the input motion is rotation and the output motion is translation, then the units of transmissibility are $(ms^{-2})/(rads^{-2})$.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

A substantial amount of research has been directed towards the effects of vibration on the human body over the past four decades and this has covered a whole range of topics. These have varied from experiments on subjective measures such as comfort, thresholds and possibly performance to those experiments with objective data, on, for example, the transmission of vibration through the body and the effect of various parameters on this measure. The aim of this literature review is to assess the state of current knowledge on the study of transmission of vibration through the human body to the head.

The review of literature is divided into nine main sections with the last forming conclusions from the reviewed studies. The various sections and a brief account of the contents is shown below:

2.1 Introduction

Brief description of the content of each section in the literature review.

2.2 Methods of head motion measurement

This section covers the studies in which different experimental methods have been used to monitor head motion including photographic, acceleration measuring transducers, etc.

2.3 *Input motions used during whole-body vibrations*

There are different kinds of input vibrations that could be used in the study of biodynamics. For laboratory based experiments, this includes sine waves of different frequencies, random data and for field measurements, different form if transport provide the various vibration spectra.

2.4 *Location of measurement of motion*

Some of the studies dealing with coordinate systems proposed for the head and anthropometric measures of the head have been reviewed in this section. For a seated person, input vibration would mostly be at the seat but motion can be measured at different places on the body, e.g. head (mouth, crown), shoulder, etc. Such studies are reviewed.

2.5 *Methods of analysis of head motion data*

There may be various reasons for using one method of analysis over another such as ease of computation, suitability, etc. Some commonly used methods are discussed in this section.

2.6 *Variables affecting the transmission of vertical seat vibration to the head*

This section covers previous research conducted on the effects of vertical seat vibration to the head, studies include the effect of intrinsic variables (peculiar to the individual) and extrinsic variables (set-up of the equipment and not controlled by the subject).

2.7 *Seat motion in other axes*

Studies reviewed in this section concern the transmission of horizontal (fore-and-aft and lateral) and rotational (roll, pitch and yaw) vibration to the head for seated subjects.

2.8 Head motion for standing subjects

The few studies that deal with the transmission of floor vibration to the heads of standing subjects are reviewed in this section. This includes floor vibration in all axes.

2.9 Conclusions

This is a general discussion of the current status of biodynamic studies and the possible areas requiring further investigation.

2.2 METHODS OF HEAD MOTION MEASUREMENT

Equipment used to monitor head motion can be put into two categories: equipment that can be used only in a laboratory under controlled conditions and the others, depending on the degree of portability of the equipment, which can be used in 'field' conditions.

2.2.1 Accelerometer methods

One of the now most widely used and suitable forms of transducer for measuring vibration is the accelerometer. The accelerometer itself has advanced in its construction from a heavy '$^{3}/_{4}$ pound accelerometer' used by Mozell and White (1958) to small light-weight 0.5 gram accelerometers (e.g. Entran EGAX) available for research. Numerous investigators have used translational accelerometers in their studies on biodynamic response (e.g. Rowlands, 1972; and Griffin, 1975).

Rotational accelerations have not been as widely measured as translational accelerations. Barnes and Rance (1974, 1975) measured motion of the head in the three rotational axes (roll, pitch and yaw) using an instrumented bite-bar which the subjects held between their teeth. Motion of the head in the six axes of freedom (three translational and three rotational) was measured by Johnston et al. (1978) using a 300 gram bite-bar to investigate the effect of a reclined seat on motion transmitted to the heads of seated subjects. In general, accelerometers designed to monitor rotational accelerations are greater in size, mass and are more prone to damage than translational accelerometers.

2.2.2 Electro-magnetic field

Position and motion of the head has been measured by surrounding the subject's head with an electro-magnetic field and attaching a detecting coil to the head, thus inducing eddy currents in the coil (Johnson, 1954). Wells (1984) used a similar but a sophisticated system to monitor pitch and yaw motions of the head during vertical vibration for seated subjects to determine their ability to maintain a specified line-of-sight.

2.2.3 Optical devices

An optical device consisting of a head gear with small light bulbs attached to it was employed in an investigation by Begbie et al. (1963) and Walsh (1966). Light beams from two lamps on the head gear were made to pass through a system of mirrors and lenses and, the resulting light was directed on to photographic paper. This apparatus enabled the three translational axes of motion at the head to be monitored.

Three photo-emitting diodes mounted on the head were used by Sandover and Soames (1975) to monitor head movements at low frequency whole-body vibration. Position of the diodes was photographed and analyses consisted of following the points as the head moved during one cycle of input sinusoidal motion (frequency range 1 to 5 Hz in 1 Hz steps).

High speed photography has been used to record head motion during whole-body impact studies (Ewing et al., 1968). The analyses of short duration data are very complex and tedious unless a computer system is employed and used to recognise predetermined landmarks and thus provide a motion waveform.

2.2.4 Gyroscopes

Gyroscopes have been used to determine the rotational motions of the head during laboratory experiments and during aircraft manoeuvres (Johnson, 1956). These experiments were conducted to investigate airsickness among aircrew.

2.2.5 Potentiometers

An apparatus consisting of a bite-bar connected to a light-weight helmet, and this in turn joined to a potentiometer was used to follow head position in the yaw axis in an investigation by Barnes and Sommerville (1978) to determine tracking performance using a helmet-mounted sight. (A rotational accelerometer was also used to measure head motion.)

2.2.6 Pulleys, etc.

A linen thread attached to the subject's head and connected to a pen in a pulley system was used by Johnson et al.(1951) to monitor head motion in subjects seated on a swing. This was to investigate the movements of the head required to induce the symptoms if motion sickness. Waters et al. (1973) conducted experiments to observe translational displacements of the head during normal walking. Subjects walked on a treadmill at different speeds while their head motion was monitored using an arrangement of light-weight fiberglass cords attached to the head via a headband and to displacement transducers. Accelerations of the head were measured using accelerometers rather than the calculation of accelerations from displacements due to errors involved in such analyses.

2.2.7 Acoustic methods

A method which has been used to measure movements of the hand during a counter positioning task (Fleischer and Lange, 1983) could be employed to record displacements of the head during, for example whole-body vibration, treadmill running, etc. This apparatus consists of a small transmitter emitting ultrasonic waves which are picked up by a receiver. The transmission time between emission and detection of the ultrasonic wave is determined, which in turn allows the calculation of the separation between the two transducers. Such a system has been used to monitor head movements in a military vehicle during rough cross-country rides (Paddan and Griffin, 1987).

2.2.8 Discussion

Seven different methods of measuring head motion have been mentioned in this section. They would all have their merits and demerits in one way or another. The accelerometer would provide an acceleration waveform covering a wide range of frequencies and can be used in many environments. The main disadvantage with this transducer is that the signal is affected by the Earth's gravitational field and this, in some cases, can give misleading data. Both potentiometer and pulley methods have a limited range - this being as large as the potentiometer or the thread on a pulley system. This space limitation also applies to electro-magnetic and acoustic methods: the receiver must be within the field of the transmitter or loss of signal will occur. Also, it is essential that the surrounding equipment does not generate or interfere with the waves as this would introduce erroneous measures. As was the case for above methods, the optical systems rely on the assumption that the head remains within a fixed surround and deviation from the enclosure would result in a loss of signal. Gyroscopes are not so well used as other equipment in biodynamics, they are comparatively expensive and fragile.

In the above systems, apart from the accelerometers and gyroscopes, all the others require a surround for one piece of equipment, this makes them more suitable as laboratory based apparatus than for field measurements. Accelerometers can be put into small, compact and highly portable systems ideal for field measures, although the determination of displacements from acceleration signals may not be an error free process.

2.3 INPUT MOTIONS USED DURING WHOLE-BODY VIBRATION

The investigation of the transmission of vibration through the body to the head has been conducted in both controlled laboratory conditions and in somewhat less repeatable field conditions. Within the laboratory, the input motion can be generated and fed into a vibrator by a computer or a previously recorded analogue signal replayed into the vibrator. In a study to investigate the effect of some variable on head motion (such as posture, head angle, etc.) or other studies such as individual differences, it is important to keep the effect of other variables to a minimum. The effect of different input motions on the transmission of vibration through the body to the head could be minimised by using the same vibration waveform each time. In field conditions, rather less control over the experiment is available to the investigator as there are many factors which may be very difficult to control. There may be variables such as speed of the vehicle, terrain conditions, weather conditions, etc. which may influence the measurements.

Laboratory experiments reported in the literature have been conducted on a motor-cam arrangement or some other electro-dynamic or electro-hydraulic device. The motion at the seat to which a seated person is exposed may fall into a variety of categories: discrete sine waves, sine swept, random, transient.

This section reviews literature reporting on different input motions used in both laboratory and field experiments on the biodynamic response of the body to the input vibration.

2.3.1 Laboratory experiments

Discrete frequency

The most common used input motion and possibly the method requiring the simplest of analyses is sinusoidal motion at discrete frequencies. Some of the early work on transmissibilities was on the determination of the effect of different seating position in Armoured Fighting Vehicles (Dennis and Elwood, 1958). The equipment used was of a rather basic form consisting of a vibration platform connected to an electric motor. Different discrete frequencies were obtained by varying the motor speed.

Guignard (1959) conducted some of the fundamental investigations on the transmission of vertical seat-to-shoulder vibration. An electro-dynamic vibrator was used in the studies and discrete frequencies ranging from 8 Hz to 60 Hz. After steady-state conditions had been reached, data of seat and shoulder motion were recorded. (Head motion was also measured using a bite-bar but the results had to be discarded due to equipment problems.)

In a study to determine the effect of variables such as subject posture, vibration magnitude and frequency on motion transmitted to the heads of seated subjects, Griffin (1975) exposed 12 male subjects to vertical vibration at the seat with 12 different discrete frequencies ranging from 7 Hz to 75 Hz and with 6 vibration magnitudes ranging from 0.2 ms^{-2} to 4.0 ms^{-2} r.m.s. The subjects were instructed to adopt such a posture of the feet, hands and the body so as to either minimise or maximise motion at the head depending on what the experimenter required. Head motion was monitored when the subjects indicated that the required condition had been reached. Such an experiment could not be conducted using input waveforms such as sine sweeps, random, etc. since no 'steady-state' conditions of head motion could be reached due to the varying nature of seat motion.

The effect of two individual (2.5 Hz and 5.0 Hz) and mixed frequencies (2.5 Hz and 5.0 Hz in equal magnitudes) on head motion was investigated by Cohen et al. (1977). This was in an attempt to explain the effect vibration frequency had on human performance. Transmissibilities between vibrator plate and head motion were calculated as a ratio of acceleration magnitudes. The mean results of six male subjects shown in Table 2.1 tended to suggest that the body acted as a band-pass filter "maximally amplifying" the 5 Hz resonance component in the mixed frequency input waveform. This study demonstrated the use of both individual and mixing of discrete frequencies.

Table 2.1 Mean transmissibility at the shoulder and head for each vibration condition (Cohen et al., 1977).

	Vibration condition		
	2.5 Hz	5.0 Hz	2.5 & 5.0 Hz
Head/Table	1.06	0.90	0.92
Shoulder/Table	0.96	1.27	1.27

There have been very few studies of the transmission of rotational seat vibration to the head; examples of these include roll and pitch seat motion by Barnes and Rance (1974) and yaw seat motions by Barnes and Rance (1975). In both these studies, head motion was monitored using a bite-bar held between the teeth while the seat was oscillated at various discrete frequencies ranging from 0.5 Hz to 20 Hz.

Swept sine

The use of sine swept motion as the input to a vibrator has been widely used in biodynamic research. The main advantage of using sine swept motion is that it covers a specific range of frequencies in one run, however, the analysis is difficult which might require the use of a computer. (A computer is not necessarily required during discrete frequency sine wave motion since the steady state amplitudes can be measured using such devices as a voltmeter or an oscilloscope!)

The duration of the input motion and the rate of sweep are important as the input waveform can range from a transient to a waveform resembling a series of discrete sine waves joined end on end. Some of the sweep rates used in determining seat-to-head transmissibilities have been 0.62 Hz/s (Lewis and Griffin, 1980), 0.66 Hz/s (Wilder et al., 1982), 1.15 Hz/s (Johnston et al., 1978). In all these experiments, the effect of postural variables, vibration magnitude and the effect of headrest have been investigated on the transmission of seat-to-head motion.

Discrete frequency sinusoidal and sine swept motions are rarely encountered in real situations with some possible exceptions such as fairground rides. Motion to which the human body is exposed during, for example, a tractor ride on a rough terrain could be termed pseudo random. Motion in most vehicles could be put into this category. The vibration would cover a wide range of frequencies and acceleration magnitudes depending on factors such as speed of the vehicle, axis of vibration, position of measurement within the vehicle, etc.

Random

Motion stimuli used in a study by Pradko et al. (1965) had narrow-band white noise spectra (equal magnitudes of motion at all frequencies) covering a frequency range of 2 Hz (i.e. band-pass filter) centred at various frequencies. Data obtained were mainly to determine human tolerance to vibration limits. The experiments were repeated with the same white noise stimuli but this time, a 10 Hz band-pass filter was used. (Seat-to-head transmissibility curves were obtained using sinusoidal seat motions.)

There is only one known study in which comparisons have been made between seat-to-head transmissibilities during exposure to different types of input motion: Griffin et al. (1979) reported an investigation in which three different motions were used; discrete sines, sine sweep and random. Discrete sine wave motion consisted of the determination of transmissibility at each one-third octave frequencies from 1 to 100 Hz. The sine sweep and random motions were of 100 second duration at 1 ms^{-2} r.m.s. Transmissibility results obtained are shown in Figure 2.1, and suggest that there are some differences, although they are small. It would be difficult to be sure whether these differences were directly attributable to the varying input motion or repeatability.

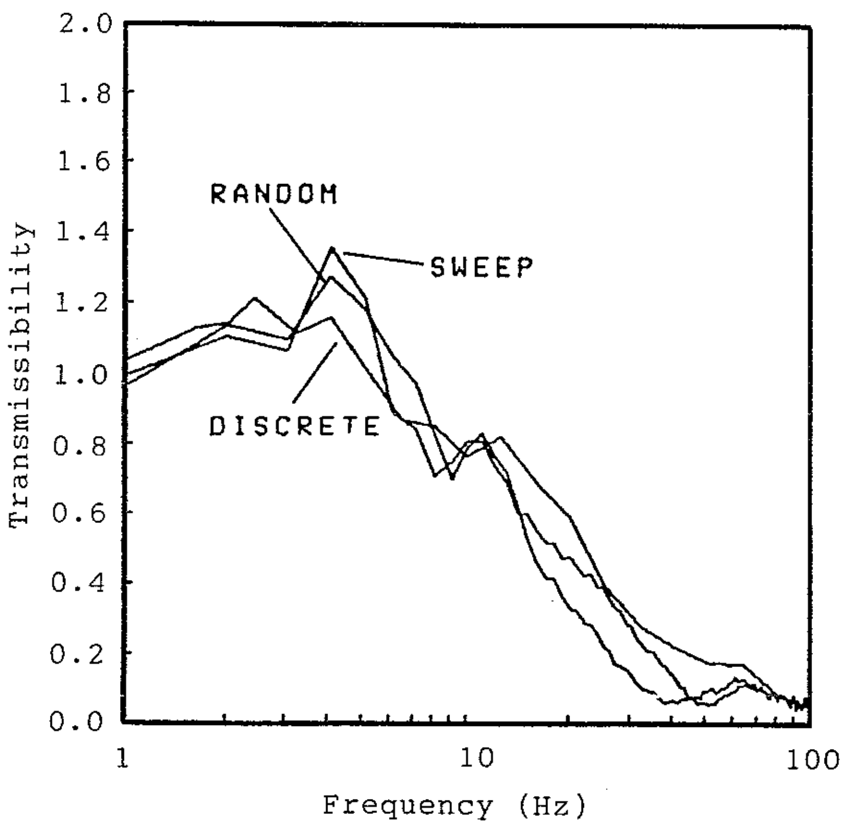


Figure 2.1 Comparison of seat-to-head transmissibility of a single subject determined with three types of input motion: random vibration spectrum, swept sine and discrete sinusoidal vibration (Griffin et al., 1979).

In an experiment conducted by Page et al. (1977), subjects were exposed to the same random vibration in the fore-and-aft and vertical axes simultaneously with a 0.33 second lag in the horizontal axis motion. This was further complicated by introducing impulses in the vertical axis motion at regular intervals. The vertical motion was low-pass filtered at 1.5 Hz and of an acceleration magnitude of 0.12g r.m.s. (1.18 ms^{-2} r.m.s.) while the fore-and-aft was low-pass filtered at 1.2 Hz and of 0.14g r.m.s. (1.37 ms^{-2} r.m.s.). (This was used to simulate the motions encountered in cross-country vehicles.) Seat-to-head transmissibilities were obtained up to about 20 Hz for a single subject seated in different postures. The results showed that seat-to-head transmissibility was mainly unaffected by posture, the postures included 'leaning forward', 'upright' and backrest angles of 20°, 30°, 40° and 60°.

Sandover (1978) investigated the transmission of seat-to-head motion using broad-band random vibration at an acceleration level of 2 ms^{-2} r.m.s. in the vertical axis. Measurements of head motion were made at the top of the head and at the mouth using a bite-bar. These data were obtained to suggest possible methods of measuring and analysing data for the development of biodynamic models.

Transients

Using transients as the input motion to study human vibration characteristics has been the topic of only one study though 'pseudo-transients' have been used by other researchers. A motion is termed as 'pseudo-transient' in this context if impulses or transients are present in the input motion superimposed on other (e.g. random) motion. Bennett et al. (1978) conducted an experiment to investigate the effect of vibration on many parameters of which the transmission of seat vibration to the head was one. The motion used consisted of a narrow-band random signal with impulses of 125 ms duration interspersed at regular intervals. The impulses were superimposed on random motion such that the crest factor of the combined signal was 8. Transmissibilities were calculated between vertical seat and head motion and vertical floor and head motion. The results showed that the transmission of floor to head motion depended on the seat characteristics.

Macduff (1969, 1971) exposed his subjects to individual transients in an experiment which included a see-saw mechanism with the subjects seated or standing on one end. When the unloaded side of the see-saw was released, the subject and the see-saw were allowed to fall freely under gravity through a distance of about 0.3 inch (7.6 mm). Velocity measurements of head motion were made during impact and recorded on to a strip chart recorded. Effects of leg postures such as locked knees and flexed knees (slightly forward stance) were investigated which showed higher velocities and accelerations at the head for the locked knees posture. Responses of seated and standing persons to horizontal transient displacements were also investigated.

2.3.2 Field measurements

Measurement of head motion during field trials has been the topic of a few investigations. These have usually included monitoring head motion in a vehicle, for instance traversing a rough terrain. The vehicles used in the reviewed literature include trucks, trains and aircraft.

In a study conducted by Simons et al. (1956), measurement of motion transmitted from a truck to the driver's hip and the neck was made as the military truck was driven over a test track. Transmissibilities are presented of motion transmitted to the hip under field conditions though input motion on the vehicle was measured slightly behind the seat on which the driver sat rather than directly under the seat. Comparisons are made between transmissibilities of hip motion data obtained in the field and under laboratory conditions.

Dupuis et al. (1975) made measurements of head motion during various forms of activity ranging from walking to riding a motor boat. In order to obtain a measure of transmissibility, motion was measured near the point of entrance to the body (e.g. near the ankle for running, walking; on the backrest for a car ride) and at the head. Main frequencies of vibration were measured and transmissibility value calculated as a ratio of peak-to-peak accelerations at the head and the input. No thorough analyses were conducted on the data. (These results were mainly used to explain motion of the eye during various forms of activity.)

Using a set of lamps fixed on to a head gear and an optical device consisting of a series of mirrors and prisms, Walsh (1966) was able to monitor motion of the head in all the axes of motion during a train ride. Displacements of the head were recorded on to photographic paper as a mobile laboratory went over a section of jointed rail. Data were split into three main categories, an 'A' rhythm, a 'B' rhythm and a 'C' rhythm. 'A' rhythm corresponded to vertical oscillation of the head over the 3 Hz to 4 Hz frequency range with displacements of about 2 mm to 4 mm peak-to-peak. 'B' rhythm was associated with lateral oscillation of the top of the vertebral column over a lower frequency range of 0.5 Hz to 1.5 Hz. Displacements in this case were somewhat larger of the order of 1 to 2 cm. Fore-and-aft motion of the head observed in standard coaches was called 'C' rhythm. This motion consisted of 2 Hz to 4 Hz frequency with displacements of about 1 cm. Measurements of vibration on the coach floor were made although no correlative calculations between floor and head motion were carried out.

Some studies of head motion in aircraft have been conducted, mainly in helicopters. Seris and Auffret (1965) carried out a study in which head motion was monitored in the three translational axes during various manoeuvres of a helicopter flight. Frequency of motion at the head consisted mainly of about 20 Hz - the main rotor speed frequency with some content of low frequency below about 3 Hz, possibly caused by air turbulence. During a 260 km/hr flight, it was found that over a frequency range of 1 to 100 Hz, acceleration magnitude at the seat was generally greater than head motion for the three translational axes of motion. The recordings showed that in most cases, head motion was greater than shoulder motion over the 25 Hz to 30 Hz frequency range.

Griffin (1972) carried out experiments in a Scout helicopter to determine the vibration experienced by pilots. Two sets of measurements concerning head motion were made; the first set was to determine the magnitudes of triaxial head motion during different flight conditions and an attempt to obtain correlations between subject characteristics and head motion. The second set was to calculate transmissibilities between seat and head motion. Seat-to-head transmissibilities for vertical motion were obtained for eight pilots and the results showed an amplification at the head relative to seat motion for frequencies between 2 Hz and 10 Hz with a point of resonance at about 5 Hz. (An inertia harness was worn by all pilots.) Some correlations were found between head motion and the frequency of vibration generated by the rotor blades. Comparisons between motion in different axes at the head showed that fore-and-aft and vertical axes contained more motion than the lateral axis.

A Puma HC Mk I helicopter was used by Wells (1982) in the measurement of vertical seat, pitch head and pitch helmet motion during various flight manoeuvres. Pitch motion at the head showed peaks at frequency corresponding to the rotor passage frequency and its harmonics - the helmet also showed these data. A poor agreement was obtained between pitch head motion recorded in a helicopter and a laboratory during vertical seat vibration. There were many factors that might account for the differences, multi-axis motion in a helicopter and single axis during laboratory conditions being only one of them.

These three studies of head motion during flight trials in helicopters have shown that vibration at the main rotor passage frequency and its corresponding harmonics are transmitted to the head with greater amplitude than other frequencies. This is thought to be due to the dominance of rotor passage frequency and its harmonics over the presence of other frequencies.

Measurements of seat and head motion in field conditions should ideally be made of vibration in all the axes in which motion occurs (although this depends on the aim of the measurements). For a land based vehicle traversing over rough terrain, motion at the seat would be in all axes, i.e. three translational and three rotational. It is shown in Chapter 5 that motion at the head need not necessarily be in the same axis as the excitation at the seat. This indicates the need for measurement of motion at both the seat and the head in all axes of motion.

2.3.3 Discussion

Laboratory experiments have mainly involved vibration excitation of the subject in one axis, mostly the vertical axis. In these investigations, different kinds of signals have been used during whole-body head vibration measurements. One type of motion that has not been seen in any of the literature is a vibration signal recorded in a vehicle and then used to operate a motion simulator in order to measure head motion under such conditions. However, such an arrangement would only partly simulate vehicular motion since motion in a vehicle would normally be present in all the six axes of freedom (i.e. three translational and three rotational). Generally, motion simulators are used for single axis motion, simulators for more than one axis have rarely been used. The main differences between laboratory measurements and those made in a vehicle (e.g. motor car, train, aircraft) is that vibration in a laboratory is normally in limited axes and field measures would also include the effect of environmental factors (e.g. terrain, seating).

Comparisons need to be made between data obtained in laboratory conditions and in field measures to determine the differences or similarities in transmissibilities.

2.4 LOCATIONS OF MEASUREMENT OF MOTION

In every aspect of research, data from a particular experiment can be obtained which would subsequently have to be verified to determine whether the results were as would be expected. There are many ways this can be done of which one is to compare the results with those obtained by other researchers. This approach does not always lend itself as a possibility without some assumptions. There may be many factors that differ between the investigations such as experimental set-up and conditions, subject characteristics.

In biodynamics, and to be more specific, in the determination of transmissibility of vibration from the seat to the upper body of a seated person, this approach of validation is complicated by the use of different locations for the measurement of vibration on the body. Motion of the head has been measured by placing transducers at different points on the head, thus making comparisons difficult since the head itself is free to move in any of the six axes of motion. Each point on the head would demonstrate different motion; shoulders and different points on the spine have also been the locations for the attachment of transducers for motion measurement.

2.4.1 Coordinate systems

A coordinate system that is normally used is biodynamics and is widely accepted is that defined in ISO 2631 (1985); this defines the axes of the human body. A separate coordinate system is required for the head which can be used for the measurement of motion at a specific point. Such a system has been used (Ewing and Thomas, 1974) and is defined in Draft International Standard 8727 (1984) (a standard is in preparation). Figure 2.2 shows the head based coordinate system used by Ewing and Thomas (1974) and is defined as:

> "The head anatomical coordinate system is derived from an anatomical plane specified by the superior edge of each auditory meatus and by the infraorbital notches. The origin is at the midpoint of a line connecting the superior edges of the right and left auditory meati. The +X-axis is from the origin through the midpoint of a line connecting the infraorbital notches in the anatomical plane. The +Z-axis is from the origin in the superior direction perpendicular to the anatomical plane."

Measurements of head motion are unlikely to be made at the defined origin of the coordinate system, however calculations can be made of motion at the origin or measurements can be reported with respect to such a point.

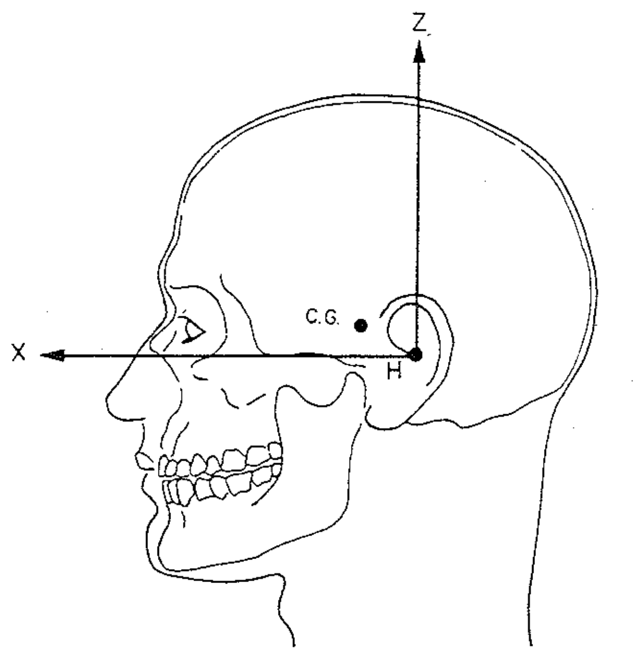


Figure 2.2 Head anatomical coordinates (Ewing and Thomas, 1974).

2.4.2 Anthropometry of the head

In some of the studies on the measurement of head motion, some of the many anthropometric measurements of the head might be required. This might involve determining the effect of added mass on head motion and in such an experiment, the mass of the head might be required to calculate the percentage mass added to the mass of the head. The average mass of the head will, of course, depend on the size of the subject, approximate figures from cadavers of adults of 4.376 kg and 4.305 kg have been reported (Walker et al., 1973; Beier et al., 1979). Other parameters that might be useful include moments of inertia in different axes. These would be required to estimate an increase in the total moment of inertia of the head and motion measuring instrumentation. Linear dimensions of the head have been given in some studies which might be useful in determining precise location of measurement with respect to a defined origin of a coordinate system.

2.4.3 Location of measurement

Head

Many measurements of head motions have been made to investigate the effect of different parameters on vibration transmitted to the head (e.g. backrest, posture, head angle). The use of instrumented bars held between the teeth (bite-bars) is wide spread because this overcomes the problem of strapping transducers to the head. Guignard (1959) noticed that the position of the accelerometers in the measurement of vertical head motion was crucial in that pitch motion of the head (nodding) would result in different signals being detected. To reduce the effect of pitch motion on the measured vertical motion of the head, the accelerometer was positioned to be near the 'axis of flexion of the head on the neck' by an arrangement of an extended bite-bar.

Griffin (1975) and Johnston (1979) used bite-bars of different types and weights and they presented their results as transmissibility curves of motion between the seat and the head. Gross comparison between their investigations can be made but their results lack one main feature, that is motion at the head was measured at different positions. This would not allow close comparison of data unless motion at the head could be calculated at known specific points, for example, at the centre of gravity of the head (Ewing and Thomas, 1974).

Kobayashi et al. (1981) realized that different results could be obtained by measuring motion at different points on the head. To further understand motion of the head, two different measurement sites were used in their investigations: the mouth (using a tooth impression mould) and at the forehead.

Coermann (1962) reported on some of the early work on biodynamics and presented transmissibilities from seat to head where head motion was measured at the top of the head using elastic bandages to secure accelerometers. The effects of rotational motion of the head and location on the results obtained was not discussed.

A 'mouldable lead skull cap' (mass not reported) containing an accelerometer was the set-up used by Gunther (1969) to monitor head motion during walking and running. No comparison with previous published data was presented. Motion at the head and the pelvis was also measured.

Rowlands (1977) conducted an extensive study on the transmission of vertical vibration at the seat to the heads (and shoulders) of seated male subjects. Motion was measured at the top of the head by an accelerometer secured using a head harness. It was realized in the investigations that rotational motion of the head would occur and concluded that the effect of rotation of the head would be small on the results presented.

In some of the above studies where head motion was measured at the crown, one point that is clear is the difficulty encountered in securing accelerometers to the head. Slippage of the transducers on the head and the determination of the precise location of the transducer with respect to the head may show up as erroneous results. No such problems would occur when using a bite-bar to measure head motion.

Shoulder

The shoulders of subjects have been used as the position of measurement during whole-body vibration in some experiments. The main drawback with such a location is the difficulty in attaching accelerometers to the body. Data obtained of shoulder motion can be used, for instance, to determine the amount of attenuation provided by the neck in neck-to-head motion or the attenuation provided by the arm in the transmission of vibration from the hand to the shoulder. This may be required in evaluating the ability of the hand to carry out manipulative tasks during whole-body vibration. One of the advantages of measuring motion at the shoulder may be that rotational motion would be small (roll, pitch, yaw), thus reducing the effect of such motions on the translational motion measured at the shoulder.

Guignard (1959) measured the transmission of vertical seat vibration to the shoulders of male subjects at various discrete sinusoidal frequencies ranging from 8 Hz to 60 Hz. The results from the experiments are considered as some of the preliminary data available on the effect of such variables as muscle tension, posture and comfort.

The response of the shoulder to low frequency vibration during exposure to lateral and vertical vibrations was investigated by Woods (1967). The transmission of vibration from the seat to the shoulder was analysed as a transmissibility curve. Vertical vibration at the seat and the shoulder demonstrated one main resonance peak at about 5 Hz, while for lateral vibration, two peaks were observed;

at 1.5 Hz and 4 Hz. These data were used in conjunction with the discomfort caused to evaluate the effect of vibration on task performance.

Rowlands (1977) measured both head and shoulder vibration in his study: head vibration to provide estimates of motions at for example, the eyes, and shoulder vibration as an input to motion transmitted to the head through the hand/arm system. A shoulder harness was constructed so as to allow for the natural shape of the shoulder; this was used to mount and orientate an accelerometer in the vertical direction. The effects of many variables on vibration transmitted from the seat to the shoulder (and the head) were measured, these included body posture, arm position, leg position and vibration magnitude. Some of the results are discussed elsewhere in this chapter (Section 2.6.1.2).

Other positions

There have been only a few studies which concentrated on the transmission of vibration to any one point on the body other than those already discussed.

Zagórski et al. (1976) measured motion at four different vertebrae and at the head during vibration of seated subjects to establish the nature of transmission of vibration from the seat through the vertebral column to the head. It was shown that attenuation of the applied vibration was greater towards the top of the spine and with the greatest attenuation being at the head; attenuation varied with distance from the applied vibration.

Vibration at the thorax of subjects exposed to vertical seat vibration was measured by Donati and Bonthoux (1983) to investigate the effect of different motion at the seat on that transmitted to the thorax. The results tended to show that the human body behaved mostly like a linear system and the response could be roughly modelled as that of a single degree of freedom system. It is interesting to note that although measurements were made at the thorax, results showed a main 4 Hz resonance peak which is normally found in seat-to-head and seat-to-shoulder transmissibility curves. This indicates that the whole of the upper body responds maximally to the 4 Hz frequency content in the seat motion.

2.4.4 Discussion

It is seen from the above reviewed studies that comparison of results obtained from separate investigations would be difficult due to the different locations used to measure motion on the body. Ideally, all data would be measured with the capability of calculating motion with respect to one known point on the body (e.g. a specified point on the head). Generally, more instrumentation would allow this; by using six or nine accelerometers (depending upon the accuracy and conditions), total motion of a solid body can be measured and used to calculate vibration at other points on the body (Padgaonkar et al., 1975). This is further explained in detail in Appendix 6.

The attaching of accelerometers to the body always poses problems in that some harness or adhesive material is required to secure the accelerometers. Attaching accelerometers to the skin has its own drawbacks as they would tend to display relative motion between the skin and the bony structure underneath. In the measurement of head motion, this can be partly overcome by using a bite-bar held between the teeth. This set-up has been used to obtain data for this research and is reported in later sections.

2.5 METHODS OF ANALYSIS OF HEAD MOTION DATA

A number of different methods can be employed to analyse data on the transmission of seat vibration to the head. Each method provides the results in either a different form or a deeper understanding than the other methods. This section reviews studies in which seat-to-head vibration has been analysed using different methods. Some of the terms commonly calculated in such studies include transfer function and transmissibility; these have been defined in ISO 2041 (1975). Transfer function is defined as:

> "Transfer function (of a system): A mathematical relation between the output (or response) and the input (or excitation) of the system.
> NOTE - It is usually given as a function of frequency, and is usually a complex function."

The definition of transmissibility is

> "Transmissibility: The non-dimensional ratio of the response amplitude of a system in steady-state forced vibration to the excitation amplitude. The ratio may be one of forces, displacements, velocities or accelerations."

2.5.1 Peak-to-peak

A method employed by Garg and Ross (1976) was to calculate a magnitude ratio of the peak-to-peak value between measured head and floor displacements (for standing subjects). (Displacements were measured using an oscilloscope and a paper trace recorder.) Such a method is more suited (and possibly applicable only) to sinusoidal inputs since it relies on a steady-state response of head motion. Measurement of peaks and valleys of head movements during random motion at the floor would be meaningless since transients in the input motion would not result in a steady-state response of head motion. Dupuis et al. (1975) measured peak-to-peak acceleration values of head motion and the input for a number of different forms of travel ranging from walking to a motorboat ride. Transmissibility was calculated as a direct ratio of peak-to-peak values at the main frequency of motion.

2.5.2 Root-mean-square

Pradko et al. (1965) determined head motion transmissibility as a ratio of root-mean-square, r.m.s., values of head and seat acceleration. A sinusoidal waveform was used in their experiments. A similar method was employed by Griffin (1972) where seat-to-head transmissibilities in a helicopter were calculated by the division of r.m.s. acceleration levels at individual frequencies. Another method used by Griffin et al. (1979) was to use a sine sweep waveform with a rate of 1 Hz per second from 100 Hz to 0 Hz, then calculate r.m.s. head acceleration over each one second period for each frequency. Transmissibility was calculated as a ratio of head to seat r.m.s. acceleration. This method was shown to have many drawbacks such as timing errors, distortion in signals and assumption of a single frequency over each second (Griffin et al., 1979).

2.5.3 Frequency spectral analyses

Two frequency spectral methods used to determine seat-to-head transmissibility are the 'cross-spectral density function' (csd) and the 'power spectral density function' (psd) methods (Bendat and Piersol, 1966). They are defined as:

Cross-spectral density function method
$$H_c(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

and

Power spectral density function method
$$H_p(f) = \left[\frac{G_{oo}(f)}{G_{ii}(f)} \right]^{\frac{1}{2}}$$

where

$H_c(f)$ = 'cross-spectral density function method' transfer function,

$H_p(f)$ = 'power spectral density function method' transmissibility,

$G_{io}(f)$ = cross-spectral density between input and output motion,

$G_{oo}(f)$ = power spectral density of output motion, and

$G_{ii}(f)$ = power spectral density of input motion.

Griffin et al. (1979) conducted laboratory experiments with vertical motion at the seat and measured vertical motion at the head. They used the two above frequency spectral methods and obtained seat-to-head transmissibilities. Both methods gave similar results indicating the high degree of linearity of the body. Above about 7 Hz, the two frequency spectral methods and the ratio of r.m.s. method all gave similar results. The r.m.s. method appears to show the largest deviation below 7 Hz.

It is clear from the above expressions for the transfer functions that the psd method of calculation would result in higher values than the csd method. (This is because the psd method is a direct ratio of powers of output to input motions whereas the csd method accounts only for the linearly correlated motion at the output with the input (see Chapter 4 on 'Analysis of head motion data').) If the two methods are to be used in determining seat-to-head transmissibility, then the psd method is likely to give similar data to the csd method for laboratory data where there is only one axis of input motion (e.g. vertical axis). The csd method would be more suitable for field data where the input motion is multi-axis.

In a study by Wells (1982), pitch-axis head motion was measured during vertical seat motion in the laboratory and transmissibilities were calculated using the csd method; and in-flight measurements (in a helicopter) using the psd method. He concludes that laboratory data under estimated field seat-to-head transfer functions; this would have been expected due to the effect of vibration of the seat in other axes on head motion. In the analyses, data recorded in laboratory conditions could have been analysed using either the csd or the psd method since there was only single axis excitation at the seat (i.e. vertical only). Data collected during in-flight measurements might have benefited from analyses using the csd method as motion at the head would have been affected by vibration in the other axes at the seat.

2.5.4 Phase

Phase can be determined between input and output motion using some of the analyses. Garg and Ross (1976) were able to measure phase lags between vertical floor and head motion for standing subjects by visually comparing the traces of motion at the floor and the head. Calculation of phase was made easy by the use of input sinusoidal vibrations. Barnes and Rance (1975) were able to compare phase angles between the seat and the head for rotational motion of the seat; this was using the 'cross-spectral density function method' of analyses which provides phase information, whereas the 'power spectral density function method' would give the magnitude only.

2.5.5 Discussion

The peak-to-peak and r.m.s. methods of analyses could be carried out with sinusoidal input motion by using an oscilloscope or a voltmeter. The use of a strip-chart recorder would provide information of phase between the input and output motion. A computer would be required if spectral analyses were to be conducted. Generally, magnitude (transmissibility) and phase information should be calculated if conditions allow.

2.6 VARIABLES AFFECTING THE TRANSMISSION OF VERTICAL SEAT VIBRATION TO THE HEAD

The transmission of vibration from the seat to the head is a complex phenomena governed by many factors. These can be put into two main categories: those that are dependent on the experimental set-up (extrinsic variables) and those that are peculiar to the individual (intrinsic variables).

Comparisons between investigations have been made difficult by the fact that each experimenter would have a different set-up. Also, as the aim of each experiment would be different, the instructions given to the participating subjects would differ, and hence, some differences in results would be expected in similar experiments.

Most of the literature available on this subject deals with the transmission of vertical seat vibration to the head, and in most cases, head motion has been measured only in the vertical axis. Data on the transmission of other axes of seat vibration to the human body consist of only a few papers per axis, in some cases only one paper per axis!

This section reviews some of the literature available reporting the effects of various factors on the transmission of seat vibration to the head. Literature concerned with only vertical vibration at the seat are reported, other sections deal with motion in other axes at the seat. Results of other investigations are reviewed as either extrinsic variables including vibration magnitude, backrest angle and effect of harness, or intrinsic variables including intra-subject variability (repeatability), inter-subject variability (individual variability), posture, subject characteristics, head angle and other less investigated variables.

2.6.1 Intrinsic variables

This section covers the effect of those variables on seat-to-head transmissibility which are generally difficult to monitor and are normally peculiar to an individual.

2.6.1.1 Effect of head angle

In almost all situations where a person is exposed to some form of vibration, the tilt of the head has to be altered in order to carry out some task. Examples of this include drivers who constantly move their head to direct their line of sight in other directions.

Five main studies have been cited in the literature concerned with the effect of head pointing angle on motion transmitted from the seat to the head during whole-body vertical vibration. The first investigation was by

Guignard (1959) in which a logical order of conditions was planned. Seated subjects maintained their head in five different pitch angles, these were 0° (normal horizontal), 12° above and below the horizontal and, 30° above and below the normal position. To aid the subjects in ensuring that they kept their head at the required angle, the subjects were instructed to look through a collimating tube placed in front of them at the appropriate elevation. Due to equipment inefficiencies, seat-to-head transmissibilities were not obtained. However, the subjects commented that a 30° up posture resulted in more vibration at the head and being uncomfortable than the other angles of the head. Also, that the 30° down posture was the most comfortable.

The second investigation was conducted by Griffin et al. (1979) in which quantitative data were obtained unlike the subjective results obtained by Guignard (1959). A seated subject was exposed to whole-body vertical vibration over the 1 Hz to 50 Hz frequency range. Each exposure lasted 100 seconds and was of 1 ms^{-2} r.m.s. magnitude. The subject was required to sit in a normal relaxed posture and to orientate his head at five different pitch angles, these were: normal (forward facing looking horizontally ahead), 25° and 50° above and below the horizontal. Transmissibilities between seat vibration and head motion were calculated and these are shown in Figure 2.3 for the different head positions. Head angle appeared not to affect motion transmitted to the head above about 30 Hz whereas large differences occurred at about 16 Hz; substantially more motion was present when the head was above the horizontal than when below the horizontal.

In a fairly recent study, Cooper (1986) investigated the effect of head pointing angle on the transmission of seat vibration to the head. Fourteen male subjects took part in the experiment, they sat in an 'erect' posture with no backrest or harness. Random vibration over the 1 Hz to 30 Hz frequency range, 60 seconds duration and 2 ms^{-2} r.m.s. magnitude was used at the seat. The main difference between this study and the two cited above is that all

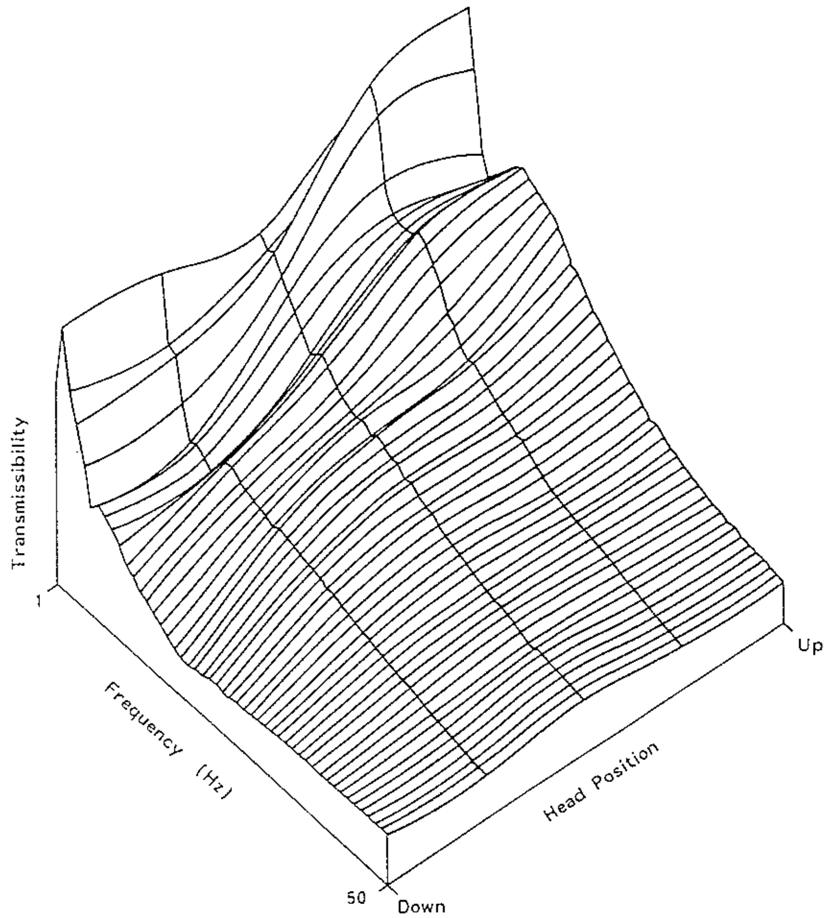


Figure 2.3 The seat to head transmissibility from 1 to 50 Hz of a single subject sitting with 5 head positions (25 and 50 degrees down, horizontal, and 25 and 50 degrees above horizontal) (Griffin et al., 1979).

aspects of posture were controlled in this study. A posture measuring device was used to remind the subjects of their chosen 'erect' posture before the start of each run. Vertical and pitch motion at the head was measured, vertical being with respect to the Earth's gravitational field and not with respect to the head. Angles of the head included 20°, 40° and 60° below and above the horizontal (i.e. in the pitch axis) together with normal horizontal head position (i.e. 0°). Results of seat vibration to head motion transmissibility are shown in Figure 2.4 of pitch head motion and different head angles; mean data for only 5 Hz, 10 Hz and 15 Hz are presented. It is seen that there was more pitch axis head motion for angles below the horizontal than the corresponding higher angles for frequencies less than about 6 Hz. The trend was reversed for frequencies above 6 Hz. An increase in pitch axis head motion was found for angles both below and above the horizontal. Transmissibilities of vertical motion at the head showed greater values for angles above the horizontal than those below the horizontal. In Figure 2.5 are shown the mean transmissibilities for vertical vibration at the head for three different frequencies, the trend is clearly seen in this figure.

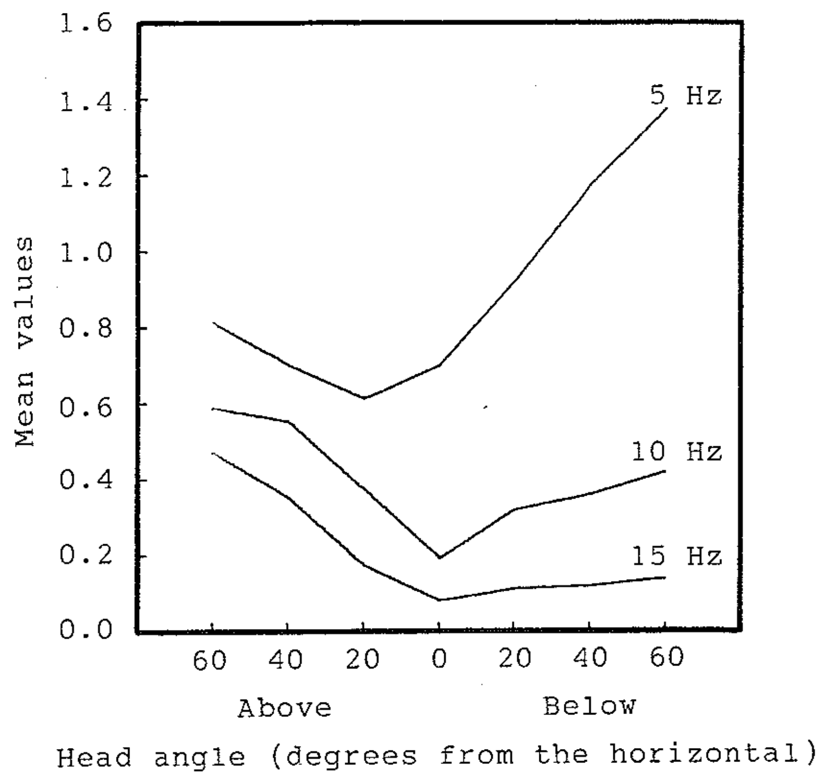


Figure 2.4 Mean increases and decreases in pitch axis head motion in the seven head angle conditions at 5 Hz, 10 Hz and 15 Hz (Cooper, 1986).

Furness (1981) reports on an experiment in which two subjects were exposed to vertical seat vibration while they maintained their head in different orientations. The angles included were in both the yaw axis (azimuth) and in the pitch axis (elevation). Table 2.2 shows the various angles used.

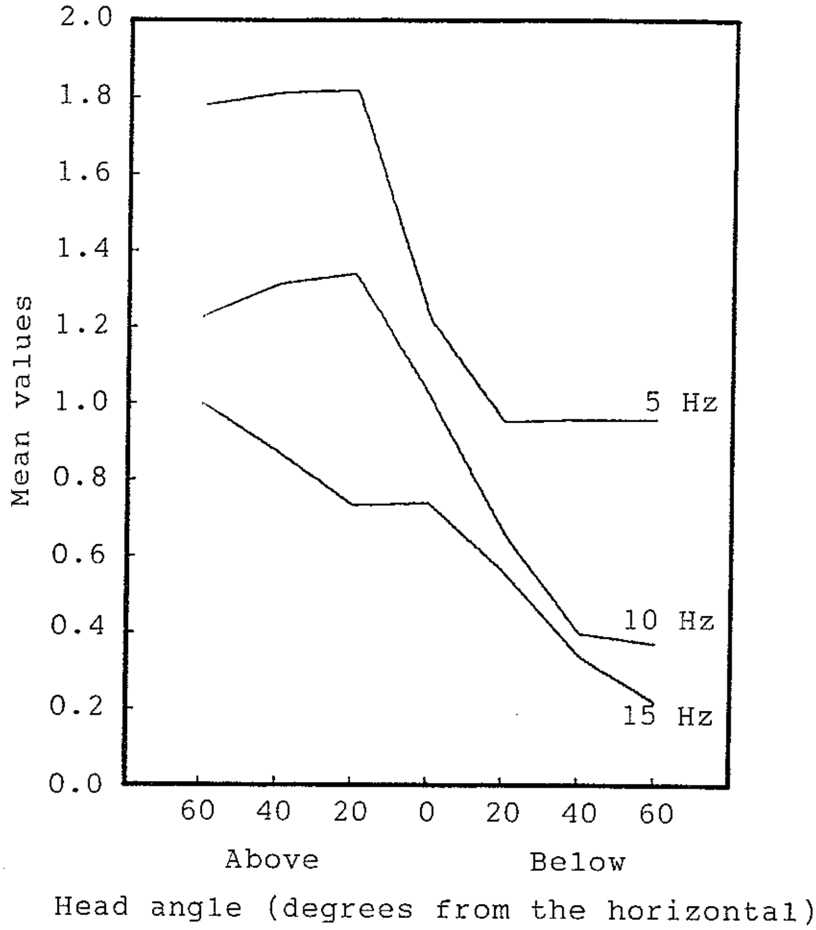


Figure 2.5 Mean increases and decreases in vertical vibration transmitted from seat to head in the seven head angle conditions at 5 Hz, 10 Hz and 15 Hz (Cooper, 1986).

Table 2.2 Head orientation angles used in a two subject study on the effect of head angle in seat-to-head transmissibility (Furness, 1981).

Azimuth	Elevation
0	0
0	+36.9 up
0	-36.9 down
45 left	0
45 left	+36.9 up
45 left	-36.9 down

The results tended to indicate that the angle of azimuth had far greater effects on seat-to-head transmissibility than elevation angles.

Single subject experiments were conducted by Messenger and Griffin (1989) to investigate the effect of roll and yaw angle on the transmission of vertical seat vibration to the head. In the first study, roll angle of the head was varied between horizontal and 40° to the left in 10° steps. All other postural variables were controlled and maintained constant. The subject was required to sit on a rigid flat seat with no backrest or harness. It was seen that motion in the lateral, roll and yaw axes at the head tended to increase with increasing roll angle of the head. The same subject took part in the second study to determine the effect of variation in yaw angle on the transmission of vertical seat vibration to the head. The different angles were 'looking straight ahead' (i.e. 0°) to 60° on the subjects right hand side in increments of 20°. The results showed increased head motion for lateral, roll and yaw axes with increasing yaw angle of the head from 0° to 40°. The two higher angles of 40° and 60° produced similar results.

Discussion

From these studies, it is seen that more motion was transmitted to the head when pitch angles of the head were above the horizontal and least motion when pointing below the horizontal. This is possibly due to the centre of mass of the head becoming in line with the transmission of vibration, i.e. the vertebral column when the head is above the horizontal. The single subject study showed that increase in roll and yaw angles of the head from looking straight ahead are likely to increase seat-to-head transmissibility in the lateral, roll and yaw axes. Though it is not known how representative the single subject study was of a group of subjects.

2.6.1.2 Effect of posture and muscle tension

The effect of posture on the transmission of seat vibration to the head is possibly the most important and the least controllable variable. This can be seen from data obtained elsewhere (Griffin, 1975) that change in posture can result in a change in magnitude of head motion by a factor of 6:1. In experiments to determine seat-to-head transmissibility of motion, it would be ideal if posture could, in some quantifiable manner, be standardised and measured to ensure, for example, similar conditions to investigate the effect of other variables. A standard method of reporting of posture might be necessary to ensure that results of different experiments could be compared.

The terms 'posture' and 'muscle tension' are completely different and have their own definition. In experimentation, some researchers have attempted to investigate the effect of these on the transmission of seat vibration to the head but have not clearly identified the differences between them. Posture, in this context, is the nature in which a person sits. Examples of this include the different postures a person can adopt, e.g. slumped, upright, sitting facing to the left. Muscle tension is concerned with the amount of tension applied in the muscles, e.g. slack, highly tensed, and an investigation into the effect of this on body transmissibility would involve no change in posture.

Some of the terms that have been used to describe posture and muscle tension include 'slumped', 'relaxed', 'normal', 'tense', 'stiff' and 'erect'. Following are investigations to determine the effect of muscle tension and posture on the transmission of seat vibration to the heads of seated subjects.

Guignard (1959) conducted an experiment on the manner in which two body postures affected transmissibility of vertical sinusoidal vibration from the seat to the shoulders of five male subjects. The subjects were required to sit in two different postures, these being 'relaxed' and 'tensed'. An attempt was made to ensure that all subjects sat in a standard posture by instructing them to look though a collimating tube - any sideways movement, sway and slump would have been reduced. Results showed that greater levels of vibration occurred at the shoulder when the subjects sat in a 'tensed' posture than a 'relaxed' posture. Although no vibration data were collected of head motion (due to experimental problems), subject's comments suggested increased vibration transmissibility when the subjects sat in a 'tensed' posture.

A one-subject study was undertaken by Guignard and Irving (1959) to determine the effect of 'relaxed' and 'pulling of linked hands - tensed' postures on waist to shoulder transmissibility of vertical sinusoidal motion. High speed cinephotography pictures were taken of the subject under vibration and relative displacements measured at the waist and the shoulder were used to calculate vibration transmissibility. Results of the investigation showed that for frequencies below about 3 Hz, both the waist and the shoulder demonstrated similar magnitudes of vibration and maximum transmissibility in the 5 to 6 Hz frequency region. The data also show increased transmissibility for increased muscle tension and a slight increase in the resonance frequency. This was confirmed by a subsequent experiment conducted using accelerometers to measure acceleration at the seat and shoulders for 10 male subjects (Guignard and Irving, 1960). The results of the latter study are shown in Figure 2.6 as changes in mean transmissibility for the subjects sitting in the relaxed and tensed postures.

The above studies have dealt with the effect of muscle tension on the transmission of vibration to the shoulder. The following researchers investigated the effect of posture and muscle tension on motion transmitted through the body to the head. Coermann (1962) measured motion at the top of the head using accelerometers mounted with an elastic bandage for subjects exposed to vertical vibration

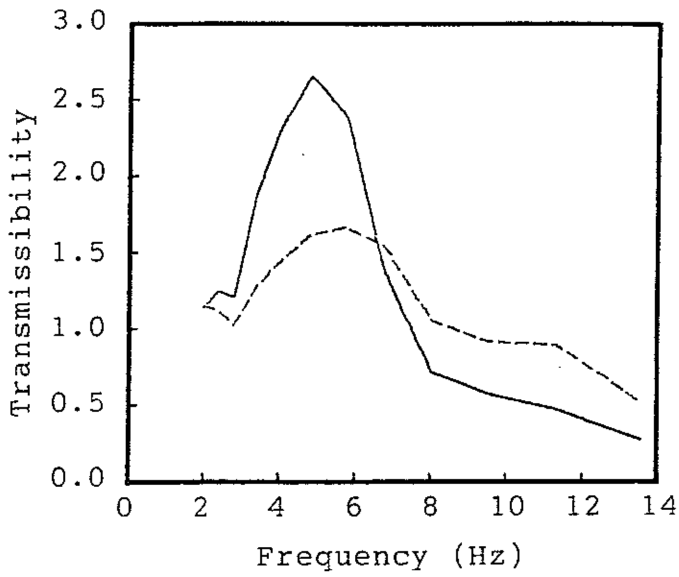


Figure 2.6 Effect of muscular tensing upon seat-shoulder transmissibility (relaxed ———; tensed - - -). Mean values for ten men at an acceleration amplitude of 0.25g (Guignard and Irving, 1960).

of the seat. The frequency range investigated was up to 20 Hz using sinusoidal vibration at the seat. The subjects were instructed to sit in two body postures: relaxed and erect. Although eight subjects took part in the experiment, data for only one subject were presented and these are shown in Figure 2.7. The transmissibility results show that, for this one subject, a relaxed posture transmitted more motion to the head for frequencies below about 5 Hz and substantially more head motion occurred with the subject sitting in an erect posture for frequencies greater than 5 Hz up to 20 Hz. A slight increase in resonance frequency from 4.5 Hz to 5.2 Hz was observed when the posture changed from relaxed to erect. Also, four resonance peaks are seen in the transmissibility figure (Figure 2.7) for an erect posture, these being at 3 Hz, 5.2 Hz, 10.8 Hz and 14.8 Hz. The lowest resonance frequency has been attributed as that caused by motion of the abdominal mass.

Clearly, from the above reviewed studies, it is seen that posture and muscle tension are important variables in the measurement of seat-to-head vibration. However, no

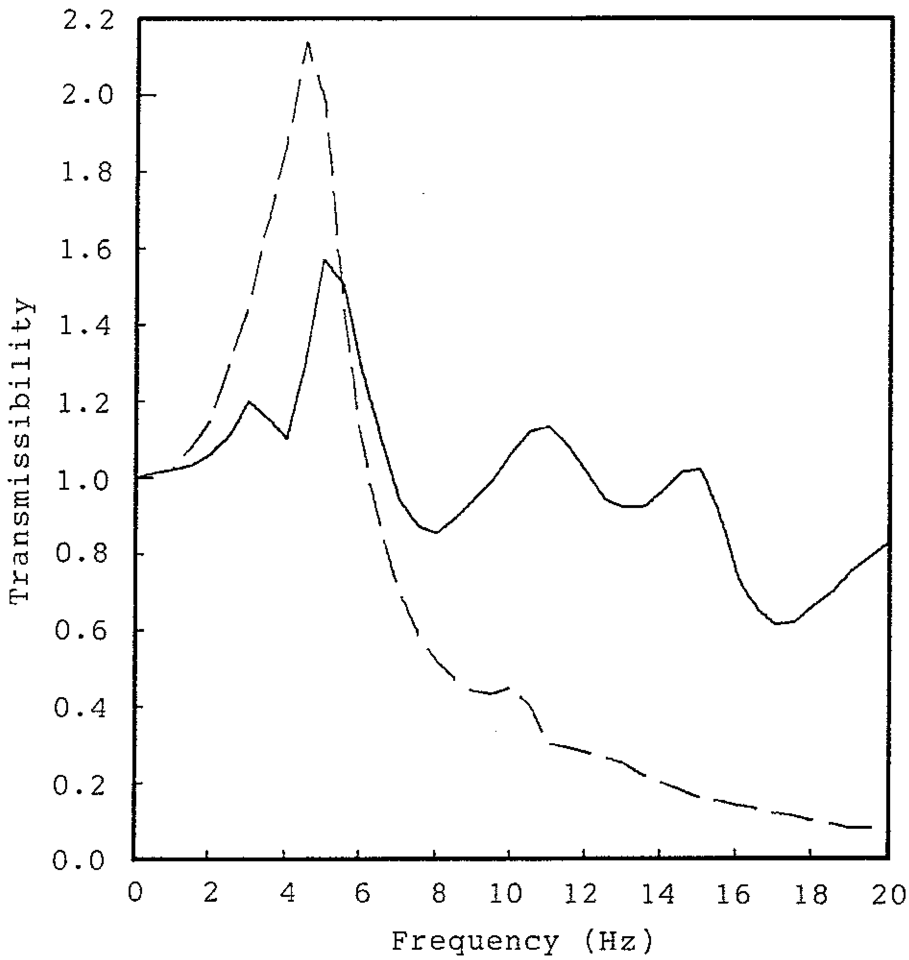


Figure 2.7 The transmission of vibration from the seat to the head for one subject sitting in relaxed (- - - -) and erect (———) postures (Coermann, 1962).

consistent study to look at the range of postures and the effect of these on head motion had been reported. A single-subject experiment was conducted by Griffin et al. (1979) to establish the effect of posture on the transmission of seat vibration to the head. Eight different postures were requested ranging from 'slouched' to 'erect' and the effect of these at different frequencies ranging from 1 Hz to 100 Hz was determined. Transmissibilities up to 50 Hz are presented in a three-dimensional form in Figure 2.8 to show the variation with posture. This shows that generally, there was substantially more motion at the head for the subject sitting in an erect posture for frequencies greater than 3 Hz. Also, two clear body resonance peaks occurred when the subject sat in an erect posture; one near 6 Hz and the other over the 15 Hz to 25 Hz frequency region. In a separate study, the effect of muscle tension was also determined on the same subject: the subject sat in two conditions, normal and tensed. The tensed condition involved increased muscle tension of the arms, neck, shoulders, abdomen and the legs. The results showed a higher transmissibility for the tensed condition, however, the effect was smaller than that of changes in posture.

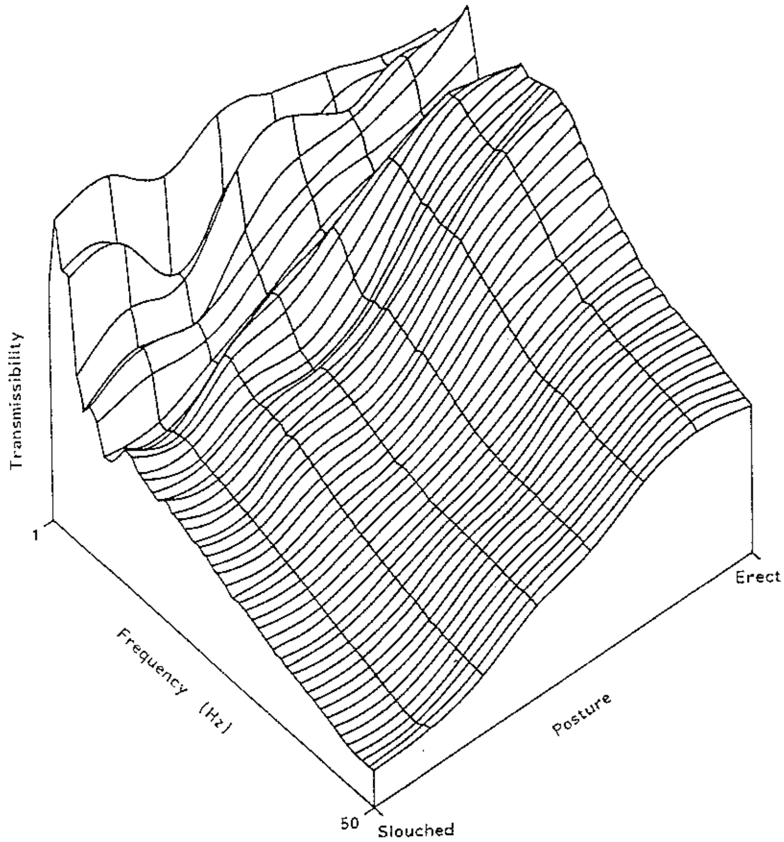


Figure 2.8 The seat-to-head transmissibility from 1 to 50 Hz of a single subject sitting in 8 postures from slouched to erect (Griffin et al., 1979).

In a slightly earlier study than the one mentioned above, Griffin (1975) undertook an experiment to look at two extreme postures and the effect of these on head motion. Twelve male subjects took part in the tests and were instructed to sit in two postures: these being to ensure firstly, maximum vibration at the head ('most severe posture') and then minimum vibration at the head ('least severe posture'). The subjects were told that they may have to alter their back posture, neck orientation and the manner in which they sat in order to achieve the required head vibration. Transmissibilities were obtained at discrete sinusoidal frequencies ranging from 7 Hz to 75 Hz. Head motion was monitored using a bite-bar which the subjects held between their teeth. It was shown that large differences occurred in transmissibility between individuals and that a consistent difference occurred between the 'most severe posture' and the 'least severe posture'. At some frequencies (35 Hz to 45 Hz), ratios of mean transmissibility for the twelve subjects between the 'most severe posture' and the 'least severe posture' were greater than 6, i.e. six times as much head motion occurred for the 'most severe posture' than the 'least severe posture' over the stated frequency range. This clearly shows the range of transmissibilities that could be obtained by differing postures.

The effect of three postures on the transmission of seat vibration to the head was reported by Rowlands (1977), the postures were 'slumped', 'normal' and 'erect' - all with the back in contact with the backrest. Six subjects took part in the experiment and each subject was allowed to make their own interpretation of the postures although the experimenter gave instructions on the positions of the arms, back on backrest, head position, etc. Vibration characteristics included sine swept motions covering the frequency range 1 Hz to 25 Hz and three vibration magnitudes: ±2.0 ms^{-2}, ±2.8 ms^{-2} and ±4.0 ms^{-2} (1.41 ms^{-2}, 1.98 ms^{-2} and 2.83 ms^{-2} r.m.s.). (Three magnitudes were used so as to determine the linearity characteristics of vibration transmission through the human body.) Mean transmissibility results for the subjects showed that only small differences occurred with the subjects sitting in normal and erect postures for the three vibration magnitudes. The slumped posture resulted in higher levels of head motion for frequencies below 7 Hz and lower transmissibilities for frequencies greater than 7 Hz compared with the other two postures. (It was also found that a posture in which no contact was made between the back and the backrest resulted in significantly lower levels of head motion for frequencies above 10 Hz.)

Approximately similar postures to the above were investigated in a study by Griffin et al. (1979); the postures were 'normal upright', 'relaxed' and 'stiff'. Thirty male subjects (12 boys and 18 men) took part in a vertical seat vibration study. Transmissibilities between seat vibration and head motion were calculated as ratio of r.m.s. accelerations at 21 third-octave frequencies ranging from 1 Hz to 100 Hz. It was found that the 'stiff' posture showed lower transmissibility values than the other two postures below 6 Hz and higher values above 6 Hz. There were only small differences in seat-to-head transmissibility between the 'relaxed' and the 'normal upright' postures.

The above two studies have looked at the effect of three similar postures on the transmission of vibration from the seat to the head and found differing results. However, it is difficult to compare the results directly since, though the postures were similar, they were not identical and small deviations in posture have been shown to have a large effect on seat-to-head transmissibility. There were other differences such as seating conditions: Rowlands (1977) used a backrest whereas no backrest was present in the study reported by Griffin et al. (1979). This has been shown to greatly affect head motion (see Section 2.6.2.2).

It has been demonstrated by some of the above studies that a tensed posture results in a slight increase in the resonance frequency when compared with a normal posture (Guignard, 1959; Guignard and Irving, 1959, 1960; Coermann, 1962). This is associated with a combination of stiffening of the muscles and change in posture which increases the resonance frequency. Mertens (1978) reported an increase in resonance frequency in transmissibility for subjects exposed to vertical seat vibration while under increased gravity. (This was tested with subjects in a centrifuge.) Main resonance frequency of the human body increases when exposed to increased static acceleration - this has the same effect as tensed muscles.

There are other studies concerned with the transmission of seat vibration to the heads of seated subjects but the factors under investigation have been either irrelevant or the effect of a less reported variable has been determined. One such study is by Wilder et al. (1982) in which a large number of subjects were used and the investigation included the effect of seven different postures (neutral relaxed, 5° forward flexion, 5° extension, 5° left lateral bend, 5° right lateral bend, maximal left axial rotation, maximal right axial rotation) plus neutral position with a Valsalva manoeuvre. This large number of variables makes comparison between specific variables difficult. The variable that would be of interest in this context is the Valsalva manoeuvre (maintaining an increased air pressure in the lungs with the nasal and mouth passages blocked). The effect of this when compared with the neutral posture was that, at the first resonance frequency (approximately 5 Hz), greater levels of head motion were measured, resonance increased to a slightly higher frequency and, the human body appeared to become stiffer. The percentage changes in these factors were different for the two sexes.

One of the most recent studies to determine the effect of body posture on the transmission for vertical seat vibration to the head is by Messenger and Griffin (1989). Two experiments involving the effect of body posture were reported: the first was to investigate the effect of pelvic angle and the second to determine effect of upper back inclination. In the first investigation, eight male subjects were required to sit on a rigid flat seat with no form of backrest or harness. Many postural variables were controlled in order to reduce the effect of other factors on the results: variables controlled included head angles in roll, pitch and yaw axes, position of the legs, angle of knee joint and position of the arms. The posture of the back was controlled using an anthropometric stand - this ensured small deviation in posture between vibration exposures. The subjects sat with three different pelvic angles, these were 105°, 95° and 85°. A fourth vibration exposure was conducted with the subjects seated in a 'normal upright' posture - interpretation of this posture was left to the subjects judgement. Vibration stimulus was random in nature covering a frequency range of 0.5 Hz to 40 Hz and the magnitude was 1.0 ms^{-2} r.m.s. Head motion was measured in the three translational axes and in the pitch axis using a bite-bar gripped between the subject's teeth. Results showed that changing hip angle had only a small effect on head motion in the lateral and pitch axes. Significant effects occurred in x-axis and z-axis head motion. A forward tilt (anterior) of the pelvic region increased transmissibility in the fore-and-aft axis for frequencies above 3 Hz; the increase in transmissibility was for frequencies above 6 Hz for motion in the vertical axis. Figure 2.9 shows these changes for mean transmissibility data for eight subjects. There was a change in posture associated with change in pelvic angle which could also have contributed to the above differences in transmissibility.

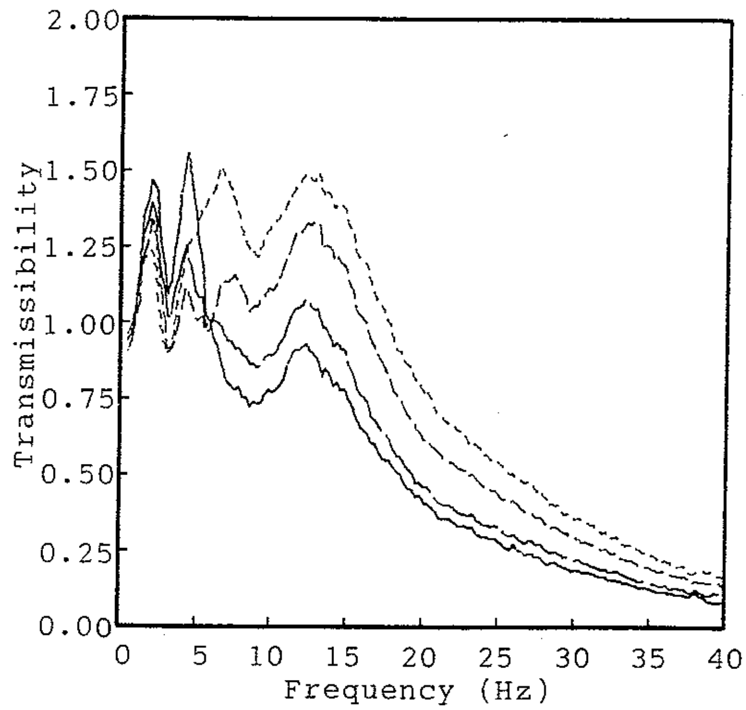


Figure 2.9 Seat-to-head transmissibility for z_{head} motion with four sitting postures (mean of 8 subjects). (A = pelvic angle of 105° (————); B = 'normal upright' posture (—— —— ——); C = pelvic angle of 95° (— — —); D = pelvic angle of 85° (- - - -)) (Messenger and Griffin, 1989).

The second experiment by Messenger and Griffin (1989) was to determine the effect of upper back inclination on head motion. Twelve male subjects were exposed to vertical random vibration of magnitude 1.0 ms^{-2} r.m.s. and covering a frequency range of 0.5 Hz to 35 Hz. The subjects sat on a rigid flat seat with no backrest contact. Accelerations at the head in the mid-sagittal plane were monitored using a bite-bar. Five postures of the back were investigated with different angles of the back measured at T5; angles at T5 were 20°, 30°, 40°, 50° and 60°, these were measured using accelerometers as inclinometers. Results from this investigation showed that increasing upper back angle increased head motion in the fore-and-aft and vertical directions at the mouth for frequencies below 5 Hz and decreased motion above 5 Hz. It was concluded that these changes in transmissibility could not only be attributed to variation in upper back angle but also to postural changes in the lower back and in the pelvic region.

Discussion

All the above studies have shown that posture and muscle tension are important variables when investigating the transmission of vibration through the body to the head. Postures which look identical to the experimenter can give different results and vice-versa (Griffin et al., 1979). Overall, it has been established that erect and tensed postures both result in an increase in resonance frequency. This increase in frequency might indicate an increase in whole-body stiffness. Also, greater levels of head motion occur when seated in an erect posture or with tensed muscles, although this depends on frequency.

2.6.1.3 Intra-subject variability

When determining the effect of any variable on the transmission of vibration through the human body to the head, it would be ideal if all the other parameters could be kept constant and only the variable under investigation altered. When attempting such an investigation, it would also be helpful if an estimate was known of the variability that should be expected over repeat measures. There are many factors which would have to be kept constant in the determination of transmissibility, these include both intrinsic variables (those peculiar to the subject) and extrinsic variables (those inherent in the experimental set-up). The extrinsic variables can be maintained with ease between repeat measures. The difficulty arises in keeping intrinsic variables the same (these include posture, muscle tension, head position), although attempts can be made.

Small differences have been reported elsewhere (Sandover, 1978) in repeatability measures and effectively, the only variable was time. If only small differences are found in the response, then this is a good indication if the effect of other variables is required. Rowlands (1977) conducted repeatability measures (2 runs only) for many subjects and conditions while maintaining constant all extrinsic variables. He concluded that since the variability between runs was small, the effect of other factors could be evaluated.

One factor that can be important and can affect repeatability results, this being the duration between successive runs and whether the subject alights from the seat between the runs. Less variability would be expected for runs conducted immediately one after the other than those in which a long duration separated the runs. This may be the case due to the subject not being able to recall the precise seating position e.g. posture. Griffin et al. (1979) reported on the results of an intra-subject variability study in which a subject (male, 68 kg) was exposed to the same vibration condition on 20 occasions and this being over a period of two weeks. Transmissibilities were calculated between seat and head vibration at 21 different frequencies ranging from 1 Hz to 100 Hz using sinusoidal vibration. Median, 10^{th} and 90^{th} percentile of transmissibility of seat-to-head vibration is shown in Figure 2.10. This demonstrates that response in head motion can vary by more than 35% at some frequencies (e.g. 5 Hz). It is interesting to note that the individual peak and trough data are not lost but retained even after averaging. Distinct resonance peaks are seen for this subject at 2 Hz, 5 Hz and 12.5 Hz.

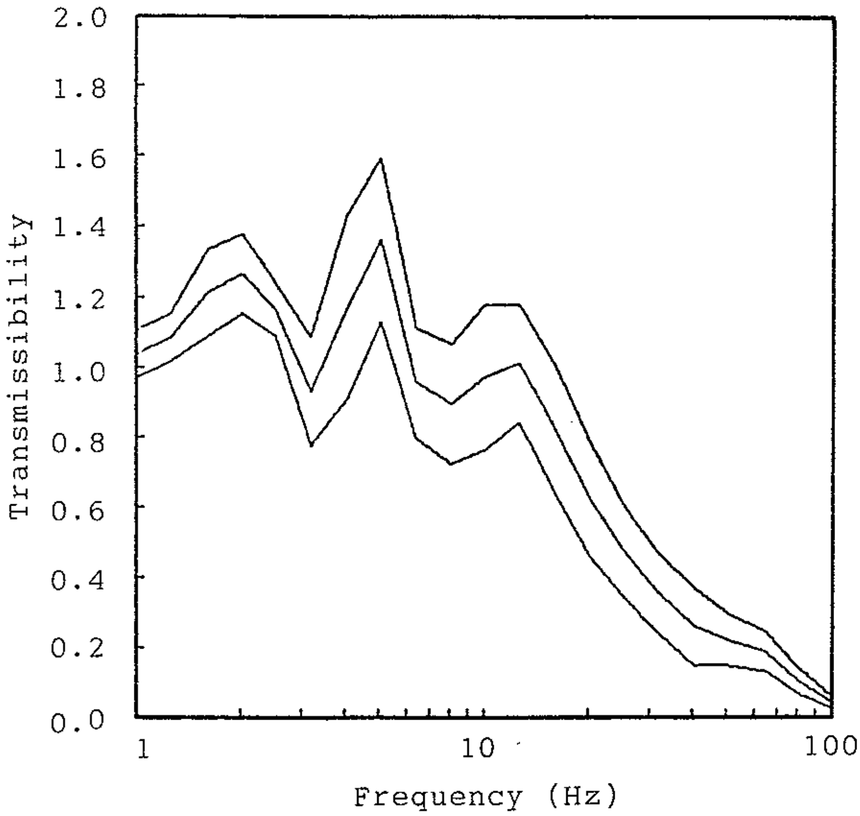


Figure 2.10 Intra-subject variability in seat-to-head transmissibility of a single subject during 20 repeat exposures of vertical seat vibration. Shown are median, 10th and 90th percentiles of transmissibility (Griffin et al., 1979).

Intra-subject variability estimates would be essential when determining the effect of other variables. It has been shown that small unnoticeable changes in posture can alter the transmission of motion to the head. Repeatability would obviously have to be smaller than the effect of the variable under investigation for a true genuine trend to emerge. It is unknown as to whether repeatability depends upon the seating condition e.g. the difference between a set-up in which a backrest is used and in which no backrest is present. Attempts will be made to provide answers to this question in the following sections.

2.6.1.4 Inter-subject variability

Variability in transmission of seat vibration to the heads of seated subjects has been demonstrated by many investigators though quantitative data on individual variability has usually been inadequate. Value judgements such as 'large variability' have been made without numerical or graphical data which poses problems when comparing data from different studies. In determining the variation in seat-to-head transmissibility of vibration for different subjects, it is essential that the experimental set-up is maintained constant. Subject instructions would be needed to ensure they sat in the required posture, maintained the requested muscle tension, etc. Three studies are reviewed below all reporting on inter-subject variability.

Rowlands (1977) conducted an experiment on inter-subject variability of transmissibility with only six subjects. The subjects sat on a hard flat seat with no harness; input vibration characteristics were swept sine motion, frequency range of 0.5 Hz to 40 Hz and, three vibration magnitudes: $\pm 4.0\ ms^{-2}$, $\pm 2.8\ ms^{-2}$, and $\pm 2.0\ ms^{-2}$ ($2.83\ ms^{-2}$, $1.98\ ms^{-2}$ and $1.41\ ms^{-2}$ r.m.s.). Transmissibilities were calculated between seat vibration and acceleration measured at the top of the head. Numerical data on the variation in transmissibility peaks and troughs and the corresponding frequencies were determined. Mean resonance values were calculated for the six subjects and are shown in Table 2.3. The results show that, generally, the variability in transmissibility and frequency was ±16% for the first and second resonance peaks for the two postures investigated: normal (back-on) and back-off. Higher levels of variability were found for transmissibility magnitude for the second resonance peak with the subjects seated in a back-off posture - no explanation has been put forward for this.

Table 2.3 Mean transmissibility amplitudes, frequencies and deviations for inter-subject variability (Rowlands, 1977).

Peak	Sitting Condition	Mean Amplitude/Frequency	% Maximum Deviation Amplitude/Frequency
First	Normal (Back-on)	1.25 @ 3.59 Hz	-14 → 15/-12 → 14
	Back-off	1.40 @ 4.07 Hz	-9 → 16/-12 → 11
Second	Normal (Back-on)	1.87 @ 12.8 Hz	-16 → 16/-6 → 5
	Back-off	0.86 @ 12.2 Hz	-36 → 37/-7 → 12

Bennett et al. (1978) reported on measurements of vertical head motion during exposure to whole-body vertical vibration. Head motion was measured using accelerometers attached to a close fitting safety helmet. Twelve male subjects participated in the study involving random vibration of the seat with three magnitudes of vibration: 0.21g, 0.28g and 0.35g r.m.s. (2.06 ms^{-2}, 2.75 ms^{-2} and 3.43 ms^{-2} r.m.s.). Transfer functions were calculated between both seat and head motion, and between vibrator plate and head motion. This was to evaluate the effect of the seat on the transmission of vibration to the human body. Unfortunately, data above about 10 Hz were unreliable as relatively high levels of noise occurred. However, some good data were obtained and showed a "very wide range" in transmissibility magnitudes for the variability between subjects. Though figures similar to Figure 2.11 were presented of mean (and range) transmissibility between seat and head motion (and between vibrator plate and head motion), no numerical values stating, for example, the percentage differences are included which could have been useful in making comparisons with data from other studies.

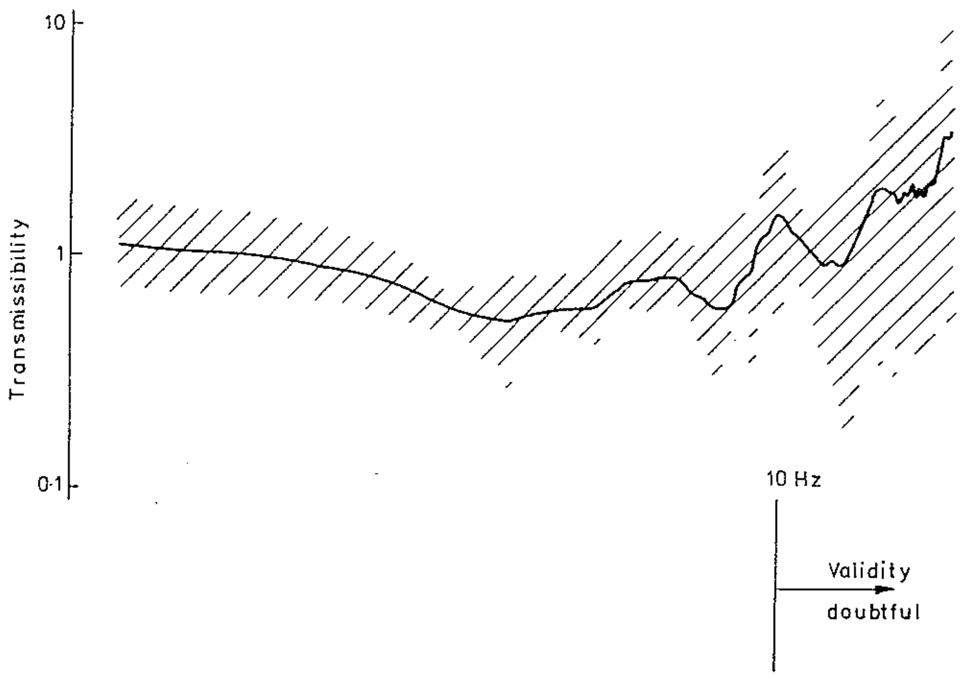


Figure 2.11 Mean and range of seat-to-head transmissibility for 12 male subjects during vertical seat vibration at 0.28g r.m.s. (2.75 ms^{-2} r.m.s.) (Bennett et al., 1978).

An investigation was conducted by Griffin and Whitham (1978) to determine inter-subject variability in seat-to-head transmissibility during whole-body vertical vibration. This was a major study involving a large group of subjects (56 men, 28 women and 28 children). All were required to sit in an upright comfortable posture; head motion was measured by an accelerometer attached to a bite-bar held between the subject's teeth. Vibration at the seat consisted of two individual frequencies, 4 Hz and 16 Hz, each with a vibration magnitude of 1.0 ms^{-2} r.m.s. and a duration of 20 seconds. Results from the experiment are shown in Table 2.4 as mean and standard deviation of transmissibilities for the three groups of subjects and the two vibration frequencies. This shows that there were differences in mean transmissibility responses between the groups but these were small. Lower levels of transmissibility occurred for 16 Hz than 4 Hz and standard deviation was also lower. Mean transmissibilities were about 1.40 at 4 Hz and 0.62 at 16 Hz.

Table 2.4 Means and standard deviations of seat-to-head transmissibilities at 4 Hz and 16 Hz (Griffin and Whitham, 1978).

Group	Transmissibility mean(variance)	
	4 Hz	16 Hz
Men	1.35 (0.11)	0.58 (0.04)
Women	1.40 (0.11)	0.74 (0.06)
Children	1.42 (0.10)	0.53 (0.03)
Average	1.38 (0.11)	0.61 (0.04)

The above three studies have demonstrated the differences that should be expected in transmissibility between individuals. Some explanations have been proposed that may account for the difference but these would only partially explain the variation. These include physical characteristics peculiar to the subjects (such as weight, age, height, hip circumference (see Section 2.6.1.5)) and those peculiar to the sitting condition (e.g. posture, head angle, muscle tension). Although attempts can be made to ensure consistent sitting conditions, it has been shown that these can greatly affect the transmission of seat vibration to the head (see Sections 2.6.1.1 and 2.6.1.2).

The third paper reviewed (Griffin and Whitham, 1978) presents data from a wide range of subjects although these are limited to only two frequencies. (Also included are subjective responses of participants to these two vibration frequencies.) When presenting data of this nature, it is essential to include a measure of spread in responses which would be 'lost' if only averages are reported. An indication of variation could include variance, standard deviation, percentiles, range, etc.

2.6.1.5 Physical characteristics of subjects

It would be beneficial in understanding the nature of variation in head motion between individuals in response to seat vibration to determine any correlations that exist between subject characteristics and head motion (e.g. height, age, weight, sex). It has been shown that variability in the transmission of vibration from the seat to the heads of seated subjects can vary by 6:1 at some frequencies (see Section 2.6.1.4). It is clear that as 'no two people are the same', a wide spread of subject characteristics is found. The next step would be to calculate correlations between the various factors, e.g. transmissibility versus weight, transmissibility versus height. Such data would be valuable in the development of biodynamic models of the human body.

In such a study, it is essential to include a large number of subjects (greater that approximately 10); the larger the number of subjects the more reliable the final conclusions. An example of this is a study by Woods (1967) in which only three subjects took part. Measurements were made of motion at the shoulder while the subjects were exposed to whole-body vertical vibration. This is too small a number for valid results to emerge. (No significant correlations were found between seat-to-shoulder transmissibility and subject characteristics including build, weight and height.) It has been shown elsewhere (Griffin et al., 1979) that after using a large number of subjects (18 men, 18 women) and various subject characteristics (height, weight, age, hip size, thigh size, leg size), only one factor might show significant correlations with transmissibility. This would be an important result in that the factor showing high significance (which in this study was subject weight) may require further investigation and the other factors may be excluded.

Following are studies reviewed on the possible correlations between subject characteristics and head motion during whole-body vertical seat vibration.

Age

Rowlands (1977) conducted a study in which shoulder motion was measured for six subjects exposed to whole-body vibration; their mean age was 32 years and a range of 19 to 55 years. Two postures of the body were investigated in the experiment; a 'back-on' posture in which the subjects' backs were in contact with the seat backrest and, a 'back-off' posture in which no backrest was used. The results showed a significant positive correlation between age and the resonance frequency of shoulder motion (around 4 Hz) in the 'back-on' posture ($p<0.01$) and, age and transmissibility when subjects were seated in the 'back-off' posture ($p<0.05$).

For statistically significant differences in data, a large number of subjects would be required with possibly, a greater spread of ages. (The spread of age amongst subjects might have been sufficient for statistical analyses in the above study.) Griffin et al. (1979) report of an experiment conducted with 18 men and 12 boys (mean age 7 years, range 9 to 16 years). The subjects sat in a 'normal upright posture' and were exposed to 21 third-octave sinusoidal frequencies ranging from 1 Hz to 100 Hz. Transmissibilities were calculated between seat vibration and head motion at each of the 21 frequencies, these are shown in Figure 2.12 for the men and the boys. It is seen that the mean transmissibility for the boys was generally lower than that for the men over most of the frequencies, especially over the 10 Hz to 100 Hz frequency range. Lower transmissibilities have been reported elsewhere for children at 16 Hz though no significant differences were found (Griffin and Whitham, 1978).

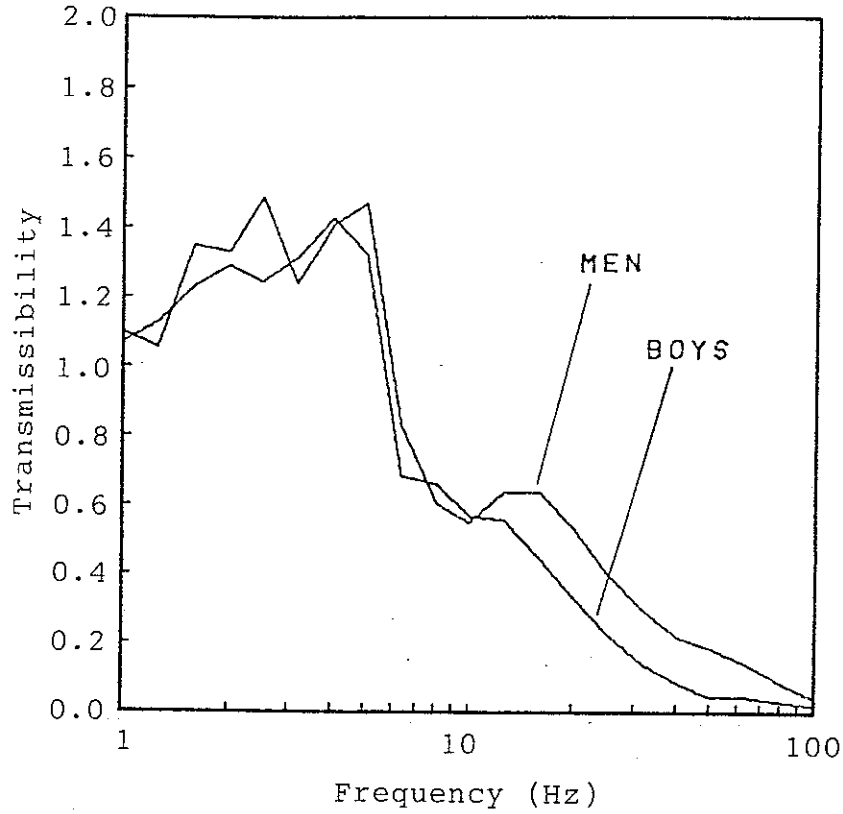


Figure 2.12 Mean seat-to-head transmissibilities of 18 men and 12 boys (Griffin et al., 1979).

Weight

Ten male subjects comprising of two different builds (5 small: mean weight 140.2 lb (63.7 kg) and 5 large: mean weight 160.2 lb (72.7 kg)) took part in an experiment carried out by Guignard and Irving (1960) to investigate the nature of vibration transmission through the body. Vibration input was of a sinusoidal nature covering a frequency range of 2 Hz to 13.5 Hz and a magnitude of ±0.25g (1.73 ms^{-2} r.m.s.). Transmissibilities were calculated between seat and shoulder vibration. The results showed that at resonance (approximately 4.8 Hz), the 'smaller' subjects displayed a mean transmissibility of 2.68 and for the larger subjects it was 2.16. This tended to show that heavier subjects demonstrated significantly more damping than the lighter subjects ($p<0.01$).

Wisner et al. (1964) reported of an experiment with 12 subjects exposed to vibration over the 1 Hz to 20 Hz frequency range and ±1 mm to ±7 mm displacement range. It was found that subject weight had no effect on transmissibility between seat and head motion.

Griffin (1972) made vibration measurements of head and seat motion of eight pilots in a helicopter during various flight manoeuvres. The weights of the pilots ranged from 79.0 kg to 90.7 kg with a mean of 80.7 kg. Vibration at the seat consisted mostly of the main rotor frequency of 7 Hz together with its harmonics (14 Hz, 28 Hz, 56 Hz). It was found that vertical vibration at the head correlated negatively ($p<0.02$) with the weight of the pilots; this was the case at the main rotor frequency. Negative correlations were also observed by Rowlands (1977) between head vibration and weights of the six subjects during a laboratory based vertical seat vibration experiment ($p<0.05$).

In a major study conducted by Griffin and Whitham (1978) involving 112 subjects (56 men, 28 women, 28 children), some interesting correlations emerged between head motion and subject characteristics. Weights of the subjects ranged from 45 kg to 95 kg for men, 45 kg to 95 kg for women and 26 kg to 64 kg for children. Correlations were calculated between age, weight, height and hip size and, head motion at 4 Hz and 16 Hz. No significant correlations were found at 4 Hz for any subject group. At 16 Hz, again no clear trends were observed for the children between head motion and subject characteristics, however, for men at 16 Hz, the results showed significant negative correlations ($p<0.05$) between head motion and weight and, head motion and hip size. The data for women showed negative correlations ($p<0.05$) between head motion and height and, head motion and weight. Further analysis of the data involving partial correlations showed that for both men and women, it was subject weight that was significantly correlated with head motion at 16 Hz ($p<0.05$).

In another study, Griffin et al. (1979) set about determining correlations between seat-to-head transmissibility and subject characteristics. Thirty-six adult subjects (18 men and 18 women) took part in the experiments and the various subject characteristics measured were height, weight, age, hip size, thigh size and leg size. From the mass of data collected, it was found that subject weight was the only factor that showed any significant correlations with head motion. Negative correlations between subject weight and transmissibility were found for men at 1.25 Hz, 1.6 Hz and 3.15 Hz and were significant at the 5% level while for women subjects, negative correlations were found at 2.5 Hz.

The above studies have measured vibration at the shoulders and heads of subjects and have been able to correlate subject weight with head motion. Vertical vibration at the thorax of subjects exposed to vertical seat vibration was measured for 15 male subjects (weight range 49 kg to 74 kg) to determine the nature of transmission of vibration by Donati and Bonthoux (1983). Frequency range of Gaussian random vibration was 1 Hz to 10 Hz and vibration magnitude was 1.6 ms^{-2} r.m.s. Subject weight was found to be positively correlated with transmissibility at 4 Hz ($p<0.05$), while at 8 Hz negative correlations existed at the same significance level.

Height

A few researchers have tried to correlate subject stature with the magnitude of head motion for subjects exposed to vertical seat vibration. Griffin (1972) was able to correlate vertical head motion transmitted to the heads of helicopter pilots during various flight conditions to the heights of the pilots (ranging from 1.68 m to 1.92 m). The analyses were conducted for two different sets of measurements. The results indicated that vibration at the head correlated significantly with subject height at the main rotor frequency of 7 Hz ($p<0.05$ for the first experiment; $p<0.02$ for the second experiment). There is a conflict between the data from the two experiments as the parameters for the first experiment (stature and vertical head vibration) were negatively correlated and whereas for the second experiment, a positive correlation was calculated. No explanation was put forward.

Two studies published at approximately the same time both reported no correlations between vertical head motion and subject height (Rowlands, 1977; Griffin et al., 1979). Six subjects took part in the former investigation and 36 in the latter extensive study.

One other researcher who found correlations between subject height and vibration transmitted to the subject's body was Donati and Bonthoux (1983) who measured vertical motion on the thorax. Fifteen male subjects took part in the experiment, mean height of subjects was 1.75 m (minimum height 1.65 m, maximum height 1.84 m). There was evidence of significant positive correlations ($p<0.05$) between height and seat-to-thorax transmissibility at frequencies of 3 Hz and 4 Hz.

Gender

Only three studies have been found in the literature reporting on the quantitative differences in the transmission of seat vibration to the head between male and female subjects; although other studies have been found to mention the matter in passing. Transmission of vertical vibration from the seat to the heads of seated subjects was measured for 18 male and 18 female participants in an experiment reported by Griffin et al. (1979). Transmissibilities were calculated between seat and head vibration over the frequency range 1 Hz to 100 Hz and compared for the two sexes, mean seat-to-head transmissibilities are displayed in Figure 2.13. This shows that men had a higher transmissibility than women over the 1.25 Hz to 4 Hz frequency range while women had the highest transmissibility over the 4 Hz to 100 Hz frequency range. The differences in transmissibility were significant at the 5% level for some frequencies (namely 2.4 Hz, 12.5 Hz, 32 Hz, 40 Hz, 50 Hz and 64 Hz) and, were significant at the 10% level for most frequencies above 8 Hz.

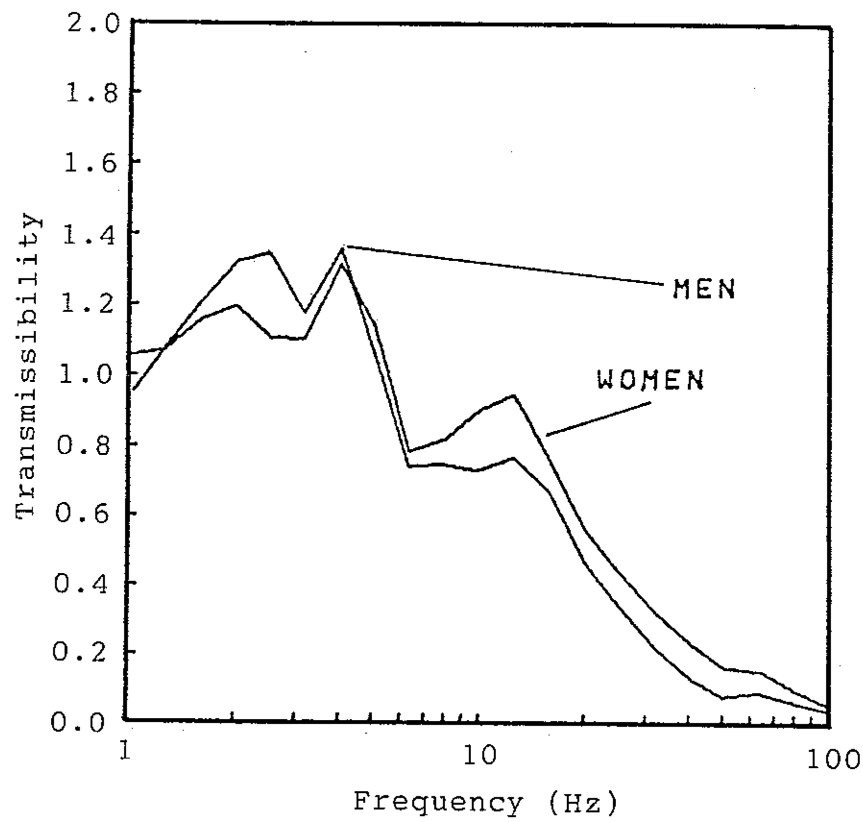


Figure 2.13 Mean seat-to-head transmissibilities of 18 men and 18 women (Griffin et al., 1979).

A study involving a large number of subjects was conducted by Griffin and Whitham (1978) to investigate individual variability to the transmission of seat vibration to the head. Gender was one of the factors to be investigated; 56 men and 28 women (and 28 children) took part in the experiment. The subjects were required to sit in a comfortable upright posture and were exposed to two 20 second periods of sinusoidal vibration at 4 Hz and 16 Hz. Vibration magnitude was 1.0 ms^{-2} r.m.s. Transmissibilities were calculated between vertical seat and vertical head motion for all subjects exposed to vibration at these two frequencies. Mean transmissibilities for the subjects were shown in Table 2.4 (see Section 2.6.1.4, inter-subject variability) and indicated that for adult subjects, lower transmissibilities occurred for males than for females at both frequencies of vibration.

Wilder et al. (1982) report of a large scale experiment with many subjects (30 male, 15 female) in which head motion was measured during exposure to vertical seat vibration. It was found that female subjects demonstrated more scatter in the transmissibility data than male subjects. It is hypothesised that the possible cause for scatter may be due to the female breast mass, although such a relationship is not entirely supported by the available data. Unfortunately, Griffin et al. (1979) presented only mean transmissibility curves with no indication of inter-subject variability for male and female subjects. In the above study (Griffin and Whitham, 1978) a greater spread in transmissibility data was seen for female subjects (variance of 0.06) than for male subjects (variance of 0.04) at 16 Hz; however, the transmissibility values were also greater for female subjects (0.74) than for male subjects (0.58). Wilder's hypothesis for the possible causes of scatter in transmissibility between the two sexes cannot be tested with data presented by Griffin and Whitham (1978).

There was one significant difference that Wilder et al. (1982) observed in the transmissibility data for male and female subjects, that was with the subjects seated in a Valsalva manoeuvre. (This was achieved by maintaining a constant pressure within the lungs - no air is allowed to pass through the mouth or the nasal passage.) Both male and female subjects were required to sit with this posture during exposure to vertical seat vibration. Transmissibilities for both sexes were compared between the neutral posture and the Valsalva manoeuvre posture: the results showed no differences for male subjects, but for female subjects, there were significant increases ($p<0.05$) in frequency and magnitude of transmissibility for the subjects seated with the Valsalva manoeuvre. No explanations have been proposed for these differences.

Others

There have been other less reported correlations between head motion and body characteristics; one such parameter is hip circumference. Griffin (1972) found a significant negative correlation between head motion and hip circumference ($p<0.005$) at 7 Hz for vibration exposure in a helicopter. Griffin and Whitham (1978) also found significant correlations ($p<0.05$) between hip size and head motion (for men only) and this was at 16 Hz. However, partial correlations revealed that hip size was significantly correlated with subject weight ($p<0.01$) and that weight was the main parameter that correlated with head motion. In the former study, hip circumference was correlated with weight ($p<0.005$) and maybe the effect of hip circumference would have partialed out. No significant correlations were found between seat-to-head transmissibility and hip size in a study conducted by Griffin et al. (1979) with 18 men and 18 women.

All the above subject characteristics have been main body parameters. Griffin (1972), in his study of transmissibility in pilots exposed to helicopter vibration, attempted to correlate head height with motion at the head. Head height (chin to bregma) was shown to be significantly positively correlated with vertical head motion ($p<0.05$) and transmissibility ($p<0.02$) at four times the main rotor frequency of 28 Hz.

Discussion

Correlations between four main body parameters and head motion have been presented above and these have shown varying degrees of significance. Subject age has shown some significant correlation with shoulder and head motion but more data would be required for firm conclusions to be made. Subject weight has shown the most significant correlation with motion at the thorax, shoulder and the head. In Table 2.5 is shown in summary form the results from the studies concerned with subject weight and measured body motion. The most interesting result of these correlations between head motion and subject weight is that the data indicate a negative correlation implying that head motion decreases with subject weight. So, heavier people demonstrate more damping than lighter people and thus attenuate greater magnitudes of vibration. Data of head motion show a significance level of at least 5% and cover a range of frequencies (1.25 Hz, 1.6 Hz, 2.5 Hz, 3.15 Hz, 7 Hz and 16 Hz).

Table 2.5 Correlations obtained by various investigators between subject weight and seat vibration transmissibility to different parts of the body.

Investigator	Shoulder	Thorax	Head
Guignard and Irving (1960)	+($p<0.01$)	--	--
Griffin (1972)	--	--	-($p<0.02$) 7 Hz
Rowlands (1977)	--	--	-($p<0.05$)
Griffin and Whitham (1978)	--	--	-($p<0.05$) 16 Hz
Griffin et al. (1979)	--	--	-($p<0.05$) 1.25 Hz, 1.6 Hz 3.15 Hz for men
	--	--	-($p<0.05$) 2.5 Hz for women
Donati and Bonthoux (1983)	--	+($p<0.05$) 4 Hz	--
	--	-($p<0.05$) 8 Hz	--

Subject stature showed some significant correlations with head motion but generally, more data would be required for conclusive evidence. Gender was found to have some effect on head motion; greater levels of head motion occurred in women for most of the high frequencies. No plausible explanations have been found in the literature on the causes for the differences.

Surprisingly, there has been only one study in which attempts have been made to correlate head motion with dimensions of the head (Griffin, 1972); this study found that head height correlated significantly with seat-to-head transmissibility at 28 Hz ($p<0.02$). It is possible that other dimensions of the head might show similar significance levels (since most dimensions of the head will be correlated with each other) and this would prove valuable in modelling the response of the human body to vibration.

2.6.2 Extrinsic variables

This section covers the effect of those variables which are easily altered and are inherent in the equipment or the hardware being used.

2.6.2.1 Effect of vibration magnitude

The effect of vibration magnitude on the transmission of seat vibration to the head has been studied by many researchers in an attempt to explain whether the human body behaves in a linear or a non-linear manner; or indeed, whether vibration magnitude has an effect at all. Seven different studies are reviewed in which the effect of this variable on head motion was investigated.

Bennett et al. (1978) conducted an experiment into the behaviour of the human body to vibration, some of the parameters investigated included physiological measures (oxygen intake, heart rate, etc.), performance measures and transmissibility measurements. Twelve male subjects took part in the study to determine the effect of different magnitudes of vibration on head motion. The waveform was of a narrow band nature and had shocks superimposed to simulate a military vehicle traversing rough ground. The magnitudes were 0.21g, 0.28g and 0.35g r.m.s. (2.06 ms^{-2}, 2.75 ms^{-2} and 3.43 ms^{-2} r.m.s.). The results showed that vibration magnitude had only a small effect. This could well be due to the small range of vibration magnitudes used.

A study was conducted by Sandover (1978) into head motion of a seated person when exposed to vertical vibration. Broad band random vibration of 2 ms^{-2} r.m.s. magnitude was used: subjects sat in an erect posture in an 'office chair'. Vertical head motion was measured using an accelerometer attached to a bite-bar. The results showed that non-linear effects were small and no apparent trends were seen in head motion that could be attributed to changes in vibration magnitude.

Griffin et al. (1979) also investigated the effect of seat vibration magnitude on motion transmitted to the head by using 100 second duration sine swept waveforms varying in seven equal magnitude increments from 0.4 ms^{-2} to 2.8 ms^{-2} r.m.s. Some trends in the transmission of seat vibration to the head were seen at lower frequencies (below about 20 Hz). However, it was pointed out that the effect of vibration magnitude on motion at the head was smaller than the variation found within and between individuals!

Pradko et al. (1965) demonstrated that the transmissibility of the human body to vertical vibration was linear by exposing 31 subjects to vertical vibration at the seat and measuring the vertical motion at the head. Discrete sinusoidal vibration frequencies ranging from 3 Hz to 60 Hz were used over the 0.1g to 1.0g r.m.s. (0.98 ms^{-2} to 9.81 ms^{-2} r.m.s.) vibration magnitude. The results of that study shown in Figure 2.14 clearly illustrate the high degree of linearity in the average transmissibility of head motion for 10 subjects.

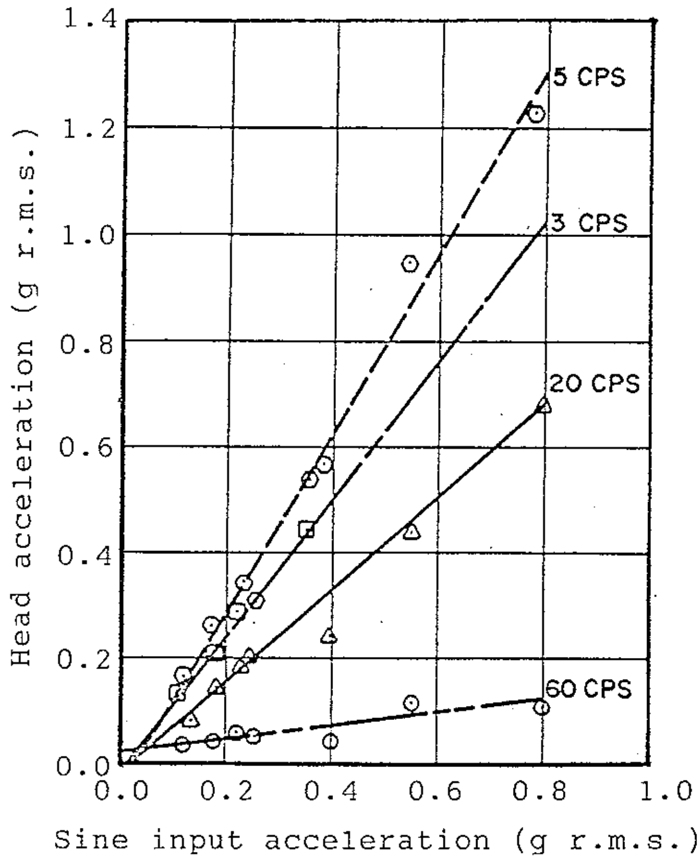


Figure 2.14 Comparison between head motion magnitude and seat vibration magnitude (Pradko et al., 1965).

Further analyses of the form of linear regression were conducted and are presented in Table 2.6 which again, shows that the body responded in a linear manner. A correlation coefficient of unity would indicate a perfect linear relationship between head motion magnitude and seat vibration magnitude. These tests were carried out for both sinusoidal and random motion of the seat and both sets showed similar results.

As did Pradko et al. (1965) try to correlate vibration magnitude with motion at the head for individual frequencies, Zagórski et al. (1976) report on an experiment involving 20 seated male subjects exposed to two differing vibration magnitudes of a sinusoidal vibration waveform: 2.30 ms^{-2} r.m.s. ("exposure limit") and 1.15 ms^{-2} r.m.s. ("fatigue limit"). Motion transmitted along the spine was monitored at four points using translational accelerometers

Table 2.6 Linear regression between head motion magnitude (y) and seat vibration magnitude (x) for different frequencies (Pradko et al., 1965).

Frequency (Hz)	Line equation	Standard Deviation	Correlation
3	y = -0.019 + 1.328 x	0.005	0.9990
4	y = -0.005 + 1.484 x	0.002	0.9998
5	y = -0.048 + 1.694 x	0.040	0.9930
10	y = +0.029 + 0.722 x	0.035	0.9767
20	y = -0.008 + 0.854 x	0.013	0.9977
30	y = -0.005 + 0.675 x	0.027	0.9835
40	y = +0.005 + 0.467 x	0.003	0.9908
50	y = +0.015 + 0.257 x	0.0003	0.9996
60	y = +0.024 + 0.126 x	0.018	0.8424

and head motion was measured at the vertex using an accelerometer fixed with an elastic tape. Data were analysed in the form of transmissibility between seat vibration and motion at the different points on the vertebral column. From the two vibration magnitudes, it was concluded that over the 2 Hz to 5 Hz frequency range, vibration transmitted and vibration magnitude showed an inverse relationship while over the 6 Hz to 12 Hz frequency range, the two parameters appeared to be directly proportional. This study tends to show that the degree of linearity depends on the input frequency.

Rowlands (1972) demonstrated that the response of the seated person to vertical vibration was linear, although the frequency and magnitude ranges were smaller than those used by Pradko et al. (1965). The conclusions were based on only visual inspection of the results. (Experiments to investigate the transmission of lateral vibration from the seat to the head showed that the body responded in a non-linear manner in this axis.)

Other researchers have also tried to measure and explain the non-linear nature in the transmission of vertical seat vibration to the head. Though some have been successful in obtaining firm conclusions on the non-linear behaviour of the body (e.g. Edwards and Lange, 1964), the analyses, experimentation, number of subjects, etc. have been 'sketchy'.

One of the few thorough studies conducted to prove the existence of non-linear behaviour of human response to vibration was by Griffin (1975). In the experimentation, vertical motion of the head was monitored for 12 male seated subjects during vertical vibration of the seat. The nature of vibration at the seat took the form of sinusoidals over the frequency range 7 Hz to 75 Hz and vibration magnitude 0.2 ms^{-2} to 4.0 ms^{-2} r.m.s. The subjects were instructed to adopt two different body postures, the first so as to minimise vibration transmitted to the head ('least severe') and the second, to maximise motion at the head ('most severe'). At these two postures, both vibration frequency and magnitude were varied and head motion recorded. Results of the ensuing analyses revealed that the subjects demonstrated differing levels of non-linear response; the greater non-linear response being at lower frequency than higher frequencies (i.e. approximately below 35 Hz for the 'most severe posture' and below 20 Hz for the 'least severe posture').

One of the few papers available on the measurement of head motion in all six axes is a study conducted by Johnston et al. (1978) to determine the vibration characteristics of head motion for subjects seated in a reclined seat. One of the parameters investigated in the experiments was the effect acceleration magnitude had on vibration transmitted from the reclined seat to the head. Input motion was of a swept sinusoidal nature covering a frequency range of 2 Hz to 25 Hz and of a 20 second duration. Two magnitudes of the input motion were used: 1.5 ms^{-2} r.m.s. and 3.0 ms^{-2}

r.m.s. After only a visual inspection of the data, results for five male subjects showed that transmissibility in all the translational axes at the head was reduced for increased vibration magnitude and that rotational motion at the head was increased for the higher input magnitude. The effect on translational motion at the head appears to be only for frequencies below about 16 Hz.

Discussion

These studies have shown differing results, there clearly is an effect of vibration magnitude on motion transmitted from the seat to the head for a seated person. Though some of the investigations have shown the response of the head to be linearly correlated with vibration magnitude, it is likely that there is some degree of non-linearity. The one study found on the effect of this parameter on the six axes of motion at the head showed that vibration magnitude affected translational and rotational motion in a different manner.

2.6.2.2 Effect of backrest angle

There are very few vehicles with seats which do not have backrests, indeed there are not many seats which do not have backrests. The purpose of the backrest is to provide support for the back which, from an ergonomic point of view is advantageous (Pheasant, 1986). The height of the backrest is also important depending on the location where support is required, e.g. a small backrest would provide support only in the lumbar region. For a seat comprising of lap and shoulder straps (e.g. an ejection seat), the backrest would be required to extend up to the shoulders. The angle between the backrest and the seat surface has been shown to be an important factor in distributing the weight of the upper body and in determining the comfort offered to the occupants. Different angles of the backrest ('rake' angle) have been cited in the literature as being optimal, these have been in the range 100° to 110° (Grandjean, 1980; Pheasant, 1986).

The first variable to be investigated should be to determine the effect a backrest has on the transmission of vibration from the seat to the head. A backrest effectively introduces another path through which vibration is transmitted and is very much dependent on the height of the backrest. Rao (1982) conducted an experiment in which 8 male subjects sat in two different body postures: one in which no contact was made with the backrest and the other in which the subjects were asked to lean against the backrest. The seat used was a car seat and the subjects were not restrained in any way on the seat. Transmissibilities were calculated between seat and head vibration by determining ratios of the r.m.s. accelerations measured at the head and the seat at various discrete frequencies. Mean results for the subjects showed that the effect of contact with the backrest was a slight reduction in head motion at about 5 Hz and a significant increase in high frequency content (10 Hz to 20 Hz) compared with a no backrest posture. The main drawback with this study was that the effect of the dynamics of the seat used on the transmission of seat-to-head vibration was unknown, a seat of known vibration characteristics should have been used. However, similar results have been obtained in other studies.

Three completely different postures and seats were used in an investigation by Dennis and Elwood (1958) to assess the effect of vertical vibration on subjects sitting in these seats. The three seats included a tank driver's seat, a reclining seat and a prone position seat. The tank driver's seat had an upright backrest and both the seat and the backrest were padded. Both the other seats had a thick soft cushions, the reclining seat (subjects lying on their back) had a padded headrest and the prone seat (subjects lying on their chest) had a support for the chin. (No geometrical dimensions about the seats were reported.) The apparatus used was somewhat basic consisting of a platform hinged at one end and connected to a motor by an adjustable arm at the other end. Motion used in the experiment was sinusoidal, covered a frequency range of 3 Hz to 21 Hz in

3 Hz steps, and the vibration magnitude ranged from 0.33g to 1.32g peak-to-peak (1.14 ms^{-2} to 4.58 ms^{-2} r.m.s.). Motion of the head was measured in the fore-and-aft and the vertical axes. The results showed that the reclined position seat imparted greater accelerations at the head compared with the tank driver's seat. This was due to the differing geometry of the seats: the subjects' heads were in contact with a vibrating surface (the headrest) when in the reclined seat whereas only a backrest (possibly extending up to just below the shoulders) was present on the tank driver's seat. Head motion measured while seated in the prone position seat was of similar magnitude to that in the tank driver's seat.

A systematic study into the determination of the effect of seat backrest angle on motion transmitted to the head would involve successive changes of the backrest angle and the corresponding motion at the head measured for each angle. This approach was taken by Johnston (1978) who investigated the effect of four different angles of the backrest, namely 20° (normal), 30°, 45° and 60° from the vertical. The seat used in the experiment was a Mk 10B ejection seat with a backrest extending up to the shoulders and a headrest on top of the backrest; a shoulder and lap harness was worn tightly during the experiment. Ten male subjects took part in the vibration experiment and motion at the head was monitored in the three translational axes (x-, y-, z-) using a bite-bar during vertical vibration of the seat. One of the main conclusions of the study was that motion transmitted to the head increased with increasing backrest angle. This was the case for all three translational axes at the head.

In some of the reported studies concerned with head motion during whole-body vibration of seated subjects, the differing experimental conditions include a 'back-off' posture involving no contact between the subject's back and the backrest and, the subjects in contact with the backrest while wearing a harness. In such a set-up, three different postural conditions would provide information on the gradual addition of backrest and then the harness on the transmission of seat vibration to the head. Two seats and two main postures were investigated in a study by Moseley et al. (1981); the two seats were an actual Westland Sea King helicopter seat and a hard wooden simulated version of a Westland Sea King helicopter seat. The two postures were: a 'back-off' posture in which no contact was made between the subject's back and the backrest and, a 'back-on' posture in which the subject was in contact with the backrest and wore a five point harness. (Both seats had a five point harness.) Mean transmissibility data of vertical seat-to-head vibration for 12 male subjects in both seats showed that greater levels of vibration occurred at the head when the subject sat in a 'back-on' posture (in contact with the backrest and using a five point harness) than a 'back-off' posture. Pitch motion of the head showed different transmissibilities for both seats: more pitch motion at the head for a 'back-off' posture below 9 Hz for the actual Sea King seat while for the simulated seat, only small differences occurred in pitch head motion between the two postures up to 20 Hz; a 'back-on' posture resulted in increased head motion in the pitch axis.

Parsons et al. (1982) report of an experiment conducted using a similar set-up to the one above (Moseley et al., 1981): the measurement of vertical head vibration during vertical whole-body vibration and the effect of two body postures on head motion. The different conditions were a 'back-off' posture (comfortable upright, no backrest) and a 'back-on' posture (back in contact with the backrest and wearing a five point harness). Again, as was the case above, the effect of a combined backrest and harness would be determined rather than just the backrest. Mean seat-to-head transmissibilities were calculated for 12 subjects over the frequency range 2 Hz to 50 Hz. Results showed that for frequencies greater than about 8 Hz, significantly more vibration was transmitted to the head when the backrest and harness were used than a 'back-off' posture; at around 16 Hz, over 2.5 times as much motion occurred at the head in a 'back-on' posture than a 'back-off' posture.

One variable that becomes important when a headrest is present is the effect it has on motion transmitted to the head. Many seats are provided with headrests, some have variable geometry such as height and angle. The purpose of a headrest is to support the head during normal circumstances (e.g. driving a motor vehicle) and can prove to be invaluable during extreme conditions, e.g. in reducing the effect of whiplash in an accident. Johnston (1978) and Johnston et al. (1978) conducted experiments in which head motion of seated subjects was measured while the head was in contact with the headrest and then no contact with the headrest. Motion of the head was measured in the three translational axes (fore-and-aft, lateral, vertical) during exposure to whole-body vertical seat vibration. Another factor introduced was backrest angle, four angles were investigated (20°, 30°, 45°, 60°). Average transmissibility curves showed that for all the different backrest angles, head motion was considerably greater when the head was in contact with the headrest compared with the condition in which no contact was made with the headrest.

Discussion

In the above reviewed studies, although some fundamental data were obtained, the aims of the experiments were possibly to establish the effect of the parameters investigated when exposed to vibration in a particular seat. Overall, the data tend to suggest that contact with a backrest will result in increased head motion than a posture in which no backrest is used. The disadvantage of using a commercially available seat, used for instance in vehicles is that the vibration characteristics of the seat would be unknown and this would complicate the measurements of vibration to which the subjects were exposed. It is well known that a car seat can greatly affect the frequency content of the vibration transmitted through it (Griffin, 1978). Maybe the seat to use in such experiments should be a hard flat seat with no padding which would not alter the transmission of vibration from the floor to the person-seat interface; the subjects would be exposed to the same vibration whether they sat on the seat or the floor! Such a seat could have a backrest with an adjustable height, adjustable angle, etc.

2.6.2.3 Effect of body harness

There are many situations in which some kind of harness is required (e.g. car seat belt, aircraft) and in others, though restraints may be necessary, they are not present (e.g. public transport trains, buses, etc.). There are three main conditions which need to be investigated to determine the nature of the effect of a harness on motion transmitted to the head:

(i) a no backrest condition,
(ii) leaning against a backrest and,
(iii) the effect of a harness.

(The effect a backrest has on vibration transmitted to the head is discussed in Section 2.6.2.2.) Essentially, the aim of a harness is to ensure that the body remains in contact with the seat and the backrest depending on the type of restraint system used (it may only be to reduce injury in an accident).

Rowlands (1972) conducted an experiment with 7 male subjects to determine the effect of a harness on the transmission of seat vibration to the head. Two postures were used: a no harness condition with the subjects leaning against a backrest and then with a three point harness (shoulders and a mid-seat strap). It was observed from the results that the effect of a harness was a reduction in vertical head motion over the 1 Hz to 10 Hz frequencies (1 Hz to 2.5 Hz at 0.5 Hz steps; harmonics were used of these for higher frequencies). A slight increase in the frequency of whole-body resonance and a marginal increase in the amplitude was seen as a result of using the harness.

Griffin et al. (1979) carried out an investigation into the effect a combined backrest and harness had on the transmission of seat vibration to the head. Twelve male subjects took part in the two-condition experiment: the two body postures included a 'normal upright comfortable' posture without a backrest and a condition involving a slightly tilted backrest on a hard seat replica of a Sea King helicopter seat with a five point harness (shoulder straps, lap straps and a mid-seat strap all joined at a common point). Vibration took the form of discrete frequencies ranging from 2 Hz to 50 Hz. The results showed that when the subjects sat in the latter posture (backrest and harness), there was an increase in vertical head motion transmissibility at the three higher frequencies investigated (i.e. 16 Hz, 32 Hz and 50 Hz) and a decrease at 2 Hz when compared with the normal posture. These differences are shown in Figure 2.15.

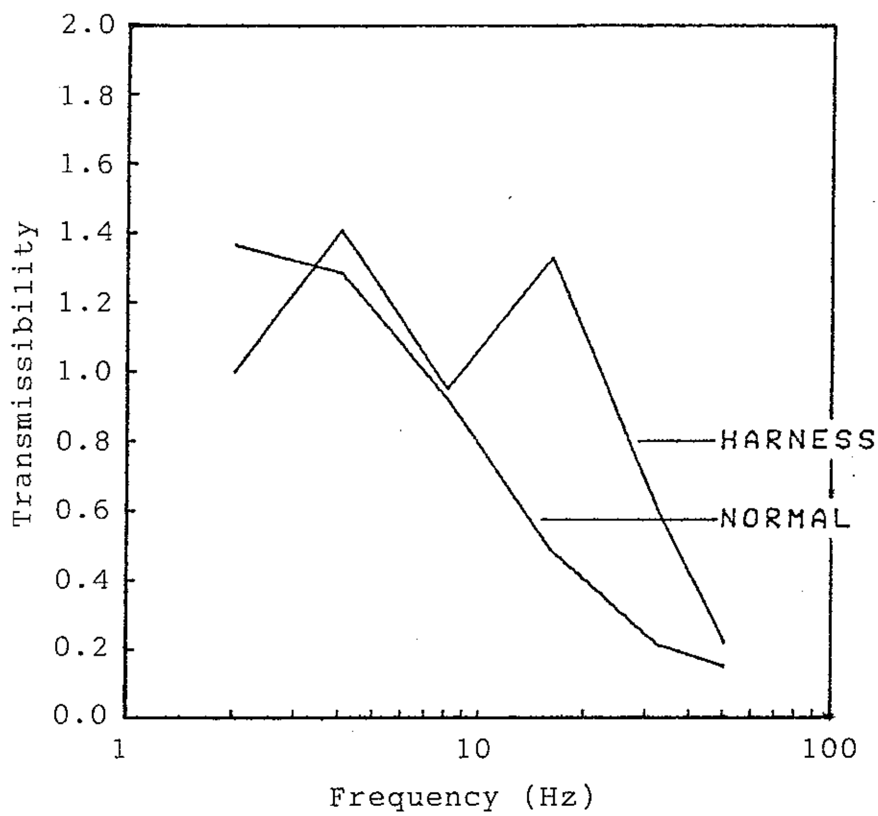


Figure 2.15 Comparison of the mean seat-to-head transmissibility for 12 subjects sitting in a normal posture (no harness or backrest) and sitting with a harness and backrest (Griffin et al., 1979).

A similar experiment to the one reported above (Griffin et al., 1979) was undertaken by Moseley et al. (1981), although rather than only use a replica of a Sea King helicopter seat, simulated and actual Westland Sea King helicopter seats were used. Again, 12 male subjects took part in the experiment to understand the effect of a backrest and a harness on head motion during whole-body vibration compared with a 'normal upright comfortable' no backrest posture. Vertical vibration transmissibilities of head motion confirmed the results of the above study that contact with the backrest and a harness results in significantly greater magnitudes of vibration being transmitted to the head, this being the case for both seats. Pitch motion was also monitored during the experiment and these data showed that, generally more pitch motion occurred during a posture involving the backrest and the harness than the normal upright posture.

A complex study conducted by Rao (1982) was to investigate the effect of many variables on the transmission of seat vibration to the head. Three of the postures included the above stated conditions: no backrest, leaning against a backrest, and the effect of a harness. Eight male subjects took part in the experiment and the subjects sat in an 'erect upright' posture on a car seat mounted on a vertical motion simulator. The restraint system on the seat was a normal car seat belt comprising of a lapstrap and a strap from one shoulder to a point near the pelvis on the opposite side. Transmissibility results of the first two postures (no backrest and leaning against a backrest) showed that there was a slight increase in vertical head motion over the frequency range 4 Hz to 6 Hz, and a substantial increase in head motion over the frequency range 8 Hz to 30 Hz when the subjects were instructed to lean against the backrest. The effect of using the harness was an even greater increase in vertical head motion over the higher frequency range. The data broadly confirm the findings of Griffin et al. (1979).

Discussion

During whole-body vertical vibration, the transmissibility of vertical head motion consists mainly of two resonance peaks - one at about 6 Hz and a comparatively broad peak near 12 Hz. Though not reported, a close inspection of the results obtained by Rao (1982) reveals a slight increase in frequency of the second peak as the postures changed from a no backrest, backrest, and then a backrest and harness condition. This was also seen by Rowlands (1972) though at a lower frequency (possibly the main body resonance). Generally, an increase in the transmission of seat-to-head motion is observed as a result of using a restraint system of some form.

2.7 SEAT MOTION IN OTHER AXES

A great deal of investigative work has been conducted since about 1950 on human response to vibration. Most of the work has concentrated on vertical vibration at the seat and the research has advanced so much that the effects of a large number of variables is known with varying degrees of success. This, unfortunately, is not the case for seat vibration in the other axes, that is, x-, y-, roll, pitch and yaw.

Following is a review of some of the literature available concerned with the transmission of seat vibration in various axes to the heads of seated subjects.

2.7.1 Horizontal seat vibration

2.7.1.1 Fore-and-aft seat vibration

Three research papers are reviewed in this section dealing with the transmission of fore-and-aft seat vibration to the heads of seated subjects. Two of the papers date back to the late 1950's and early 1960's. No very recent work has been reported on this matter.

Dieckmann (1957a, 1958) conducted some of the early transmissibility experiments with seated subjects and x-axis seat vibration. The frequency range covered was 1 Hz to 5 Hz and the motion was sinusoidal. No details could be obtained about the equipment used (due to language translation difficulties) which could greatly affect the transmission of seat vibration to the head (e.g. seat backrest). With the subjects undergoing whole-body vibration, their heads were seen to move in an elliptical manner in the x-z plane. Pitch motion of the head was also induced and this in turn demonstrated z-axis motion (depending on position on the head). Figure 2.16 shows transmissibility of seat-to-head motion calculated from measurements made using an "acceleration meter". A distinct resonance peak is seen at around 2 Hz. It is interesting to note that at about 1.5 Hz, the head demonstrated minimum motion before the main resonance at 2 Hz.

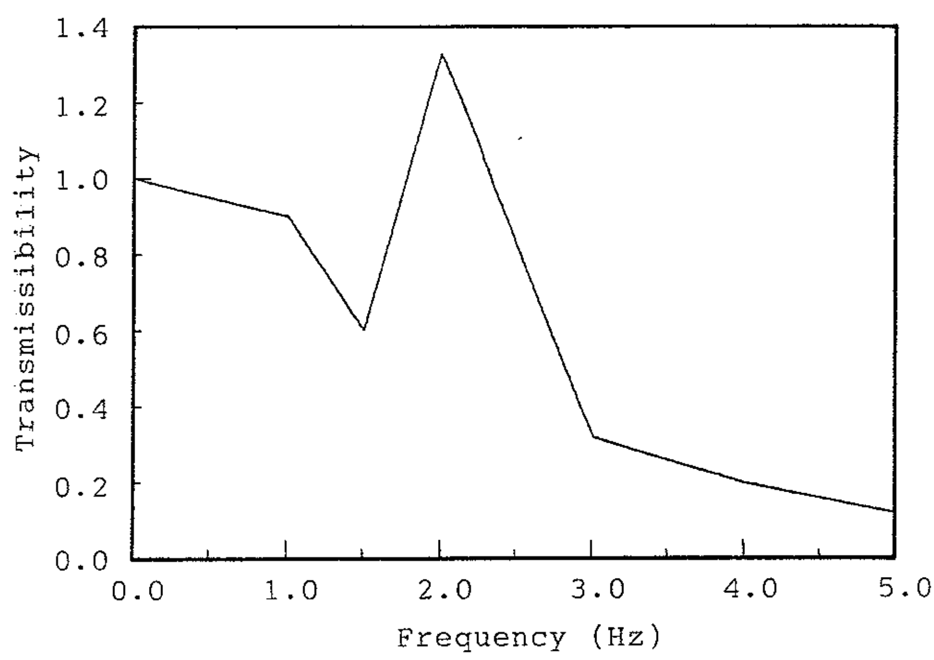


Figure 2.16 Transmission of fore-and-aft vibration from the table to the head for seated subjects (Dieckmann, 1958).

Hornick et al. (1961) reported on a study in which 20 male subjects took part. They were required to sit on a hard rigid wooden chair with a backrest. Head motion was measured using an accelerometer tied firmly around the subject's head. Vibration at the seat was sinusoidal covering 1 Hz frequency steps from 1.5 Hz to 5.5 Hz. Vibration exposure was of three magnitudes, these being 0.15g, 0.25g and 0.30g peak accelerations (1.04 ms^{-2}, 1.73 ms^{-2} and 2.08 ms^{-2} r.m.s.) for the five stated frequencies. Transmissibilities were calculated as a ratio of peak-to-peak acceleration at the head and peak-to-peak acceleration at the seat for the different frequencies. The combined mean for the different vibration magnitudes is shown in Figure 2.17 with a variation of one standard deviation. No clear distinct resonances are present although an increase in transmissibility is seen at 5.5 Hz with respect to the other frequencies. The mean data show that over the frequency range studied, there was an attenuation of vibration transmitted to the head, i.e. transmissibility was less than unity.

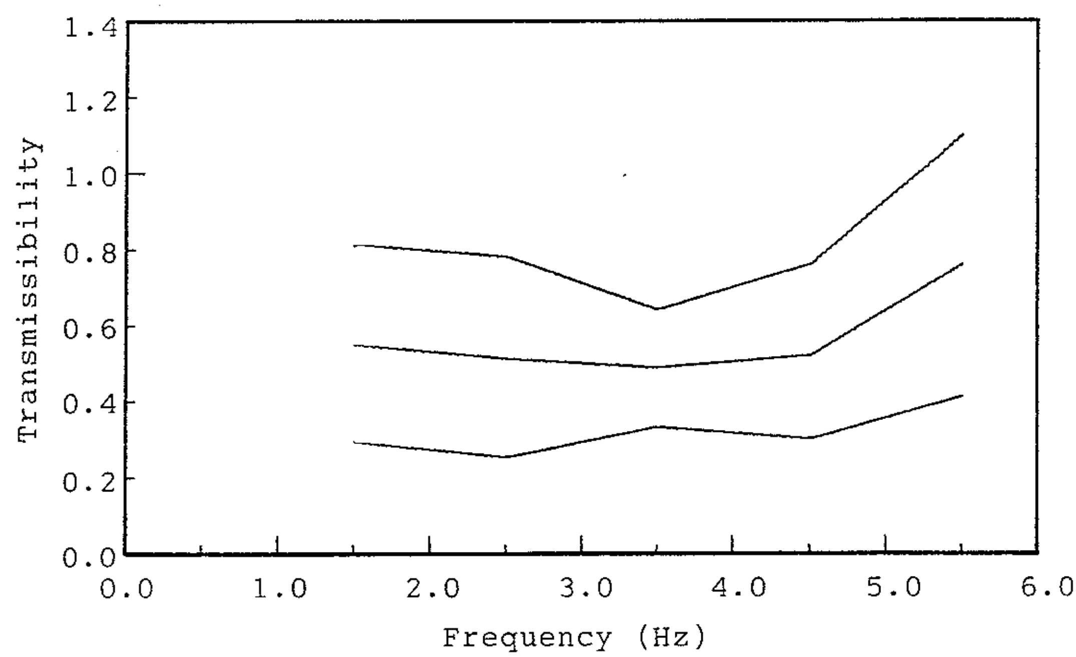


Figure 2.17 Mean transmissibility and variation of one standard deviation of fore-and-aft seat vibration to the head (Hornick et al., 1961).

Approximately two decades later, Lewis and Griffin (1980) carried out an experiment to investigate the effect of seating on the transmission of fore-and-aft vibration to the head. Vibration exposure consisted of a sine swept waveform of a duration of 100 seconds covering a frequency range of 2 Hz to 64 Hz and of a magnitude of 1.6 ms^{-2} r.m.s. Head motion was measured in the vertical and pitch axes using a bite-bar weighing 128 g; unfortunately, fore-and-aft head motion was not monitored. Ten male subjects were required to sit in two different seats; the first was a simulated helicopter seat with a hard wooden seat and backrest. A footrest was provided which moved with the seat and the subjects were restrained by a tight five point harness. The second seat consisted of a flat rigid surface with no backrest and a stationery footrest. Transmissibilities were calculated between seat and head motion; mean transmissibilities for the 10 subjects with ±1 standard deviation for the two axes at the head (vertical and pitch) and the two different seats are shown in Figure 2.18. It is clear that significantly greater levels of vibration occurred in the vertical and pitch axes at the head for the subjects seated in the simulated helicopter seat than the flat seat. The increased levels of head vibration would have been caused by a combination of backrest and harness. With the flat seat (no backrest), only low levels of head motion occurred for frequencies greater than about 20 Hz for vertical head motion and 50 Hz for pitch motion at the head. There was also substantial variability in transmissibility between subjects for the helicopter seat, however, the levels were also greater.

From the above three studies, it is clear that there is a shortage of data concerned with the transmission of fore-and-aft seat vibration to the heads of seated subjects. The first two studies present data using completely different seating conditions. Lewis and Griffin (1980) showed that contact with the backrest (and a five point harness) resulted in greater levels of head motion in the vertical and pitch axes. Had measurements been made of fore-and-aft head motion, further fundamental data would have been provided, this would have also confirmed (or not, whatever the case may be) data obtained by Dieckmann (1958) and Hornick et al. (1961).

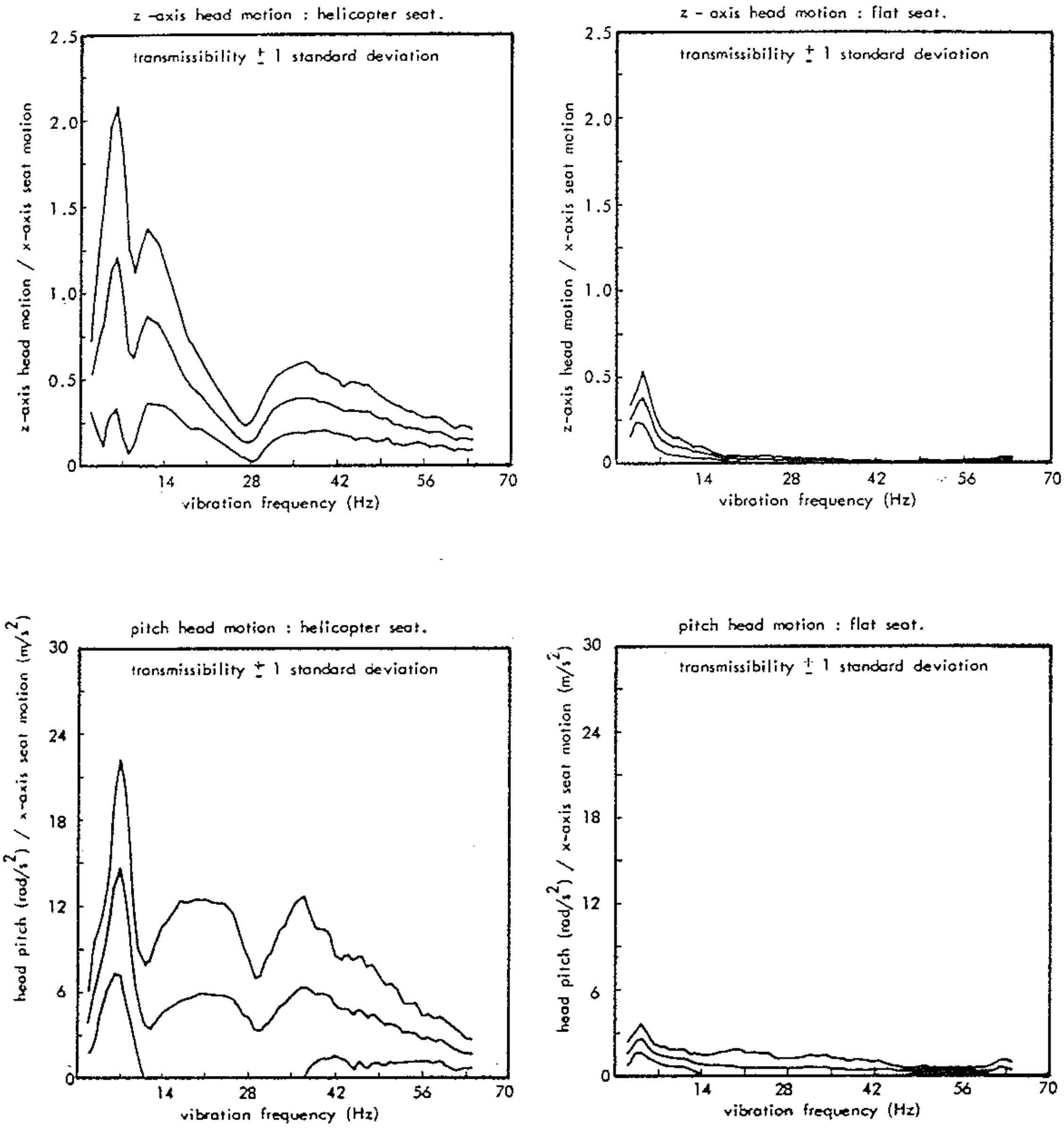


Figure 2.18 Mean translational (z-axis) and rotational (pitch) head motion at bite-bar, in response to fore-and-aft (x-axis) seat motion with simulated helicopter and flat seats (Lewis and Griffin, 1980).

2.7.1.2 Lateral seat vibration

Only a few studies exist in which the transmission of lateral seat vibration to the head is discussed and experimental data presented. Five investigations are reviewed below in which transmissibilities have been obtained.

Hornick et al. (1961) conducted experiments to determine seat-to-head transmissibility for 20 male subjects seated on a rigid chair with a backrest. Lateral head motion was measured using an accelerometer strapped around the subject's head. They were exposed to sinusoidal vibration at five frequencies (1.5 Hz, 2.5 Hz, 3.5 Hz, 4.5 Hz and 5.5 Hz) and at three different vibration magnitudes (peak accelerations of 0.15g, 0.25g and 0.35g: 1.04 ms^{-2}, 1.73 ms^{-2} and 2.43 ms^{-2} r.m.s.). Transmissibilities were calculated between seat and head motion as a ratio of peak-to-peak acceleration at the head and the seat. Mean transmissibilities are presented in Figure 2.19 for the 20 subjects and the three vibration magnitudes. A clear resonance is seen to exist at a frequency of 1.5 Hz or below. Unfortunately, the lowest frequency investigated was 1.5 Hz making it impossible to determine the actual resonance frequency. The graphs show significant attenuation of vibration at the head for frequencies greater than about 4 Hz. Also, it is interesting to note that data show a decrease in transmissibility for increased seat vibration magnitude.

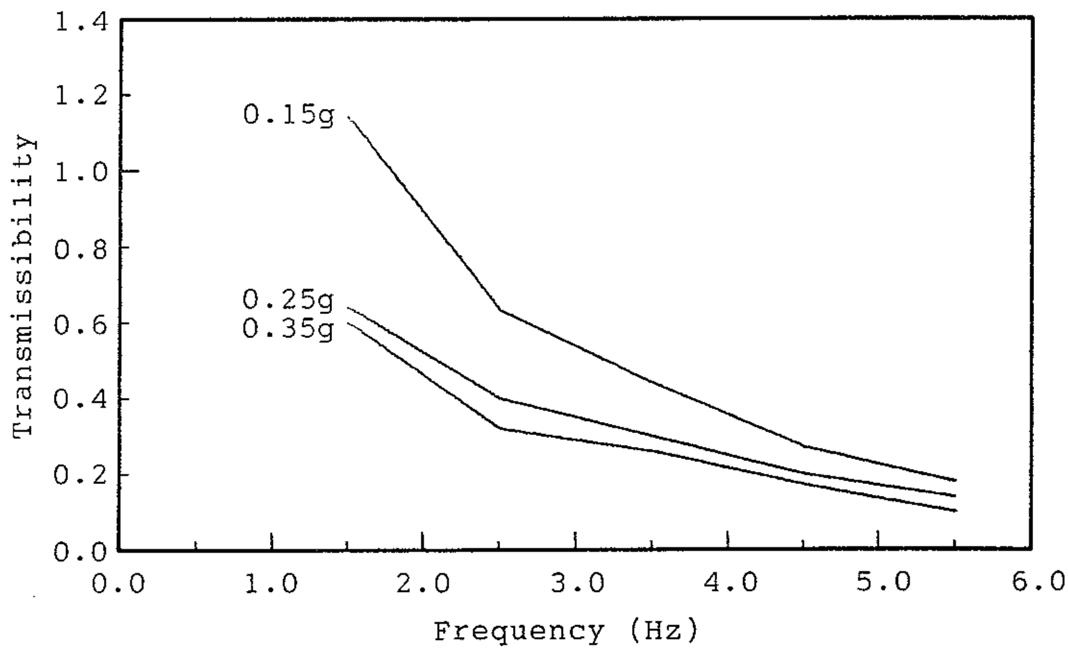


Figure 2.19 Mean transmissibilities for lateral head and seat motion for three vibration magnitudes (Hornick et al., 1961).

Woods (1967) investigated the transmission of lateral vibration through the body for seated subjects. Four subjects took part in the experiment; they sat on a hard seat with a backrest and with no lateral restraint. Each subject was exposed to sinusoidal motion at discrete frequencies over the range 0.8 Hz to 7 Hz. The magnitude of vibration at the seat was 0.1g r.m.s. (0.98 ms^{-2} r.m.s.). Transmissibility between lateral motion at the seat and the head was calculated as a ratio of vibration magnitudes for 15 individual frequencies over the specified frequency range. Average transmissibility curves for the four subjects are shown in Figure 2.20. Three resonances are seen from the data at 1.5 Hz, 4 Hz and 6 Hz; the main being at 1.5 Hz with a maximum transmissibility of just over unity. One point that merits attention is the realisation of a whole-body resonance at a low frequency (≃1.5 Hz) and, hence, the use of a fine frequency resolution to investigate this (i.e. 0.25 Hz) and the use of a coarse resolution at high frequencies (i.e. 0.5 Hz steps from 2 Hz to 6 Hz and a 1 Hz step from 6 Hz to 7 Hz).

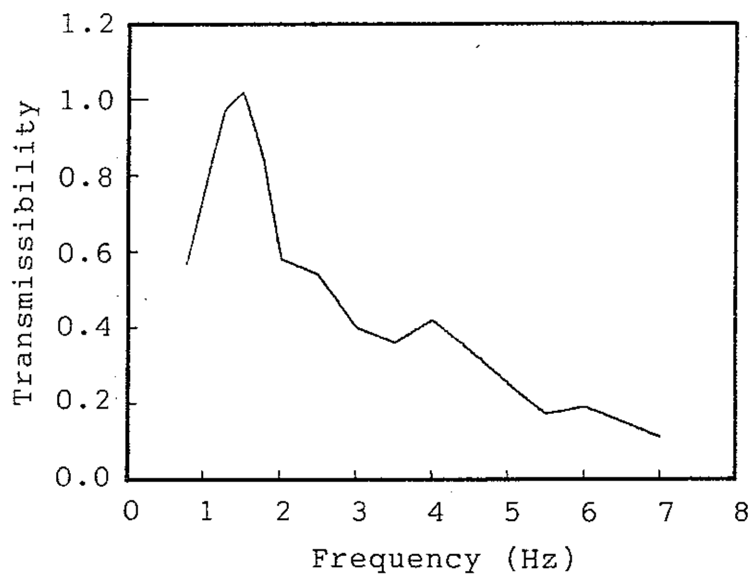


Figure 2.20 Average transmissibility for lateral seat and head motion (Woods, 1967).

Seven male subjects were used in an experiment undertaken by Rowlands (1972) to obtain transmissibility of lateral seat vibration to the head. The subjects sat in a modified

Martin-Baker Mk 8 ejection seat with a three point harness. Motion of the head was measured by attaching an accelerometer on the temple of a subject using an elasticated head harness. Characteristics of the vibration input included discrete sinusoidals at steps of 0.5 Hz from 1 Hz to 4 Hz. The vibration magnitude for all runs was 0.4g r.m.s. (3.92 ms^{-2} r.m.s.). One parameter under investigation was the effect of a harness on transmissibility, so each run was conducted twice: once with a three point harness and once without the harness. Average transmissibility results indicated the presence of a resonance at about 1 Hz with an amplitude of 1.1 for a non-harness condition and 1.3 when a harness was used. This shows that greater levels of head motion occurred with the subjects seated wearing a harness than a no harness condition.

Johnston et al. (1978) reported on the measurement of transmissibility between lateral seat vibration and six axes of motion at the head. Five male subjects sat in an experimental reclined ejection seat and were restrained using a tight harness comprising of shoulder and lap straps. The backrest on the seat was reclined with a shoulderrest and a headrest. Subjects were instructed to wear a Mk 2/3 flying helmet and measurements of head motion were made using a bite-bar weighing 300 g. Vibration at the seat covered a frequency range of 2 Hz to 25 Hz and was swept over a 20 second duration. Two vibration magnitudes were used: 1.5 ms^{-2} r.m.s. and 3.0 ms^{-2} r.m.s. Head motion measurements were made with the head on the headrest and with the head off the headrest. Transmissibilities were calculated between lateral seat vibration and the six axes of motion using spectral methods. The results mainly show that for the condition in which the head was on the headrest, transmissibilities between seat vibration and, lateral and vertical motion at the head showed a peak at around 13 Hz. No explanation has been put forward on the cause of this relatively high resonance frequency. Data also showed that head motion was reduced to about half the level when the head was not in contact with the headrest compared with the head on the headrest condition. Transmissibilities for translational axes at the head (i.e. x-, y-, z-) indicated a reduction as the vibration magnitude was increased from 1.5 ms^{-2} r.m.s. to 3.0 ms^{-2} r.m.s. whereas transmissibilities for the rotational axes showed an increase.

Finally, Lewis and Griffin (1980) present transmissibilities between seat vibration and head motion with 10 male subjects and two different seats. The first seat consisted of a hard flat surface with a stationary footrest and no backrest. The geometry of the second seat was similar to that used in a Sea King helicopter but it had hard wooden surfaces. The backrest and the footrest were attached to the main frame of the seat and were thus vibrated with the seat. The subjects were instructed to wear a tight five point harness. The vibrator on which these seats were mounted was operated using a sine swept waveform covering frequencies from 2 Hz to 64 Hz over a duration of 100 seconds. The vibration magnitude at the seats was 1.6 ms^{-2} r.m.s. A bite-bar was used to monitor head motion in the lateral and roll axes. Mean transmissibilities were calculated for measurements in the two seats and for the two axes at the head; these are presented in Figure 2.21. These show that greater levels of lateral motion occurred with the simulated helicopter seat than with the hard flat seat and that roll motion at the head was greater at higher frequencies for the helicopter seat.

The above five studies have shown some fundamental data but the three latter studies have lacked in presenting low frequency information. Hornick et al. (1961) and Woods (1967) demonstrated that a main body resonance occurred at about 1.5 Hz; Johnston et al. (1978) and Lewis and Griffin (1980) started the frequency range from 2 Hz thus completely ignoring the low frequency resonance. These studies do, however, present some interesting high frequency data showing that greater levels of vibration are transmitted to the head when the back is in contact with a

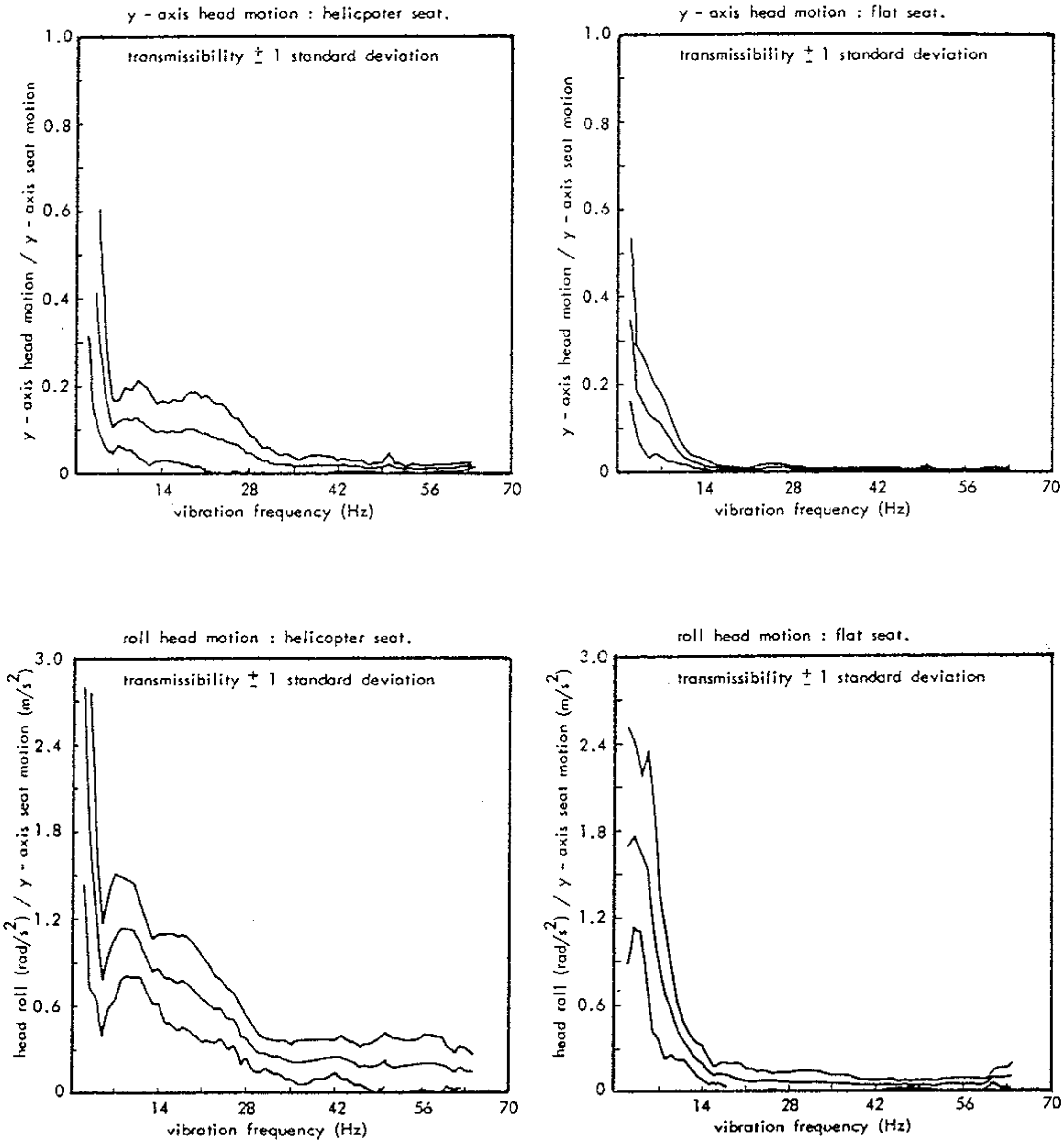


Figure 2.21 Mean translational (y-axis) and rotational (roll) head motions at bite-bar, in response to lateral (y-axis) seat motion with simulated helicopter and flat seats (Lewis and Griffin, 1980).

backrest, head in contact with a headrest and that a harness will also increase transmission.

Johnston et al. (1978) presented data of lateral transmissibility but no 'base line' data were included, for example, transmissibilities while seated on a hard flat seat with no backrest. The data included are very specific for a subject seated in a reclined seat wearing a helmet and a harness. This makes comparison with other studies very difficult unless other studies are conducted under similar conditions.

2.7.2 Rotational seat vibration

Motions in vehicles usually occur in all six axes to some extent and with varying magnitudes. Generally, greater magnitudes occur in the vertical axis for road vehicles and smaller levels for rotational axes. The situation would be different in, for example, a tractor traversing across a ploughed field or a vehicle travelling over a cross-country track.

Studies have been published on the discomfort caused by rotational vibration of the seat for a seated person (Parsons and Griffin, 1978; Parsons and Griffin, 1982) but there appears to be a shortage of data concerned with the transmission of rotational seat vibration to the head. Only one study has been found on the quantitative measurements of head motion during seat vibration for each of the three rotational axes. One of the important parameters that would affect vibration transmission is the distance between the centre of rotation and the point of measurement on the body e.g. the head. There are many positions that could be used for this parameter; centre of rotation at the seat surface has been shown to cause least discomfort (Parsons and Griffin, 1978). The greater the separation between centre of rotation and the head, the greater the translational motion at the head and hence, higher transmissibilities. This would apply equally to roll, pitch and yaw axis seat motion.

2.7.2.1 Roll seat vibration

One of the early investigations on human exposure to roll motion of the seat was by Walsh (1968). Centre of rotation was arranged to be just below the subjects' feet. A seat was mounted on to a tilting platform and driven by a variable speed electric motor. The frequency range covered by this apparatus was 0.25 Hz to 6 Hz with a maximum sinusoidal tilt angle of 1° (maximum rotational acceleration magnitude of 8.77 rads^{-2} r.m.s.). No numeric measurements of the head were made but visual observation showed large oscillations occurring at around 1 Hz to 1.5 Hz. (The axes in which dominant motions occurred were not reported.) At higher frequencies up to 6 Hz, the head appeared to be stabilized with the body attenuating the vibration.

Sjoflot and Suggs (1973) conducted a study to investigate the transmission of vibration to the subjects' shoulders using seat motion as a series of sinusoids of different frequencies (1 Hz, 1.7 Hz, 2.5 Hz, 4.0 Hz). The centre of rotation was 1.57 m below the subject (precise location of measurement was not reported) - this would induce significant magnitudes of lateral motion together with rotational roll motion. There is a slight confusion over the vibration magnitudes used: the lateral acceleration magnitudes were 0.25g (2.45 ms^{-2})and 0.50g (4.91 ms^{-2}) but it is unclear as to whether this was measured at seat floor level, seat pan level or shoulder height. Nevertheless, measurements of acceleration at the shoulder for the higher input acceleration magnitude showed maximum response for lateral and vertical axes at frequencies of 1.7 Hz and 2.5 Hz. (Note that both lateral and vertical axes are in the same plane as the excitation motion, i.e. the mid-coronal plane.)

The final study to report data of the inducement of head motion by roll seat vibration is by Barnes and Rance (1975). They conducted an experiment with eight male subjects and a rigid seat with armrests and an aircraft harness. The subjects were instructed to sit with a relaxed posture of the head. To ensure that the visual system had no effect on head motion, the subjects sat in a darkened room with their eyes closed. The seat was placed such that with the subject seated, the centre of rotation was approximately near the second or the third lumbar vertebrae. Input motions took the form of sinusoids at 16 frequencies ranging from 0.5 Hz to 20 Hz with peak amplitudes of ±10 rads^{-2} (±572 degrees/s^2). A bite-bar weighing 250 g was used to measure motion of the head in the roll, pitch and yaw axes. Mean seat-to-head transmissibility for the eight subjects together with ±1 standard deviation is shown in Figure 2.22. The transmissibility tends to show a resonance at around 4 Hz with a mean peak value of 4.0. Significant magnitudes of motion were induced at the head in the other rotational axes; transmissibility ratios of 0.96 at 4 Hz for pitch axis head motion and 1.74 at 3 Hz for yaw axis motion at the head.

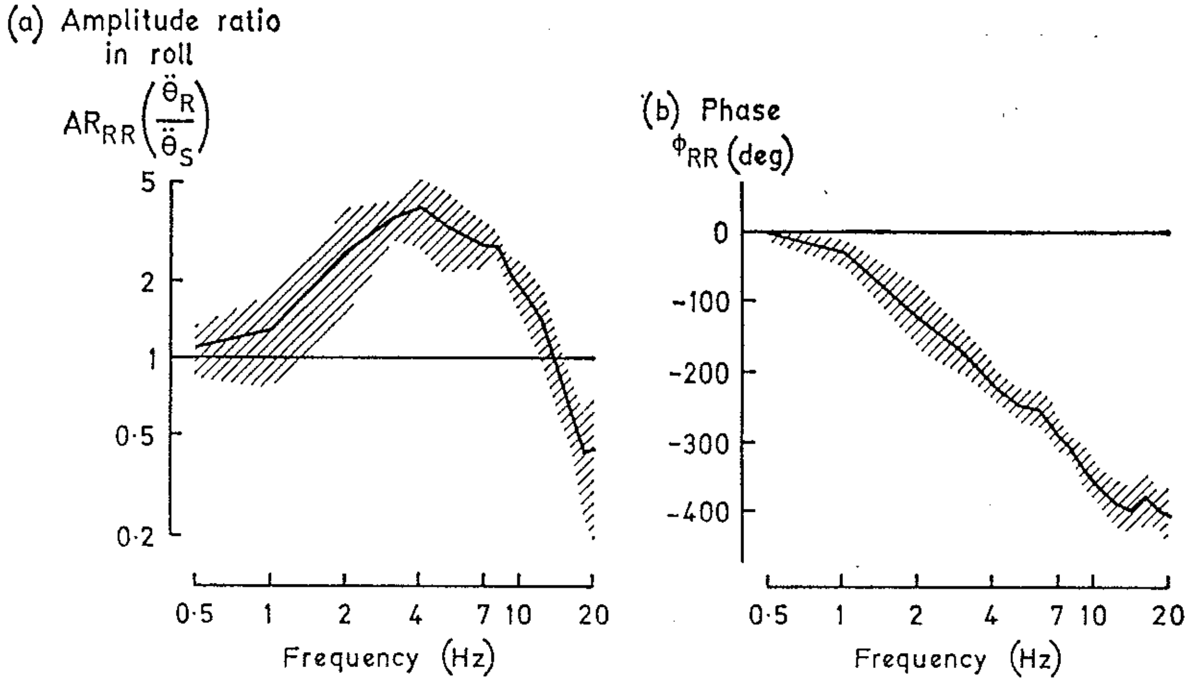


Figure 2.22 Mean transfer function between roll seat and head motion with shading for ±1 standard deviation (Barnes and Rance, 1975).

The above studies have all had differing distances between the centre of rotation and the subject's head. This might have had an effect on the rotational motions transmitted to the head. This separation would be an important factor when measuring translational motion as the translational acceleration induced by rotational motion is directly proportional to the separation between the centre of rotation and the point of measurement.

2.7.2.2 Pitch seat vibration

The only study found in the literature in which experiments were conducted to determine the transmission of pitch seat motion to the head was by Barnes and Rance (1975). The apparatus and procedure was the same as that for the determination of transmission of roll seat motion to the head (see above Section 2.7.2.1); namely, 8 male subjects were exposed to sinusoidal motion at 16 frequencies between 0.5 Hz and 20 Hz. A lower vibration magnitude of ±5 $rads^{-2}$ (±286 $degrees/s^{2}$) was used than that for roll seat motion. The subjects sat on a rigid seat restrained with an aircraft harness; they maintained their head in a relaxed posture. To exclude the influence of the visual system, the subjects were instructed to close their eyes while sitting in a darkened room. The centre of rotation was at approximately between the second to the third lumbar vertebrae and head motion was measured in the rotational axes using a bite-bar. The mean transmissibility results for the eight subjects are shown in Figure 2.23 with a spread of ±1 standard deviation. Almost unity transmissibility is seen up to about 1 Hz then an increase to about 3.35 over the frequency range 3 Hz to 9 Hz. Relatively lower magnitudes of roll and yaw motion occurred at the head during pitch motion of the seat.

2.7.2.3 Yaw seat vibration

Barnes and Rance (1974) appear to be the only investigators to have conducted experiments to determine the transmission of yaw motion as the input and measured head motion. Two seating conditions were used: unrestrained and restrained. In the first condition, the subjects sat on a rigid wooden seat with an erect back and head held horizontal. In the second, the subjects sat on a seat with a backrest and wore a shoulder harness. In both setups, the subject's legs were fastened to prevent influence on trunk motion and the centre of rotation was arranged such that the centre of gravity of the body was directly over the centre of rotation. In order to exclude any effects of visual

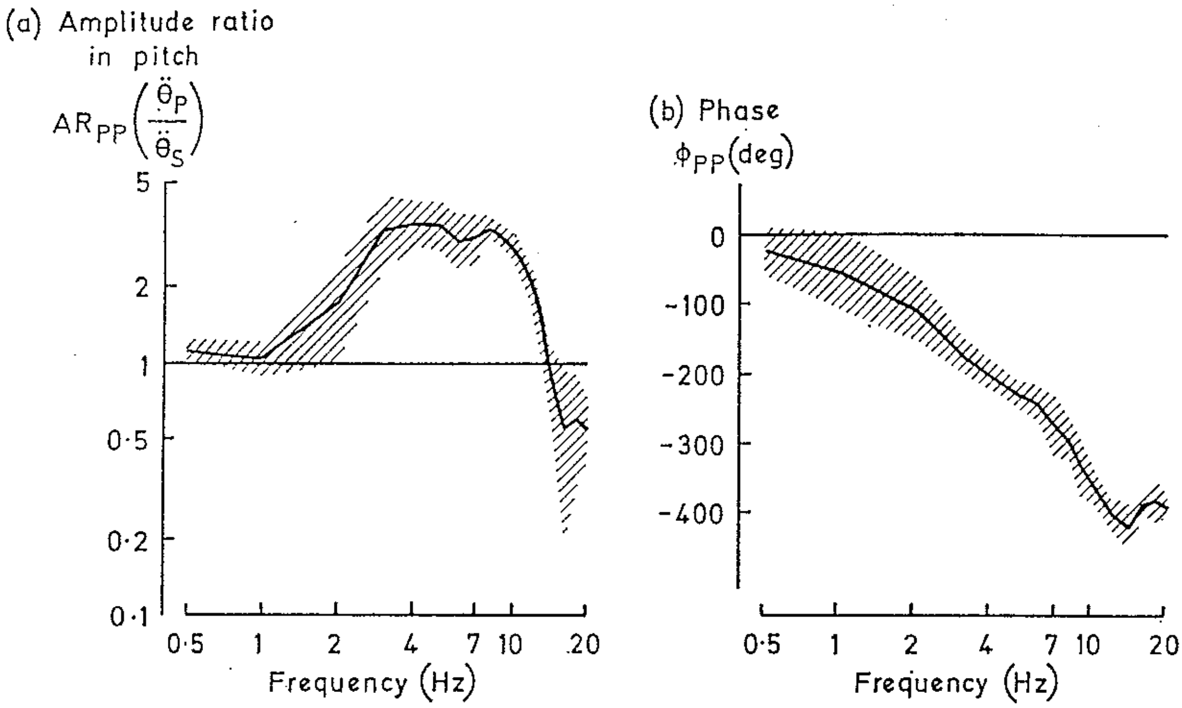


Figure 2.23 Mean transfer function between pitch seat and head motion with shading for ±1 standard deviation (Barnes and Rance, 1975).

feedback, the experiment was carried out in a dark room and the subjects were required to close their eyes. Eight male subjects participated in the experiment and their head motion was measured in the rotational axes using a bite-bar weighing 250 g. Input motion was sinusoidal covering a frequency range of 0.5 Hz to 20 Hz and had an acceleration magnitude of 1150 degrees/s^2 (20 rads^{-2}) peak-to-peak (7.07 rads^{-2} r.m.s.). Mean transmissibility results between yaw vibration at the seat and yaw motion at the head are shown in Figure 2.24 for the restrained and unrestrained seating conditions. A resonance peak of about 1.5 is seen at 2 Hz for the unrestrained condition although there is large variation between subjects. Above 4 Hz, there is a rapid decrease in head motion. The restrained condition showed maximum motion at low frequency and a steady decrease in head motion with increasing frequency. Significant levels of motion were reported in the roll and pitch axes with resonance peaks at 4 Hz. There was slightly more roll motion at the head in the restrained condition than with the unrestrained condition.

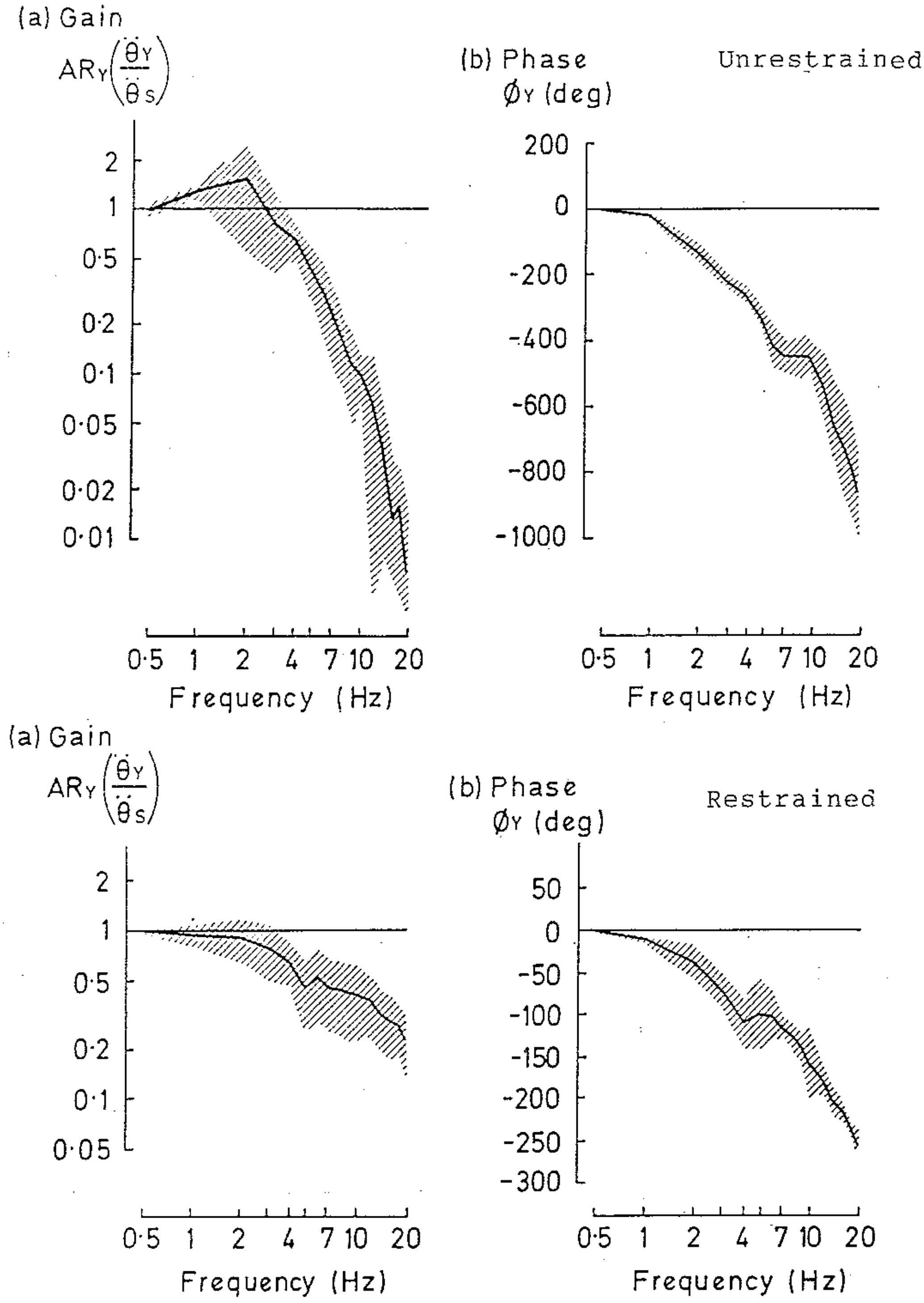


Figure 2.24 Mean transfer functions between seat and head motion for yaw axis vibration and two seated postures with shading for ±1 standard deviation (Barnes and Rance, 1974).

2.7.3 Discussion

The few studies reviewed investigating the transmission of fore-and-aft and lateral seat vibration to the heads of subjects have presented basic fundamental data. These show the characteristic transmissibility curves to be expected during horizontal vibration of the seat. Some studies have attempted to investigate the effect of variables on seat-to-head transmissibility (Johnston, 1978; Lewis and Griffin, 1980). It is seen for lateral seat vibration that a main body resonance possibly occurred in the region of 1 Hz to 2 Hz, this was demonstrated by the early studies on transmissibility. The later studies, however, appear to have completely missed the significance of this by investigating the lowest frequency around or above 1 Hz to 2 Hz. This shows one area that requires further investigation and will form the basis of some of the experiments to be reported in this thesis.

The above studies have demonstrated the shortage of data available on the transmission of rotational seat vibration to the head. Large masses of data exist concerned with, for example, the transmission of vertical vibration to the head but only basic data are available for rotational seat vibration. Barnes and Rance (1974, 1975) successfully measured such data and presented transmissibilities to the rotational axes at the head. Some of the questions that arise from their work for future investigation would be the measurement of translational motion at the head, effect of position of centre of rotation with respect to the human body, effect of posture, effect of seating, etc. Their work showed that much of the activity at the head was below 20 Hz and whole-body resonances occurred at frequencies below 5 Hz, therefore it would be worth conducting experiments at these low frequencies to further establish this. Also, at very low frequencies, active postural control might play an important role and the effect of this is, as yet, unknown.

2.8 HEAD MOTION FOR STANDING SUBJECTS

There are many vehicles and machinery that require people to stand upon vibrating platforms, examples of these include buses, trains, etc. In the previous section (Section 2.6), literature was reviewed presenting data of the transmission of vibration to the head for seated subjects - this including different axes of vibration and the effect of many variables. All these experiments could be conducted equally for standing subjects with the exception of a few variables (e.g. backrest). There would be different postures of the body that could be investigated (standing erect, standing with legs bent, etc.), different foot separation (for stability), the effect of holding on to a vibrating structure while under going whole-body vibration, etc.

The basic transmissibility results to be expected for standing subjects and the main frequencies of interest were partially resolved in the late 1950's by Dieckmann (1957a). Frequencies up to 100 Hz were investigated and the results showed that for fore-and-aft vibration of the platform, the head moved in a complex manner with significant motions in the fore-and-aft and vertical axes. The magnitudes of head motion depended upon the frequency excitation, see Figure 2.25.

The available literature investigating the transmission of floor vibration to the heads of standing subjects is reviewed below. As was the case for experiments with seated subjects, most studies are reported for vertical vibration while no studies exist for some of the other axes.

2.8.1 Vertical floor vibration

Goldman and von Gierke (1961) report of data presented elsewhere (Dieckmann, 1957b) on the transmission of vertical vibration from the floor to the head of a standing subject, the transmissibility is shown in Figure 2.26.

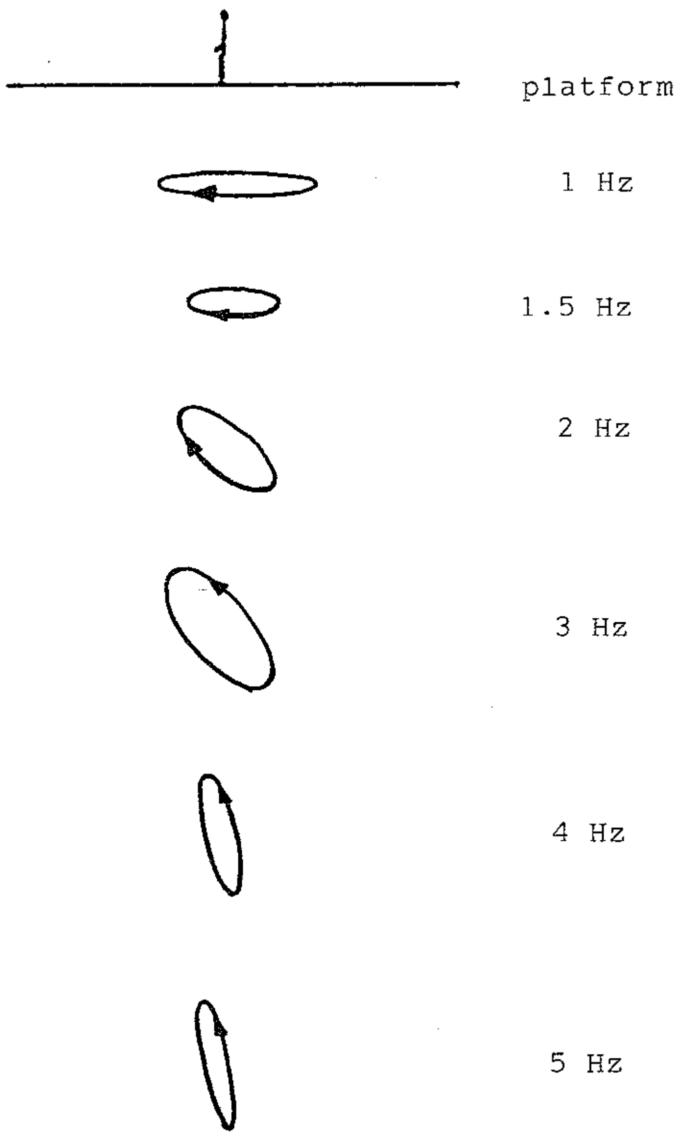


Figure 2.25 Head movement of a standing subject during fore-and-aft vibrations of the platform (Dieckmann, 1957a).

Though no details are given about the experimental set-up and procedure (due to difficulties in language translation), the results show a main resonance peak at about 4 Hz with a second, but of lower magnitude at around 20 Hz. This gives the basic information on the frequency range that required further investigation.

An experiment involving eight standing subjects was conducted by Coermann (1962) in which vertical head motion was measured using an accelerometer tied to the subject's head with an elasticated bandage. The subjects were

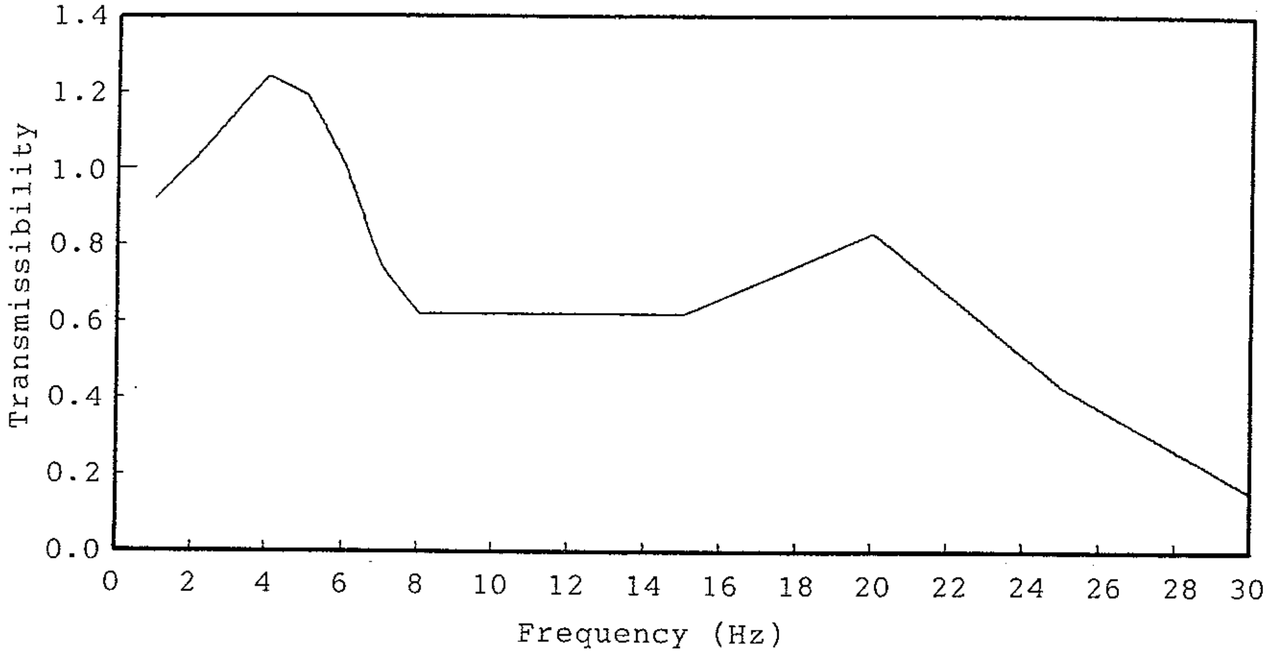


Figure 2.26 The transmission of vertical vibration from table to the head of a standing subject (Goldman and von Gierke (1961) adapted from Dieckmann (1957b)).

required to stand in an erect posture with 'stiff knees' (presumably knees locked to maintain a straight legs posture). The frequency range investigated was 1 Hz to 20 Hz (1 Hz to 14 Hz at 0.5 Hz steps, 14 Hz to 20 Hz at 1 Hz steps) and a vibration magnitude of 0.5g (4.91 ms^{-2}). Transmissibility data for a single subject are shown in Figure 2.27. A clear resonance peak is present at about 5 Hz and the occurrence of significant head motion over the frequency range 11 Hz to 15 Hz. This demonstrates that for that subject standing in a 'stiff knees' posture, there were two main resonance peaks up to the frequency investigated, i.e., 20 Hz. An experiment carried out with subjects standing with legs bent at the knees showed a lower resonance frequency and significant attenuation of vibration above 2 Hz.

Hornick (1962) attempted to determine the effect of standing in such a posture so as to reduce the transmission of vibration from the floor to the head. Six male subjects took part in the experiment and were instructed to stand in a slightly "crouched position" to "soak up" vibration in

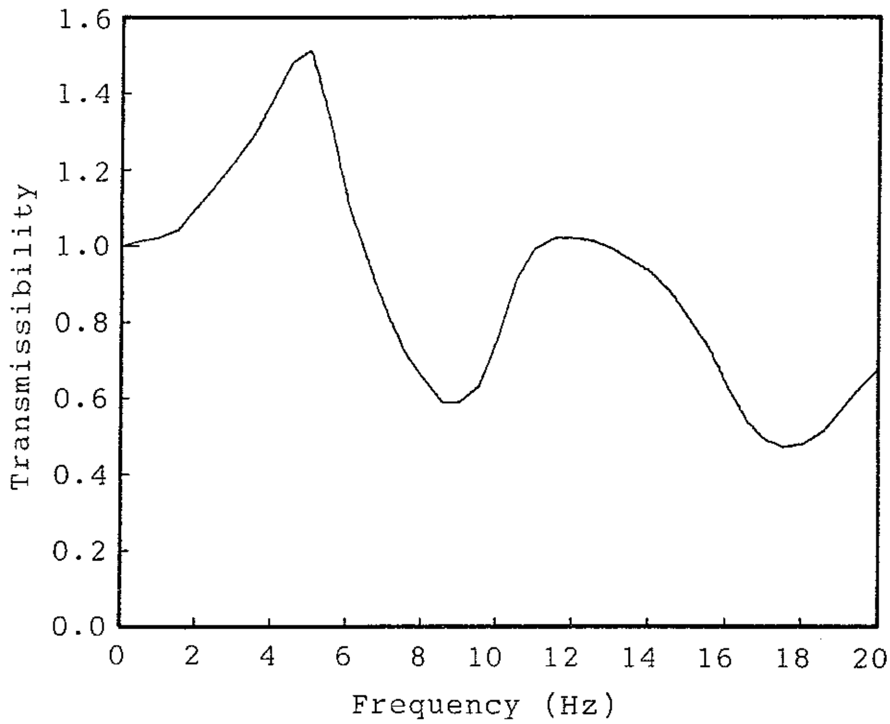


Figure 2.27 The transmission of vibrations from floor to head for one subject standing in an erect posture (Coermann, 1962).

the legs - thus attenuating vibration transmitted to the head. Motion at only two frequencies was investigated: 2 Hz and 5 Hz. Mean transmissibility data between vertical floor and vertical head motion for the subjects showed values of approximately 84% for 2 Hz motion and 35% for 5 Hz motion. It was demonstrated that head motion at 2 Hz was affected by time (there was a gradual increase in transmissibility with increased exposure to the same vibration) this indicating that the legs appear to become stiffer (i.e. higher transmissibility) with time. Duration had a similar effect at the 5 Hz frequency. Though interesting transmissibility data were obtained in this experiment, there was no 'standard' posture to compare the data with, e.g. standing upright with straight legs.

Vertical head motion was measured during vertical floor vibration in an experiment conducted by Garg and Ross (1976) with 12 subjects (8 male and 4 female) standing in a normal stance. Vibration at the floor was sinusoidal covering a frequency range of 1 Hz to 50 Hz and amplitudes of 0.003 inch to 0.02 inch (0.076 mm to 0.508 mm). Average transmissibility results showed four distinct resonance peaks in this frequency range, these are noted in Table 2.7 with the corresponding transmissibility magnitudes. It is hypothesised that the 2 Hz peak may be due to a resonance of the internal organs; 6 Hz peak caused by a resonance of the vertebral column; 20 Hz being a response of the legs and the 33 Hz peak possibly caused by the neck stiffness. Attempts were made at explaining these frequencies by developing a biodynamic model. A higher resonance frequency was also observed at about 43 Hz which was thought to be caused by pitching motion of the head.

Table 2.7 Resonance frequencies and amplitudes between vertical floor and head motion for standing subjects (Garg and Ross, 1976).

Resonance Number	Frequency (Hz)	Amplitude
1	1.99	1.35
2	6.14	1.71
3	19.44	1.53
4	33.20	-

The effect of different leg-postures on head motion while undergoing whole-body vibration was investigated by Rao et al. (1975): the postures were standing erect with straight legs and then to stand with knees bent so as to absorb as much of the vibration as possible. Vertical head motion was measured for 8 male subjects using an accelerometer gripped between the teeth. Each subject was exposed to random vibration covering frequencies up to 50 Hz and at four different vibration magnitudes: 0.030g, 0.064g, 0.132g and 0.240g r.m.s. (0.29 ms^{-2}, 0.63 ms^{-2}, 1.30 ms^{-2} and 2.35 ms^{-2} r.m.s.). Interesting results emerged from the experiment, mean transmissibility data for a straight legs posture showed two resonance peaks, one over the frequency range 3.5 Hz to 5.5 Hz and the second around 12 Hz to 15 Hz. When standing in a knees bent posture, only one resonance peak occurred and this around 2 Hz to 3 Hz. The legs bent posture greatly attenuated vibration transmitted to the head above 6 Hz. The transmissibilities for the different vibration magnitudes showed that for both postures, greater levels of head motion occurred for lower magnitudes of floor vibration although there were no linear changes.

In a later investigation, Rao (1982) reported of the effect of the arms on head motion while standing on a vibrating platform. Eight male subjects were required to stand in two postures: (i) standing straight with arms at the sides and (ii) standing straight with arms stretched out in front. Head motion was measured for each subject whilst being exposed to sinusoidal motion at 11 discrete frequencies (ranging from 2.5 Hz to 30 Hz) at three different vibration magnitudes (0.64 ms^{-2}, 1.32 ms^{-2}, 2.0 ms^{-2} r.m.s.). In Figure 2.28 are shown mean transmissibility curves between vertical floor and vertical head motion for the subjects standing with their arms hanging down at their sides, while being exposed to the vibration magnitude of 1.32 ms^{-2} r.m.s. The figure shows two resonances, one at about 5 Hz and the second around 16 Hz. The differences in transmissibility for the subjects standing in the arms stretched posture were small: a slight reduction in head motion at the first resonance peak and a slight increase in transmissibility at the second resonance peak.

As the head is free to move in all of the six axes of motion, it must not be assumed that no head motion would occur in axes other than the vertical during vertical floor vibration for a standing subject. This was demonstrated by Kobayashi et al. (1981) in an experiment where fore-and-aft and vertical motions at the head were monitored during exposure to whole-body vertical vibration. Fore-and-aft

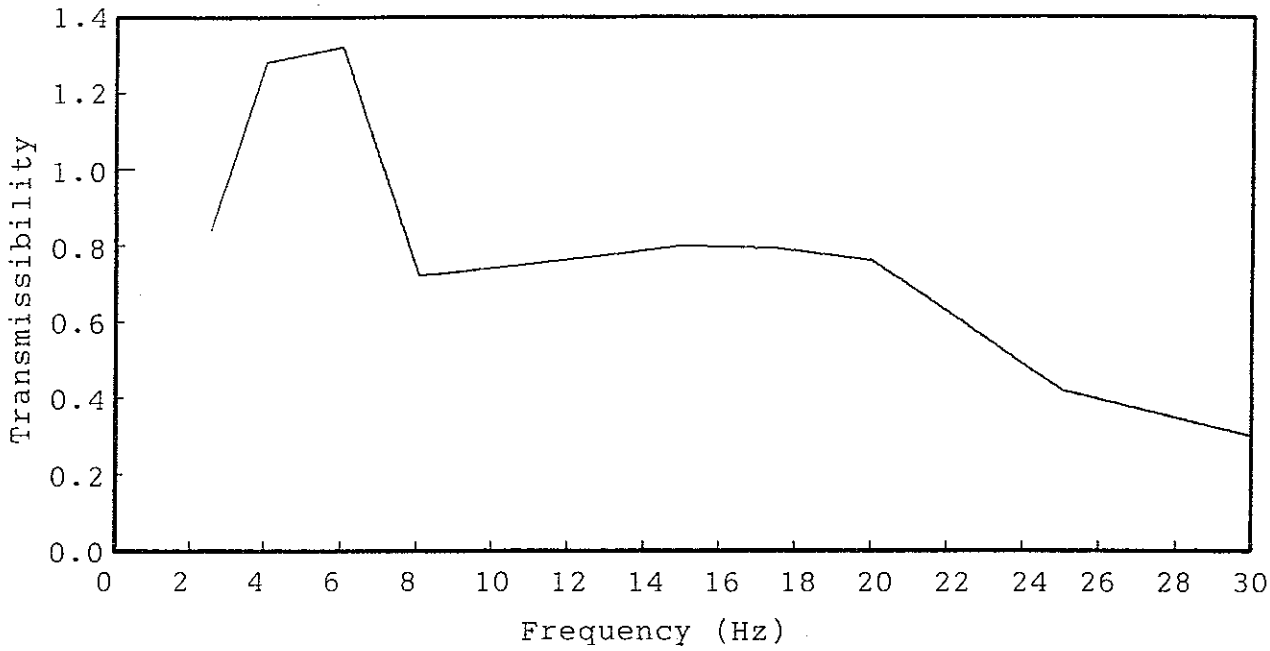


Figure 2.28 Mean transmissibility between vertical floor and head motion for standing subjects (Rao, 1982).

motion at the head showed transmissibilities of approximately the same magnitude as vertical motion at about 5 Hz. Though measurements were not made of motion in the other axes at the head, significant magnitudes of motion might have resulted in the pitch axis (i.e. the third axis in the mid-sagittal plane).

2.8.2 Horizontal floor vibration

One study is known of where the transmission of fore-and-aft vibration from the floor to the head for standing subjects has been investigated. This was a study by Dieckmann (1958) (cited by Goldman and von Gierke, 1961). No details about the experiment set-up could be found, however Figure 2.29 shows the transmissibility measures obtained. It appears that the lowest frequency investigated was 1 Hz with increments of 0.5 Hz and the greatest transmissibility for fore-and-aft motion at the head occurred below 1 Hz. This clearly shows the lack of a fine frequency resolution to investigate the most important frequency range. Vertical motion at the head was also measured and these data showed that above 5 Hz, the transmissibility between vertical head motion and fore-and-aft floor vibration was between 0.1 and 0.3. This would depend very much on the position of measurement on the head as pitching motion would also be excited and thus would result in differing magnitudes of vertical motion (Dieckmann, 1958).

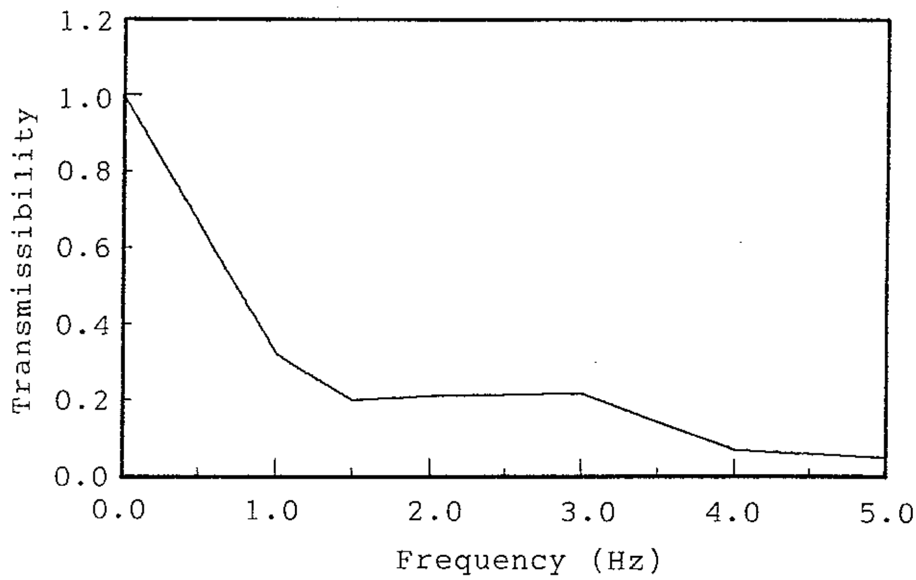


Figure 2.29 Transmission between fore-and-aft table and head motion (Goldman and von Gierke (1961) adapted from Dieckmann (1958)).

No reportings have been found concerned with the transmission of lateral floor vibration to the heads of standing subjects.

2.8.3 Rotational floor vibration

There are three axes that could be included in this section: roll, pitch and yaw. Unfortunately, no reports of experiments have been found dealing with the exposure of standing subjects to roll and pitch vibration of the floor. For yaw motion, only one study has been found in the literature and this mainly concerned the effect of vibration on vision (Benson, 1972). In the experiment, 10 subjects were exposed to sinusoidal yaw oscillation of the floor covering a frequency range of 0.5 Hz to 10 Hz and peak accelerations of ±280 degrees/s^2 (vibration magnitude of ±4.89 rads^{-2}). Head motion was measure using a dental mould bite-bar with a rotational accelerometer attached to it. The subjects were instructed to stand in two postures; relaxed and tensed. The data were analysed in the form of transmissibilities and are presented in Figure 2.30. It is seen that head motion occurred mainly up to 5 Hz with rapid attenuation above this frequency. This appears to be the case for both postures. Standing in a tensed posture resulted in the transmission of larger magnitudes of motion to the head and, for both postures, the variability in transmissibility between subjects was large for frequencies below 5 Hz.

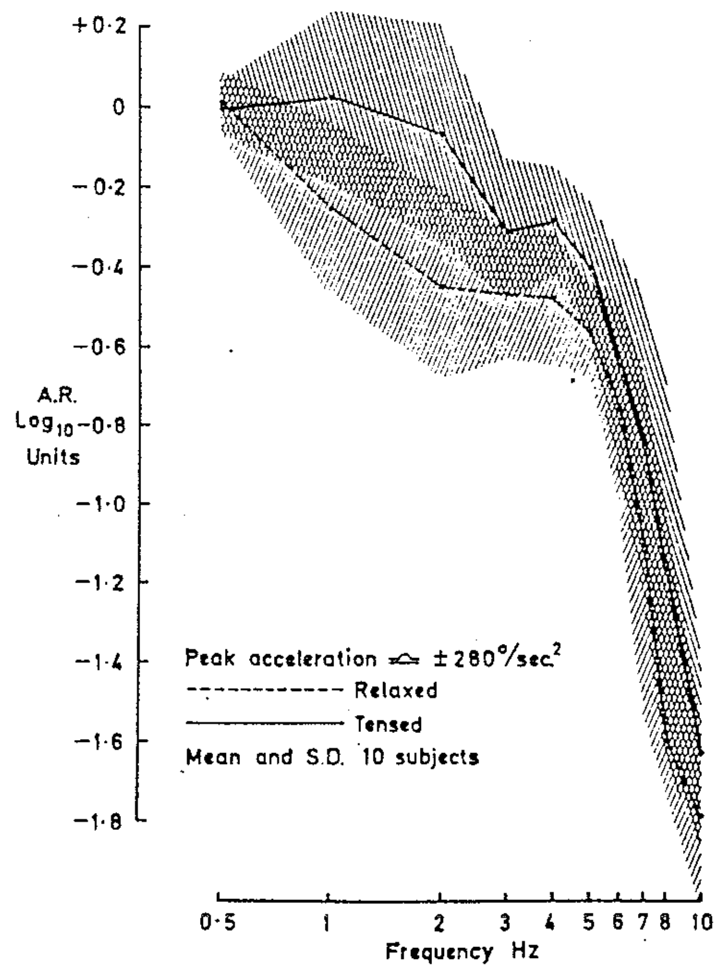


Figure 2.30 Mean transmissibility for yaw axis motion between floor and head vibration for standing subjects (Benson, 1972).

2.8.4 Discussion

Most of the research conducted on the transmission of floor vibration to the heads of standing subjects has been for vertical vibration, and this amounts to only a few studies. These data indicate that the body demonstrates two resonance peaks in the floor-to-head transmissibility; one at around 5 Hz and the second of lower magnitude in the region of about 15 Hz to 20 Hz. This has been for only vertical vibration at the head. It has been recognised that the head also moves in other axes although measurements made have not been as comprehensive.

Only individual studies exist of the exposure of vibration in fore-and-aft and yaw axes while no reportings have been found of vibration in the lateral, roll and pitch axes. Results from these studies would not only provide fundamental biodynamic data but may prove valuable in determining postural stability of people standing in vibration environments.

2.9 CONCLUSIONS

This section discusses the work that has been done by previous researchers together with the current status of studies reporting the biodynamic response of the human body to vibration. Also, the possible areas that require further investigation are examined.

2.2 Methods of head motion measurement

From the several different types of instrumentation reviewed in the measurement of head motion, the accelerometer appears to be the most commonly used. This kind of apparatus could be used in various environments and need not be constrained to only laboratory conditions. Some of the other methods would be more suitable to the laboratory rather than in 'field trials' (e.g. pulleys, optical-photographic, potentiometers). The effect of the Earth's gravitational field on the accelerometer signal can, in most cases, be accounted for.

The equipment should ideally be capable of monitoring motion in all axes at the head, that is, x-, y-, z-, roll, pitch and yaw. Such a set-up, if attached to the head, should be light enough so as not to affect the motion of the head. A six-axis bite-bar will be developed and discussed in a later section.

2.3 *Input motions used during whole-body vibration*

Variations in vibration spectra have been shown to have a small effect on seat-to-head transmissibility, this was concluded from an experiment involving a single subject and three types of motions: random vibration spectra, sine swept and discrete sinusoidal vibration. However, it must be emphasized that the effect was small and was of the order of intra-subject variability. For the investigation of a whole range of frequencies, a random vibration spectra would be advantageous. Vibration spectra used in the experiments reported below were computer generated where the frequency content could have been carefully selected. Some studies exist where head motion measurements were made in, for example, vehicles where the vibration would have a spectrum peculiar to that vehicle and more than one axis at the seat would be active. Further studies on this topic might concentrate on comparison between transmissibility data obtained in laboratory and field conditions. Also, the variation in transmissibility could be investigated when using recorded vehicular motion and computer generated vibration. This will be addressed in a later section.

2.4 *Locations of measurement of motion*

There are a whole range of measurement sites on the upper body that could be used to measure vibration including the head. This location is not important if the body behaved in a linear manner and there was no rotational motion. However, this is not the case as the head is free to move in any of the six axes of motion. Many researchers have pointed out the effect of rotation of the head on translational motion measured but have stopped short of actually calculating the effect, i.e. have not calculated motion at other points of the head. A bite-bar appeared to provide vibration data of the head with no problems which would have been encountered with other methods (e.g. skin movement). Motion at the head can be monitored in the six axes using a bite-bar enabling motion to be calculated at any point on the head, thus overcoming any problems that rotation of the head might have posed. There are numerous positions on the head at which motion could be calculated, one of which is the centre of gravity. Such a system and analyses will be used for the current studies and will be discussed in a later section.

2.5 *Methods of analysis of head motion data*

The type of analysis used depends very much on whether a simple voltmeter, strip chart recorder or a computer is available and used. A voltmeter or an oscilloscope would be suitable for determining transmissibility values using the peak-to-peak or r.m.s. method - also, a sinusoidal input motion might be needed. For any type of frequency analysis, a digital computer would be required. It is envisaged that heavy use will be made of a computer in some of the complex and involved spectral analyses to be used in this study.

2.6 Variables affecting the transmission of vertical seat vibration to the head

2.6.1 Intrinsic variables

2.6.1.1 Effect of head angle

These studies showed that, generally, a head pitch angle above the horizontal resulted in the transmission of increased vertical head motion while lower transmissibilities occurred for angles below the horizontal compared with a looking straight and horizontal head position. These data might be of value in determining, for example, whether increased head motion (i.e. for pitch angles above the horizontal) resulted in a decrement of performance in a head aiming task. The increased head motion for increase pitch head angles is thought to be due to the head centre of gravity being closer to the neck (i.e. line of motion) - the centre of gravity of the head being almost vertically above the neck.

2.6.1.2 Effect of posture and muscle tension

There are two main extreme postures that have been investigated by many researchers, these are relaxed (slouched or slumped) and erect (tensed or stiff). Overall, it has been demonstrated that an erect posture results in increased vertical head motion for frequencies greater than about 5 Hz. Different results have emerged from different studies for vertical head motion at lower frequencies but a relaxed posture generally shows a large whole-body resonance peak at around 4 Hz to 6 Hz. Recent studies have concentrated on the effect of pelvic angle on the transmissibility of vertical seat vibration to the head showing this to be an important factor almost dictating the motion of the head for frequencies greater than about 6 Hz. A pelvic angle of 105° resulted in increased head motion for frequencies above 6 Hz than a pelvic angle of 85°. Posture of the body is one variable that can give completely differing transmissibilities for visually similar seating postures.

2.6.1.3 Intra-subject variability

This is one area that has been overlooked by many investigators when determining the effect of a particular variable on the transmission of vibration to the head. An indication of variability that should be expected during intra-subject measures is essential in that if the effect of a variable on transmissibility is smaller that that found during repeat measures, then it is highly unlikely that the parameter under investigation had any significant effects. Indications of intra-subject variability would ideally be required for all seating and experimental conditions to be investigated. This would include input vibration in the fore-and-aft and the lateral axes at the seat rather than just the vertical axis. This will be investigated in some of the following sections.

2.6.1.4 Inter-subject variability

Interestingly enough, more studies were found in the literature reporting inter-subject variability in seat-to-head transmissibility that intra-subject variability. Inter-subject variability is just as important as this shows the variability that should be expected between individuals. These data might be of value to, for example, designers of vehicle interiors who might need to know the range of head movements that might occur between individuals so that they can position their instruments appropriately. Biodynamic modelling is another application of such data. There is a range of factors that might contribute to such variation between people such as physical characteristics, muscle tension, seating condition, head orientation and the most important (and likely) parameter, subject posture. It has been shown that slight postural variations can lead to surprisingly different transmissibilities. Detailed studies will be reported in the later sections dealing with inter-subject variability.

2.6.1.5 Physical characteristics of subjects

Correlating physical characteristics of subjects with head motion would be one step in the right direction in attempting to explain differences in head motion between individuals. Several studies exist in which such correlations have been determined between head motion and subject characteristics including age, weight, height and gender. From these bodily parameters, data have shown that subject weight correlated significantly with head motion: lower magnitudes of head motion are likely to occur in heavier people than with relatively lighter subjects - this finding was significant at the 5% level. Other significant correlations were found between the other parameters but no plausible explanations have been offered. Such a finding was that greater levels of head motion were likely to occur in female subjects than male subjects. It must be borne in mind that some significant findings would be expected as just chance due to the large number of subjects. One point to remember is that a small difference in posture or muscle tension is likely to cause greater changes in seat-to-head transmissibility than those to be found due to subject physical characteristics!

2.6.2 Extrinsic variables

2.6.2.1 Effect of vibration magnitude

This is one parameter that has been studied by several investigators with differing results. Some have concluded that the human body behaves like a linear biodynamic system while others have shown large non-linearity in seat-to-head transmissibility. Attempts were made by one researcher (Pradko et al., 1965) in determining a linear regression between seat vibration magnitude and head motion. These data showed almost perfect linear relationship between the two factors for some frequencies. Such a finding would be invaluable in the development of biodynamic models. Ideally, if such linear relationships could be obtained (or exist) between physical characteristics of subjects and head motion, this could be a sure step in explaining the transmission of vibration through the human body.

2.6.2.2 Effect of backrest angle

This section discussed the effect a backrest and backrest angle had on head motion transmissibility. The studies have shown that when contact is made with a backrest, head motion will increase compared with a condition in which no backrest is used. The data also show that the magnitude of head motion will generally increase with increasing backrest angle. One study of the effect of headrest indicated that head motion was considerably increased when contact was made with a headrest. In conducting such studies, it is important to realise that the surfaces at the seat, backrest and the headrest must not alter the vibration characteristics, i.e. should not have a foam cushion as this will affect vibration transmission. The effect of contact with a backrest on head motion will be reported in detail in later sections.

2.6.2.3 Effect of body harness

There are essentially three seating conditions that could be investigated, these are 'back-off' (no backrest contact), 'back-on' (back on backrest) and harness (back on backrest with harness). The previous section (Section 2.6.2.2) showed that when contact is made with a backrest, more vibration is transmitted to the head than a no backrest condition. This section showed that even greater levels of vibration occur at the head when a harness is worn. This conclusion comes from only a few systematic studies.

2.7 *Seat motion in other axes*

2.7.1 *Horizontal seat vibration*

Fore-and-aft seat vibration shows some whole-body resonances and these have tended to appear at different frequencies in the few reported studies. This could be due to the differing seating conditions which has been shown to greatly affect seat-to-head transmissibility. A whole-body resonance occurs possibly around 2 Hz to 8 Hz.

For lateral seat vibration, a whole-body resonance has been reported to occur at low frequencies (≅ 2 Hz). The studies include the effect of some other variable on head motion such as body harness, headrest and seating condition. It is difficult to determine whether the transmissibility data were greatly affected by these variables since only one-off studies exist investigating the effect of a particular parameter.

It is clear that there is a shortage of information dealing with the transmission of horizontal seat vibration to the head. One main point that appears to have been overlooked in the reported studies is the need for low frequency measurements. The studies of the transmission of vertical vibration have advanced so much that the effects of many variables are well documented. This is far from the case for horizontal seat vibration - basic fundamental transmissibility data are required for these axes of excitation. These topics will be addressed in a later section.

2.7.2 Rotational seat vibration

A search through the literature showed that there appears to be only one study per axis to yield transmissibility data between rotational seat and head motion, these studies were conducted by Barnes and Rance (1974, 1975). These data provided a basic insight into the frequency response to be expected. Transmissibilities between seat and head motion for both roll and pitch seat vibration have shown that maximum transmissibilities can be of the order of 4 over the frequency range 2 Hz to 10 Hz. The body tended to attenuate frequencies above 2 Hz in the transmission of yaw vibration to the head and this was heavily dependent on whether a restraint system was used or not. Unrestrained subjects tended to display maximum yaw axis head motion at about 2 Hz while no amplification of seat motion occurred for restrained subjects. This shortage of information concerned with the transmission of rotational seat vibration to the head shows the need for more studies on this topic.

2.8 Head motion for standing subjects

The transmission of vertical vibration from the vibrator table to the heads of standing subjects has been investigated by a few researchers and reports included the basic transmissibilities. In general, two vibration peaks can be seen in the data, one at around 5 Hz and the second (a broad peak) over the frequency range 11 Hz to 20 Hz. Most of the studies have measured vertical motion at the head and one study reported of the measurement of both fore-and-aft and vertical vibration. Resonance peaks occurred in both axes at about 5 Hz and were of similar magnitude. This implies that other axes at the head (e.g. pitch) may have also been excited and shows the need for motions in other axes at the head to be measured. Also, the posture of the legs has been shown to greatly affect floor-to-head transmissibility: a legs bent posture will substantially attenuate vibration transmitted to the head compared with a normal stance straight leg posture. These points will be investigated in a set of experiments and reported in a later section.

Only two studies were found concerned with floor vibration in other axes: one on fore-and-aft vibration and one on yaw vibration at the standing subject's feet. The one reporting horizontal floor vibration is an old study (written over three decades ago) and showed that mainly low frequencies (<1 Hz) were transmitted to the head and high frequencies (>1 Hz) were attenuated by the body. The study of experiments with yaw motion at the floor also showed that high frequencies (>5 Hz) were greatly attenuated by the human body. There is a whole new area of research that could be studied for these axes of vibration (e.g. body postures, position of centre of rotation for rotational motion, etc.). The transmission of horizontal vibration from the floor to the heads of standing subjects will be discussed in detail in a later section of the thesis.

This section has reviewed most of the work conducted so far concerned with the transmission of vibration through the body to the head for seated and standing subjects. A great deal of research has been directed towards vertical seat vibration and knowledge of this topic is well advanced. However, as always is the case, many questions arose from the studies and information gaps were found which needed more and specific experiments to be conducted. In the case of vibration in other axes than the vertical direction, much advancement is required for both seated and standing subject data. It is hoped that the following sections of the thesis will shed light on some of the questions posed above and generally provide detailed information on the study of biodynamics.

CHAPTER 3

EQUIPMENT

3.1 INTRODUCTION

Most of the experiments conducted within the laboratory required similar apparatus which is discussed briefly under the appropriate section (see Chapters 5, 6 and 7). This chapter discusses in detail some of the apparatus used for those experiments, such as the bite-bar. Details are also given of other equipment used including vibrators for vibration generation, a seat for seated subjects and some portable vibration measurement and recording equipment used primarily for field trials.

3.2 DEVELOPMENT OF THE SIX-AXIS BITE-BAR AND SIT-BAR

Motion of the head during whole-body vibration could be measured at several alternative locations of the combined head and helmet system. Since most helmets have a rigid shell, accelerometers could be easily attached to the surface using a screw or adhesive attachment. However, measurements made on a helmet would only be an approximation of the motion since there are relative movements (translational and rotational) between heads and helmets (Jarret, 1978; Wells, 1982).

A bite-bar with attached accelerometers allows more accurate monitoring of the movements of the head than can be achieved by mounting accelerometers on the helmet. A bite-bar with three translational and three rotational accelerometers can be used to determine the motion of the head in all six axes. However, since rotational accelerometers are both large and delicate, they make a bite-bar heavy and delicate. The weight might affect the motion of the head while the lack of robustness will limit applications in harsh environments.

An accelerometer mount was designed so that it could be used with a bite-bar to measure six axes of head motion. The design was based on a method employed by Lawther and Griffin (1980) for the measurement of ship motion. In this method the rotational accelerations are determined from signals provided by pairs of translational accelerometers. The bite-bar is shown in Figure 3.1. Translational accelerations were taken as those measured by three mutually perpendicular accelerometers on block 3, i.e. A_{x1} for x-axis, A_{y1} for y-axis and A_{z1} for z-axis motion at the head. The signals A_{z1} and A_{z2} and the separation between blocks 2 and 3 enabled roll accelerations to be calculated, A_{z1} and A_{z3} together with the separation between blocks 1 and 3 were used to determine pitch; yaw motion was calculated using A_{x1}, A_{x2} and the separation between blocks 2 and 3. (This concept has been previously used by many investigators: Padgaonkar et al., 1975; Morris, 1973; Lawther and Griffin, 1980). The formulae required for calculating rotational accelerations were:

$$\text{roll acceleration} \quad r_x = \frac{A_{z2} - A_{z1}}{d_y}$$

$$\text{pitch acceleration} \quad r_y = \frac{A_{z3} - A_{z1}}{d_x}$$

$$\text{yaw acceleration} \quad r_z = \frac{A_{x2} - A_{x1}}{d_y}$$

where: A_{x1}, A_{x2}, A_{z1}, A_{z2} and A_{z3} are accelerations in various axes and at different locations, and
d_x and d_y are distances between accelerometers on blocks 1 and 3, and between blocks 2 and 3 respectively.

The mass of the bite-bar including accelerometers was 135 g and with the dental mould, it was 158 g. This compares favourably with the heavier bite-bars used by previous researchers to monitor fewer axes of motion (e.g. 300 g used by Johnston (1978), 250 g used by Barnes and Rance (1975)).

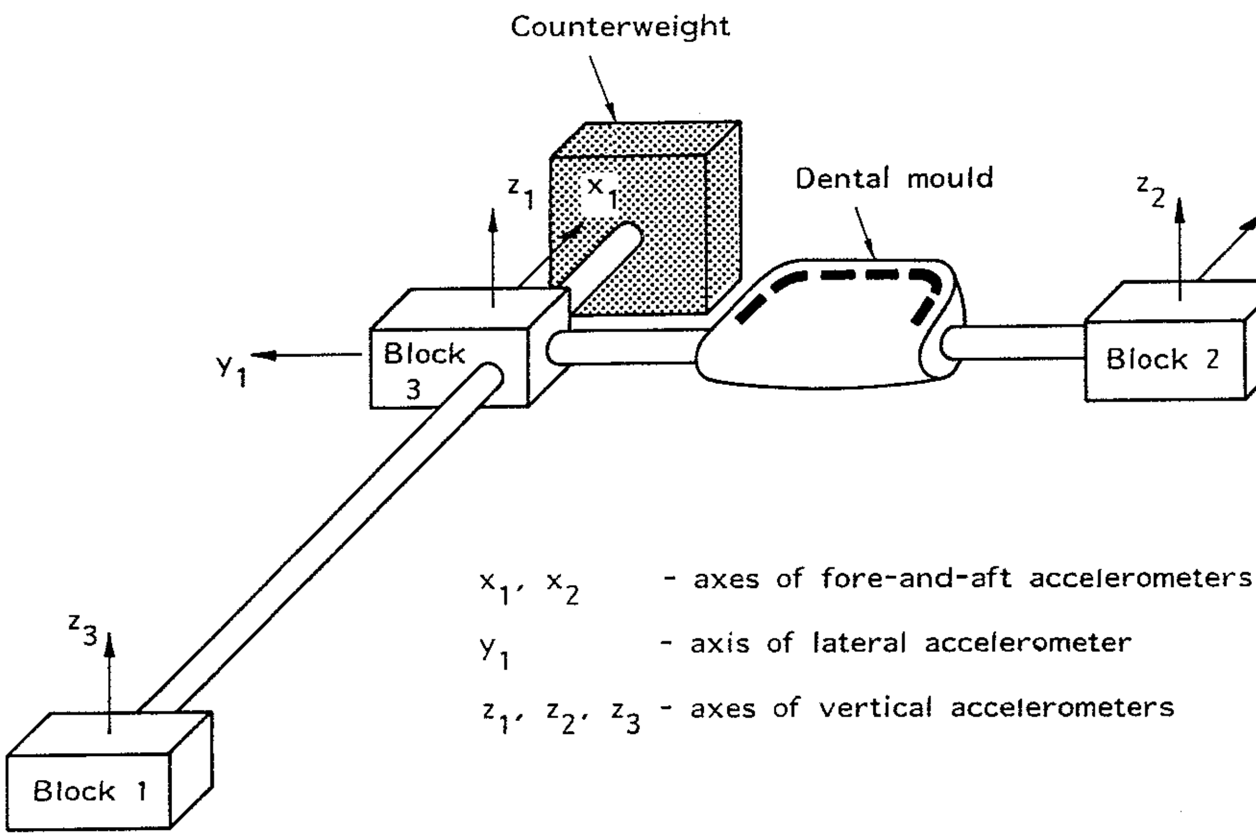


Figure 3.1 Bite-bar with relative positions of the accelerometers, mounting blocks and a counterweight.

The design of the bite-bar was such that the lowest inherent resonance frequency of the various attachments was of the order of 60 Hz. The mode shape of the bite-bar at this resonance was vibration in the vertical axis between block 1 and block 3. This frequency was measured assuming the rod joining blocks 2 and 3 is held rigidly at the dental mould. This was greater than the frequency of interest to be used during these studies (i.e. 25 Hz).

It was also desired to measure motion at the principal input to the body which, for a seated subject, is the motion on the seat surface. In the case of a subject seated on a laboratory vibrator the motion may be unidirectional. More generally, the motion of a seat in a vehicle occurs in all six axes of motion. A device for measuring seat motion in all the six axes was therefore needed.

A SIT-BAR (Seat Interface for Transducers indicating Body Acceleration Received) could be used to measure seat vibration. This would allow both translational and rotational accelerations to be monitored (Whitham and Griffin, 1977). If rotational accelerometers were used they would have to be attached on to a 'leg' which sticks out from the SIT-BAR: this could pose space problems in the confines of some of the military vehicles this was to be used in. Also, rotational accelerometers are generally larger, heavier, dearer and more prone to damage due to impacts when compared with translational accelerometers.

Figure 3.2 shows the arrangement for a six-axis SIT-BAR containing the same three mounting blocks on the bite-bar. (The alloy rods joining the blocks and the dental mould are removed before placing the accelerometer blocks in the SIT-BAR.) This design was closely based on that used by Whitham and Griffin (1977). A perspex block with space for the accelerometers and the cabling is shown in Figure 3.2. A thin alloy plate is screwed on to the perspex to protect the transducers and the layer of felt material was glued on the alloy plate to ensure that the subjects did not sit directly on to the cold metal plate. The total mass of the SIT-BAR was 1.07 kg.

Both the bite-bar and the SIT-BAR were designed such that translational and rotational accelerations could be calculated using the same analyses: same equations as above were used to calculate rotational accelerations for both head and seat motion.

The accelerometers mounted on the bite-bar (and SIT-BAR) vibration measuring blocks were miniature translational accelerometers manufactured by Entran. These were full-bridge piezo-resistive (strain gauge) type

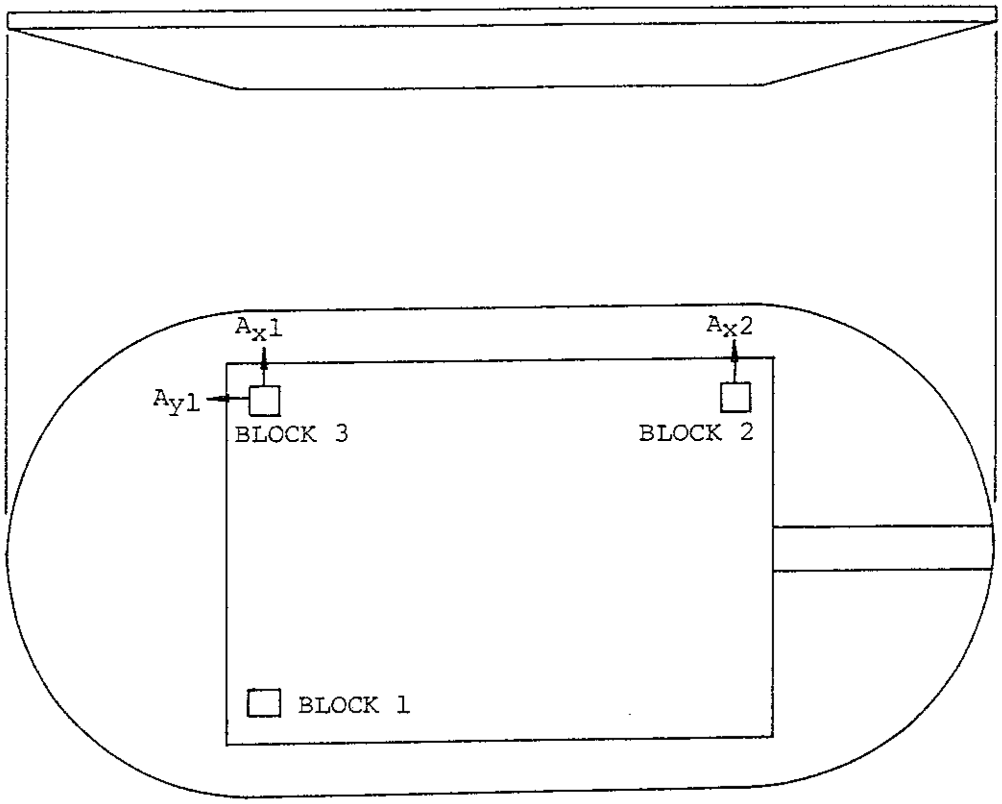


Figure 3.2 SIT-BAR with the relative positions of the accelerometers.

accelerometers, the model number was EGAX±5 with an operating range of ±5g (gravity). The accelerometers had a viscous fluid medium to provide damping which was nominally 0.7 critical to protect the transducer against damage should excitation occur at the resonance frequency or be exposed to a severe impact. Also, the accelerometers had internal mechanical overrange stops making the accelerometers capable of sustaining accelerations of ±10000g which reduced the possibility of damage due to shock or impact. A temperature compensation module was present on all accelerometer cables near the transducers which ensured that temperature changes within a specified range (30°F to 130°F) had no significant effects on the acceleration signals measured. The useful frequency range over which the accelerometers would faithfully provide acceleration signals was from d.c. up to about 200 Hz; the deviation in frequency response of the acceleration was less than 1 dB at 200 Hz. Each accelerometer weighed

0.5 gram and there were six accelerometers on the bite-bar. The weight contributed by the accelerometers was small (i.e. 3 gram) compared with the total weight of the bite-bar (i.e. 158 gram). Also, the total weight of the bite-bar was small when compared with the weight of the head which would be around 4.5 kg.

Before each experiment, the accelerometers were calibrated using two different types of tests. A static calibration of the accelerometers was performed by turning the sensitive axis of the accelerometer through the Earth's gravitational field (±1g). A typical example of the output is shown in Figure 3.3 for an accelerometer calibrated to give ±1 volt per gravity (i.e. 1/9.81 volts per ms^{-2}). The second calibration (called the jerk calibration) was to determine the correct polarity of the system (i.e. accelerometer, cabling, signal conditioning). This was carried out by holding the accelerometer in the position as

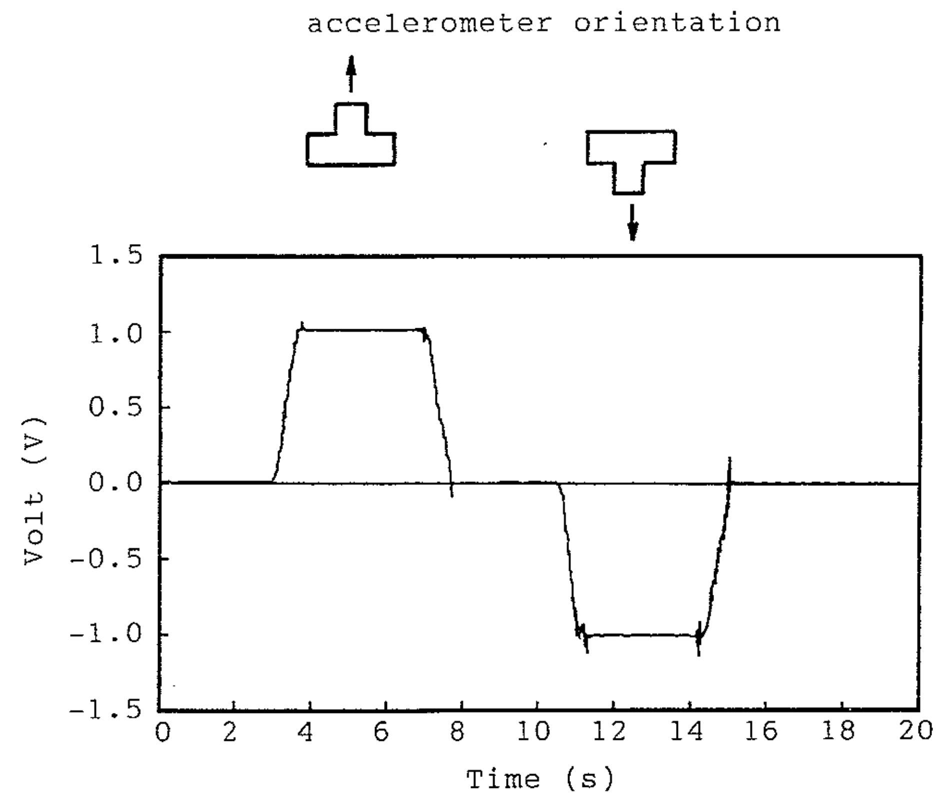


Figure 3.3 Static calibration voltage signal from an accelerometer calibrated at 1 volt per gravity and the corresponding accelerometer orientations.

would be used in the experiment and then rapidly moving it in the positive direction, then in the negative direction; the accelerometer was moved in each direction only once. The expected output from an accelerometer with a positive sense is shown in Figure 3.4. Should the system demonstrate a reversed polarity, the acceleration waveform acquired into a digital computer can be inverted to give the correct sense. A dynamic calibration procedure was conducted between paired accelerometers (by calculating transfer functions between accelerometers on the bite-bar) to check for any differences in relative sensitivity.

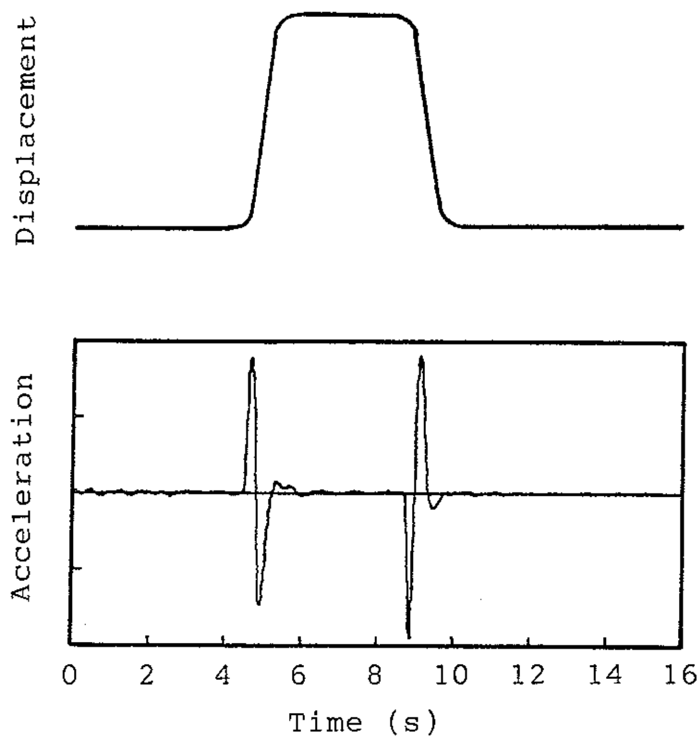


Figure 3.4 Acceleration signal from an accelerometer moved through the above displacement during a jerk calibration.

3.3 EXPERIMENTAL SEAT

In the determination of transmission of vibration through the human body to the head, it is essential that vibration is measured at the input to the body. For a seated person, this would be at the person-seat interface and at the floor for a standing person. If a seat with some form of cushion or foam is used, then the vibration characteristics of this would be required. In laboratory experiments, a seat which had no effect on vibration transmitted from the base of the seat to the seat-person interface would be advantageous as this would not involve dynamics of the seat.

A rigid flat seat was to be used in all of the major experiments carried out to determine the transmission of seat-to-head vibration (intra- and inter-subject variability experiments with seat vibration in all translational axes). A diagram of the seat is shown in Figure 3.5. The frame work was made of steel square tube and angle sections to give the structure rigidity in all axes. Sections on to which the backrest was attached extended up to the subjects head so that, if required, a headrest could be fitted on the frame work. The seat and backrest surfaces were made of wood; the supporting surface of the seat was 480 mm above the moving footrest and inclined backwards at an angle of 3° to the horizontal. The backrest was inclined backwards at an angle of 6° to the vertical. The lower and upper edges of the rigid flat backrest were 145 mm and 533 mm above the seat surface. It was found that neither the seat nor the backrest had any resonances within the frequency range (studied maximum frequency of 25 Hz) during exposure to vibration in any of the three translational axes. A thin layer (3 mm) of high stiffness, high friction rubber was glued on to both the seat and the backrest surfaces to reduce relative movements between the subjects and the seat due to sliding. A lap strap was worn by all subjects for safety purposes.

3.4 FIELD VIBRATION MEASUREMENT SYSTEM

Portability of equipment is usually not essential for apparatus used within a laboratory since normally a suitable place can be found for each item and then left there. The situation is quite the opposite when making measurements in, for example, vehicles. Compactness, portability, size and number of items was important when making vibration measurements in military vehicles due to the small confines within the vehicle.

A 'belt-pack' system was developed for making field

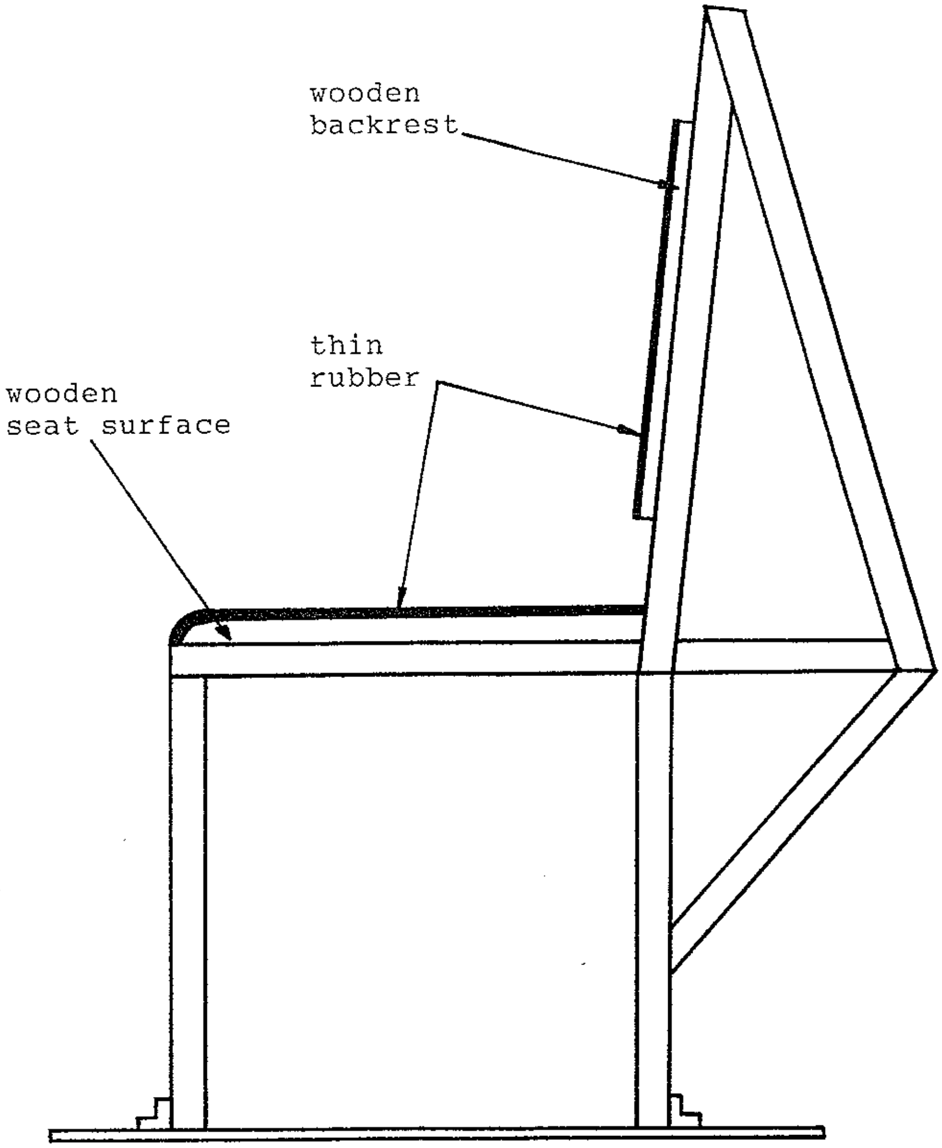


Figure 3.5 Hard flat experimental seat used in some of the studies.

measurements where the environment required the equipment to be small and portable; the system is shown in Figure 3.6. The system consisted essentially of three small boxes:

i) a connections box containing all the signal conditioning, balancing potentiometers and connections to the accelerometers, battery box and data cassette recorder,

ii) a battery box and,

iii) a data cassette recorder.

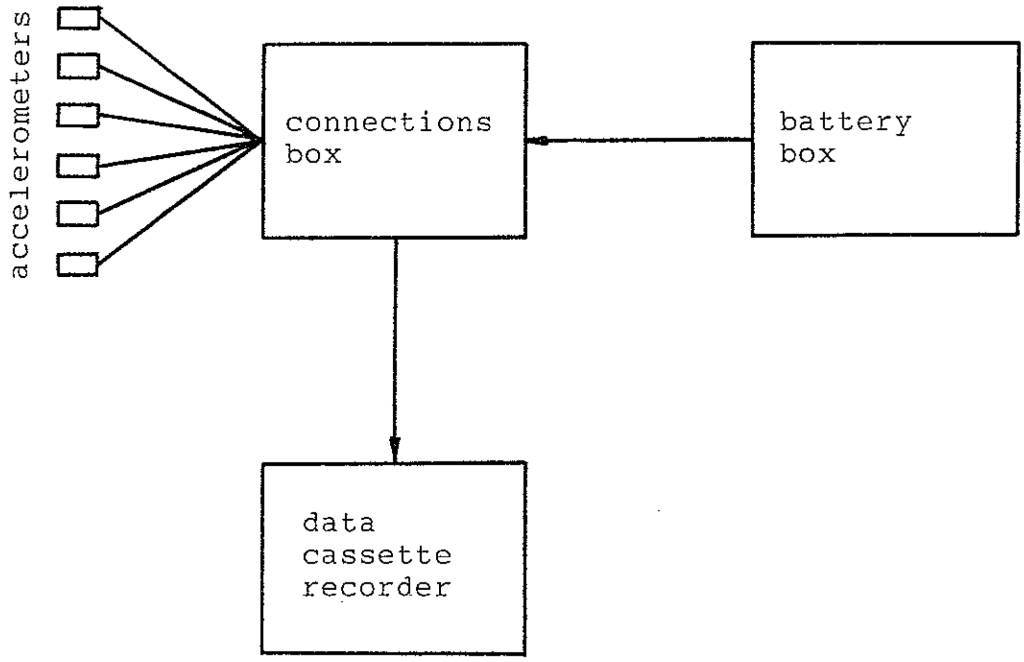


Figure 3.6 Diagram of the portable vibration measuring system: the 'belt-pack' system.

The three boxes could be attached on to a waist belt so that the experimenter could walk into a vehicle with the system. The whole system weighed 3.3 kg.

The system was designed so that six full-bridge accelerometers could be attached to the connections box. Normally, the bite-bar or the SIT-BAR arrangement was used, see Section 3.2. The accelerometers need not all be at one position (e.g. head or seat), they could be split up so that measurements were made at two or more locations. This was convenient in determining seat-to-head transmissibilities since simultaneous vibration measures would be required of both seat and head motion. A transfer function of one channel showed a flat frequency response with a low-pass filter at 2000 Hz which showed a decrease in response of 3 dB. This fully covers the frequency range used for whole-body vibration measurements in field conditions (see Chapter 7). All the other channels on the connections box showed similar frequency characteristics.

The battery box contained two lead acid rechargeable batteries and was the heaviest of the items weighing 1.74 kg. When fully charged, the batteries were capable of maintaining power to the system with six accelerometers for up to six hours.

Acceleration signals from the connections box were recorded on small high quality magnetic tapes using a compact FM (frequency modulation) data cassette recorder TEAC HR-30E. It was a 7-channel record only machine and was lightweight (600 g), portable and battery operated. It covered a frequency range of d.c. to 1250 Hz with a frequency response deviation of +0.5/-1.0 dB and had a recording duration of 45 minutes. The signal-to-noise ratio of the FM recording system was >38 dB. Replay of data was carried out using a TEAC R-71 recorder, this had similar frequency characteristics to the HR-30E.

3.5 VIBRATORS

Two vibrators situated within the Human Factors Research Unit, Institute of Sound and Vibration Research, Southampton University, were used in the studies to investigate the transmission of vibration through the human body. One was used to expose subjects to horizontal vibration and the other for vertical motions.

3.5.1 Horizontal vibration simulator

The horizontal electro-hydraulic vibrator was manufactured by Silverridge Technology Limited and is capable of producing displacements of 1 metre. It consists of an aluminium platform 1.57 m x 1.00 m which is attached to two hydraulic actuators via piston rods. Depending on the sign of the demand signal, both pistons work together to drive the platform in one direction or the other. The vibrator can simulate waveforms over the 0.05 Hz to 50 Hz frequency range. The response of the vibrator could be adjusted using a bank of in-built filters to obtain a reasonably flat response. This could be further modified by equalising for the response of the vibrator - this involves frequency spectral analysis and is explained in detail in Appendix 1.

The vibrator was capable producing accelerations of ±20 ms^{-2} and displacements of ±0.5 m; for safety reasons, these were limited to ±10 ms^{-2} and ±0.35 m respectively. There were other safety features built in the system to ensure that the subjects were exposed to controlled and safe vibration. Both the subject and the experimenter had emergency stop buttons, these operated a controlled shutdown of the complete hydraulic system of the vibrator. There were end buffers on each piston to reduce the magnitude of transient in the event of the platform impacting its maximum displacement limit with maximum velocity. These end buffers consisted of a cone shaped piston and trapping a volume of oil in the buffer which is expelled through a small annular gap.

Vibration was measured on the platform using a calibrated accelerometer attached on firmly using double sided sticky tape. This method of attachment has been shown to be sufficient for frequencies up to 50 Hz (Wells, 1982).

3.5.2 Vertical vibration simulator

The vertical electro-hydraulic vibrator was manufactured by Servotest and is capable of producing displacements of up to 1 metre. It basically consists of an actuator supported vertically by four struts, fixed on top of the actuator is a 1.50 m x 0.89 m aluminium platform. The vibrator had a nominally flat response from 0.05 Hz to 50 Hz and this could be further modified using a spectral equalisation procedure explained in Appendix 1. Acceleration waveform distortion was of the order of 5% and this was achieved by the use of hydrostatic bearings on the piston and no oil seals which minimised friction. Motions in the cross-axes were less than 1.5% of those in the axis of excitation.

The vibrator was capable of producing displacements of ±0.01 m to ±0.5 m and accelerations of ±0.5 ms^{-2} to ±20 ms^{-2} though these were limited to ±0.35 m and ±10 ms^{-2} respectively for safety reasons. The system had a dynamic force capacity of 10 kN and a static force capacity of 8.8 kN. It had been tested to accelerations of ± 20 ms^{-2} with a pay load of 400 kg on the platform.

Safety was of the utmost importance and the vibrator was designed to reproduce motions which are suitable and safe for the study of human response to vibration. It's safety features and performance was in accordance with BS 7085 (1989) (Guide to safety aspects of experiments in which people are exposed to mechanical vibration and shock). Built in the system were electrical, mechanical and hydraulic safety switches. These were necessary in order to prevent subjects from being exposed to hazardous motions. In addition to these safety measures, both the experimenter and the subject were equipped with emergency (panic) buttons which dumped the hydraulic pressure in a controlled manner, this in turn bought the platform (with the subject) to rest.

CHAPTER 4

ANALYSIS OF HEAD MOTION DATA

4.1 INTRODUCTION

Head motion data can be analysed using different methods, each method providing either the same data in differing forms or showing various depths of information. Biodynamic data gathered from whole-body vibration experiments and used for the calculation of transfer functions normally consist of an input signal (e.g. seat vibration) and an output signal (e.g. head motion). Most of the data collected for this research are in this form, i.e. excitation and response. The number of axes measured might vary between field trials and laboratory measurements thus differing methods of analysing data would be required for the two cases: laboratory experiments are normally confined to single axis excitation whereas all six axes would be active during field trials.

This chapter presents different methods of analysing data collected during laboratory experiments and those collected during field trial measurements.

4.2 TRANSMISSIBILITIES

There are many types of transfer functions that can be used in the analyses of biodynamic data, the two spectral analysis transfer functions used in this study are 'power spectral density function method' and the 'cross-spectral density function method'. Consider a simple single-input single-output system with the addition of extraneous noise in the process as shown in Figure 4.1.

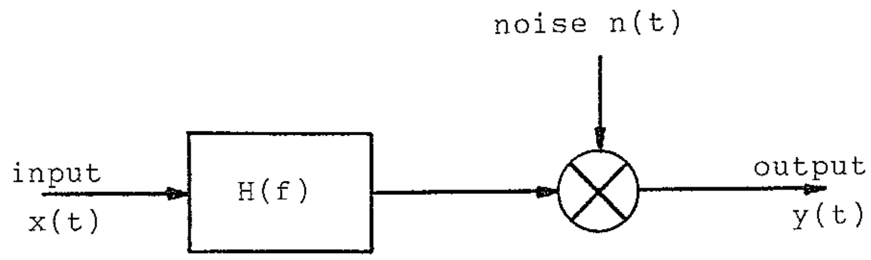


Figure 4.1 Single-input single-output system with noise addition at the output.

The first transmissibility, $H_p(f)$ can be obtained using the 'power spectral density function method' (sometimes referred to as the 'input/output autospectrum method'), it is defined as:

$$H_p(f) = \left[\frac{G_{yy}(f)}{G_{xx}(f)} \right]^{1/2}$$

where:

$G_{yy}(f)$ is the power spectrum of the output motion

$G_{xx}(f)$ is the power spectrum of the input motion.

The total energy present in the output signal is taken into account in the calculation of $H_p(f)$.

The second transfer function, $H_c(f)$ considers only the linearly correlated proportion of the output motion with the input motion, it will be called the 'cross-spectral density function method' (it is sometimes referred to as the 'input/output cross-spectrum method') and it is calculated using the equation:

$$H_c(f) = \frac{G_{xy}(f)}{G_{xx}(f)}$$

where:

$G_{xy}(f)$ is the cross-spectrum of the input and output motions.

The first method ($H_p(f)$) is a direct ratio of energies between the output motions, therefore, it produces only a real part of the transfer function, i.e. modulus. The second method ($H_c(f)$) uses a complex quantity ($G_{xy}(f)$) which contains phase information between the input and output signals. So the transfer function can be split into its two components, i.e.

$$\text{modulus} = ((R(H_c(f)))^2 + (I(H_c(f)))^2)^{1/2}$$

$$\text{phase} = \tan^{-1}\left[\frac{I(H_c(f))}{R(H_c(f))}\right]$$

where

$R(H_c(f))$ is the real part of the transfer function

$I(H_c(f))$ is the imaginary part of the transfer function.

Ordinary coherency can be calculated for the cross-spectral density function method and this would provide an indication of the amount of motion at the output which was linearly correlated with the input motion. It can be calculated as:

$$\text{ordinary coherency} \quad \gamma^2_{xy}(f) = \frac{|\,G_{xy}(f)\,|^2}{G_{xx}(f)\;G_{yy}(f)}$$

The coherency will show values between 0 and 1; a coherency of 0 would indicate no correlation between input and output motions whereas 1 would imply perfect correlation between the two motions.

Since the first method of calculation of transmissibilities takes into account all the energy in the output and the second method uses only the linearly correlated energy, the magnitude of transmissibility obtained using the power spectral density function method will always be greater or equal to that calculated using the latter method. For the ideal condition when there is no noise present in the system and the system is linear, both transmissibility methods would show identical moduli values and the coherence function would be equal to unity.

4.3 THREE-INPUT SINGLE-OUTPUT SYSTEM

The above analyses were developed for a single-input single-output system which in some cases can be adequate. Complex systems can be developed which would provide a better understanding of real situations. An example of this is the measurement of transmission of vibration through the human body during a laboratory experiment and a field experiment. In the laboratory, a single axis input vibration can normally be used (e.g. vertical) and one or more axes of motion measured at the head. A single-input single-output system might be sufficient for such a set-up. The situation is different for the analyses of field measurement data where input vibration might be in all the axes of motion (i.e. three translational and three rotational). For the analysis of such data, a six-input single-output system might be required.

A three-input single-output system would be required for the analyses of biodynamic data collected during triaxial seat vibration and head motion in, for example, a vehicle. (All six axes at the seat might be active during a vehicle ride though vibration in some axes can be considered to be comparatively small in magnitude.) A three-input single-output system with the addition of noise at the output is shown in Figure 4.2. The procedure required for the analyses of a two-input single-output system has been described elsewhere (Bendat and Piersol, 1966) and this can be extended for a three-input single-output system. The complete analyses for a three-input single-output system is given in Appendix 2 and the various important terms are described below.

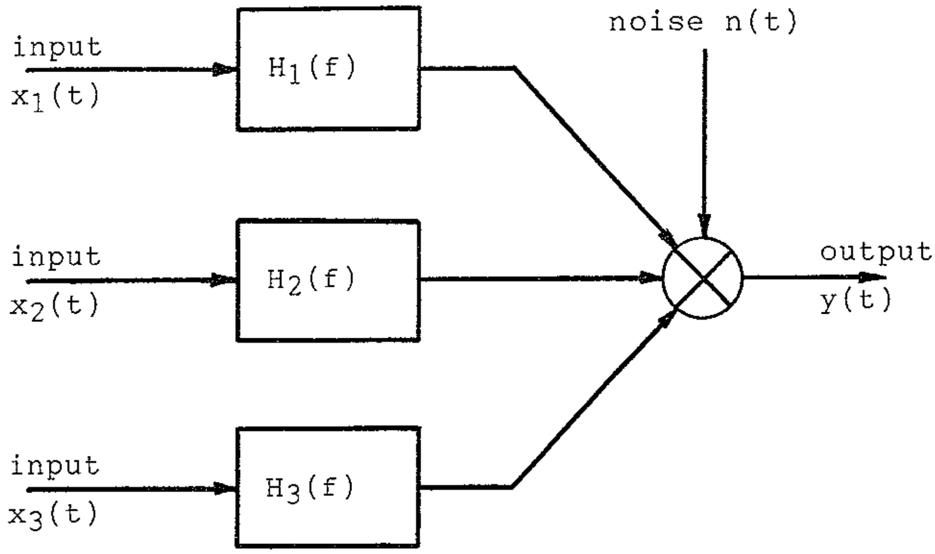


Figure 4.2 A three-input single-output system.

4.3.1 Coherencies

The term 'ordinary coherency' was discussed in Section 4.2 above and was explained as providing an indication of correlation between two waveforms, e.g. an excitation signal and a response signal. This quantity can be calculated for a single-input single-output system and is given by the equation in Section 4.2.

The ordinary coherence function cannot be usefully employed for a three-input single-output system, e.g. for the calculation of $\gamma^2_{x1y}(f)$ for the coherency between input $x_1(t)$ and output $y(t)$ since both $x_1(t)$ and $y(t)$ might have been affected by inputs $x_2(t)$ and $x_3(t)$. That is, the ordinary coherency cannot account for the proportion of the output motion caused by the other inputs. To overcome this problem, partial coherencies can be determined between the various inputs and output motions: input $x_1(t)$ and output $y(t)$ can be 'conditioned' for the effect of inputs $x_2(t)$ and $x_3(t)$, that is, the effect of $x_2(t)$ and $x_3(t)$ can be removed from $x_1(t)$ and $y(t)$. Then a partial coherence function $\gamma^2_{x1y.x2x3}(f)$ can be calculated as:

$$\gamma^2_{x1y.x2x3}(f) = \frac{| G_{x1y.x2x3}(f) |^2}{G_{x1x1.x2x3}(f)\, G_{yy.x2x3}(f)}$$

where:

$G_{x1y.x2x3}(f)$ is the cross-spectrum between input $x_1(t)$ and output y(t) conditioned for inputs $x_2(t)$ and $x_3(t)$,

$G_{x1x1.x2x3}(f)$ is the power spectrum for input $x_1(t)$ conditioned for inputs $x_2(t)$ and $x_3(t)$, and

$G_{yy.x2x3}(f)$ is the power spectrum for output y(t) conditioned for inputs $x_2(t)$ and $x_3(t)$.

4.3.2 Conditioned spectra

The above analysis can be taken further to determine the various correlated and conditioned spectral components for one signal. For example, consider the output signal y(t) and three input signals $x_1(t)$, $x_2(t)$ and $x_3(t)$. The output signal can be divided into its components as follows:

Power spectrum of output y(t)

= proportion of output y(t) linearly correlated with input $x_1(t)$

+ proportion of output y(t) linearly correlated with input $x_2(t)$ after conditioning input $x_2(t)$ and output y(t) for input $x_1(t)$

+ proportion of output y(t) linearly correlated with input $x_3(t)$ after conditioning input $x_3(t)$ and output y(t) for inputs $x_1(t)$ and $x_2(t)$

+ proportion of output y(t) after conditioning for inputs $x_1(t)$, $x_2(t)$ and $x_3(t)$.

All the above terms and expressions are explained in detail in Appendix 2.

CHAPTER 5

TRANSMISSION OF TRANSLATIONAL SEAT VIBRATION TO THE HEADS OF SEATED SUBJECTS

5.1 INTRODUCTION

Many factors can influence the transmission of vibration through the human body. It has been demonstrated that posture and seating conditions can completely dictate seat-to-head transmissibility (e.g. Rowlands, 1972; Griffin et al., 1979; Lewis and Griffin, 1980). The response of the head during seat vibration can vary from moment to moment for an individual and there will be greater variation between individuals. Experiments conducted elsewhere have reported large variabilities between individuals in head motion (Griffin, 1975; Griffin et al., 1979; Johnston, 1978). There are other factors such as position of the seat, the legs, the pelvis, the spine and the head which may all affect the nature of transmission of vibration through the body.

The experiments presented in this chapter were conducted so as to obtain some fundamental data to determine the repeatability of the transmission of translational vibration from the seat to the head for an individual and the variability that occurs between subjects. The main measures were obtained using two different repeatable body postures: a 'back-on' posture which involved a backrest and a 'back-off' posture with no backrest. Effects of some other parameters were also to be investigated. Data presented in this chapter have been published elsewhere (Paddan and Griffin, 1988a, 1988b).

5.2 FORE-AND-AFT SEAT VIBRATION

5.2.1 Introduction

People are exposed to vibration in all axes during any vehicle ride. In the case of people in a motor car, they would normally be seated facing in the same direction as motion of the vehicle. There may be sudden jerky movements to which the occupants are exposed due to, for example, improper gear changes or sudden acceleration or braking. These vibrations would be transmitted to the head and normally result in large displacements of the head in the fore-and-aft direction. Depending on the restraint system used and the motion of the vehicle, occupants might even impact with the interior of the vehicle. This would particularly be true in the case of an accident. Only a few studies have been conducted to investigate the nature of transmission of vibration in the fore-and-aft direction from the seat to the heads for seated subjects (see Section 2.7.1.1).

This section presents data from experiments conducted to determine the transmission of fore-and-aft seat vibration to the heads of seated subjects. Factors including repeatability of data, individual variability and the effect of a backrest are discussed. Also to be investigated was the centre of rotation for pitch motion at the head caused by fore-and-aft seat vibration.

5.2.2 Intra-subject variability

5.2.2.1 Introduction

In the determination of the effect of a particular variable on the transmission of seat vibration to the head, an estimate is required of the variation in data that should be expected during repeat measures. Then, if any trends are seen in the data that are greater than intra-subject variability, these might have been due to the parameter under investigation.

This section presents data from experiments to determine the repeatability of transmission of seat vibration to the head for a single subject. Also, data are included of the effect of two body postures on head motion, these two postures being back in contact with the seat backrest and no backrest condition.

5.2.2.2 Apparatus

Vibration generation

This experiment was conducted using an electro-hydraulic vibrator capable of producing horizontal displacements of up to 1 metre. A rigid seat with flat seat and backrest surfaces was mounted on the vibrator. The seat pan was inclined backwards at an angle of 3° to the horizontal and the backrest was inclined at an angle of 6° to the vertical. A thin layer of high stiffness, high friction rubber was glued on to the seat and backrest surfaces to reduce sliding movements of the subjects on the seat. More details about these are given in Chapter 3.

A computer-generated Gaussian random waveform of 60 seconds duration was fed into the vibrator. The waveform had a flat spectrum limited by 36 dB Butterworth band-limiting filters set at 0.20 Hz and 16 Hz. The subject was exposed to a vibration magnitude of 1.75±0.05 ms^{-2} r.m.s.

Vibration measurement

Motion of the head was measured using a six-axis bite-bar explained in detail in Section 3.2. It consisted of six translational piezo-resistive full-bridge Entran type EGAX±5 accelerometers located and orientated so as to enable the three translational and three rotational axes of motion of the head to be monitored. A personal sterilised dental mould was fixed on the bite-bar; the subject was able to grip this part between his teeth.

The signals from the accelerometers were passed through signal conditioning amplifiers and then low-pass filtered at 16 Hz via 48 dB/octave anti-aliasing filters. The acceleration signals were sampled into a DEC PDP11-34 computer at a sample rate of 128 samples per second. Seven acceleration channels of data were acquired into the computer simultaneously (6 from the bite-bar and 1 from the vibrator platform).

All seat-to-head transfer functions were calculated for motion occurring at 100 mm to the left of the mid-sagittal plane at mouth level. Transfer functions, $H_c(f)$ between motion in one axis at the head (output) and in the fore-and-aft axis on the seat (input) were determined using the 'cross-spectral density function method':

$$H_c(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

where

$G_{io}(f)$ = cross-spectrum of input and output motions,
$G_{ii}(f)$ = power spectrum of input motion.

A frequency resolution of 0.25 Hz was used giving 58 degrees of freedom. Ordinary coherencies were also calculated between seat and head motion using the following equation:

$$\gamma^2_{io}(f) = \frac{|G_{io}(f)|^2}{G_{ii}(f)\ G_{oo}(f)}$$

where $G_{io}(f)$ and $G_{ii}(f)$ are as above and $G_{oo}(f)$ is the power spectrum of output motion.

5.2.2.3 Procedure

Subjects

A male subject (38 years old, 1.85 m tall and weight 80 kg) took part in the intra-subject variability study. He attended the laboratory on two separate occasions, once for each of the two postures. On the first occasion, he sat with a 'back-on' posture (leaning slightly against the backrest) and on the second occasion, he sat with a 'back-off' posture (a comfortable upright posture with no contact with the backrest). A loose lap strap was placed around the subject for safety purposes only. The subject was instructed to direct his eyes at a cross marked on a stationery wall approximately 1.6 m distant. The subject was given a set of written instructions, a copy of these is include in Appendix 3.

Experimental design

In each of the two postures, the subject was exposed twelve times to the vibration stimulus while his head motion data were acquired by the computer. There was a five minute pause between each exposure during which the subject stood up and left the seat.

5.2.2.4 Results

Transmissibility curves (i.e. moduli of the transfer functions) determined for the six axes of head motion are shown in Figure 5.1 for the subject seated in a 'back-on' posture. Two main resonances are seen for x-axis head motion, one at 1.5 Hz and a broad peak near 8 Hz. Vertical head transmissibility shows one peak at 6.5 Hz. The pitch axis transmissibility is greatest at about 7.5 Hz. Lateral, roll and yaw axes show comparatively smaller transmissibilities, thus indicating that motion at the head occurred mainly in the mid-sagittal plane.

In Figure 5.2 are shown the transmissibilities for the 'back-off' condition. Only one peak is present for x-axis head motion, this being at 2 Hz. Vertical and pitch axes display values much smaller than those for the 'back-on' posture.

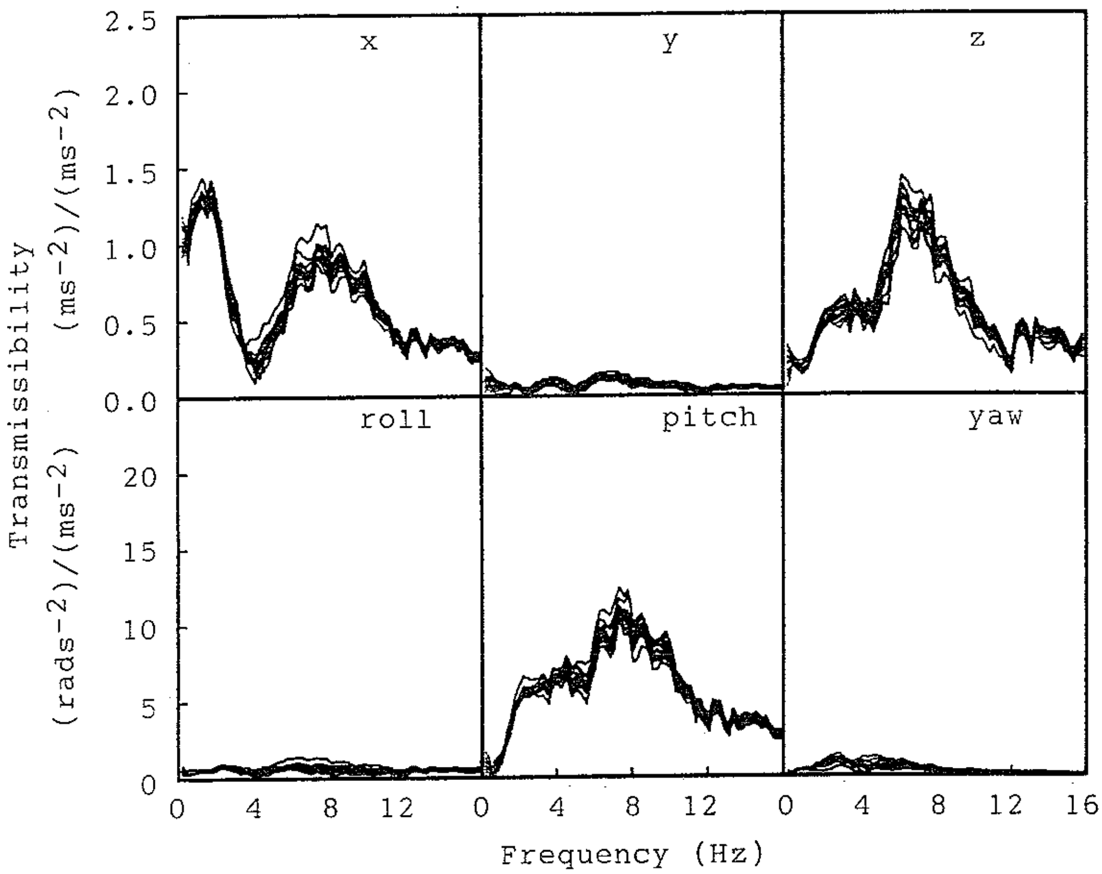


Figure 5.1 Transmissibilities for 1 subject in a 'back-on' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

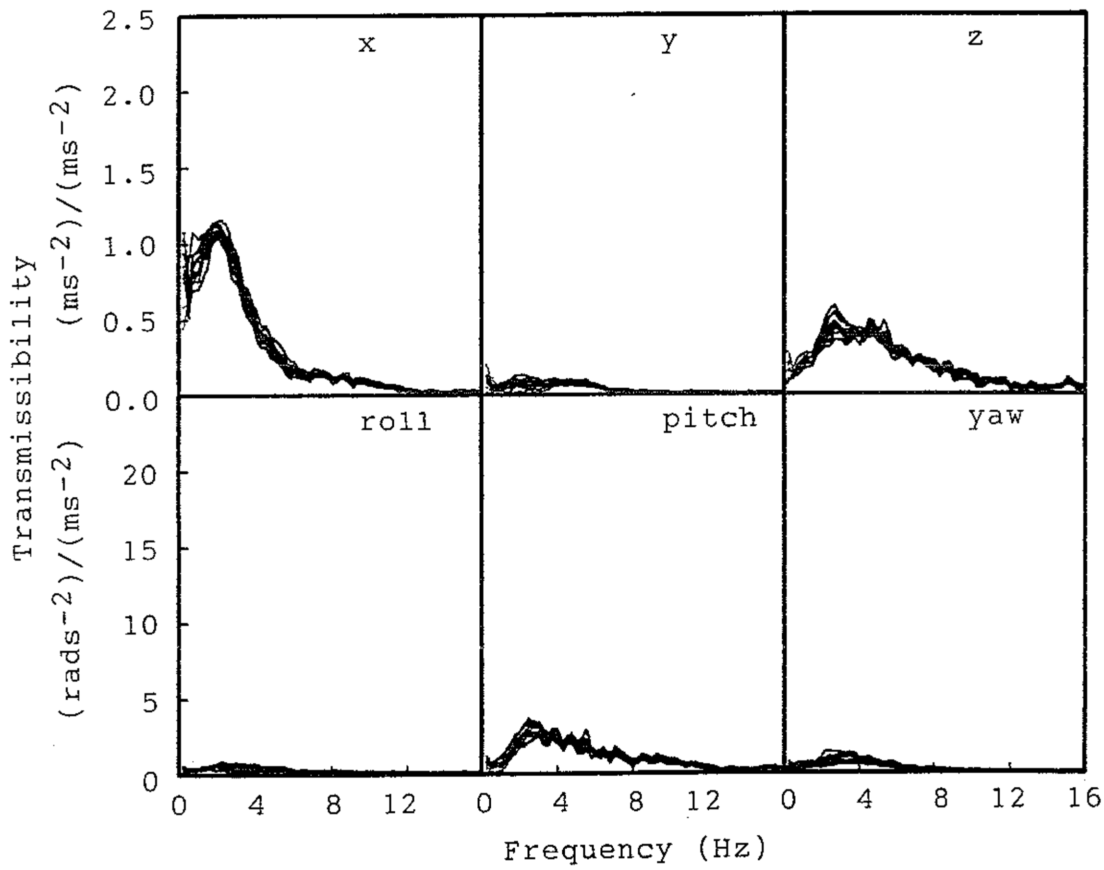


Figure 5.2 Transmissibilities for 1 subject in a 'back-off' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

It is seen from Figures 5.1 and 5.2 that head motion occurred mainly in the mid-sagittal plane (fore-and-aft, vertical and pitch axes) so phase data for only these axes are presented. Figure 5.3 shows phase between fore-and-aft seat vibration and head motion in the mid-sagittal plane for the 'back-on' and the 'back-off' postures.

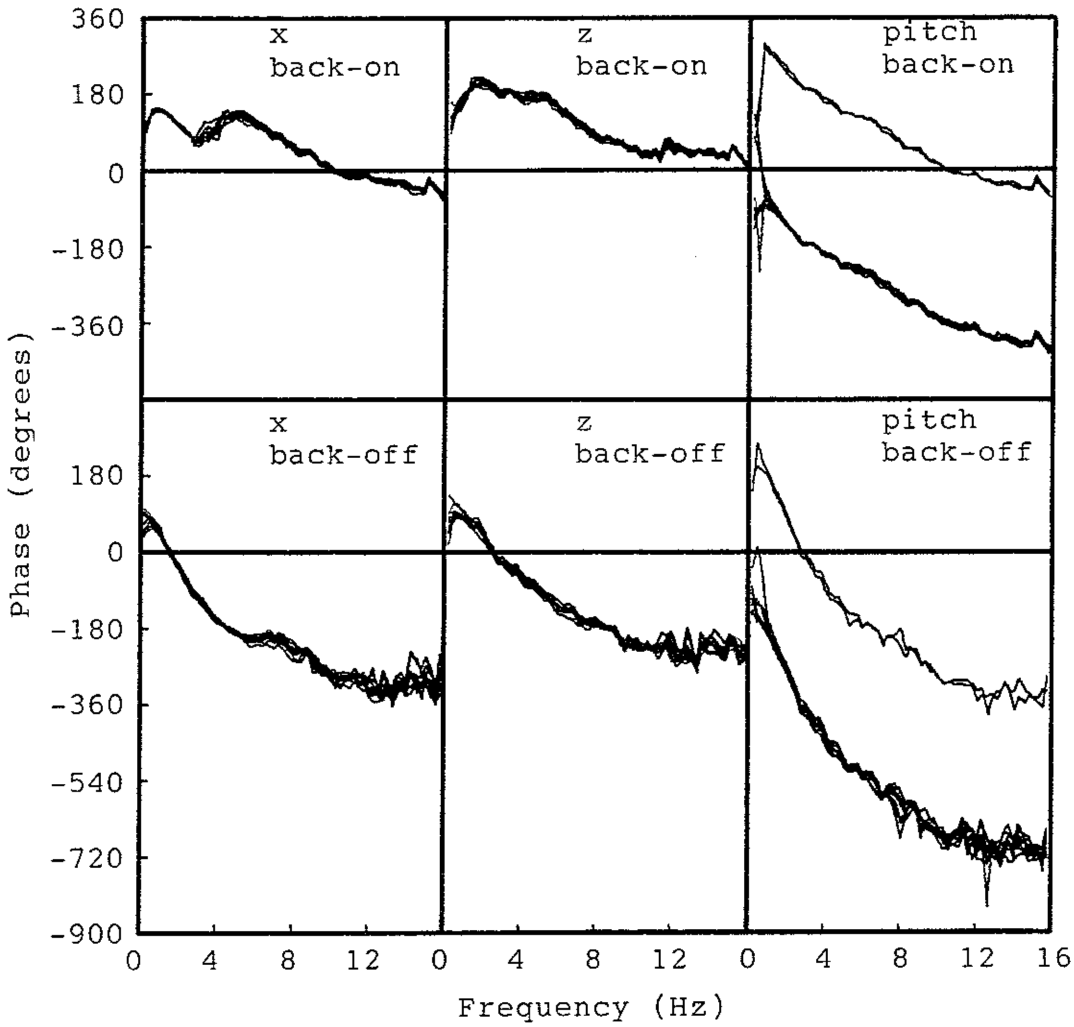


Figure 5.3 Phase for 3 axes of head motion for 1 subject in a 'back-on' and a 'back-off' posture during fore-and-aft seat motion.

Ordinary coherencies were also calculated for these data and are included in Appendix 4 for all the axes at the head and for both postures. Coherencies for motion in the mid-sagittal plane axes with the 'back-on' posture were higher than the other coherencies. Data for the lateral, roll and yaw axes show incoherent motions.

5.2.2.5 Discussion

Median transmissibilities for head motion in the six axes for the twelve vibration exposures with the subject seated in both 'back-on' and 'back-off' postures are shown in Figure 5.4. Comparison between the transmissibilities for the two conditions shows that a resonance peak occurs in the 6 Hz to 8 Hz region solely due to the backrest contact. In the x- and z-axes of the head, contact with the backrest increases vibration at frequencies above about 4 Hz. In the pitch axis of the head, the motion is increased at all frequencies above about 1 Hz. This dramatic increase in head motion in the mid-sagittal plane axes may be associated with back-slap (constant impacts between the back and backrest), these sudden impacts being transmitted to the head. These results are in broad agreement with those obtained by Lewis and Griffin (1980) who showed that contact with the backrest increased the transmission of x-axis seat motion to the head.

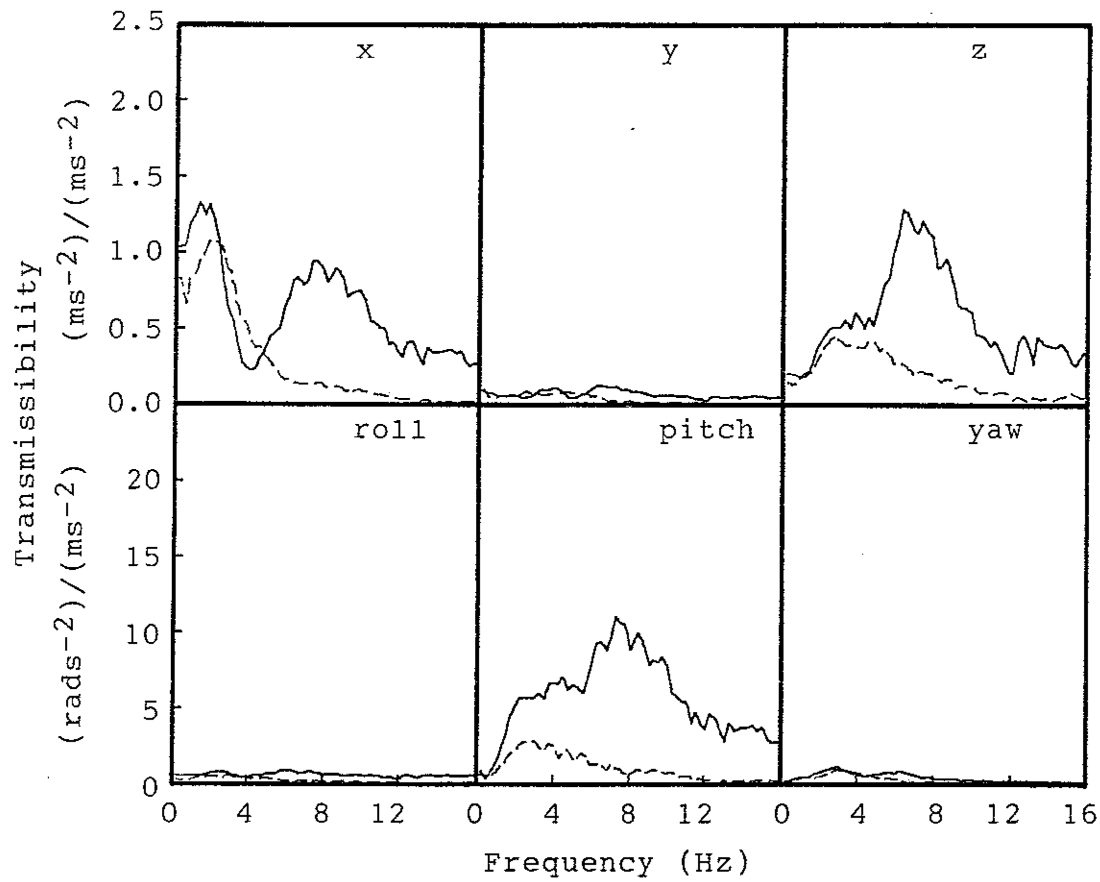


Figure 5.4 Median transmissibilities for 1 subject in a 'back-on' (———) and a 'back-off' (- - - -) posture during fore-and-aft seat motion.

The transmissibilities presented in Figures 5.1 and 5.2 show that at some frequencies (e.g. 'back-on', vertical head motion, 6 Hz) variation in head response between repeat measures was as large as 27%. Variation in response between individuals would be expected to be larger than that found during repeat measures (see Section 5.2.3). There appear to be well defined envelopes the curves follow, this is also true for the distinct peaks and troughs in the data - such as the one around 12.4 Hz for the mid-sagittal plane axes.

Phase data showed larger phase lags for the 'back-off' posture than the 'back-on' posture. Also, the phase appear to be slightly more erratic for the 'back-off' posture. A phase lead is seen in the data at some frequencies, this is the case for the whole of the frequency range for vertical head motion during a 'back-on' posture. At low frequencies, this could be associated with active feedback of the body to keep the head still with respect to the vibration or the direction of the axes chosen are out of phase. This might also be inherent in the manner a torso (or any solid body) behaves.

5.2.3 Inter-subject variability

5.2.3.1 Introduction

In the above experiment (Section 5.2.2), data were presented of intra-subject variability in the transmission of seat vibration to the head. The next step would be to obtain similar data for a range of subjects so as to estimate the variability that should be expected between individuals. This section includes transmissibility data for 12 subjects exposed to fore-and-aft seat vibration and determines the differences in head motion while the subjects sat in two different body postures.

5.2.3.2 Apparatus

Vibration generation

The apparatus used for the generation of the vibration stimulus was the same as in Section 5.2.2.2.

Vibration measurement

Similar apparatus were used to measure the vibration as those explained in Section 5.2.2.2. The subjects were asked to bite on to a tight fitting sterilised plastic tubing attached on the bite-bar rather than a personal dental mould used in the intra-subject variability study (Section 5.2.2.2).

5.2.3.3 Procedure

Subjects

Twelve male subjects participated in this experiment, their individual characteristics are shown in Appendix 5 and are summarised in Table 5.1.

Table 5.1 Characteristics of twelve male subjects who participated in the inter-subject variability experiment.

	Age (yrs)	Weight (kg)	Stature (m)
Minimum	18	58	1.65
Maximum	34	81	1.91
Mean	26.1	70.8	1.80
Standard deviation	4.4	7.9	0.07

The procedure during the experiment and the sitting postures were the same as those explained in Section 5.2.2.3.

Experimental design

Each subject was exposed to the vibration stimulus two times: once with the 'back-on' posture and once with the 'back-off' posture. The order of presentation of the postures was arranged such that six subjects commenced with the 'back-on' posture followed by a 'back-off' posture and six subjects were exposed in the reversed order.

5.2.3.4 Results

Transmissibilities for the six axes of head motion during fore-and-aft seat vibration with the 'back-on' posture are presented in Figure 5.5. Clearly, the spread of transmissibilities is large above 2 Hz for the three dominant axes: x-, z- and pitch. These three axes show two main resonance peaks: near the frequency of 2 Hz and in the region of 6 Hz to 10 Hz. The lower frequency peak at around 2 Hz is always sharper than the second broad 'hump'. Lateral, roll and yaw axes show much smaller values.

The effect of removing the backrest (Figure 5.6) is to eliminate the second peak at around 6 Hz to 10 Hz. The first peak near 2 Hz for the 'back-on' position appears at a slightly higher frequency of about 3 Hz and is broader with the 'back-off' posture. Analysis of variance showed that there was a significant effect ($p<0.01$) of both vibration frequency and the backrest for all the axes of head motion. The interaction between frequency and backrest was also significant for all axes of head motion at the $p<0.01$ level.

Phase for the mid-sagittal plane axes is shown in Figure 5.7 for the subjects seated in the 'back-on' and 'back-off' postures. It is seen that for frequencies above about 12 Hz, the phase data appear to be erratic, this is due to

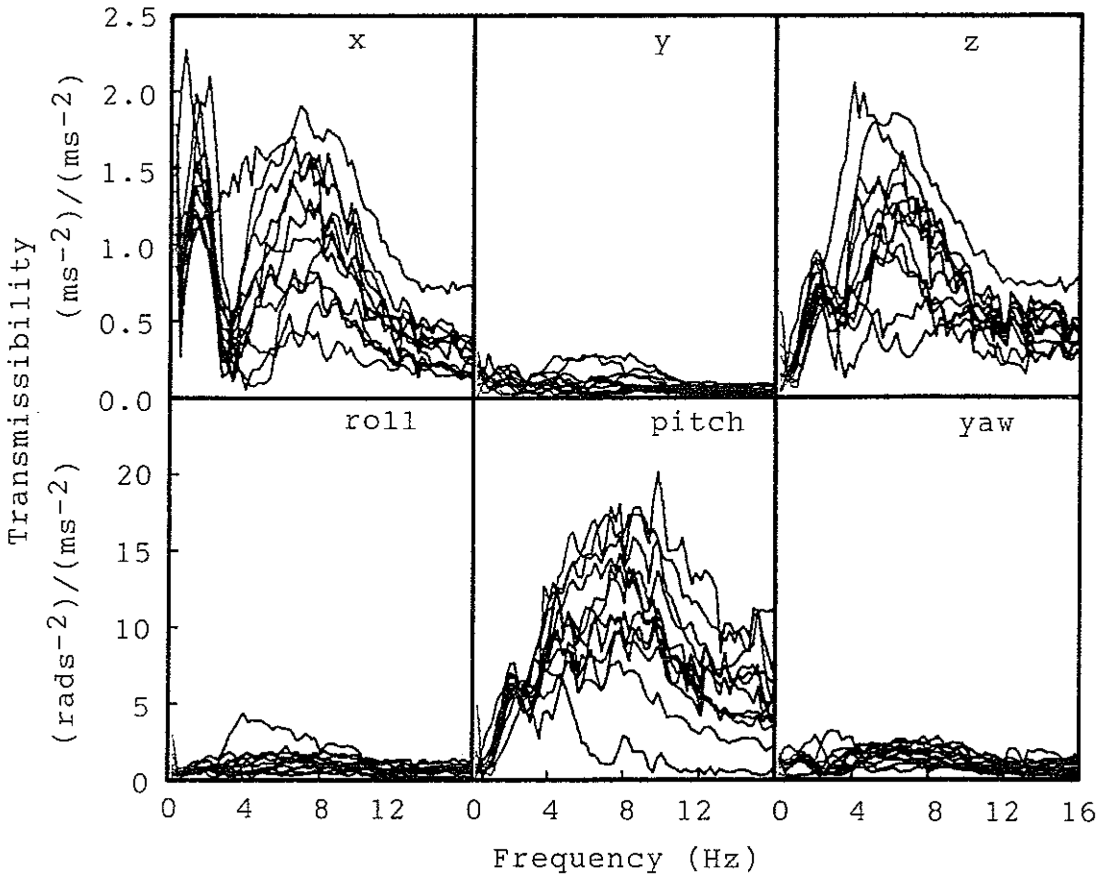


Figure 5.5 Transmissibilities for 12 subjects in a 'back-on' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

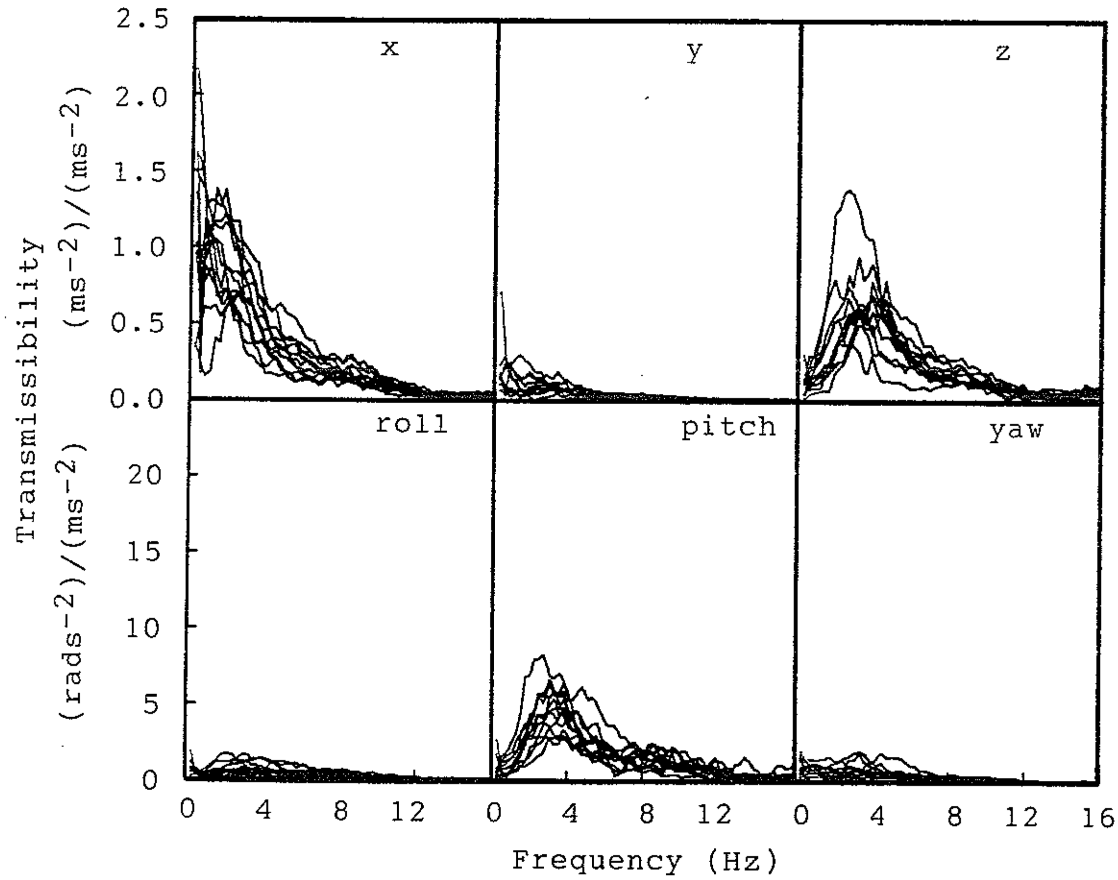


Figure 5.6 Transmissibilities for 12 subjects in a 'back-off' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

relatively low transmissibility values at these frequencies (see Figure 5.6). Also, phase data are more sensitive to noise (uncorrelated motion) than modulus data and at low transmissibilities, the phase unwrapping algorithm used was unable to correctly determine true phase values; this is a common problem encountered in phase unwrapping. The correct phase can be determined where shifts of 360° occur by either adding or subtracting 360° from subsequent phase values depending on the direction of the shift.

Coherencies of these data were calculated for all axes and are included in Appendix 4.

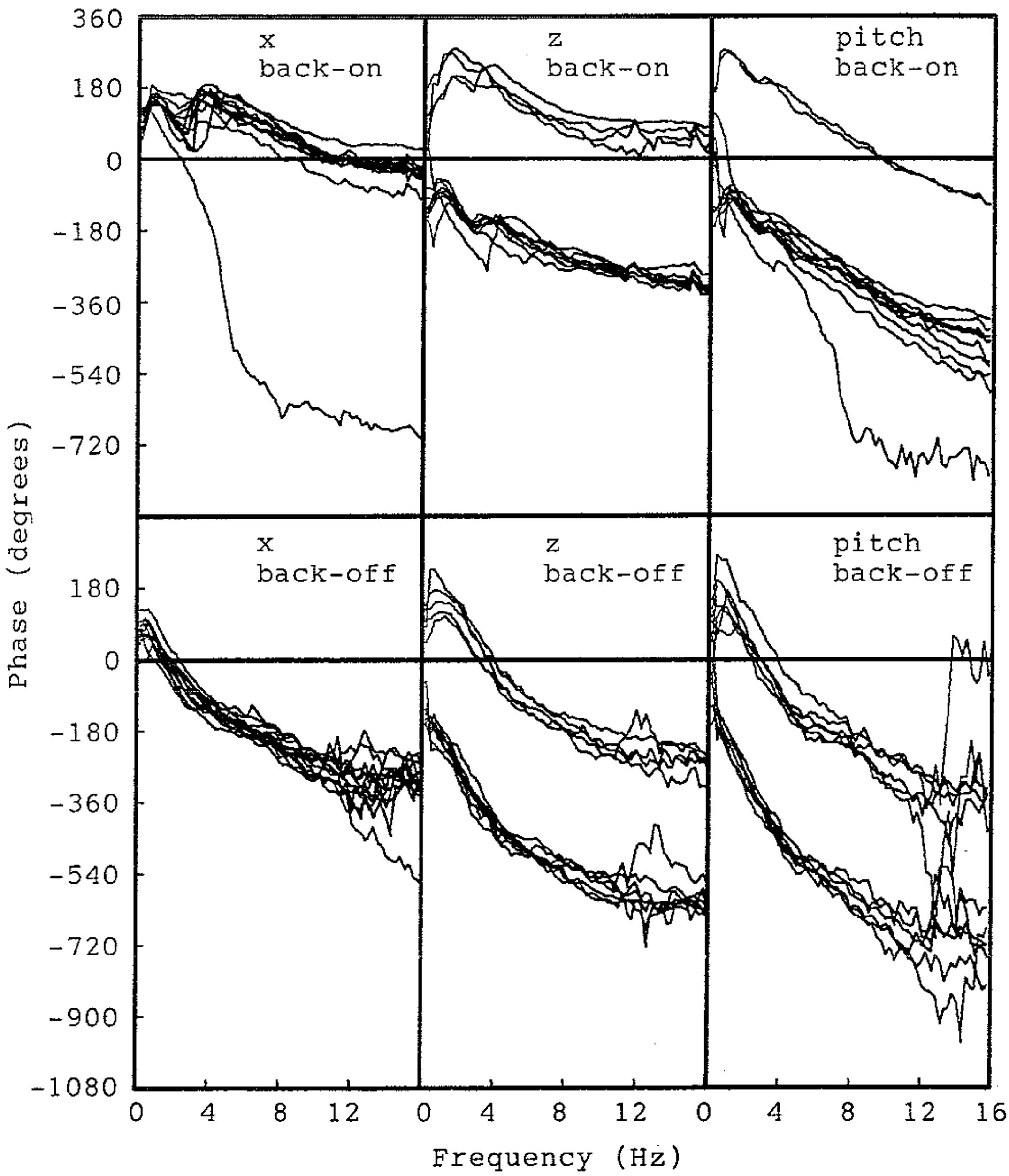


Figure 5.7 Phase for 3 axes of head motion for 12 subjects in a 'back-on' and a 'back-off' posture during fore-and-aft seat motion.

5.2.3.5 Discussion

For an easier comparison of transmissibilities between the two postures ('back-on' and 'back-off'), median transmissibilities are presented in Figure 5.8 for all axes. The 'back-off' posture showed a gradual decrease in transmissibility with frequency after about 3 Hz; there was very small head motion for frequencies above about 14 Hz. Attenuation of motion in the lateral, roll and yaw axes was so great that virtually no motion was transmitted to the head above 12 Hz. A completely different result is seen from the 'back-on' posture transmissibilities: vibration transmitted to the head was significantly higher over most of the frequency range. Although transmissibilities for motion in the y-, roll and yaw axes were low, it is still seen that higher values occurred with the 'back-on' posture.

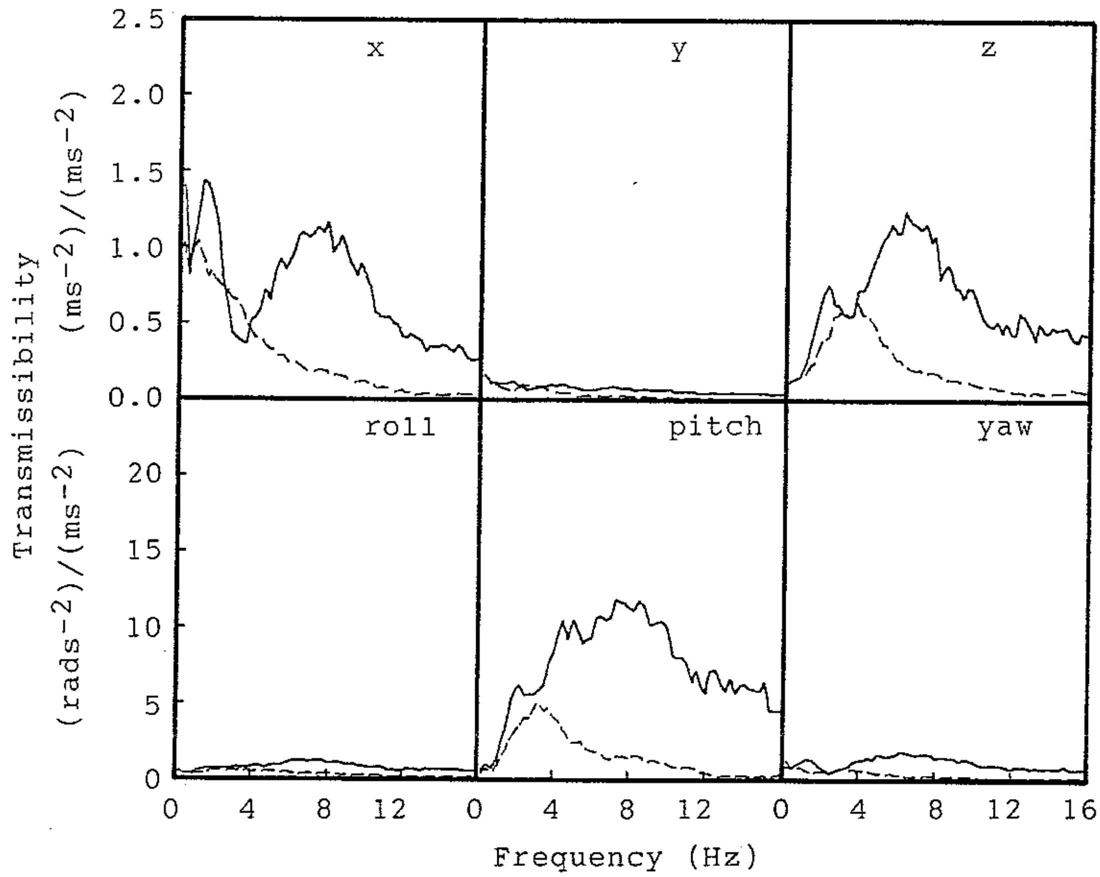


Figure 5.8 Median transmissibilities for 12 subjects in a 'back-on' (———) and a 'back-off' (- - - -) posture during fore-and-aft seat motion.

The advantage of median data is that differences (or similarities) are easily observed, however, the disadvantage is that there is no indication of the variability in data. This can be seen by looking at the original data (Figures 5.5 and 5.6) or by calculating a measure of spread (e.g. range (maximum and minimum), standard deviation or inter-quartiles).

A phase lead appears in the data for fore-and-aft motion at the head, this might be related to active postural control of the body. Data for the 'back-on' posture appears to be 'well behaved' since the backrest was able to 'guide' vibration transmitted to the head whereas in a 'back-off' situation, the body attenuated a large proportion of the vibration resulting in low transmissibility and jerky phase data. Coherency data for these axes (shown in Appendix 4) demonstrate very low correlation at frequencies above about 10 Hz for the 'back-off' posture - this would also result in unreliable data at those frequencies.

5.2.4 Centre of rotation for pitch head motion

5.2.4.1 Introduction

During pitch motion, the head rotates about a centre on the head and the actual position of this is unknown. Pitching motion of the head can be induced by many different motions at the seat including fore-and-aft, vertical and pitch motion or a combination of these. Due to convenience, it was decided to expose subjects to fore-and-aft vibration of the seat and since large magnitudes of pitch motion were required for this experiment, subjects were required to sit in a 'back-on' posture. This experiment was conducted to check the hypothesis that during pitch motion of the head, the centre of rotation lies near to an axis passing through the auditory meatus. These data could also be used to provide estimates of inter-subject variability in transmissibility since many subjects of differing characteristics would be used.

5.2.4.2 Apparatus

Vibration generation

The equipment used in this experiment was the same as that employed for the intra-subject variability experiment (see Section 5.2.2.2). The vibrator was driven using a computer-generated Gaussian random waveform of a duration of 60 seconds. The vibration magnitude of motion on the vibrator table was 1.0 ms^{-2} r.m.s. This was the same signal as that used in Section 5.2.2.2 but of a lower magnitude.

Vibration measurement

The equipment used and the analyses employed were similar to those used in the intra-subject variability study (Section 5.2.2.2). A sterilised piece of plastic tubing was used on the bite-bar for each subject. Only those channels of bite-bar acceleration which enabled head motion to be measured in the mid-sagittal plane were acquired (i.e. x-, z- and pitch axes).

In determining the centre of rotation, refer to Figure 5.9 for the derivation of the equation to be used. Assuming the head behaves as a rigid body and that all the vertical motion is caused by pitch motion of the head, then rotational pitch acceleration (A_p) is given by

$$A_p = A_z\ a$$

where

A_z is the vertical acceleration and

a is the distance of centre of rotation from the point of measurement of A_z.

But pitch acceleration A_p was measured, therefore re-arranging the above equation gives:

$$a = \frac{A_z}{A_p}$$

Using frequency domain analysis gives:

$$a = \frac{G_{pz}(f)}{G_{pp}(f)}$$

where $G_{pz}(f)$ is the cross-spectral density between pitch and vertical acceleration and, $G_{pp}(f)$ is the power spectral density of pitch acceleration.

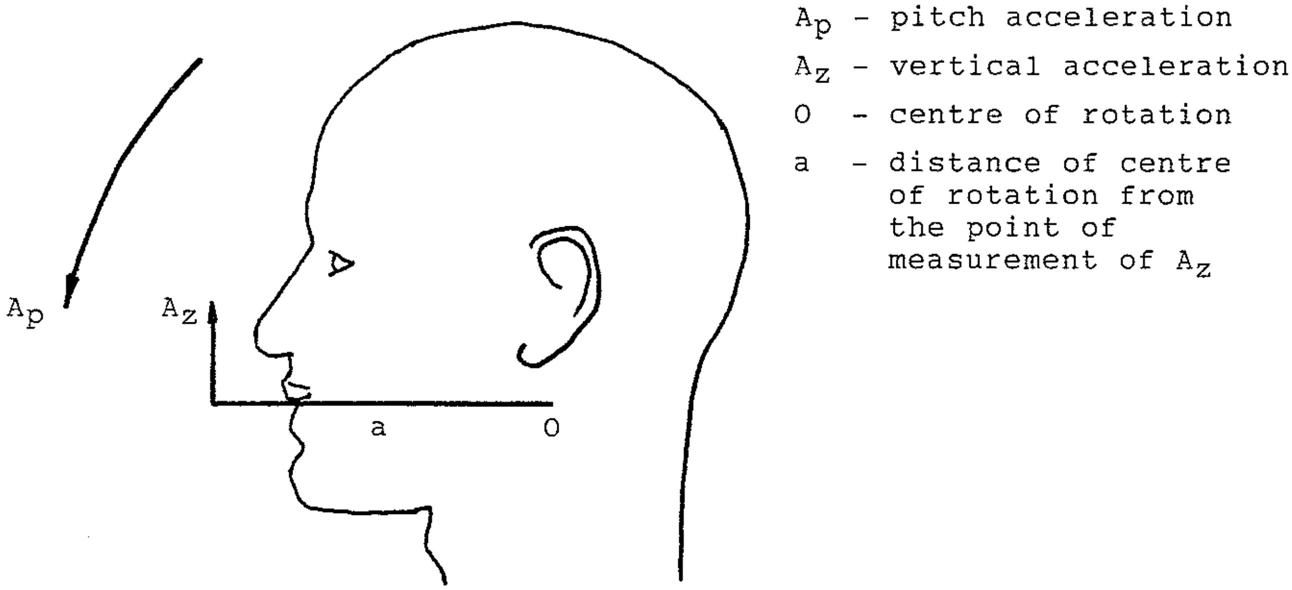


Figure 5.9 Calculation of centre of rotation for pitch motion of the head.

5.2.4.3 Procedure

Subjects

Thirty-one subjects of both sexes and varying characteristics took part in the experiments. Various subject characteristics shown in Table 5.2, were measured including sitting height to auditory meatus, sitting height to shoulder and head dimensions so as to determine whether these parameters showed any correlation to the calculated centre of rotation. Data for the individual subjects are shown in Appendix 5.

	Age (yrs)	Weight (kg)	Height (m)	Sitting height (cm)	Ear-mouth x-distance (cm)	Ear-mouth z-distance (cm)	Ear-shoulder z-distance (cm)	Ear-pelvis z-distance (cm)
Minimum	7	21	1.26	50	7	3	11	37
Maximum	69	103	1.92	83	9	7	18	62
Mean	26.00	59.55	1.71	73.0	8	4.61	15.26	53.71
Standard deviation	15.77	16.44	0.15	8	0.76	1.04	1.78	6.29

Table 5.2 Physical characteristics of 31 subjects who took part in the centre of rotation for pitch head motion during fore-and-aft seat motion.

The subjects were given clear verbal instructions on the lines of those included in Appendix 3. There was only one posture that the subjects sat in, this was a 'back-on' posture (back in contact with the backrest). For safety purposes, the subjects wore a loose lap strap during the experiment. In order to maintain the required head posture and reduce voluntary movements of the head, the subjects were required to direct their eyes at a cross marked on a stationery wall in front of them approximately 1.6 m distant.

Experimental design

Each subject underwent only one run during which motion of the head was monitored.

5.2.4.4 Results

Transmissibility curves for axes in the mid-sagittal plane at the head are shown in Figure 5.10. These data indicate the inter-subject variability in transmission of fore-and-aft seat vibration to the head - it is seen that there is a large spread of transmissibilities in the three axes.

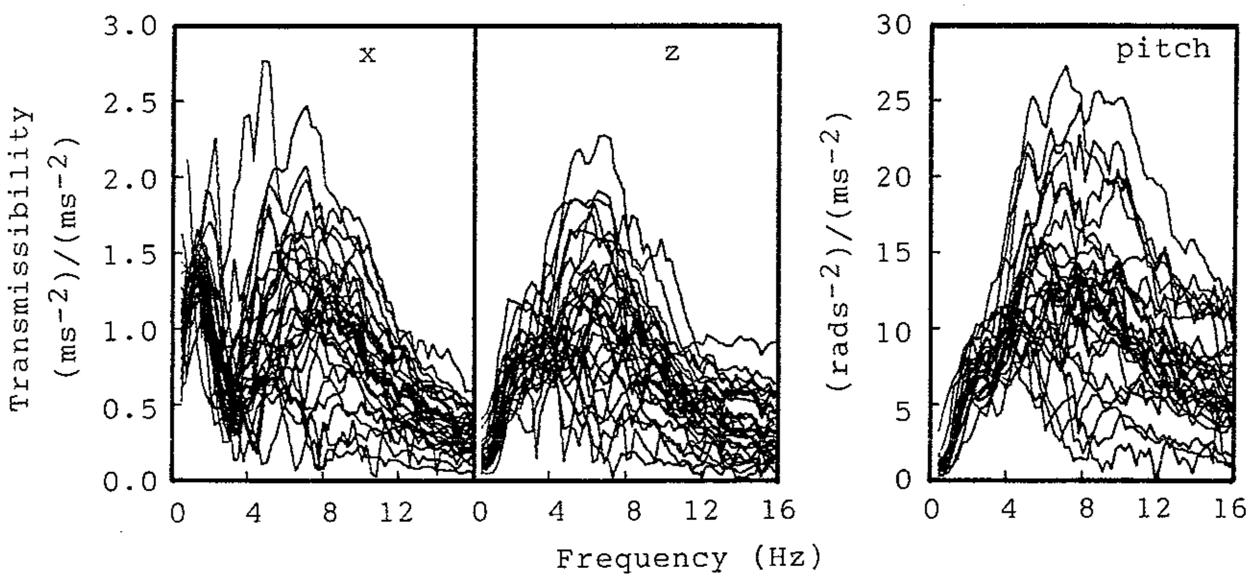


Figure 5.10 Transmissibilities for 3 axes of head motion for 31 subjects in a 'back-on' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

Phase between seat vibration and head motion for the three axes at the head are shown in Figure 5.11 for the 31 subjects. Data for most of the subjects tend to follow the main trend but data for some of the subjects appear to deviate with large phase lags. This occurs where the transmissibility and coherency (shown in Appendix 4) are both very small.

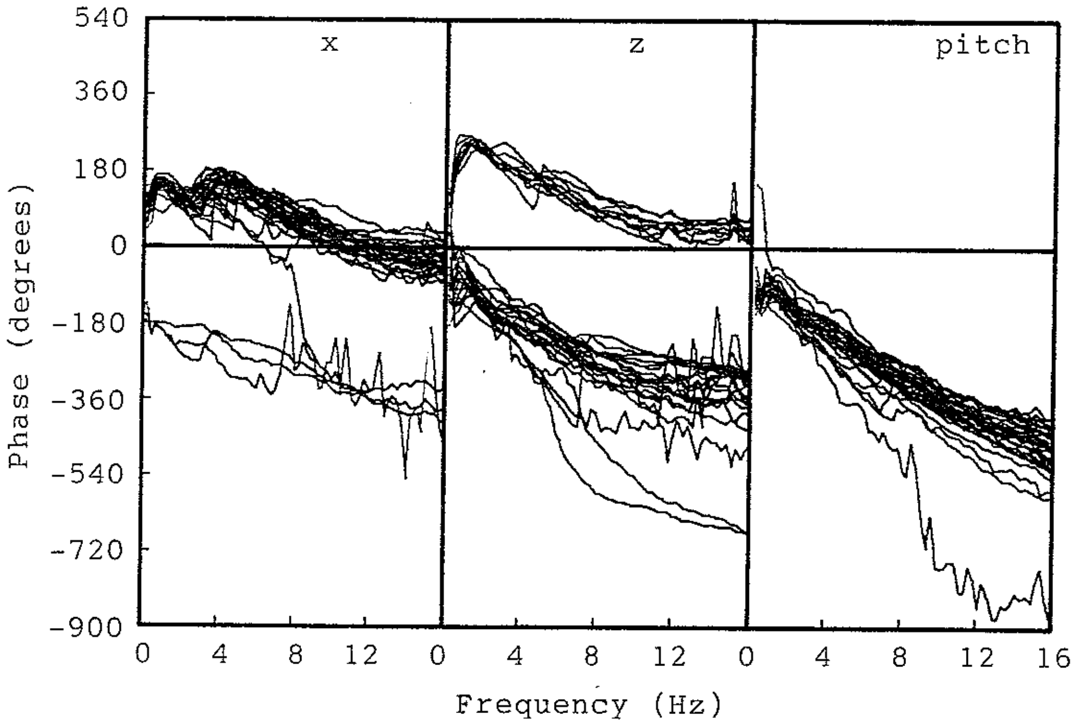


Figure 5.11 Phase for 3 axes of head motion for 31 subjects in a 'back-on' posture during fore-and-aft seat motion.

Figure 5.12 shows the centre of rotation distances calculated using the equation explained in Section 5.2.4.2; the abscissa on the figure indicates the distance of the centre of rotation from the bite-bar accelerometers horizontally backwards (i.e. in the -x direction from the subjects corner of the mouth).

5.2.4.5 Discussion

In Figure 5.13 are shown the median and inter-quartiles for transmissibility data for the 31 subjects, this gives an indication of spread of the data. The spread shows relatively low inter-subject variability for motion below

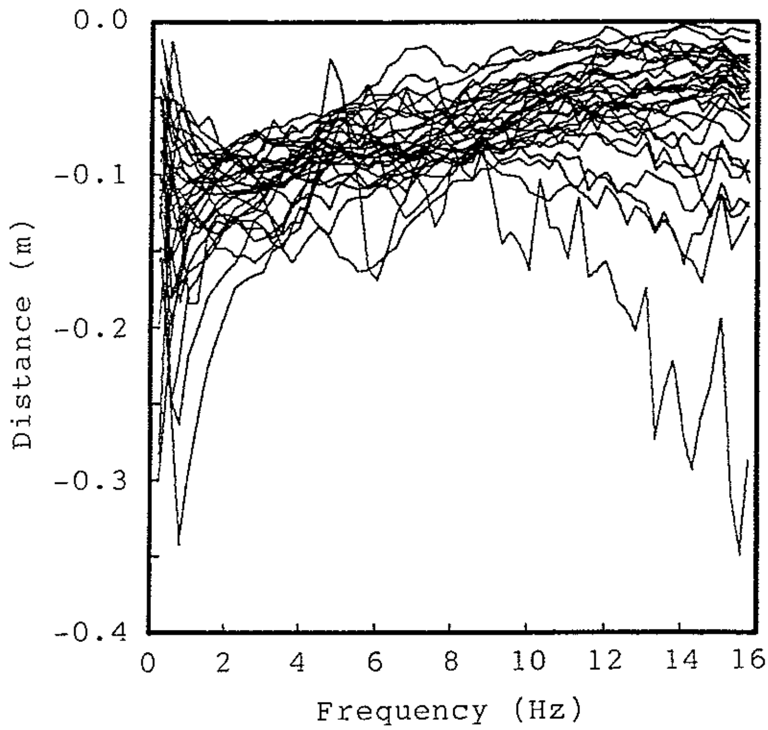


Figure 5.12 Variation in centre of rotation for head pitch from the bite-bar during fore-and-aft seat motion for 31 subjects. (Resolution = 0.25 Hz, degrees of freedom = 58)

about 4 Hz, the differences in response between subjects are very large after that frequency: at some frequencies (e.g. fore-and-aft head motion at 5 Hz), the response between individuals is seen to vary by as much as 25:1 (see Figure 5.10).

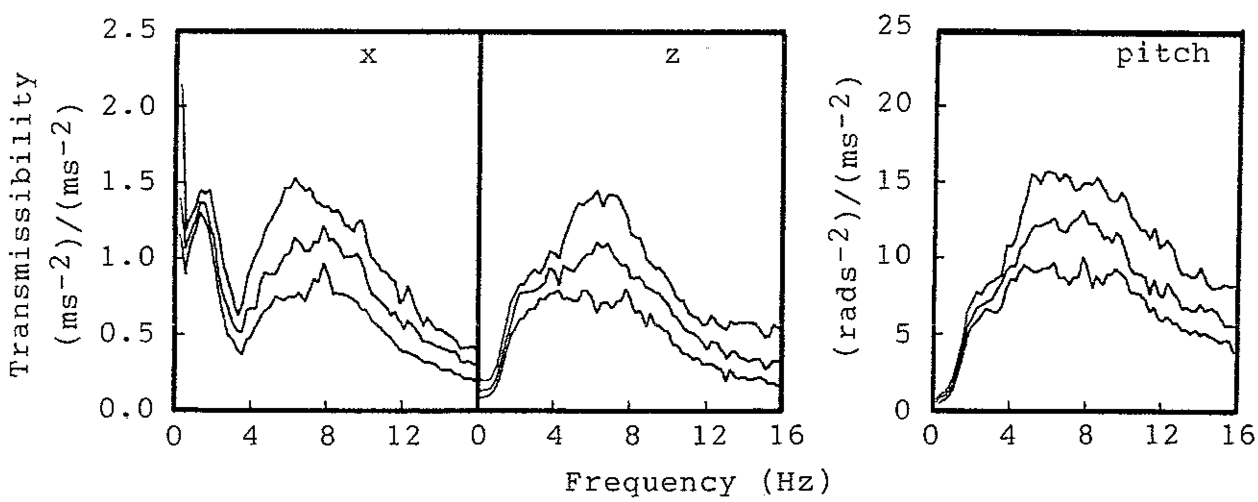


Figure 5.13 Median and inter-quartile transmissibilities for 31 subjects in a 'back-on' posture during fore-and-aft seat motion.

Median and inter-quartiles of the distance of centre of rotation were calculated from Figure 5.12 and are shown in Figure 5.14. The curves show that the 'point' of rotation for pitch motion of the head depends on frequency and is approximately 10 cm behind the bite-bar for frequencies below 4 Hz and moves closer to the mouth as frequency increases. Similar results have been reported by Sandover and Soames (1975) although seat vibration was in the vertical direction. Though it is difficult to extrapolate, data for frequencies above 13 Hz show no appreciable change in centre of rotation with frequency which might suggest that the centre of rotation remains at about 5 cm behind the mouth for frequencies immediately above 16 Hz.

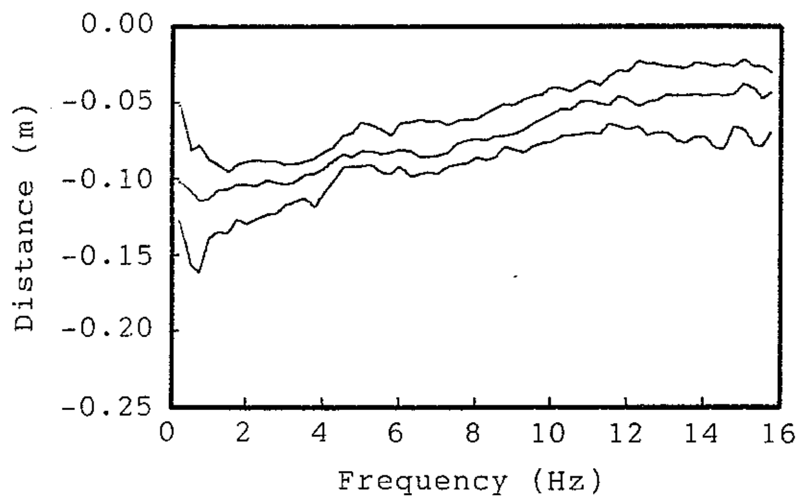


Figure 5.14 Median and inter-quartiles of distance of centre of rotation for pitch head motion from the bite-bar during fore-and-aft seat motion for 31 subjects.

These data show only rotational motion of the head and do not take into account rotation of the head and neck system around the base of the neck. Also, rotation could occur at regions lower than the neck, e.g. near the cervical vertebrae, although these rotations might be associated with relatively low frequencies.

5.2.5 Discussion and conclusions

Fundamental data have been presented in this section from experiments to determine the transmission of fore-and-aft seat vibration to the heads of seated subjects. Some previous data exist of such matter but they involved the measurement of head motion in mainly the fore-and-aft axis at the head. In this experiment, a main resonance frequency of fore-and-aft motion at the head during a 'back-off' posture was observed to be around 2 Hz. A whole-body resonance in this region was reported by Dieckmann (1957a). It would be misleading to compare these data in detail since the results depend highly on such parameters as measurement of location of head motion, seat condition and posture of subjects.

Only one study has been cited in the literature in which pitch motion of the head has measured during fore-and-aft seat vibration (Lewis and Griffin, 1980), although fore-and-aft motion at the head was not monitored. The data from these experiments are in broad agreement with their results: 'back-off' posture showed small magnitudes of pitch motion at the head while a 'back-on' posture resulted in a broad resonance peak at around 8 Hz with significantly more head motion in the pitch axis. Vertical motion at the head was also measured in their study and these data again, confirm transmissibilities obtained in their investigation.

In comparing x-axis motion at the head for the 'back-on' and 'back-off' postures, it is seen that both have a low frequency peak around 1.5 Hz to 2 Hz while the 'back-on' condition presents a second peak at a higher frequency of 8 Hz. To explain this, consider the head-neck-body system moving in the mid-sagittal plane. There are three 'points' around which rotation occurs: shoulders rotating about the hips; head and neck rotating about the base of the neck and the third being rotation of the head about its pivot, near the auditory meatus. The low frequency peak in both cases is thought to be due to pitch motion of the head and shoulders about the hips with a complementary rotation of the head/neck system around the base of the neck. This would not give rise to large pitch motions at the head but there will be large fore-and-aft displacements. This is clearly seen in the pitch motion data.

The peak at 8 Hz for x-axis motion at the head in the 'back-on' condition is due to pitch motion of the head about a point near the auditory meatus. For the 'back-off' condition, the absence of this peak implies that pitch motion of the head about this point was small - probably because of the low transmission of x-axis motion of the spine without the backrest.

In comparing vertical motion at the head for the two conditions, both show a similar transfer function up to 4 Hz, after which, the 'back-on' transmissibility rises to a peak. This can be explained by the high frequency pitch motion of the head about the auditory meatus giving rise to vertical motion at the location of the accelerometer. In the 'back-off' condition, the body attenuates these high frequencies and they do not reach the head.

Transmissibilities from the intra-subject variability study have shown that all the curves follow a distinct shape including the individual peaks and troughs. There is some variation in transmissibility but this is small. Data for most of the subjects who took part in the inter-subject variability study show the main resonance peaks and the variation in response between individuals is very large in comparison with the repeatability study. Some subjects demonstrate a large deviation in response from the main mass of data although there is no particular order.

In the above investigations, the inter-subject variability study and that to determine the centre of rotation both employed a large number of subjects. Measurement of acceleration for axes in the mid-sagittal plane were made in both studies; median transmissibilities for the three axes at the head (x-, z- and pitch) are shown in Figure

5.15 from both experiments for direct comparison. These data are of medians from Figure 5.8 ('back-on') and Figure 5.13. Approximately similar experimental set-ups were used in both cases. Transmissibilities look similar for all axes with only small differences indicating a high degree of repeatability between experiments. The small differences would have been expected and are probably due to an accumulation of a number of factors such as small experimental differences, vibration magnitude, subjects (12 for inter-subject and 31 for centre of rotation).

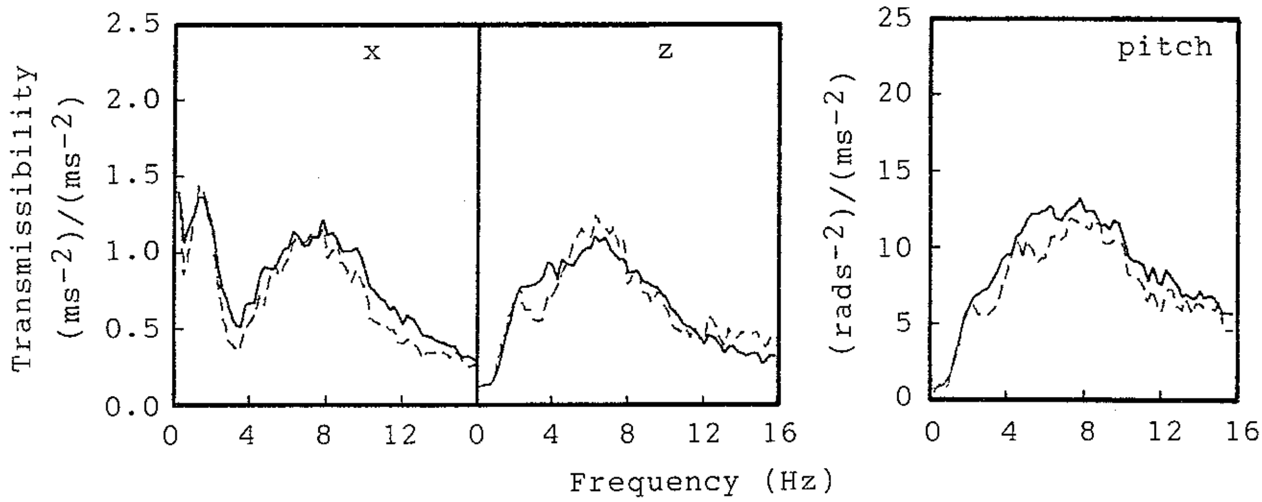


Figure 5.15 Median transmissibilities for 31 subjects (———) and 12 subjects (- - -) in a 'back-on' posture during fore-and-aft seat motion.

Median transmissibilities from intra- and inter-subject variability studies are shown in Figures 5.4 and 5.8 with the subjects seated in 'back-on' and 'back-off' postures respectively. Both figures show that the effect of contact with the backrest was to increase head motion at all frequencies up to 16 Hz in all the six axes ($p<0.01$). Only one resonance peak occurred for the 'back-off' posture (at around 2 Hz) and two resonance occurred with the subjects seated in the 'back-on' posture (2 Hz and 8 Hz). Head motion occurred mostly in the mid-sagittal plane axes during fore-and-aft vibration of the seat and substantially more head motion occurred when the back was in contact with the backrest than a 'back-off' posture. The effect of frequency and the inter-action between frequency and backrest was significant ($p<0.01$) for all axes of head motion.

A non-parametric measure of correlation (Kendall's tau) was used to determine whether subject characteristics of participants had an effect on the transmission of vibration to the head in the inter-subject variability study. Subject age and weight did not, in general, correlate with transmissibilities for either of the two seating conditions - apart from a negative correlation ($p<0.01$) between weight and x-seat to x-head transmissibility with a 'back-off' posture over the frequency range 3 Hz to 6 Hz. Stature showed a negative correlation ($p<0.01$) for x-seat to z-head transmissibility from 11 Hz to 12 Hz with the subjects seated in the 'back-off' posture. Hip size correlated negatively ($p<0.01$) in the 3 Hz to 6 Hz frequency range with x-seat to x-head transmissibility with a 'back-off' posture. Other correlations ($p<0.05$) were seen between lower leg length and motion in various seat and head axes. Since lower and total leg lengths are themselves highly correlated, similar results were found for correlations between total leg length and transmissibility. In Table 5.3 are shown the Kendall's tau correlation coefficients between the six subject characteristics. It is seen that several characteristics are highly correlated.

Table 5.3 Kendall's tau values for subject characteristics from twelve male subjects.

	Age	Weight	Height	Hip size	Lower leg length	Total leg length
Age	X					
Weight	0.000	X				
Height	-0.264	0.290	X			
Hip size	-0.095	0.719**	0.326**	X		
Lower leg length	-0.177	0.349	0.583**	0.323	X	
Total leg length	-0.286	0.188	0.605	0.254	0.807***	X

(** = $p<0.01$, *** = $p<0.001$)

Kendall's tau correlation coefficients were also determined between x-, z- and pitch axis head motion and the eight subject characteristics (sitting height, age, weight, stature, ear-mouth x-distance, ear-mouth z-distance, ear-shoulder z-distance, ear-pelvis z-distance) for the centre of rotation experiment. Also, those between subject characteristics and location of the centre of rotation were calculated. There were a few significant correlations at the 5% level; this was to be expected with such a large number of correlations. No consistent trends in the data were observed. Correlations between the various subject characteristics themselves were determined and these are presented in Table 5.4. These data are more comprehensive than those in Table 5.3 since a larger group of subjects of different ages, weights, etc. took part in this study. Some highly significant values are seen between various characteristics.

5.3 LATERAL SEAT VIBRATION

5.3.1 Introduction

Human exposure to pure lateral vibration is not common in vehicles and machinery which would require human operators. In vehicles, people would normally be exposed to large magnitudes of fore-and-aft vibration than lateral vibration if facing in the direction of motion of the vehicle though this might not be the case during, for example the vehicle manoeuvring around a corner. However, there are vehicles (for example, some buses) in which people would be facing sideways to the main motion; in such environments, the passengers would be exposed to large magnitudes of vibration in the lateral direction. Such vibrations might induce large movements of the body and affect comfort. It is not clear what effect a backrest would have on the transmission of vibration to the head in such cases and indeed the manner in which vibration is transmitted through the body.

	Age	Weight	Height	Sitting height	Ear-mouth x-distance	Ear-mouth z-distance	Ear-shoulder z-distance	Ear-pelvis z-distance
Age	X							
Weight	0.555***	X						
Height	0.431***	0.718***	X					
Sitting height	0.474***	0.723***	0.865***	X				
Ear-mouth x-distance	0.412**	0.266*	0.266*	0.269*	X			
Ear-mouth z-distance	0.093	0.184	0.253*	0.213	0.066	X		
Ear-shoulder z-distance	0.379**	0.549***	0.639***	0.767***	0.275*	0.265*	X	
Ear-pelvis z-distance	0.377**	0.631***	0.638***	0.719***	0.197	0.219	0.608***	X

(* = $p<0.05$, ** = $p<0.01$, *** = $p<0.001$)

Table 5.4 Kendall's tau values for centre of rotation subject characteristics.

This section presents data from experiments to determine the measurement of head motion during exposure to lateral seat vibration. Parameters investigated include repeatability, individual variability and the effect of contact with a backrest on the transmission of vibration to the head.

5.3.2 Intra-subject variability

5.3.2.1 Introduction

Prior to the investigation of the effect of any variables on the transmission of seat vibration to the head, it is essential to have an idea of the spread of data that might be expected. This is even more important in the study of biodynamics where many factors may influence the results.

This section concerns the collection and reporting of data to determine the repeatability in the transmission of lateral seat vibration to the head of a single subject. The effect of two body postures (back in contact with a backrest and no backrest) on head motion is also investigated.

5.3.2.2 Apparatus

Vibration generation

The equipment used in this experiment for the generation of vibration was the same as that explained in Section 5.2.2.2. The hard flat seat was mounted on the vibrator platform so as to expose the subject to lateral vibration.

Vibration measurement

The measurement of vibration and subsequent analyses of data were the same as those employed in Section 5.2.2.2.

5.3.2.3 Procedure

Subjects

One male subject participated in this intra-subject variability experiment, he had the following characteristics: 38 years old, 1.85 m tall and weight 80 kg. He was required to sit on the hard flat seat in two different body postures, these were 'back-on' (back in contact with the backrest) and 'back-off' (no backrest). The subject was asked to direct his eyes at a cross approximately 4.3 m distant on a stationary wall and for safety purposes, he wore a loose lap strap. A set of written instructions were given to the subject on the required maintenance of his posture, leg position, arm position, etc.; a copy of the instructions is included in Appendix 3.

Experimental design

The subject attended the laboratory on two separate occasions; once for each posture. He was exposed to the same vibration stimulus twelve times during which motion of the head was acquired into a computer. There was a 5 minute pause after each individual exposure during which the subject got off the seat.

5.3.2.4 Results

Transmissibilities were calculated between lateral seat vibration and motion in the six axes at the head, these are shown in Figure 5.16 for the subject seated in a 'back-on' posture. During lateral seat vibration with the 'back-on' posture, the head moved mainly in the y-axis. Roll motion was the largest of the rotational motions and this gave rise to some vertical head motion. There was also yaw motion which produced a small amount of x-axis vibration of the head. Lateral, vertical and roll motions show resonance peaks near 1.5 Hz. In all axes, motion of the head occurs only at low frequencies.

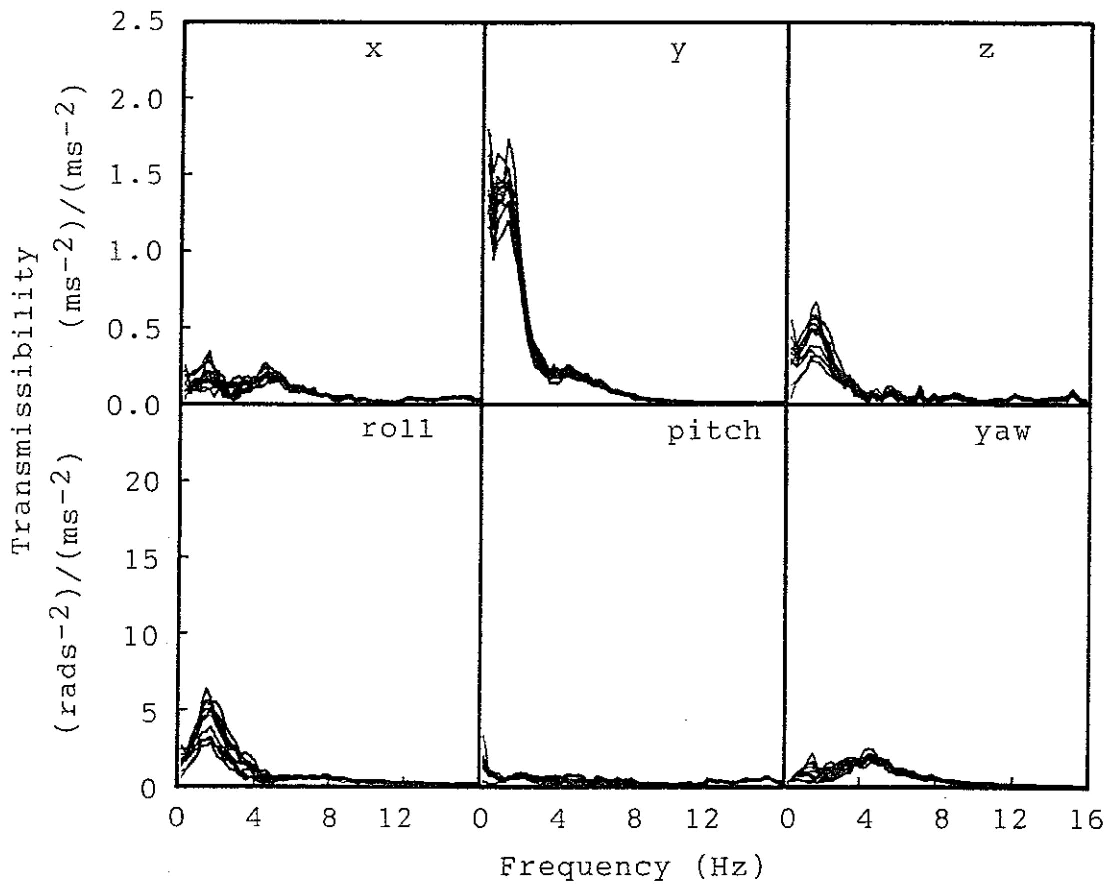


Figure 5.16 Transmissibilities for 1 subject in a 'back-on' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

Similar data were obtained with the 'back-off' condition and are shown in Figure 5.17. In x- and yaw axes, there tends to be slightly more motion around 2 Hz with the 'back-off' posture. Generally, however, contact with the backrest had little effect on transmissibility for this axis of excitation.

It was seen from Figures 5.16 and 5.17 that generally, larger transmissibilities occurred for motion in the mid-coronal plane (i.e. lateral, vertical and roll axes) although for some cases motion in the other axes was not insignificant. Phase data for axes in the mid-coronal plane are presented in Figure 5.18 for the 'back-on' and 'back-off' postures. The data for the 'back-on' posture show a slight phase lead at about 1 Hz, this may be associated with active postural control of the body and it could also be an inherent dynamic property of the human

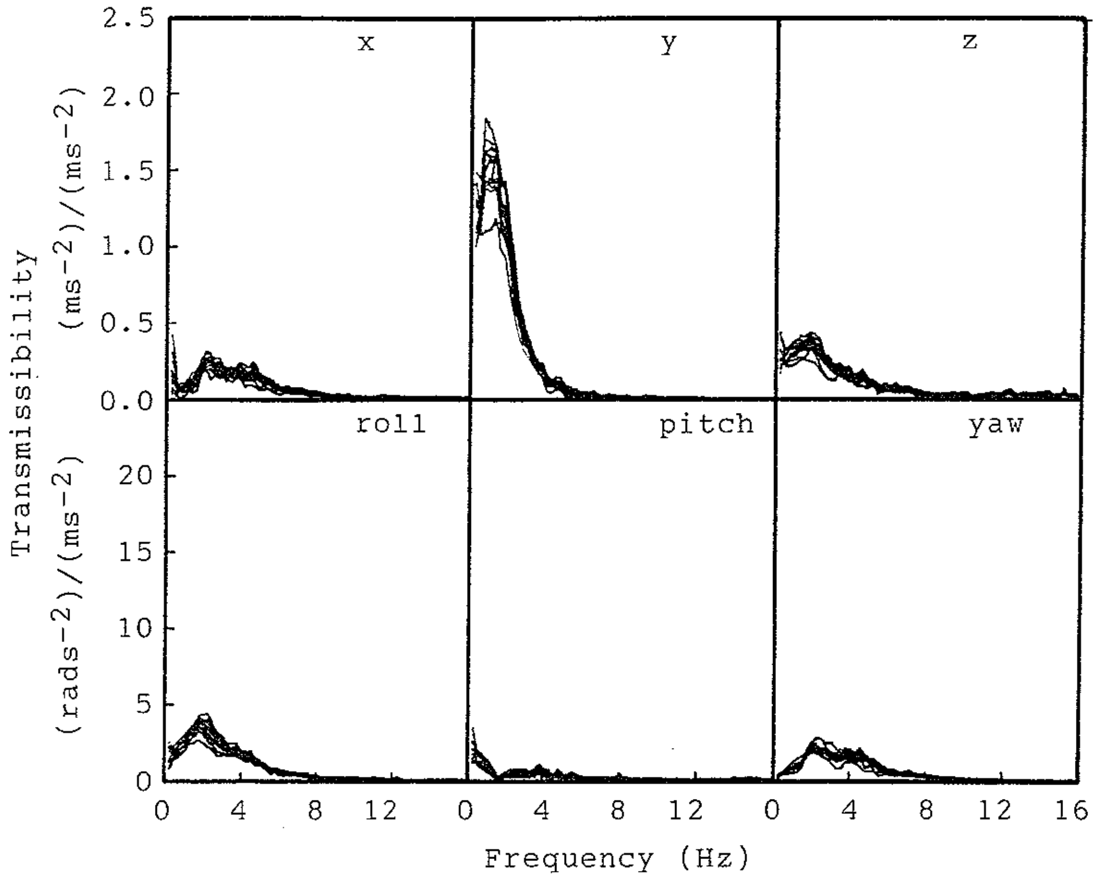


Figure 5.17 Transmissibilities for 1 subject in a 'back-off' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

torso. For both postures, it is seen that the data became erratic at some frequencies and the curves 'fork out' at a difference of about 360°.

Ordinary coherencies for these data were calculated for both postures and all axes at the head, these are shown in Appendix 4.

5.3.2.5 Discussion

Some minor differences are seen between transmissibilities for the 'back-on' and 'back-off' postures from Figures 5.16 and 5.17 but these are not clear due to the variation between the runs: Figure 5.19 shows medians of these transmissibilities for the two postures for ease of comparison. These data show only small differences and therefore, contact with the backrest had only a small effect on motion transmitted to the head.

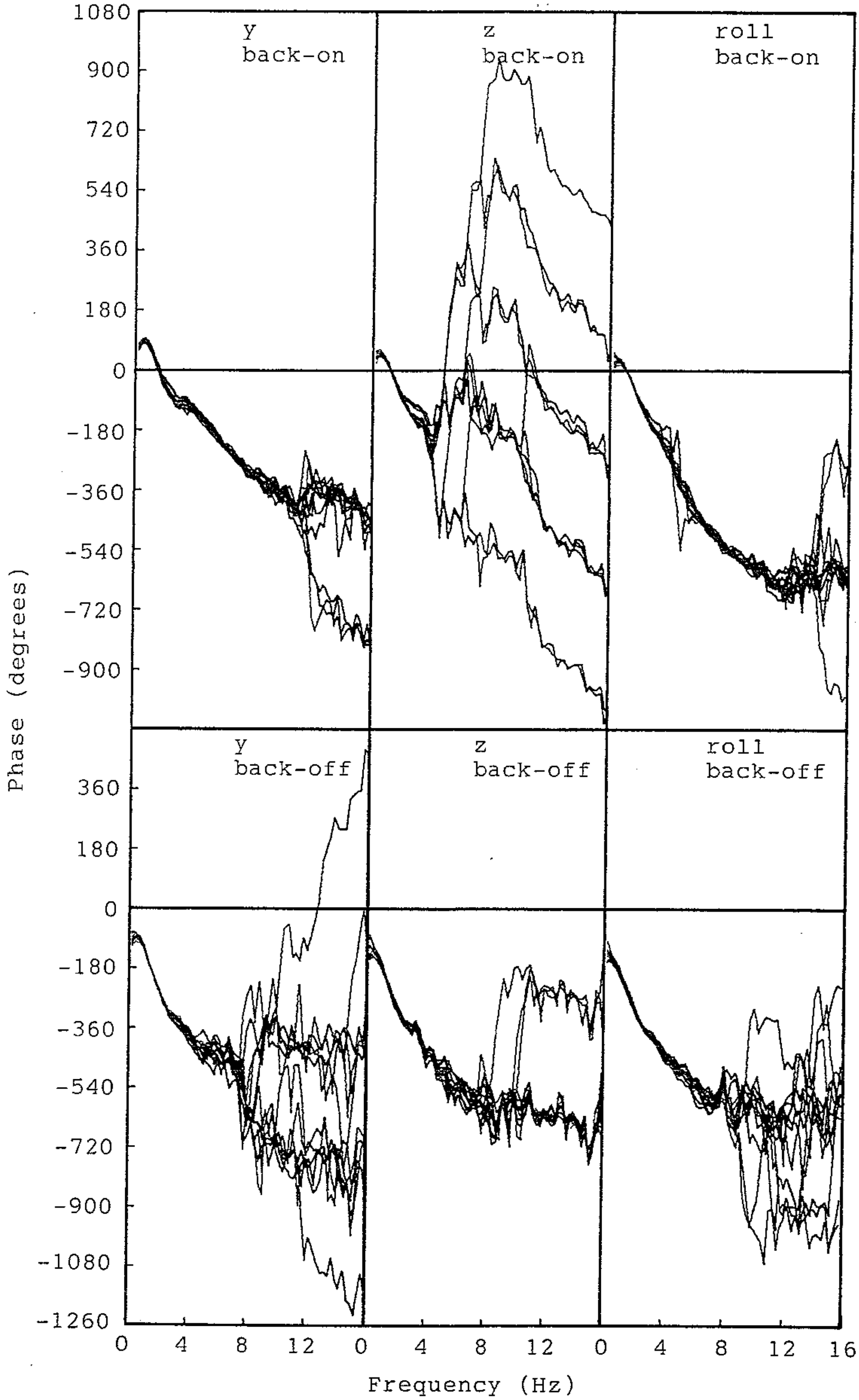


Figure 5.18 Phase for 3 axes of head motion for 1 subject in a 'back-on' and 'back-off' posture during lateral seat motion.

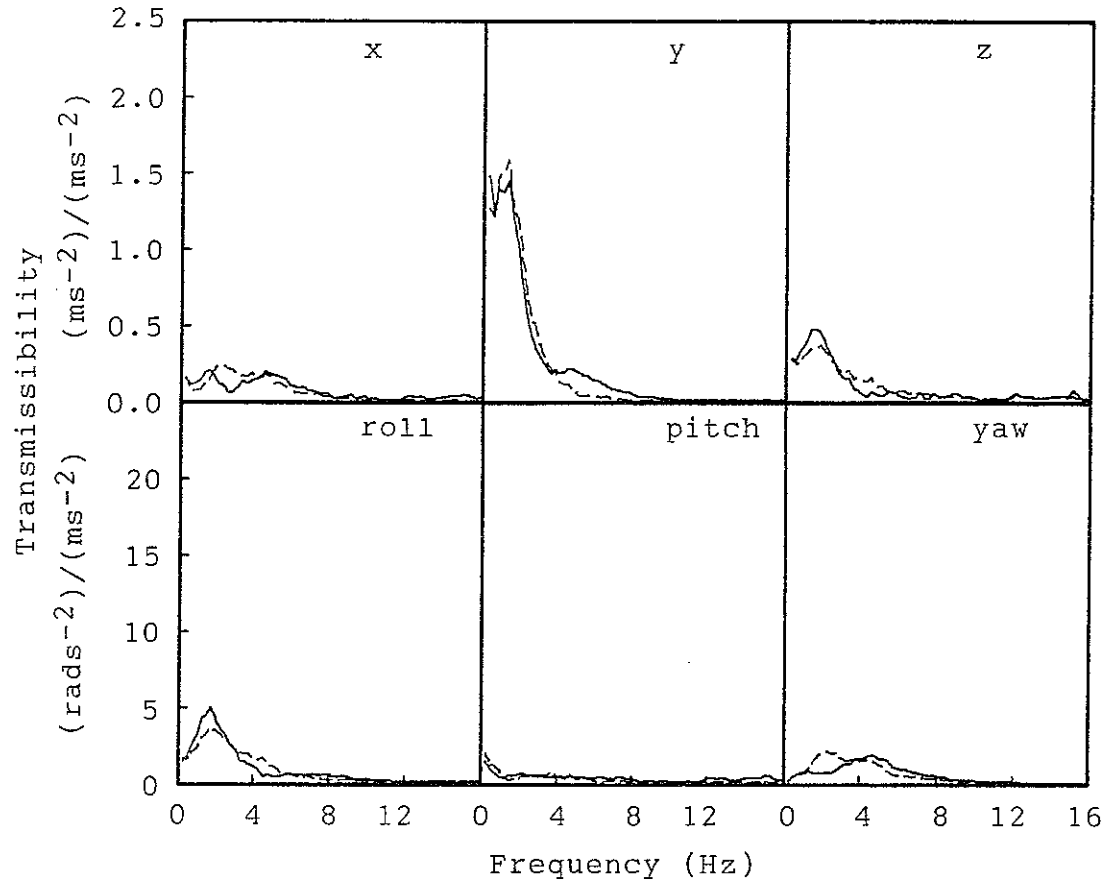


Figure 5.19 Median transmissibilities for 1 subject in a 'back-on' (———) and a 'back-off' (- - - -) posture during lateral seat motion.

Phase data were seen to demonstrate a chaotic behaviour for all axes but for differing frequency ranges. The data tend to follow the general underlying trend but at a position displaced by multiples of 360°. This is due to the low transmissibilities at (and beyond) these frequencies and also due to incoherent data; this is illustrated by the coherencies included in Appendix 4. For example, consider the phase and coherencies for lateral axis head motion when seated in a 'back-on' posture. The coherency falls sharply to about 0.3 at 8 Hz and to about 0.05 at 12 Hz. the phase becomes unpredictable and then 'forks out'. Therefore, data beyond about 10 Hz for lateral motion at the head during a 'back-on' posture might be unreliable.

It is seen from the transmissibility data that most of the head motion occurred at frequencies below about 10 Hz. The greatest variability in transmissibility appears to have been at the main resonance frequency for each axis. For lateral motion at the head, the difference between minimum and maximum response was about 1:1.5 at the resonance frequency while for vertical motion at the head, the difference was as great as 1:2.5.

5.3.3 Inter-subject variability

5.3.3.1 Introduction

The above study was concerned with the variability in the transmission of lateral vibration from the seat to the head for a single subject. It showed the results that should be expected for all axes and the possible spread in data due to repeat measures. This study repeats the above but with many subjects in order to obtain a measure of variability in response between subjects and investigates the effect a backrest has on the transmission of lateral seat vibration to the head.

5.3.3.2 Apparatus

Vibration generation

The set-up used for the generation of vibration was the same as that explained in Section 5.2.2.2. The only difference was that the hard flat seat was mounted on the horizontal vibrator platform so as to expose subjects to lateral axis vibration.

Vibration measurement

The apparatus used and the analyses employed on the acquired data were the same as those included in Section 5.2.2.2.

5.3.3.3 Procedure

Subjects

Twelve male subjects took part in this experiment, their characteristics are summarised in Table 5.1 (see Section 5.2.3.3) and data for individual subjects are shown in Appendix 5. Section 5.3.2.3 explains in detail the two postures adopted and the instructions given to the subjects (see Appendix 3).

Experimental design

Each subject was exposed to the same vibration stimulus on two consecutive runs: once for a 'back-on' posture and once for a 'back-off' posture. The order of posture presentation was balanced across the subjects such that six volunteers were required to sit in a 'back-on' posture first while the other six proceeded with the 'back-off' posture.

5.3.3.4 Results

Transmissibilities between lateral seat vibration and the six axes of head motion are shown in Figure 5.20 for the twelve subjects seated in a 'back-on' posture. A peak is present in the 2 Hz region for y-, z-, roll and yaw axes. There is little motion at the head above about 8 Hz.

Transmissibilities for the 'back-off' posture are displayed in Figure 5.21. Significant motion occurred at the head for all axes below about 6 Hz apart from the pitch axis.

Phase data were calculated for motion in the mid-coronal plane axes (i.e. lateral, vertical and roll) and these are shown in Figure 5.22 for the two postures. These data show the curves 'forking out' as seen for the intra-subject variability data (Section 5.3.2). The reliability of the transmissibility and the phase data can be estimated by

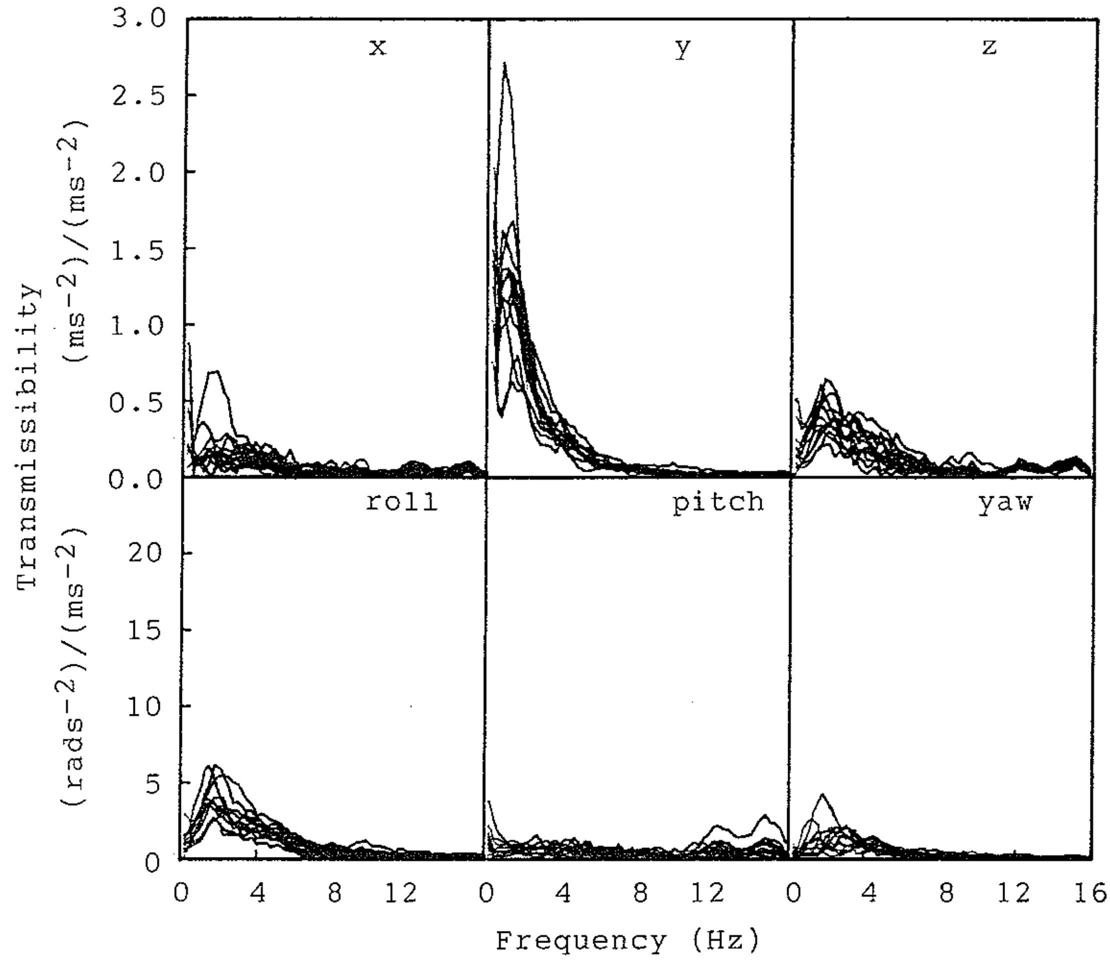


Figure 5.20 Transmissibilities for 12 subjects in a 'back-on' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

looking at the corresponding coherencies for these postures shown in Appendix 4.

5.3.3.5 Discussion

The grouped transmissibility curves do not show any obvious differences that could be attributed to change in posture. However, it is seen that the difference in response between subjects can vary by a factor of 5.5 (e.g. 'back-on' lateral head motion at 1 Hz). Figure 5.23 shows the median transmissibility data obtained from Figures 5.20 and 5.21 for ease of comparison. Visual inspection reveals no obvious differences apart from the small increase in lateral axis head motion with the 'back-on' posture at about 1.5 Hz. Analysis of variance showed that there were

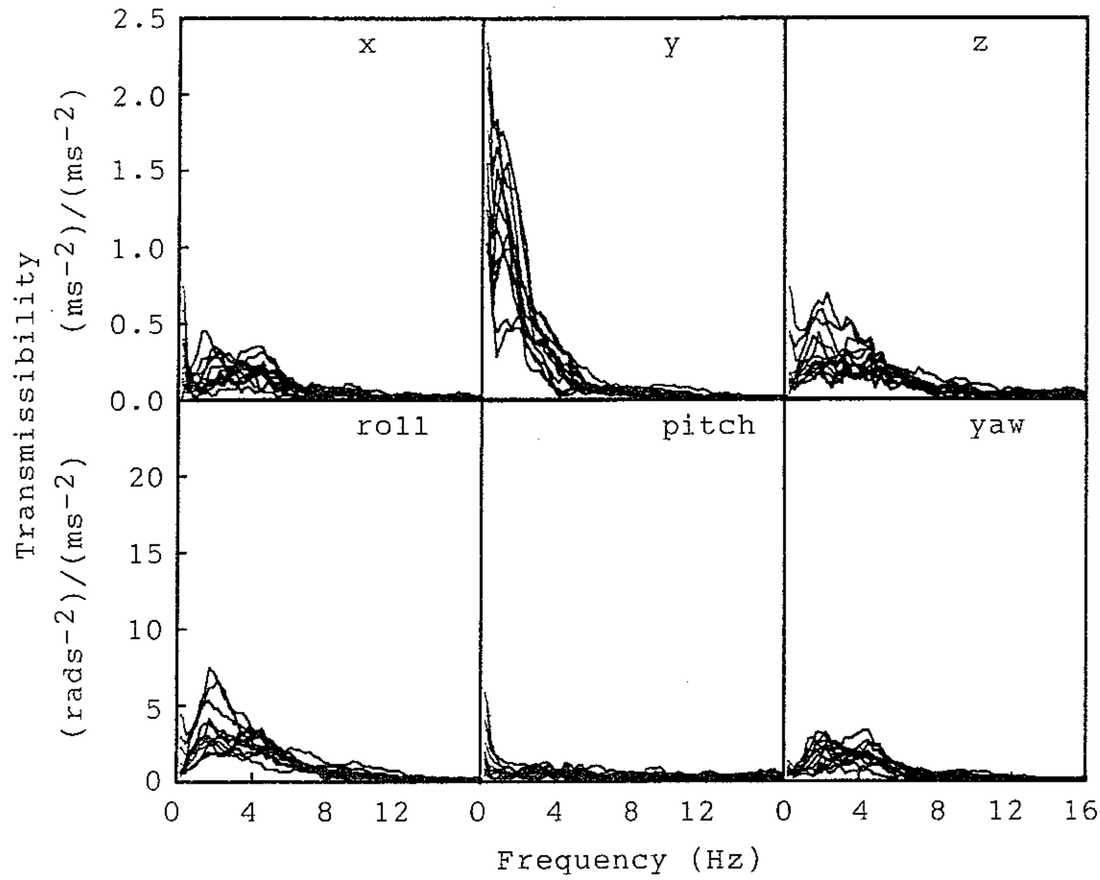


Figure 5.21 Transmissibilities for 12 subjects in a 'back-off' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

significant differences between the two postures for only the y- and yaw axes of the head ($p<0.05$ and $p<0.01$ respectively). Even in these axes the effect of the backrest was small.

The coherencies for these data showed low values for most of the frequency range and for most of the axes. This implies that beyond some frequency (which can be estimated for each axis from the coherencies), both transmissibility and phase data might be unreliable. The relatively 'high' coherencies for both postures show that most of the motion at the head occurred in these axes.

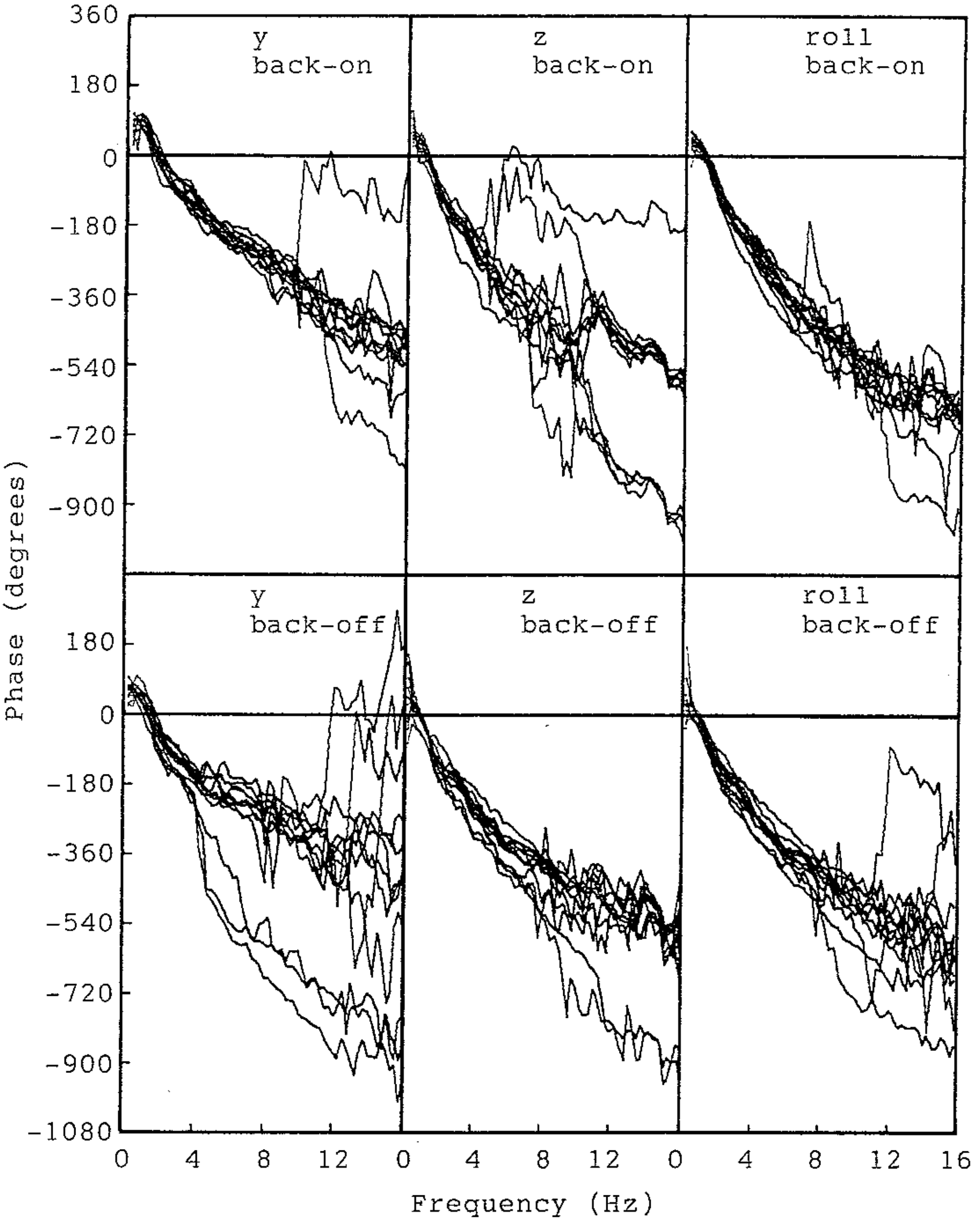


Figure 5.22 Phase for 3 axes of head motion for 12 subjects in a 'back-on' and 'back-off' posture during lateral seat motion.

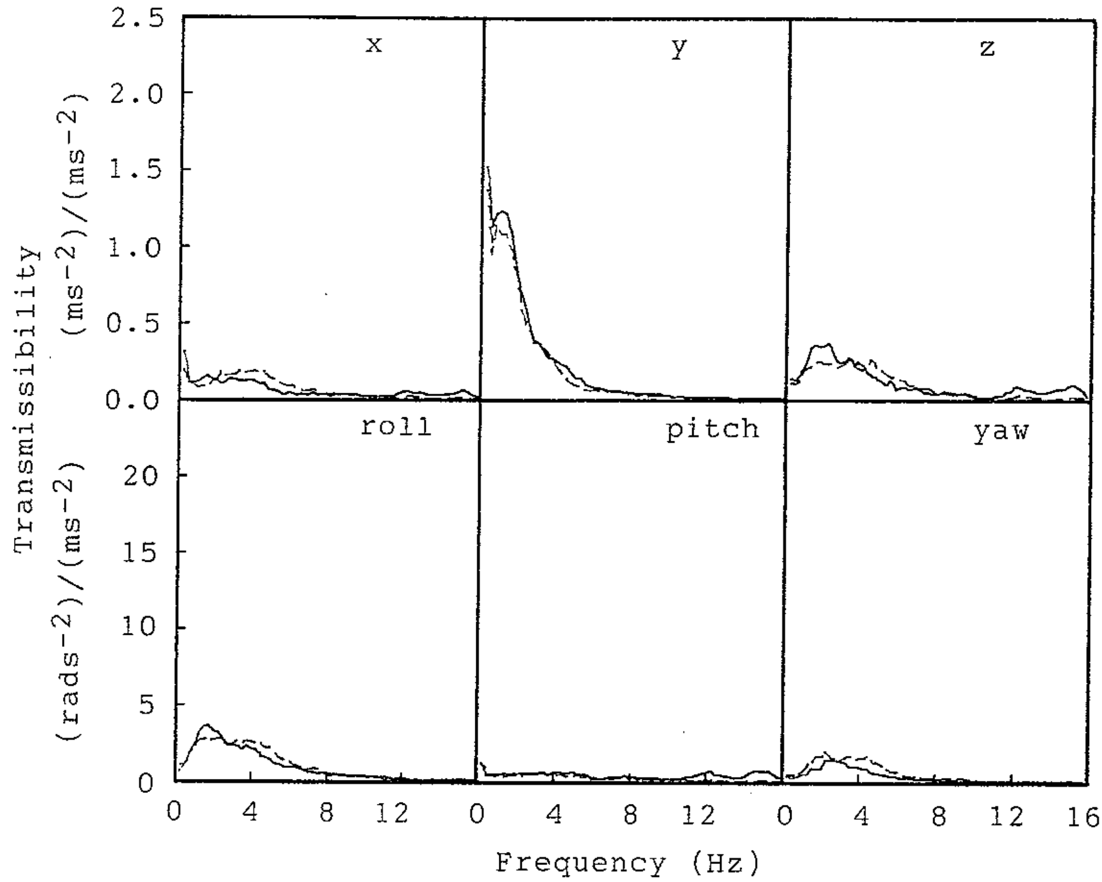


Figure 5.23 Median transmissibilities for 12 subjects in a 'back-on' (———) and a 'back-off' (- - - -) posture during lateral seat motion.

5.3.4 Discussion and conclusions

Transmissibilities obtained from these studies of the transmission of lateral seat vibration to the head for seated subjects have shown that leaning against the backrest did not have a significant effect on head motion. This might be due to the back sliding on the backrest and thus transmitting no extra motion through the body to the head. (It was shown in Section 5.2 that for a person exposed to fore-and-aft vibration of the seat, leaning against the backrest resulted in substantially more vibration being transmitted to the head around 8 Hz.) Data from both intra- and inter-subject variability studies showed that, as expected, variation in response was smaller for the repeatability study than the inter-subject variability study. It is seen from the data that variation in response depends upon the magnitude of transmissibility:

more variation for high transmissibility and less variation for smaller transmissibility values. It was expected that frequency would have a significant effect on head motion, this was found to be the case ($p<0.01$). Interaction between frequency and backrest was significant at the 1% level for all axes at the head bar fore-and-aft and yaw axes.

Comparisons can be made with studies conducted by other researchers (see Section 2.7.1.2) although one of the drawbacks with other studies has been the coarseness of frequency resolution. It is seen from this investigation that most of the activity at the head occurred below about 6 Hz and mostly around 2 Hz. Hornick et al. (1961) attempted to measure head motion while the subjects were exposed to lateral seat vibration, a resonance of the body was seen to occur at about 1.5 Hz. Unfortunately, since the frequencies used were 1.5 Hz, 2.5 Hz, 3.5 Hz, 4.5 Hz and 5.5 Hz, it would be extremely difficult to determine the precise location of the resonance. Woods (1967) found a main resonance frequency at around 1.5 Hz for whole-body vibration in the lateral axis. Lewis and Griffin (1980) also found similar results but again, the main frequency of interest in this study of around 2 Hz was the lowest frequency used in their tests. However, these data appear to confirm the transmissibilities obtained by them for motion in the lateral and roll axes at the head.

High values for y-axis head motion are seen from the transmissibilities for about 1 Hz, these are thought to be partly due to the lateral axis accelerometer on the head sensing a component of the Earth's gravitational field. Although there would be genuine lateral motion at the head caused partly by the body rocking in the mid-coronal plane (y-z plane) about the two buttocks. Roll motion at the head shows a maximum at 1.5 Hz, and this gives rise to a similar frequency of vertical motion at the head. Yaw motion at the head is due to the centre of gravity of the head being in front of the point of rotation, i.e. in front of the axis vertebra about which the head will yaw. This yaw motion will give rise to similar x-axis motion at the accelerometer - this is clearly seen from the x-axis and yaw axis transmissibility curves.

A non-parametric measure of correlation (Kendall's tau) was calculated between subject characteristics and head motion for the inter-subject study. It was found that age and weight did not correlate with transmissibility for either of the two seating conditions ('back-on' and 'back-off'). Subject stature showed a positive correlation ($p<0.05$) for fore-and-aft head motion transmissibility from 3 Hz to 5 Hz in the 'back-off' posture. A positive correlation ($p<0.01$) was found between lower leg length and fore-and-aft head motion transmissibility with the 'back-on' posture between 10 Hz to 15 Hz. Some correlations were found between total leg length and head motion, these were similar to those with lower leg length; these would have been expected since both lower and total leg lengths are themselves highly correlated (see Section 5.2.5).

5.4 VERTICAL SEAT VIBRATION

5.4.1 Introduction

The effect of vertical seat vibration on the body is the most investigated topic in biodynamics. The effect of many variables (e.g. vibration magnitude, seat condition, posture, frequency) and the effect on numerous variables (e.g. transmissibility, comfort, task performance, vibration perception) has been well documented. This can be seen by returning to Section 2.6 where most of the previous research has been concerned with vertical seat vibration while a few studies were cited in which vibration at the seat occurred in other axes. However, in some of the reported literature, there is either a shortage of data for some cases or deficiencies in the results of data reported.

This section concerns the measurement of head motion during exposure to vertical vibration of the seat. The effect of extrinsic and intrinsic variables is determined including bite-bar mass, bite grip, visual feedback, posture and vibration spectra. Also included are data which show variability in head response both within and between subjects. The effect of positions of measurement of vibration on the head is determined and discussed.

5.4.2 Effect of variables on head motion

5.4.2.1 Introduction

In most of the studies concerning the measurement of head motion during whole-body vibration, head vibration has generally been measured using either an instrumented bar which subjects grip tightly in their mouths, or through instruments attached to the head via a harness. The reliability of the mounting method and the influence of the mass of the mount on motions of the head has rarely been reported. It is important to determine the effect of these minor variables on head motion as they might mask out the effect of other variables being investigated.

The aim of this section is to determine whether variables such as bite-bar mass, bite grip and the visual field influence motion of the head. The results from these would be used to plan further experiments. Also, the effect of two contrasting body postures is investigated, the postures being 'upright comfortable' and 'erect'.

5.4.2.2 Apparatus

Vibration generation

The experiments were conducted using a 1 metre stroke electro-hydraulic vertical vibrator designed to reproduce motions which are suitable and safe for the study of human response to vibration. The vibrator consists of a moving platform (1.50 m x 0.89 m) which can carry various seats and one or more subjects. For these studies, the acceleration distortion may be considered to be less than

5%; motions in the cross axes were less than 1.5% of those in the axis of excitation. More details about the vibrator are given in Section 3.5.2.

Two different seats were used in the study. The seat used for an investigation of bite-bar mass and bite-bar grip had a rigid flat surface and a rigid flat backrest (inclined at an angle at 13° to the vertical) which extended up to the neck of the subject.

A more simple rigid flat seat was used for the studies of the effect of a visual field and postural change experiments. The supporting surface of this seat, which was 480 mm above the moving footrest, was inclined backwards at an angle at 3° to the horizontal. The lower and upper edges of a rigid flat backrest were 145 mm and 535 mm above the seat surface. The backrest was inclined at an angle at 6° to the vertical. Neither the seat not the backrest had a resonance in any axis within the frequency range studied. Both the seat and the backrest surfaces had a thin (3 mm) layer of high stiffness, high friction rubber to reduce relative movements between the subjects and the seat due to sliding. This was the same seat as that used in the fore-and-aft and lateral seat vibration experiments (see Sections 5.2 and 5.3).

All experiments employed the same computer-generated Gaussian random vibration presented for 60 seconds at 1.75±0.05 ms^{-2} r.m.s. with a flat spectrum, limited by 35dB Butterworth bandlimiting filters at 0.2 Hz and 31.5 Hz.

Vibration measurement

A six-axis bite-bar was used in this study and is described in detail in Section 3.2. It had six translational piezo-resistive full-bridge Entran type EGAX accelerometers located so that motion of the head could be determined in all three translational and three rotational axes of the head. A sterilised dental mould securely attached to the bite-bar was used to hold the bite-bar between the teeth.

The acceleration signals from the accelerometers were passed through signal conditioning amplifiers and then low-pass filtered at 31.5 Hz via 48 dB/octave anti-aliasing filters. The vibration data were then acquired into a digital computer system (DEC PDP11-34) at a sample rate of 128 samples per second. Seven channels of vibration were acquired into the computer simultaneously (6 from the bite-bar and 1 of the vibrator platform).

The data were analysed to determine seat-to-head transfer functions using the 'cross-spectral density function method' (see Section 5.2.2.2). A frequency resolution of 0.25 Hz was used which gave 58 degrees of freedom.

5.4.2.3 Procedure

Subjects

One male subject (38 years old, 1.85 m tall and weight 80 kg) took part in these experiments. He was given written instructions on the required posture of the head, body, arms and the legs; the instructions were similar to those included in Appendix 3. For the effect of bite-bar mass and bite grip experiments, the subject was restrained in the seat by a five point harness while only a loose lap strap was worn for safety purposes in the visual field and postural change experiments. A comfortable upright posture was requested for the visual field experiment.

Apart from the experiment involving postural changes, for the other three short investigations, a 510 mm long sight-tube with cross wires on either end was provided to assist the control of head position and orientation by aligning his line of sight down the tube. The sight-tube was located 460 mm in front of the subject and moved with the vibration table. The subject was instructed to look at a cross approximately 1.3 m away on a wall and moving with the vibrator table in the visual field experiment.

Experimental design

To determine the effect of bite-bar mass on head motion, the bite-bar (which in its normal configuration had a 40 g counterweight) was loaded by increasing the counterweight in increments of 40 g. The weights were positioned such that the centre of gravity of the total counterweight remained at the same point (12 mm behind and 57 mm to the left of mouth level). In its normal configuration, the total mass of the bite-bar was 135 g (excluding the dental mould) and with the heaviest counterweight, the mass was 375 g. The order of experimentation was such that the mass was increased for successive runs. There were seven vibration exposures with different bite-bar mass and there was a pause of 5 minutes between exposures.

In the determination of the effect of bite-bar grip, the subject was instructed to grip the dental mould in five different conditions: 'extremely loose', 'loose', 'normal', 'tight', 'extremely tight'. The order of experimentation was such that the grip was successively made tighter for each run.

In the study of the effect of the visual field, two runs were carried out: one with the subject looking through the sight-tube and the other with the eyes closed. The subject sat with his back in contact with the seat backrest.

The subject took part in two runs with different body postures to determine the effect of these on head motion: the postures were 'upright comfortable' and 'erect'. Both runs were conducted with the subject in a 'back-off' position (subject's back not in contact with the seat backrest).

5.4.2.4 Results

Transmissibility curves for the six axes at the head (three translational and three rotational) for the subject seated with seven different bite-bar masses are shown in Figure

5.24. The only curve that shows a systematic change with bite-bar mass is in the pitch axis: the transmission ratio increases by 18% at both the resonance frequency (i.e. about 7 Hz) and above 13 Hz with increased mass. The small differences that occurred in all the axes can be explained by intra-subject variability (see Section 5.4.3).

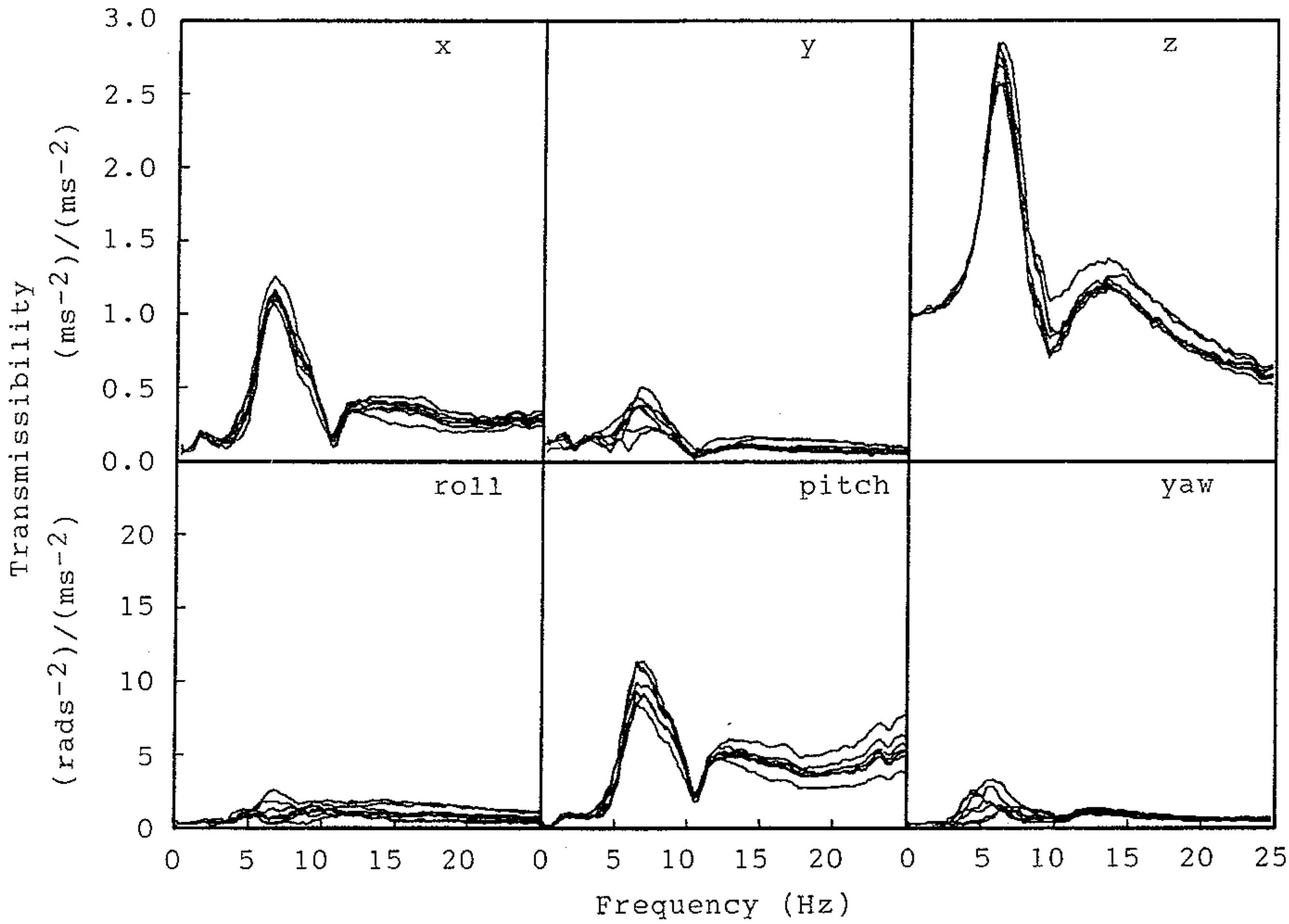


Figure 5.24 Transmissibilities for 1 subject for different bite-bar masses during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

The transmissibility curves for the single subject using the five different bite grips on the bite-bar are shown in Figure 5.25. The small differences between the curves for different bite grips occurred in no systematic order and can be explained by intra-subject variability. Even though bite grip force was altered over the widest likely range and in the extreme, muscles in the neck and head were greatly tensed, the changes in transmissibility are not important.

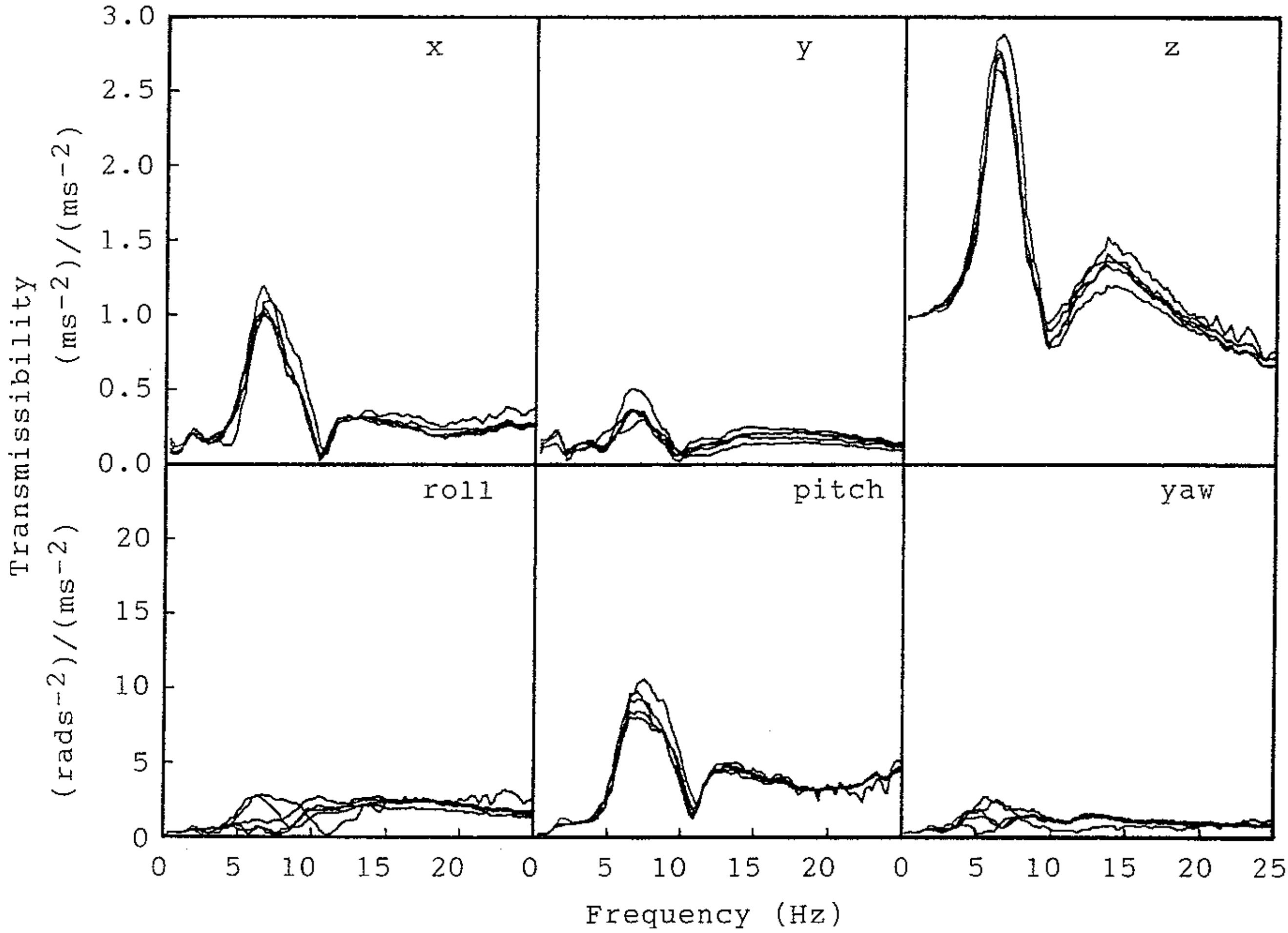


Figure 5.25 Transmissibilities for 1 subject for different bite grips during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

In Figure 5.26 are shown transmissibility data for the two visual conditions of sight-tube and eyes closed. For x-, z- and pitch axes, the curve which is slightly higher than the other at around 6 Hz corresponds to the condition in which no sight-tube was used (i.e. eyes closed). Differences between the two curves are only present around the major resonance frequency of the body, other frequencies show very small differences. The difference is of the order of intra-subject variability and a slight change in subject posture might have caused this change.

Translational and rotational transmissibility curves for the six axes of head motion for the subject seated in 'upright comfortable' and 'erect' postures are illustrated in Figure 5.27. The effect of the different postures is seen only in the x-, z- and pitch axes. A major difference

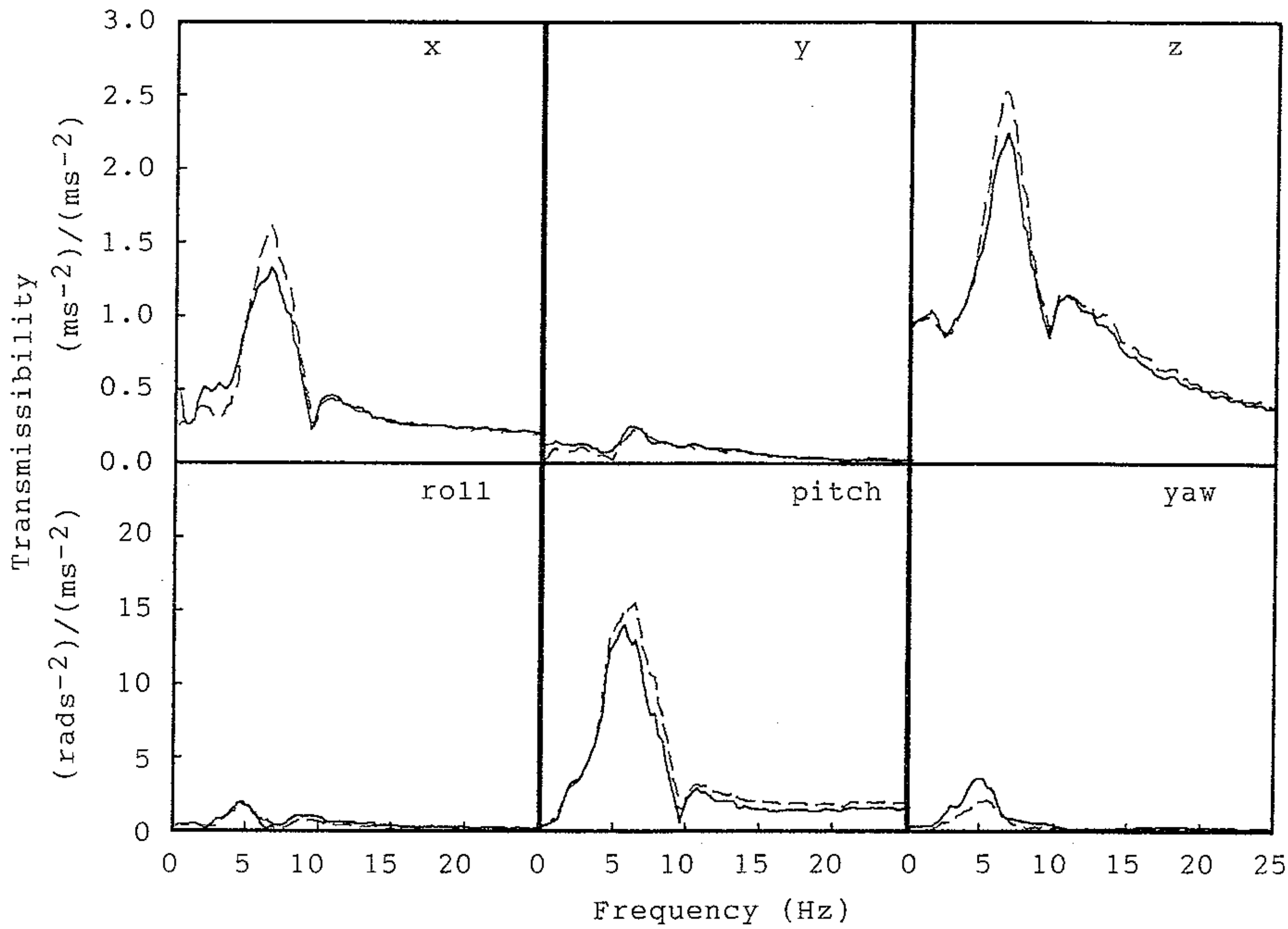


Figure 5.26 Transmissibilities for 1 subject for two visual environments (with sight-tube (———) and eyes closed (- - - -)) during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

is present in only the vertical axis at the head. The two postures gave similar transmissibilities up to about 10 Hz but differed at higher frequencies. At 18 Hz the curve for the 'erect' posture is 130% higher than that for 'upright comfortable'. The second peak in the transmissibility curve occurs at 11 Hz for the 'upright comfortable' posture but is at the higher frequency of 15 Hz for the 'erect' posture.

5.4.2.5 Discussion

The effect on the dynamics of the head of normally overlooked factors such as bite-bar mass, bite grip and the visual environment have been studied. There may have been

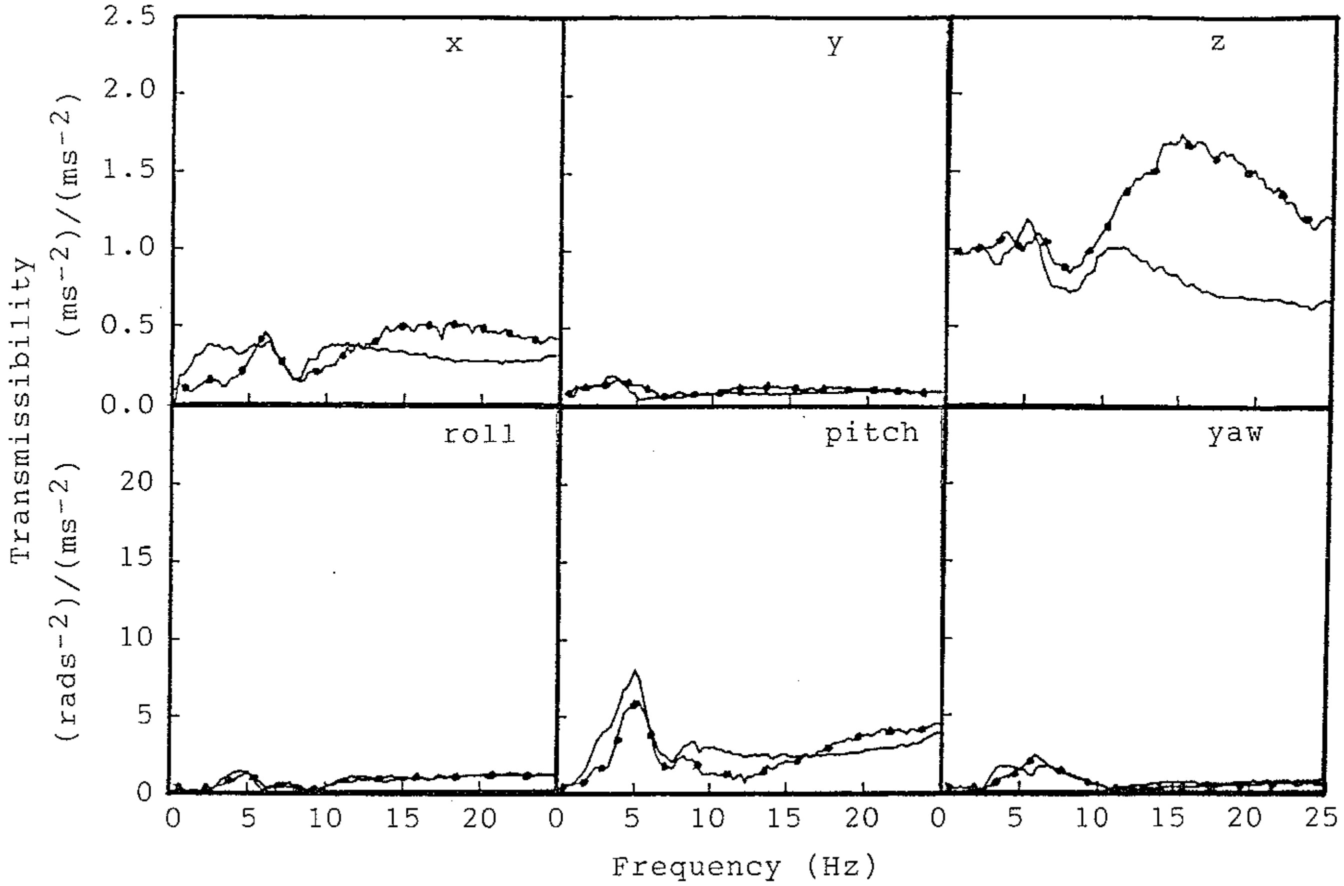


Figure 5.27 Transmissibilities for 1 subject in an 'upright comfortable' (————) and an 'erect' posture (-•-•-•-•-) during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

a small systematic effect of bite-bar mass on head motion in the pitch axis but it is difficult to be conclusive and only one subject took part in this experiment. The variation in transmissibility during different bite grips was small and could be explained by repeatability measures.

It was thought that the visual environment might influence results in that visual feedback may induce low frequency correcting movements of the head. It was considered most likely that the sight-tube would influence pitch or vertical axis head motion at frequencies below 1 Hz, however, this was not found. The small variation could again, be explained by intra-subject variability (see Section 5.4.3).

The experiment to investigate the effect of posture demonstrated that during exposure to vertical seat vibration, considerably more motion resulted at the head with the subject seated in an 'erect' posture than the 'upright comfortable' posture. These two postures appeared visually to be very similar although completely different results emerged. Smaller unintentional changes in posture might have contributed to the variability in head motion found for the other three variables.

5.4.3 Intra-subject variability

5.4.3.1 Introduction

In determining the effect of a variable on the transmission of seat motion to the head, an estimate is required of the variation to be expected during repeated measures. These measures would be conducted assuming that other parameters were not altered (e.g. posture, head angle, etc.): the only variable in such a study would be time. Some of the variation in head motion between subjects could also be partly explained by these measures of variability within subjects.

The aim of this section is to estimate the variation in head motion response that should be expected for repeat measures during exposure to vertical vibration of the seat. The effect of two body postures on the transmission of seat vibration to the head is also determined.

5.4.3.2 Apparatus

Vibration generation

The 1 metre vertical electro-hydraulic vibrator was used in this experiment and the subject sat on a simple hard flat seat which had rigid seat and backrest surfaces (see Section 5.4.2.2). The same Gaussian random waveform as that described in Section 5.4.2.2 was used for this experiment: 60 seconds at a vibration magnitude of

1.75 ± 0.05 ms^{-2} r.m.s. and over the frequency range of 0.2 Hz to 31.5 Hz.

Vibration measurement

Apparatus used in this part was the same as that employed in Section 5.4.2.2.

5.4.3.3 Procedure

Subjects

One 38 year old male subject of height 1.85 m and weight 80 kg volunteered to take part in this experiment. He was asked to adhere to the instructions shown in Appendix 3 and to maintain the required posture for the whole duration of each vibration exposure. He was required to ensure that his head remained in a forward facing posture and to direct his eyes at a stationary cross approximately 1.3 m in front of him. A loose lap strap was worn by the subject to comply with the safety regulations.

Two postures of the body were investigated: a 'back-on' posture in which he sat with his back in contact with the seat backrest and a 'back-off' posture in which case there was no contact between the subject's back and the backrest.

Experimental design

The subject was exposed to the same vibration twelve times on the first occasion with him seated in a 'back-off' posture and then again, twelve times on the second occasion with him sitting in a 'back-on' posture. There was a pause of approximately 5 minutes between the runs during which the subject left the seat and relaxed.

5.4.3.4 Results

In Figure 5.28 is shown the variation in transmissibility of vertical seat vibration to the six axes of head motion within one subject with the subject seated in a 'back-on' posture. The x-, z- and pitch axis transmissibilities are greatest and show that most of the motion occurred in the x-z plane. Although motion in other axes was much less, it may not be negligible for all applications (e.g. Wells and Griffin, 1984). The three dominant axes show a resonance near 6 Hz and least motion at 12 Hz, 9 Hz and 13 Hz for x-, z- and pitch axes respectively. There is evidence of a second broad peak for vertical head motion around 14 Hz.

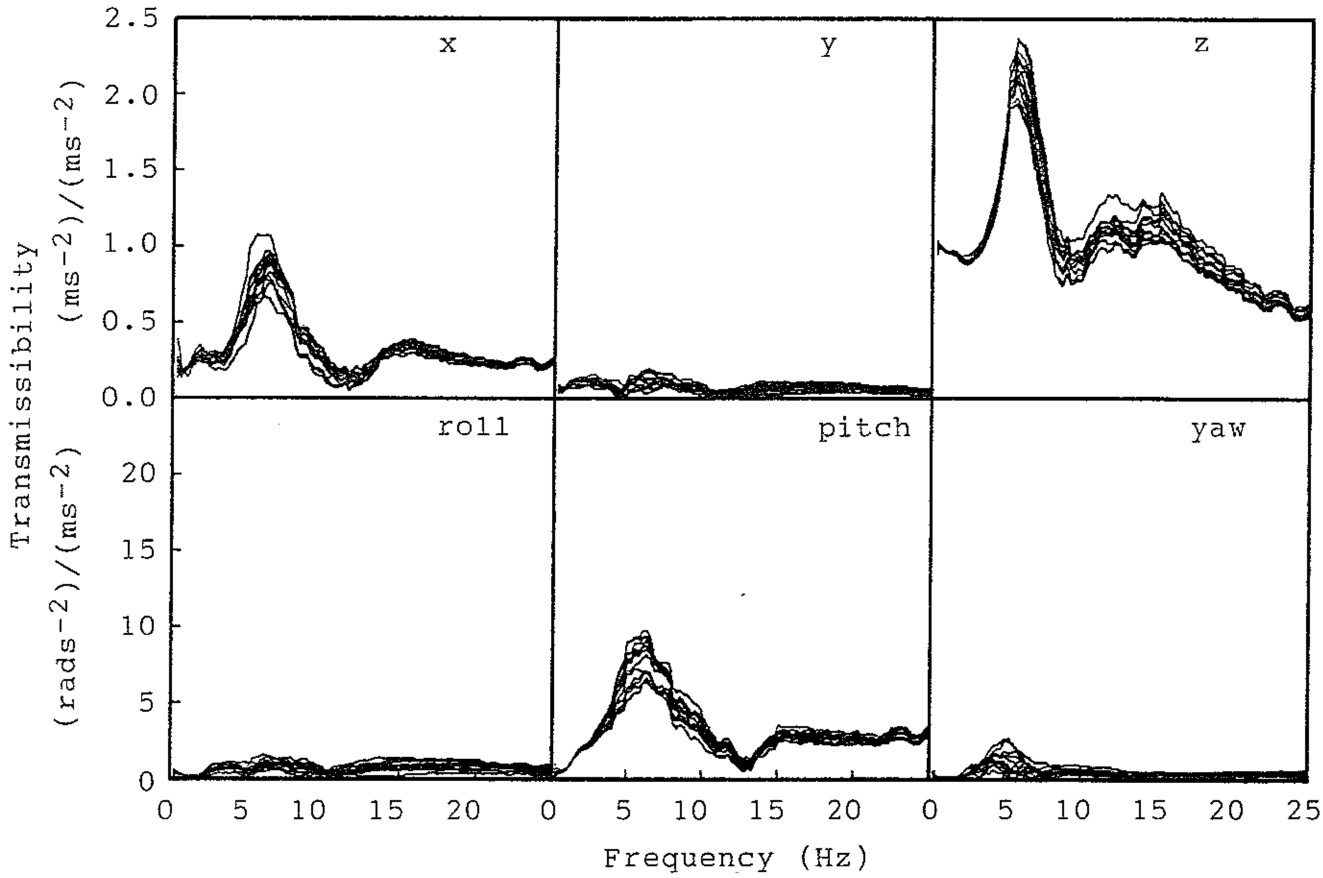


Figure 5.28 Transmissibilities for 1 subject in a 'back-on' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

Figure 5.29 shows the transmissibilities for the 'back-off' posture. At high frequencies in the vertical axis, the variability has increased: near 15 Hz the maximum response is 48% higher than the minimum response.

Since most of the motion at the head occurred in the mid-sagittal plane, phase data for only these axes (i.e. x-, z- and pitch) are presented in Figure 5.30. A slight

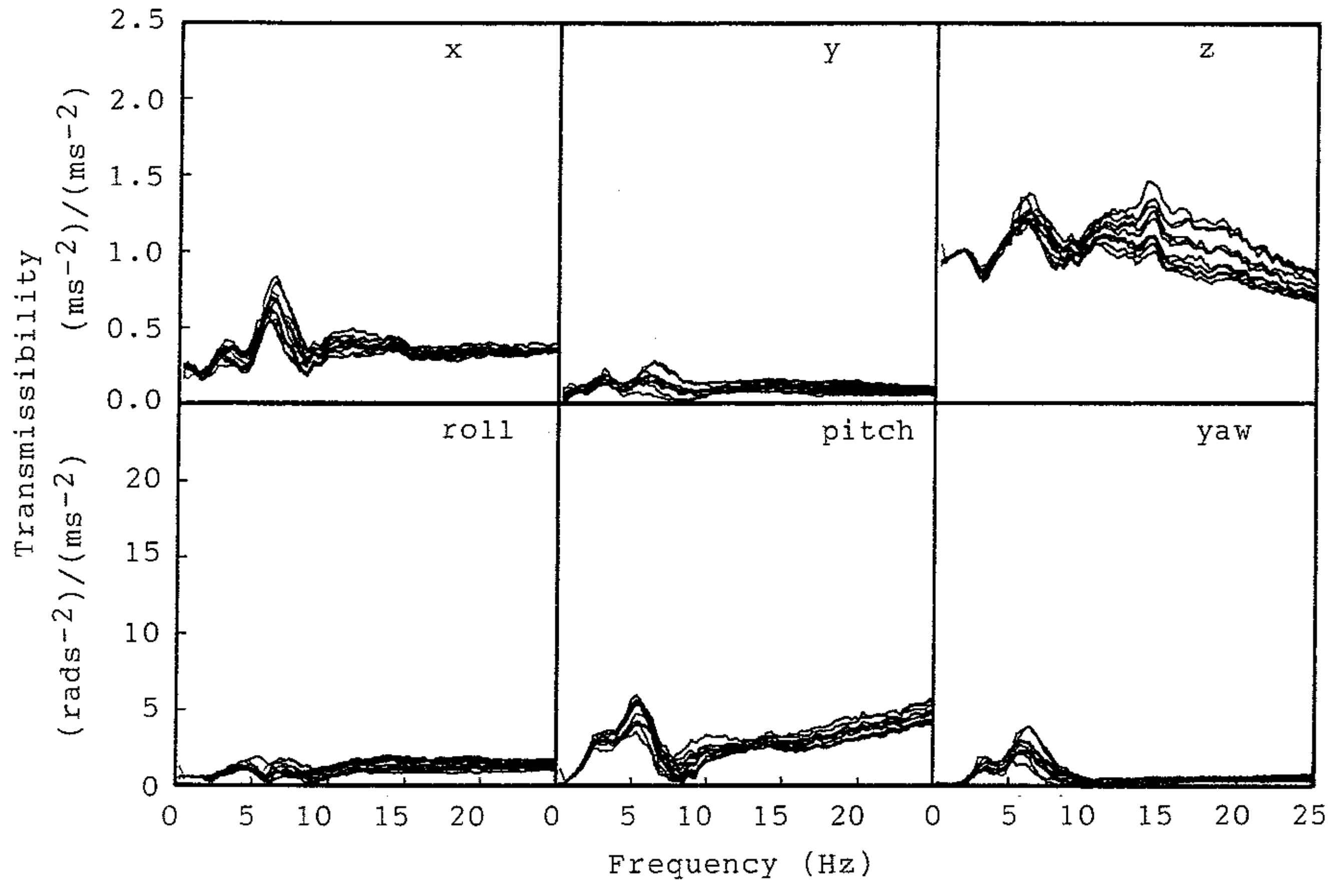


Figure 5.29 Transmissibilities for 1 subject in a 'back-off' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

peculiarity nearly occurred in the phase at about 8 Hz for the pitch axis at the head when seated in a 'back-off' posture, this is due to the very low transmissibility values at this frequency.

Coherencies for the six axes at the head for the two postures are shown in Appendix 4.

5.4.3.5 Discussion

There are notable differences between transmissibilities for the 'back-on' and 'back-off' postures, these occurred mainly in the x-, z- and pitch axes. These are easily seen from the median transmissibilities shown in Figure 5.31. Fore-and-aft head motion shows an increase over the frequency range 4 Hz to 8 Hz with the 'back-on' and a

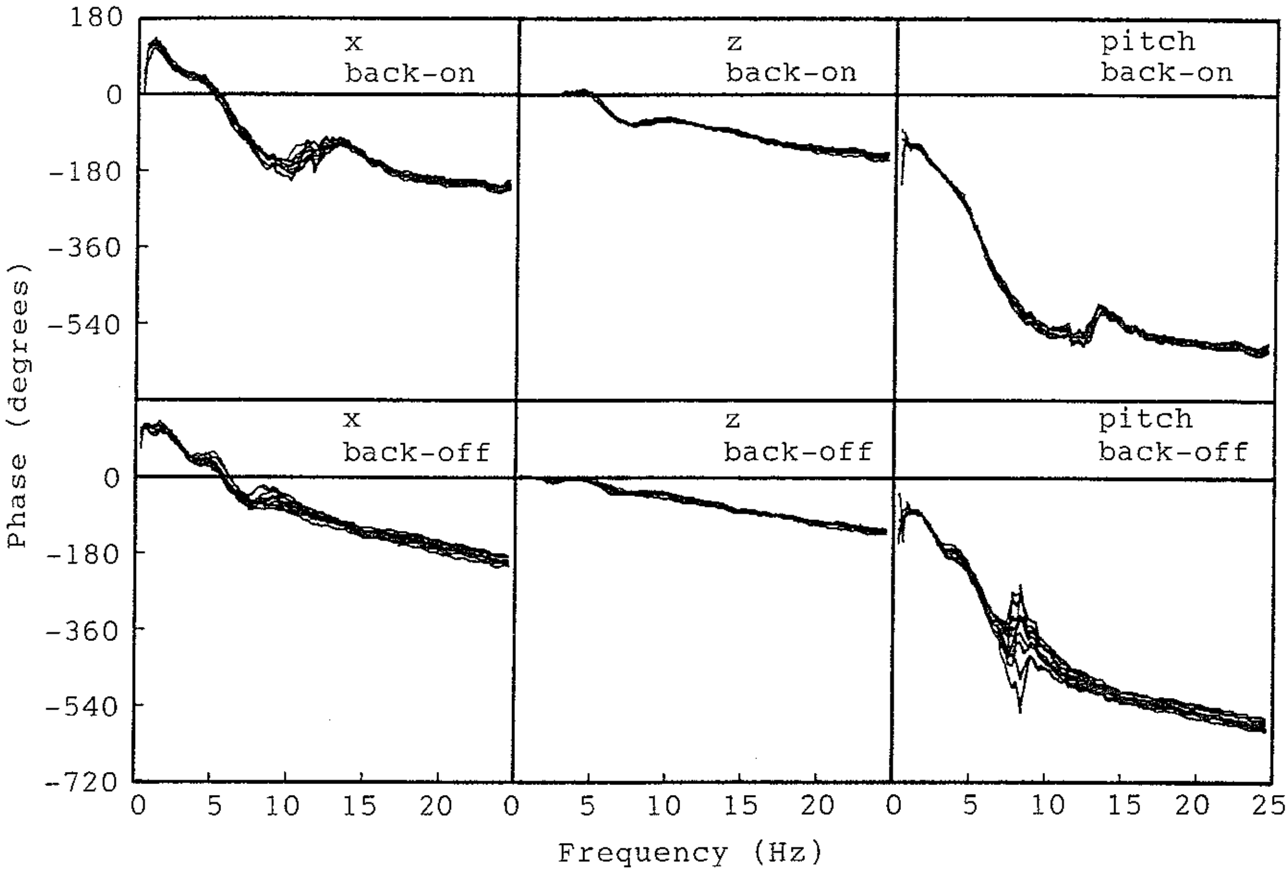


Figure 5.30 Phase for 3 axes of head motion for 1 subject in a 'back-on' and a 'back-off' posture during vertical seat motion.

definite dip at about 11 Hz. In the vertical axis, the 'back-on' posture resulted in approximately 60% more motion at the main resonance frequency of 6 Hz and, over the frequency presented, the 'back-off' posture displays a slightly greater spread between successive runs than the 'back-on' posture. In the pitch axis, there is a decrease in the frequency and magnitude of the main resonance peak with the 'back-off' posture. The point of minimum response decreases from 13 Hz for the 'back-on' posture to 8 Hz with the 'back-off' position.

It is seen that for both postures, the variation in transmissibilities is very much dependent upon frequency: for vertical motion at the head, variation between repeat measures was small for low frequencies (i.e. below 5 Hz) and large for high frequencies. It is difficult to say whether the spread depends on the magnitude of transmissibility.

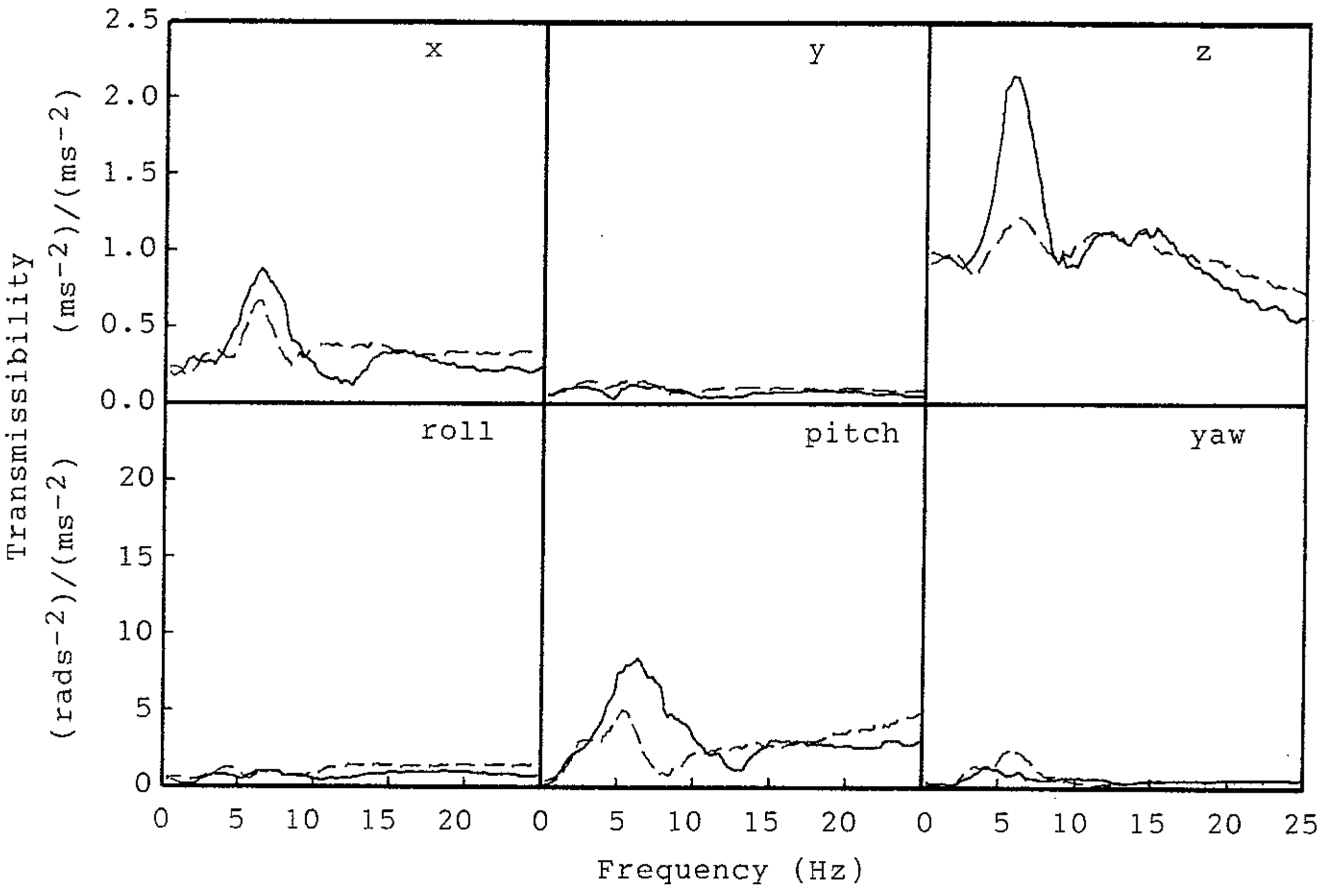


Figure 5.31 Median transmissibilities for 1 subject in a 'back-on' (———) and a 'back-off' (- - - -) posture during vertical seat motion.

Relatively high coherencies were obtained for motion occurring in the mid-sagittal plane and the differences between the two postures ('back-on' and 'back-off') varied between axes. As the coherencies were high, phase data were free from large sudden deviations that occurred in phase for other experiments (see inter-subject variability Section 5.4.4). Reliability of these data can be estimated using various spectral parameters as shown in Appendix 10.

5.4.4 Inter-subject variability

5.4.4.1 Introduction

In Section 5.4.2 it was found that variables such as bite-bar mass, bite grip and visual environment do not affect vibration transmitted from the seat to the head for seated subjects. The previous section showed the variability in transmissibility that should be expected within an individual during repeat measures. The results from these two sections will be used to explain data obtained from this section which determines variability in transmissibility across a group of individuals. Also investigated will be the effect of body posture and vibration spectra on head motion.

5.4.4.2 Apparatus

Vibration generation

Equipment used in this study was the same as that explained for the intra-subject variability (see Section 5.4.3.2). In addition to the Gaussian random waveform used for the intra-subject study, two vertical vibration recordings obtained from off-road tracked military vehicles were also used; these were from an Armoured Personnel Carrier (APC) and an Armoured Fighting Vehicle (AFV). The simulations of the vehicle motions were such that the r.m.s. accelerations of the motions on the vibrator seat were approximately the same as those recorded on the seats within the vehicles. The vibration magnitudes were:

Gaussian random	1.7 ms^{-2} r.m.s.
APC	1.5 ms^{-2} r.m.s.
AFV	0.8 ms^{-2} r.m.s.

Power spectral densities for these three vibration waveforms are shown in Figure 5.32. The Gaussian random waveform had a uniform distribution of energy across the frequency spectrum and this was of approximately equal proportions over frequency; the APC spectrum shows mostly low frequency motion below about 5 Hz; the AFV resembled a combination of the above two spectra.

Vibration measurement

The equipment employed for this study was the same as that explained in Section 5.4.2.2.

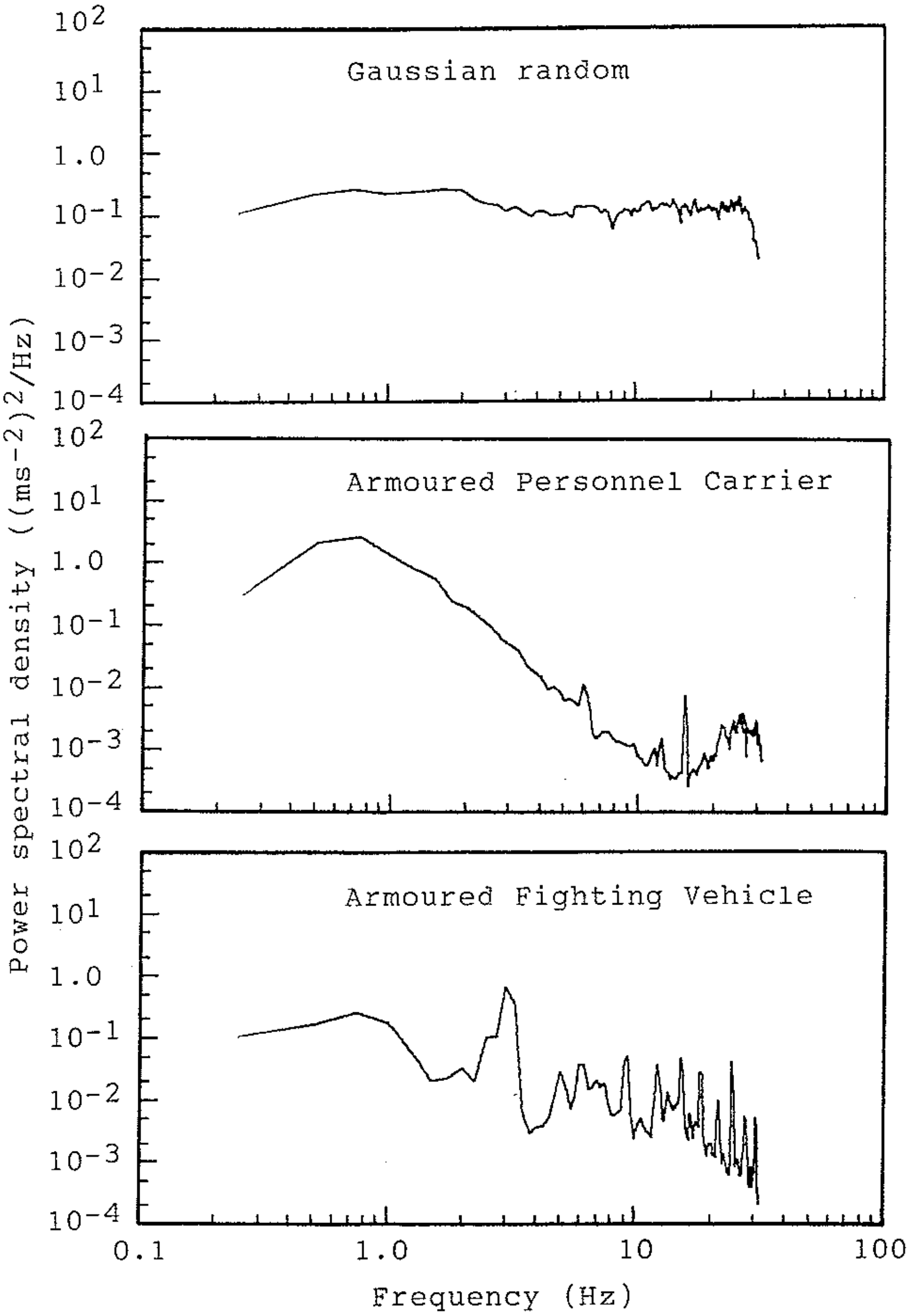


Figure 5.32 Power spectral densities of vibrator platform for different waveforms during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

5.4.4.3 Procedure

Subjects

Twelve healthy male subjects took part in this experiment, their mean physical characteristics were 26.1 years old, weight 70.8 kg and stature 1.80 m. More details about the subjects are given in Section 5.3.3.3 and in Appendix 5.

The postures required and the instructions given to the subjects about the procedure of the experiment are explained in detail in Section 5.4.3.3 and Appendix 3.

Experimental design

The order of presentation of the two body postures ('back-on' and 'back-off') were arranged such that six subjects commenced with the 'back-on' posture while the other six started with the 'back-off' posture. In the part of this experiment to determine the effect of vibration spectrum on head motion, the order of exposure of the three different waveforms was balanced across subjects in an effort to eliminate the effect of order of presentation.

Each subject was exposed only once to each body posture and waveform. There was a brief pause between successive runs. A 'back-off' posture was adopted during the investigation of the effect of different vibration spectra on head motion.

5.4.4.4 Results

Figure 5.33 shows the transmissibilities of twelve subjects with a 'back-on' posture. Again, most of the motion at the head was in the x-, z- and pitch axes with a relatively small amount of motion occurring in the y-, roll and yaw axes. All subjects exhibit a main peak in fore-and-aft head motion at approximately 7 Hz. Near this frequency, fore-and-aft motion of the head can be up to twice the magnitude of the vertical seat vibration. Vertical head motion shows a transmissibility near unity up to 2 Hz, then an increase to a maximum at around 6 Hz. It falls to within the approximate range 0.4 to 0.8 by 25 Hz. Pitch head motion displays one main resonance at 6 Hz and a point of minimum motion at about 14 Hz.

Transmissibility curves for the 'back-off' posture during vertical seat vibration are shown in Figure 5.34. The variability in the z-axis is large for frequencies greater

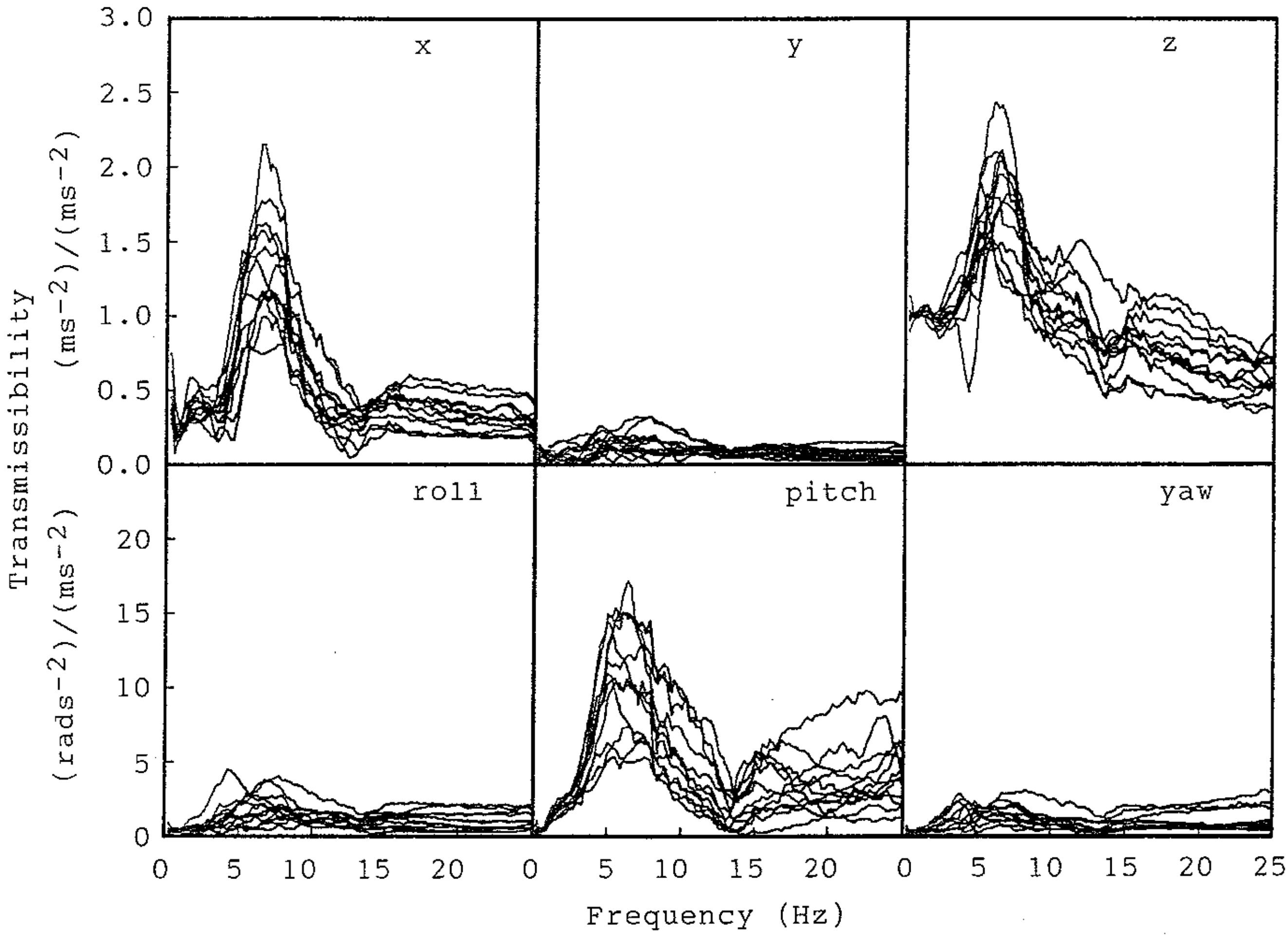


Figure 5.33 Transmissibilities for 12 subjects in a 'back-on' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

than about 2 Hz. The curve which deviates from the others in the x- and z-axes around 12 Hz and in the pitch axis around 15 Hz was from the same subject (subject 12, see physical characteristics in Appendix 5). The subject repeated the experiment at a later date and provide similar values. The difference from other subjects may be associated with his tall slender build. He was also found to have a history of neck injury.

Phase between seat vibration and head motion for the mid-sagittal plane axes are shown in Figure 5.35 for the subjects seated in the two body postures. The phase data for some subjects appear to be erratic in nature when compared with the general trend - this is associated with low coherencies for motions in these axes (see Appendix 4).

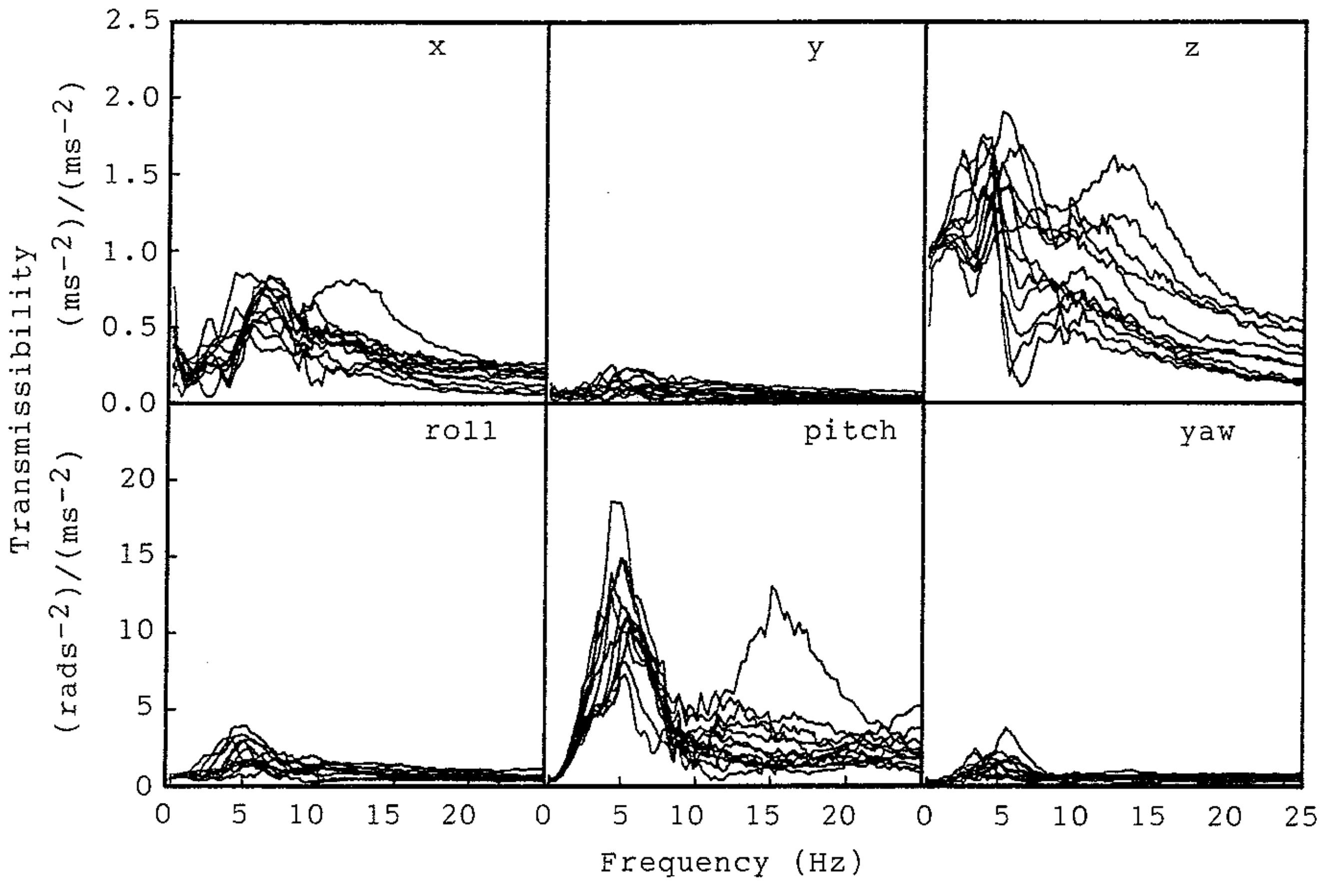


Figure 5.34 Transmissibilities for 12 subjects in a 'back-off' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

Transmissibilities were calculated between seat and head motion for the investigation of the effect of different vibration spectra; median transmissibilities for these conditions are presented in Figure 5.36. One curve in this figure (Gaussian random motion) corresponds to the median transmissibility values calculated from data shown in Figure 5.34.

5.4.4.5 Discussion

Median transmissibilities for all axes at the head and for the 'back-on' and 'back-off' postures are shown in Figure 5.37. Comparisons between the transmissibilities obtained in the two postures show that with a 'back-on' posture, fore-and-aft head motion was increased over the full frequency range with almost twice as much motion at the

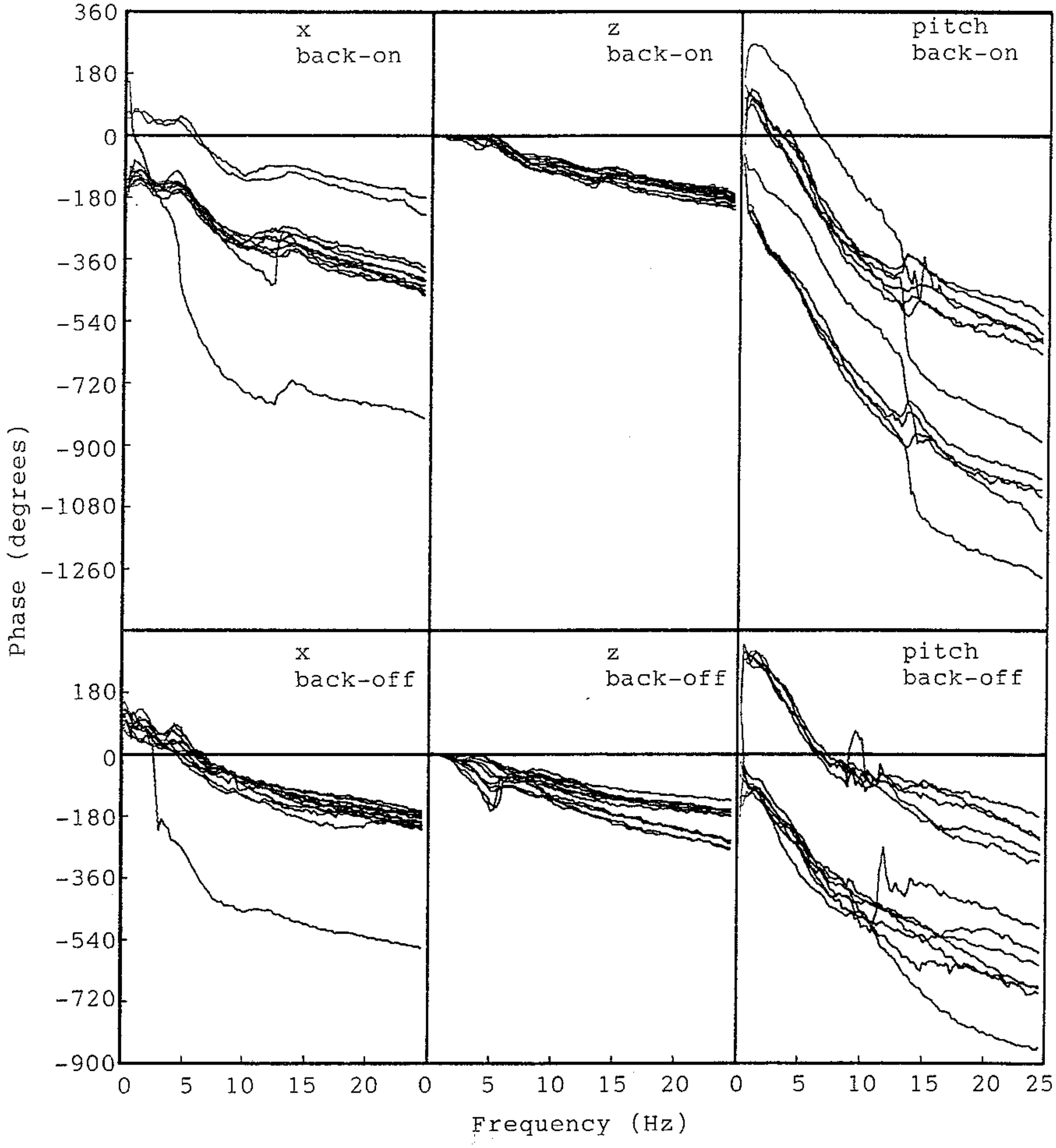


Figure 5.35 Phase for 3 axes of head motion for 12 subjects in a 'back-on' and 'back-off' posture during vertical seat motion.

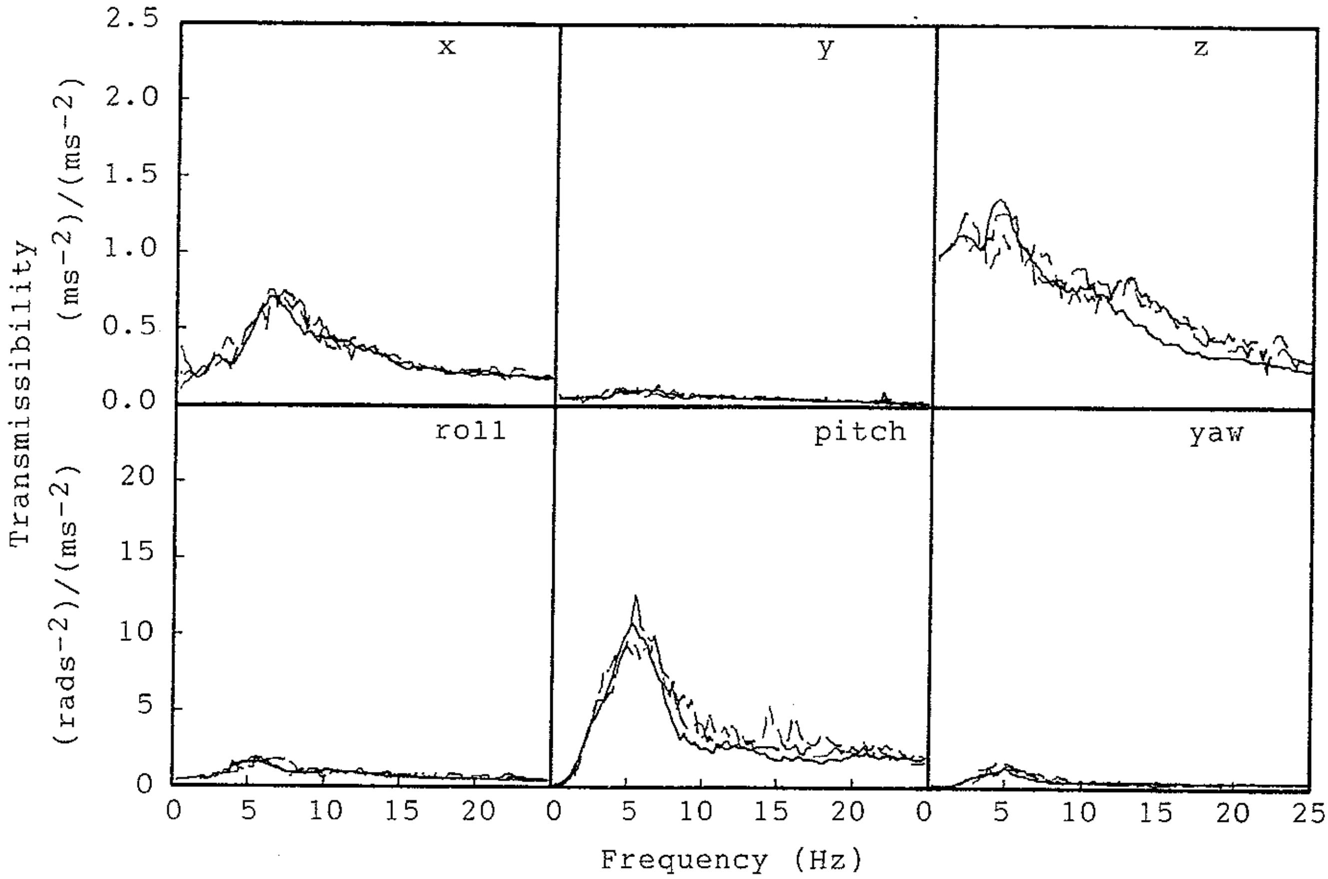


Figure 5.36 Median transmissibilities for 12 subjects while exposed to different vibration spectra during vertical seat motion (Gaussian random ———; APC - - - -; AFV — — —).

main resonance frequency of 7 Hz. With the 'back-on' posture, vertical head motion shows a distinct peak and less variation between subjects than with a 'back-off' posture (see Figures 5.32 and 5.33). With a 'back-on' posture, pitch transmissibilities have a greater spread, the resonance peak is at a slightly higher frequency and the minimum response at about 14 Hz is more definite.

Analysis of variance showed that the backrest had a significant effect on the transmission of vibration to the head for all axes of head motion except the pitch axis (x-, z- and yaw axes $p<0.01$; y- and roll axes $p<0.05$). Furthermore, the interaction between vibration frequency and backrest was significant ($p<0.01$) for all axes except the y-axis.

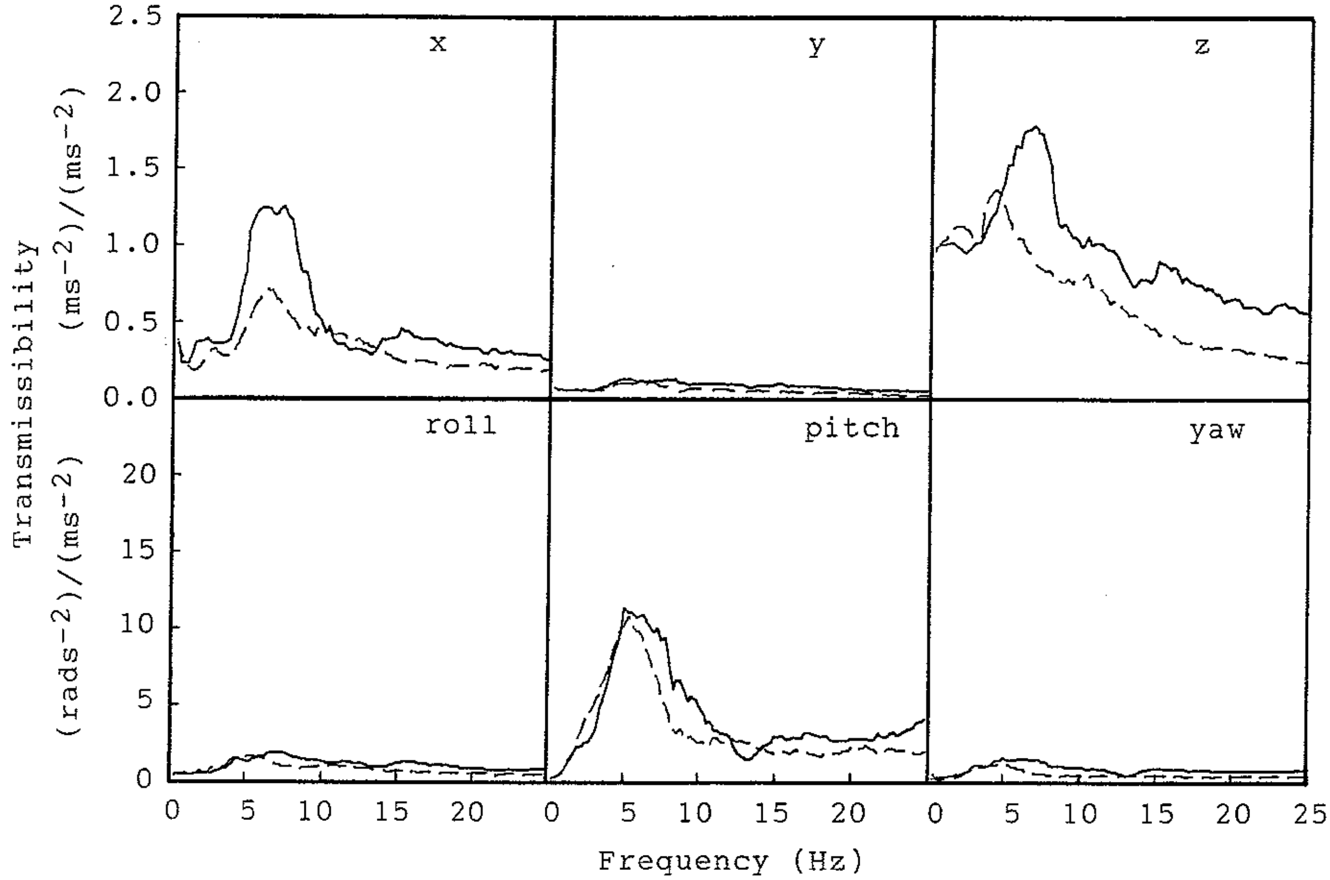


Figure 5.37 Median transmissibilities for 12 subjects in a 'back-on' (———) and a 'back-off' (- - - -) posture during vertical seat motion.

Phase and coherency data show that the only axes which may provide any useful results are those in the mid-sagittal plane. However, it is further seen that irregular results occurred for motion in the pitch axis for some subjects. The frequencies causing these irregular 'jerks' in the data correspond to those where the transmissibility was relatively low. The phase contains information necessary for modelling the response of the body and it is necessary for calculating the instantaneous position of the head and the seat. Differences in phase between the two postures are small: similar to the intra-subject variability in phase (see Section 5.4.3). The reliability of these data has been estimated and is explained in Appendix 10.

It was seen from Figure 5.36 that the type of seat vibration (i.e. Gaussian random, APC vibration and AFV vibration) had little effect on the characteristics of head motion. The only axis that gives any indication of a difference is pitch in which the curve which is slightly higher than the other two above 11 Hz corresponds to the Armoured Fighting Vehicle. Random motion produced slightly lower pitch transmissibility values over the frequency range 6 Hz to 11 Hz than the two vehicle motions. However, visually the differences appear to be small. Analysis of variance showed that, as expected, all seat vibrations affect head motion differently at the various frequencies; this was significant at the 1% level for all axis at the head. Apart from pitch ($p<0.01$) and yaw ($p<0.05$) motions at the head, the differences in head motion for other axes caused by the three seat vibrations were not significant. Interactions between seat vibration and frequencies were significant ($p<0.01$) for all but the horizontal axes at the head.

5.4.5 Effect of measurement position on the head

5.4.5.1 Introduction

Motion of the head has been measured by various investigators and the position of the transducers or the point of measurement has varied between the experiments conducted. A bite-bar has been frequently used in measuring the motion of the head (e.g. Griffin, 1975; Johnston, 1978), but the bite-bars have varied between experiments in construction, size, etc. Some studies have obtained measurements of motion at the top of the head using a head harness with accelerometers (e.g. Rowlands, 1972; Sandover, 1978), motion at the forehead has been reported (e.g. Kobayashi et al., 1981) and at the top of the spine (e.g. Messenger and Griffin, 1989).

These differing locations of measurement of head motion make comparison between different investigations very difficult. The difficulty arises because the head does not move in only the translational axes but moves also in the rotational axes - the head is free to move in all six axes! A reference point would be required on the head for calculating motions such as the head coordinates proposed by Ewing and Thomas (1974) (see Section 2.4.1).

This section presents transmissibilities calculated for motion occurring at different points on the head. Data used were the acceleration time histories for the six axes at the head for a subject who took part in one of the previous experiments (see Section 5.4.2). Motions in the translational axes were calculated using the method of analysis shown in Appendix 6 and then transmissibilities determined using the 'cross-spectral density function method'.

5.4.5.2 Results and discussion

In the head motion experiments previously reported, transmissibilities were calculated of translational motion at the head for a point at mouth level on the bite-bar, 100 mm to the left of the mid-sagittal planes of subjects. Translational motions have now been determined at different points on the head. As the point of interest is moved along one translational axis of the head (e.g. z-axis) the magnitude of the other two translational motions (x- and y-axes) will change due to the presence of two rotational motions (roll and pitch). Transmissibilities obtained with a frequency resolution of 0.5 Hz from one subject are shown in Figure 5.38 as a function of the position on the head. The individual 3-dimensional solids shown are as follows:

- Figure 5.38(a) - variation in y-axis motion transmissibility along the x-axis
- Figure 5.38(b) - variation in z-axis motion transmissibility along the x-axis
- Figure 5.38(c) - variation in x-axis motion transmissibility along the y-axis
- Figure 5.38(d) - variation in z-axis motion transmissibility along the y-axis
- Figure 5.38(e) - variation in x-axis motion transmissibility along the z-axis
- Figure 5.38(f) - variation in y-axis motion transmissibility along the z-axis

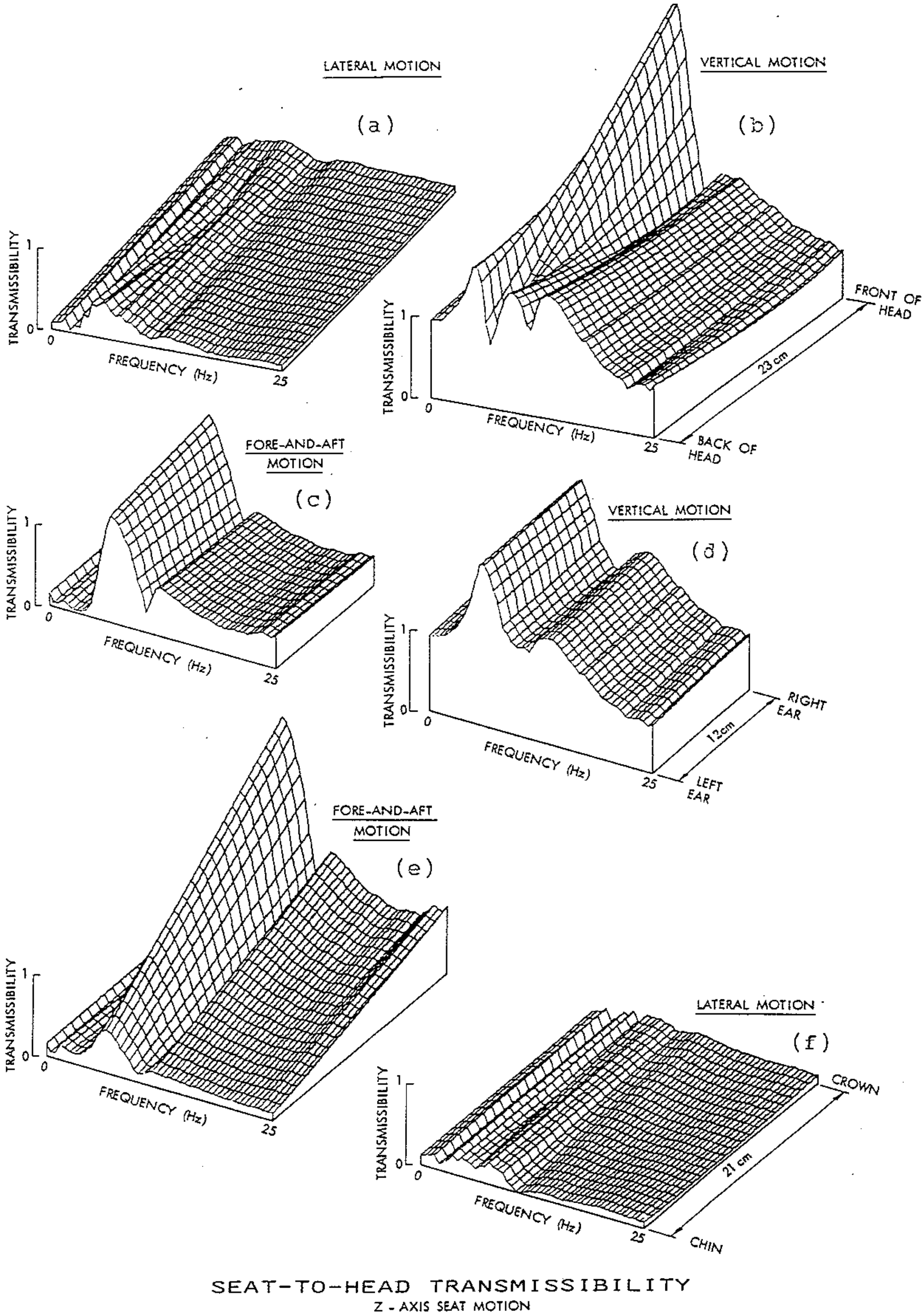


Figure 5.38 Variation in translational transmissibility with position on the head for 1 subject exposed to vertical seat motion.

The distance increment shown on all the figures corresponds to 1 cm and the unit increment of transmissibility is marked for reference. For clarity, the directions of the axes and the locations used on the head are shown in Figure 5.39. Also, for ease of referral, the transmissibilities shown in Figure 5.40 are for data used in calculating the transmissibilities in Figure 5.38 (Figure 5.40 contains data for one vibration exposure taken from the seven runs to investigate the effect of bite-bar mass on head motion; this run was with the subject biting on to the bite-bar in its normal configuration, see Figure 5.24).

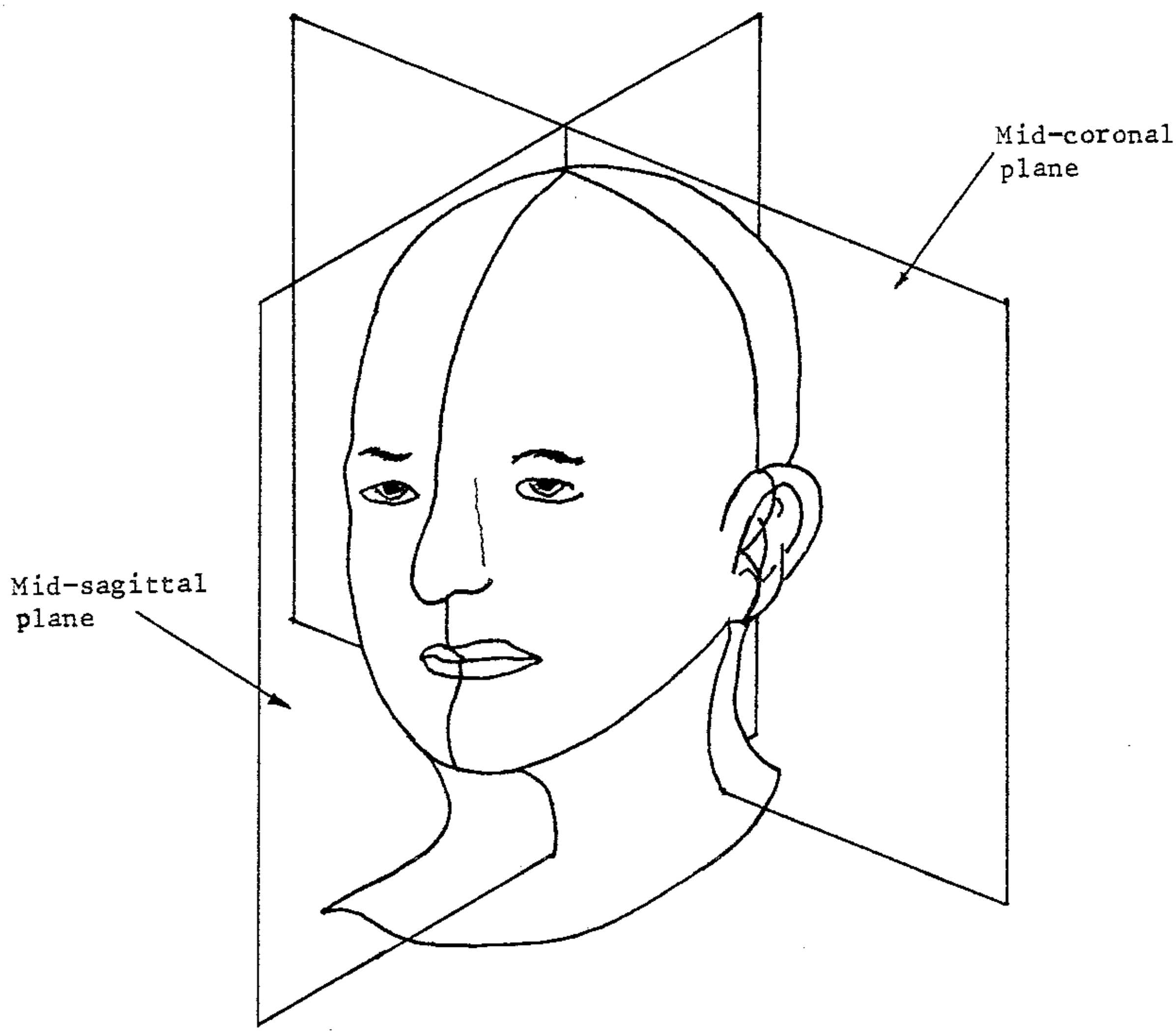


Figure 5.39 Two biodynamic planes on the human head.

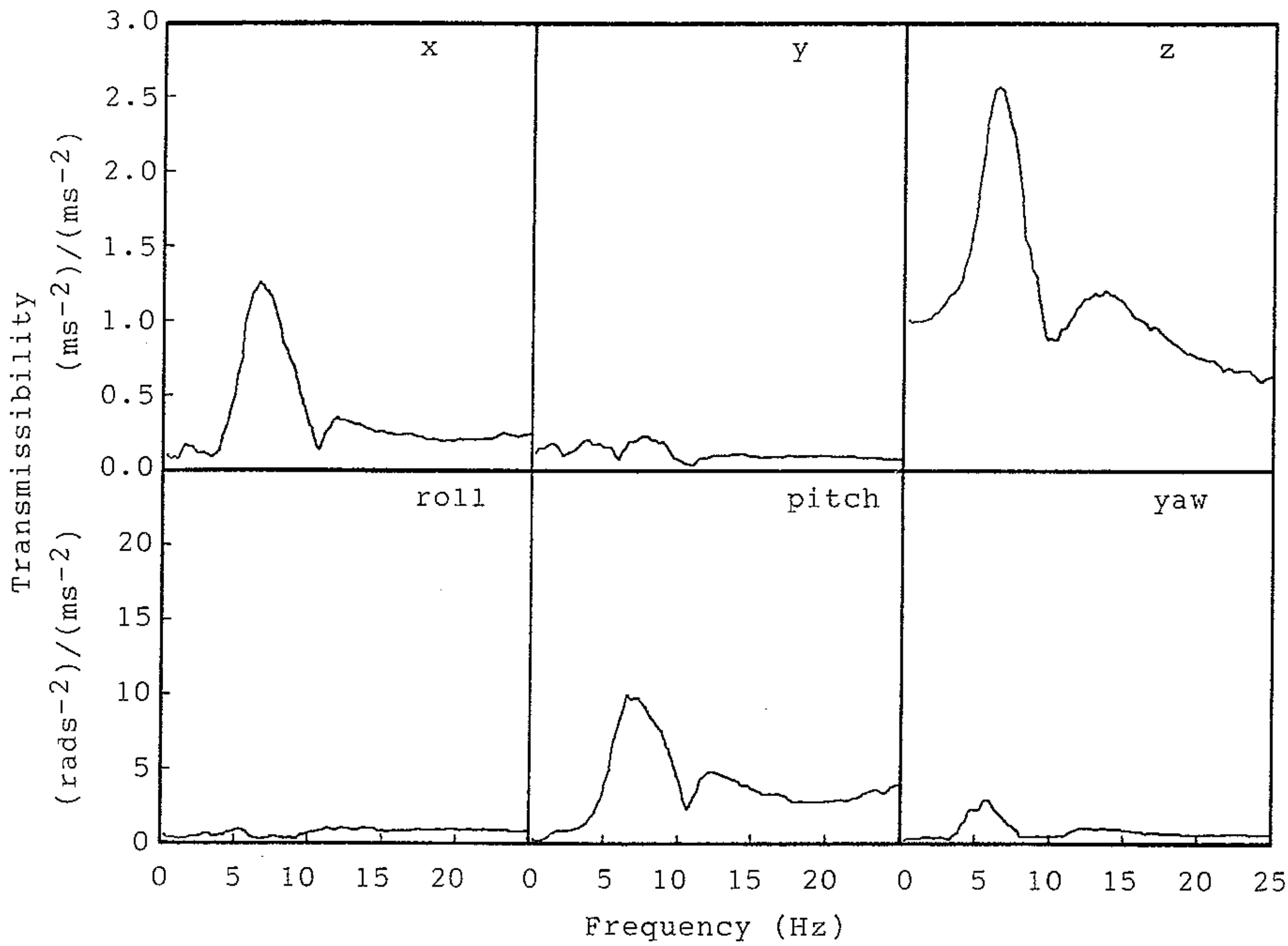


Figure 5.40 Transmissibilities for 1 subject during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

The variation in fore-and-aft motion transmissibility with distance from the left to the right ear is shown in Figure 5.38(c). From this figure it is seen that the change in the fore-and-aft motion along the y-axis of the head is small. This was to be expected since yaw motion, which would cause this variation, was small as shown in Figure 5.40.

Variation in x-axis motion with distance from the chin to the crown of the head is shown in Figure 5.38(e). This indicates that motion increases with distance up to the top of the head - the chin showing the lowest transmissibility. It can be concluded that in pitch, the head rotates about a point near the base of the neck. The centre of rotation can be calculated by extrapolating the contours on this figure and it is seen that the centre of rotation varies with frequency.

Figure 5.38(a) shows the change in y-axis motion along the x-axis from the back of the head to the front. Differences in this motion are small but it is clear that a slight dip occurs nearer to the front of the head at around 7 Hz. This might be a point about which the head may rotate in yaw at this frequency. Yaw motion was the greatest at about 6 Hz (see Figure 5.40).

Figure 5.38(f) shows how y-axis motion varies from the chin to the crown of the head. Not much variation is seen at low frequencies but at 11 Hz, motion appears to increase from chin to the top of the head. It is roll motion at the head (which showed small transmissibilities, see Figure 5.40) which would have caused the variation in lateral axis transmissibilities.

Motion in the vertical-axis is shown in Figure 5.38(b) as it changes with position from the back of the head to the front. This is a very revealing figure in that the transmissibility value at resonance not only increases with distance from the back of the head to the front but there is a slight increase in the frequency at which resonance occurs. The frequency corresponding to a major body resonance at the front of the head corresponds to a frequency with relatively low transmission at the back of the head. The second peak seen at about 9 Hz at the back of the head is not present at the front. It is clear that, for this subject, a completely different transmissibility curve would result if motion was measured at the back of the head rather than at the mouth.

No variation is seen in z-axis transmissibility curve between the left and the right ear as illustrated in Figure 5.38(d), thus indicating that roll motion (which would have been responsible for the variation) was small as shown in Figure 5.40.

These results have shown that the position of measurement of vibration on the head is a very important parameter. However, its location is of importance only in the fore-and-aft and vertical direction since motion of the head occurred mostly in the mid-sagittal plane. Variation in transmissibility for the fore-and-aft and vertical motions with position along the lateral axis was small, therefore this implies that the position of measurement along the lateral axis was not so crucial. These data apply to only head motion caused during whole-body exposure to vertical seat vibration and different results might emerge if vibration at the seat was in other axes.

5.4.6 Discussion and conclusions

The effect on the dynamics of the head of factors that are normally overlooked such as bite grip, bite-bar mass and the visual environment was investigated in the first set of experiments. These indicated that the jaw grip used to retain the bite-bar in the mouth had little effect on measurements of seat-to-head transmissibility. Similar transmissibilities were obtained when the bite-bar was almost resting freely in the mouth and when it was clenched firmly with extremely tense muscles of the jaw and neck. It can also be concluded that the mass of a bite-bar similar to that used (135 g) will not greatly affect head motion. The mass of this bar is insignificant compared to the head mass (approximately 4.3 kg). Higher masses may be acceptable but the location of the mass will influence the moment of inertia. In the present case, for a centre of rotation 90 mm from the bite-bar, the total moment of inertia of the bite-bar is 1.56×10^{-3} kgm^2 compared with the moment of inertia of the human head which is approximately 2.0 kgm^2 about the same axis. The change in the total moment of inertia due to the added mass of the bite-bar was therefore less than 0.1%. (It is interesting to note that wearing a helmet can almost double the moment of inertia of the head.) Overall, it is thought that the effect of these variables will be negligible if the bite-bar is used in its normal configuration with a normal bite grip. The small differences in response of the head can be explained by the repeatability experiments.

The intra-subject variability data suggest a high repeatability in transmissibility compared to the differences caused by changes in seat conditions and those associated with inter-subject variability. However, measurements were obtained over a short period in which the well-trained subject was able to recall the precise form of his sitting posture. It is likely that repeated measures obtained over a longer period would exhibit a wider variation in response. The scatter shown in Figures 5.28 and 5.29 therefore probably represents the minimum variability that can be expected. These results show variation in responses during repeat measures to be of the same order as that reported elsewhere (Griffin et al., 1979; Rowlands, 1977).

Large differences between subjects are particularly apparent in the vertical seat-to-head transmissibility curves shown in Figure 5.34. At 6.5 Hz, one subject had a z-axis transmissibility below 0.1 while another had a transmissibility in excess of 1.6. This variability was obtained despite instructions and aids to the maintenance of the required posture and careful observation by the experimenter. Since the reasons for the scatter are not yet clear, some caution is required in the interpretation of any single curve showing the median transmissibility of a group of subjects. These data are consistent with the findings of previous studies (e.g. Griffin and Whitham, 1978; Griffin et al., 1982). Inter-subject variability could be used to explain the spread in head motion data with different seat vibrations; it can be concluded that different vertical vibration spectra had little or no effect on the median transmission of vertical seat vibration to the head.

The change in transmissibility when contact is made with the back of the seat arises partly from the additional transmission path for vibration. However, the backrest may also alter the dynamic response of the body by providing a stiffening and so tend to increase some resonance frequencies. In addition, the process of leaning against a backrest involves a change in forces within the body and alterations in the skeletal posture. It would appear appropriate to consider changes introduced by the backrest to be of a complex type rather than solely due to an additional vibration input to the body. Contact with the backrest had a significant effect on head motion for all but the pitch axis. Interaction between frequency and backrest and head motion was significant ($p<0.01$) for all axes at the head apart from the lateral axis.

One possible reason for the scatter is the different static characteristics of the subjects. Correlations between transmissibility measures and subject characteristics (age, weight, height, hip size, leg size) were determined using a non-parametric measure (Kendall's tau) at 0.25 Hz steps, from 0.25 Hz up to 25 Hz. Although some significant correlations were observed, the results did not suggest that variability could be primarily attributed to these sources. Other studies in which a greater number of subjects have been investigated have provided clearer indications of the influence of such factors on vertical seat-to-head transmissibility (Griffin and Whitham, 1978; Griffin et al., 1982). Some high correlations were found between the subject characteristics themselves (see Section 5.2.5).

The point of measurement of motion on the head has been shown to greatly affect the results. Since the head moves mostly in the mid-sagittal plane during vertical vibration of the seat, the measurement location is more important along the x- and z-axes at the head than the lateral position. Motions in the x- and z-axes at the head were more sensitive to changes in position of measurement than motion in the lateral axis. Data measured or calculated at a particular common point could be used to compare data between different studies.

5.5 DISCUSSION AND CONCLUSIONS

The general conclusions from the study of inter-subject variability in head motion during translational seat vibration are similar to those from the intra-subject variability study, the general underlying trends have been the same. However, the inter-subject variability experiments revealed a very large spread of transmissibilities between individuals. In some axes and at some frequencies during fore-and-aft seat vibration, the difference in head response between subjects was as large as 10:1. Differences in transmissibility of the order of 9:1 and 13:1 were seen in head motion during lateral and vertical seat vibration respectively. The variability in transmissibility demonstrated by the subject during repeat measures was typical of other subjects since repeat vibration exposures for some subjects were conducted which showed similar variability (e.g. see Section 5.4.4.4).

During fore-and-aft seat vibration, motion at the head occurred in the mid-sagittal plane (i.e. x-, z- and pitch axes). Head motion with a 'back-on' posture showed a distinct peak near 8 Hz. The effect of removing the backrest is to remove this peak. The effect of the backrest on the magnitude of head motion during lateral seat vibration was small: a 'back-on' posture produced slightly more roll motion of the head than a 'back-off' posture. For vertical motion of the seat, a 'back-on' condition resulted in greater magnitudes of motion being transmitted to the head than a 'back-off' posture. This was over most of the frequency range apart from possibly frequencies below 5 Hz for vertical and pitch axes at the head and about 13 Hz for all axes in the mid-sagittal plane.

One of the assumptions involved in the measurements is that all accelerometers responded only to translational movement in their sensitive axes. In fact, they also respond to the gravitational field of the Earth - the inclination of a horizontally orientated accelerometer through θ degrees will result in an acceleration of $g\sin\theta$ (where $g = 9.81$ ms^{-2}). Pitch and roll motions of the head will therefore result in additional signals from the x- and y- orientated accelerometers. However, the magnitude of the gravitational component is dependent on the angle of head inclination and this is generally very small. For example, a pitch transmissibility of 10 $rads^{-2}$ per ms^{-2} at 5 Hz corresponds to a fore-and-aft head acceleration of only 0.1 ms^{-2} per ms^{-2} of vertical seat vibration and would have only a small effect on the measured z-seat to x-head transmissibility at this frequency. The greatest gravitational influence will arise from high pitch or roll transmissibilities at low frequencies. The high transmissibility values in the x- and y-axes of the head at very low frequencies in some conditions (e.g. inter-subject variability, lateral seat vibration, lateral head motion, 'back-off' posture) are influenced by gravitational components being detected by the horizontally orientated accelerometers as the head tilts. The magnitude of this effect may be estimated from the corresponding roll and pitch transmissibilities. Calculations show that for frequencies below 1 Hz, the gravitational component may account for around one fifth of the signal measured by the fore-and-aft accelerometer and about one third of the signal measured by the lateral accelerometer. Roll and pitch transmissibilities for head motion tended to zero as vibration frequency decreased during vertical seat vibration, therefore, the gravitational influence on these data is low.

The measurement of six axes of head motion with only six translational accelerometers involves several assumptions. In general, it is necessary to employ nine transducers to correctly determine the motions (see Appendix 6 and Padgaonkar et al., 1975). The errors introduced with six axes arise from cross-coupled motions. These could have occurred if there was rotational head motion of similar magnitudes about more than one axis. However, it is seen from the transmissibility data that the head moved mostly in the mid-sagittal plane (x-z plane) during fore-and-aft and vertical vibration of the seat: roll and yaw motions being smaller than pitch motion at the head. During lateral vibration of the seat, the head moved mostly in the mid-coronal plane (y-z plane), i.e. pitch axis and yaw axis motions at the head were small. This implies that cross-coupled motions were of small magnitudes and that the errors introduced by employing a six-accelerometer system are small.

Measures of translational head motion are always dependent on the measurement position at the head. For example, vertical head motion is partly caused by pitch motion of the head: the motion would have been smaller if the vertically orientated accelerometer had been nearer the centre of rotation of the head. Although other transmissibilities could be obtained by measuring at other locations, the position used in these studies is convenient and commonly used when measuring head vibration. The transmissibilities for rotational head vibration are unaffected by the accelerometer locations.

Changes in posture may also account for some of the variability between subjects. Although instructed in the gross sitting posture, there was no attempt to monitor or control the angle of the pelvis, the spinal position or forces at the feet or backrest. Small changes in head inclination may also have occurred. Further systematic study of the influence of these factors on the transmission of vibration to the body may provide a beneficial insight into individual variability in all responses to whole-body vibration.

CHAPTER 6

TRANSMISSION OF TRANSLATIONAL FLOOR VIBRATION TO THE HEADS OF STANDING SUBJECTS

6.1 INTRODUCTION

A search through the literature revealed a large number of studies concerned with the transmission of translational vibration from the seat to the head for seated subjects. Fewer studies have been conducted with standing subjects and those that exist have involved mainly vertical vibration at the floor (Dieckmann, 1957b; Coermann, 1962; Hornick, 1962; Garg and Ross, 1976). Even fewer studies are known of where horizontal floor vibration has been investigated (Dieckmann, 1957a; Dieckmann, 1958). The effect of many variables on head motion is known for seated subjects, most of these variables and others can be investigated for standing subjects. The main parameter for such studies that might be considered is posture of the legs since this is the main different additional path for the transmission of vibration between seated and standing subjects (Rao et al., 1975).

The aim of this chapter is to present basic and fundamental data from studies to determine the transmission of floor vibration to the head for standing subjects. Vibration at the floor was in the three translational axes and, for each axis of vibration, intra- and inter-subject variability studies were conducted. The effect of different postures of the legs on the transmission of vibration from the floor to the head has also been determined. Data included in this chapter have been published elsewhere (Paddan, 1987, 1988).

6.2 FORE-AND-AFT FLOOR VIBRATION

6.2.1 Introduction

There are some environments in which standing people are exposed to fore-and-aft vibration of the floor, examples of this include buses, trains, escalators and moving platforms. Under such conditions, people might have difficulty in maintaining their balance should certain vibrations occur and a handrail of some sort might provide postural support in such a case. The transmission of vibration to various parts of the body might provide clues in determining such vibration and provide data to understand the biodynamic response of the body to vibration.

This section presents data from experiments conducted to determine the transmission of fore-and-aft floor vibration to the heads of standing subjects. One factor investigated is the effect of a person holding on to a handrail on vibration transmitted to the head. Studies reported include intra-subject variability and inter-subject variability.

6.2.2 Intra-subject variability

6.2.2.1 Introduction

An indication of the variability over repeat measures is often required in explaining the effect of a particular variable on floor-to-head transmissibility and the variability between individuals. This section concerns the variability in the transmission of vibration from floor-to-head for a standing subject exposed many times to the same vibration waveform. This variability was determined with the subject holding rigidly on to a handrail.

6.2.2.2 Apparatus

Vibration generation

This experiment was carried out on an electro-hydraulic vibrator capable of producing horizontal displacements of 1 metre. The vibrator was safe for the exposure of human subjects to vibration and is described in detail in Section 3.5.1. The subject stood on the vibrator platform such that the motion occurred in the fore-and-aft direction. A handrail was provided 30 cm in front and 1.05 m above the vibrating platform for the subject to hold on.

A computer-generated Gaussian random waveform having a nominally flat acceleration spectrum was used with an acceleration magnitude of 0.50 ms^{-2} r.m.s. at the vibrator platform. The waveform was sampled at 32 samples per second and low-pass filtered at 12.5 Hz before being fed to the vibrator. The duration of each vibration exposure was 240 seconds.

Vibration measurement

A light-weight bite-bar was used to measure head motion. Six small translational piezo-resistive accelerometers were mounted on the bite-bar which gave it the capability of measuring motion in all six axes. It had a sterilised personal dental mould which was held tightly between the subject's teeth. The total weight of this six-axis bite-bar was 158 g, this is explained in detail in Section 3.2.

The signals from the full-bridge bite-bar accelerometers were passed through signal conditioning amplifiers and then low-pass filtered at 12.5 Hz through 48 dB/octave anti-aliasing filters. The seven acceleration signals (6 from the bite-bar and 1 from the vibrator platform) were then digitised into a PDP11-34 computer system at a sampling rate of 32 samples per second.

Acceleration data were analysed to obtain transmissibilities between the vibrator platform and the head for all translational and rotational axes at the head. This was for motion occurring at 100 mm to the left of the mid-sagittal plane at mouth level. Transfer functions, $H_c(f)$ between motion in one axis at the head (output) and in the fore-and-aft axis at the floor (input) were determined using the 'cross-spectral density function method':

$$H_c(f) = \frac{G_{io}(f)}{G_{ii}(f)}$$

where: $G_{io}(f)$ = cross spectral density of input and output motions,

$G_{ii}(f)$ = power spectral density of input motion.

A frequency resolution of 0.06 Hz was used giving 58 degrees of freedom. Ordinary coherencies were also calculated between floor and head motion using the following equation:

$$\gamma_{io}^2(f) = \frac{|\ G_{io}(f)\ |^2}{G_{ii}(f)\ G_{oo}(f)}$$

where $G_{io}(f)$ and $G_{ii}(f)$ are as above and $G_{oo}(f)$ is the power spectrum of the output motion. Ordinary coherency functions provide an indication of the correlations between motion at the output and motion at the input. A value of unity shows that all the motion at the output (e.g. motion at the head in a particular axis such as fore-and-aft) was caused by motion at the input (i.e. fore-and-aft floor vibration).

6.2.2.3 Procedure

Subjects

One 41 year old male subject took part in this study. His weight was 85 kg and he was 1.87 m tall. He was given a set of written instructions about the required posture of the legs, body, hands, etc. during the exposure of vibration, a copy of these instructions is shown in Appendix 7. The subject stood in a normal stance with an upright comfortable posture with a foot separation of 30 cm. Only one posture was used during these measurements, this was with the subject holding on to the handrail with a rigid grip. The subject was instructed to look at a cross on a stationary wall approximately 1.5 m distant in front on him. The subject was provided with an emergency button which, when activated bought the vibrator platform to rest in a controlled manner.

Experimental design

There were twelve identical vibration exposures and during each run, the subject maintained the required rigid grip posture. There was a 5 minute pause between successive runs during which the subject was asked to relax.

6.2.2.4 Results

Transmissibilities between floor vibration and the six axes of motion at the head are shown in Figure 6.1 for the one subject. Higher transmissibilities occurred for motion in the mid-sagittal plane axes than the other axes. Transmissibilities for the different runs all closely follow a specific pattern with only small deviation showing a high degree of repeatability.

Phase data were calculated for all axes and for all runs but, since most of the motion occurred in the x-, z- and pitch axes and that these axes also showed higher coherency values (shown in Appendix 8), data for only these axes are

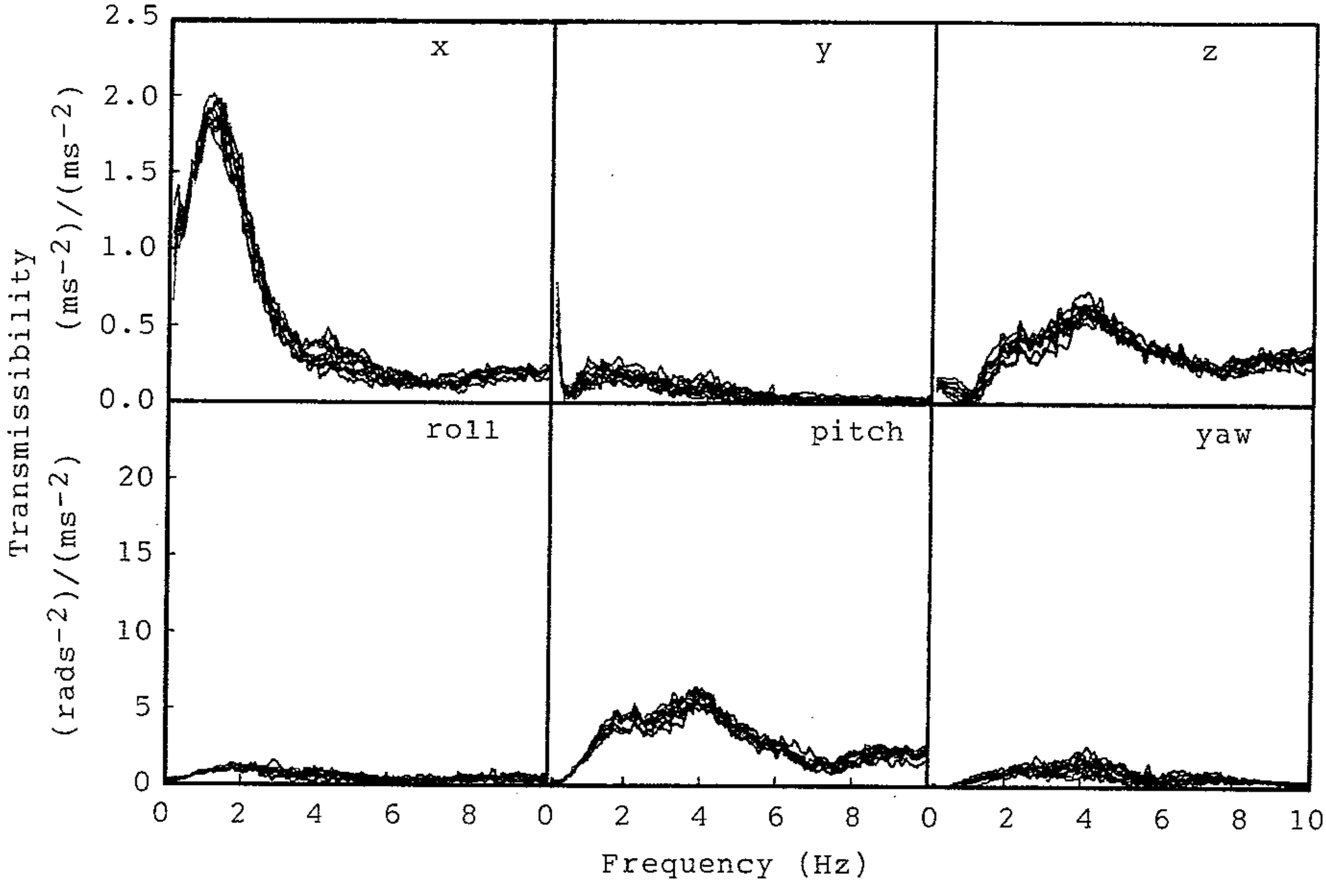


Figure 6.1 Transmissibilities for 1 subject in a rigid grip posture during fore-and-aft floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

presented here. Figure 6.2 shows phase data for motion in the x-, z- and pitch axes at the head.

6.2.2.5 Discussion

Transmissibilities between fore-and-aft floor vibration and fore-and-aft head motion showed one main resonance peak at about 1.1 Hz, the magnitude was approximately 1.85. Both the vertical and pitch axes demonstrate a peak at about 4 Hz with possibly a lower peak at about 2.2 Hz masked by the 4 Hz peak. Although transmissibilities for the other axes were small, they were not insignificant. The variation in transmissibility response appears to be small over all the frequency range showing a high degree of repeatability between the twelve vibration exposures.

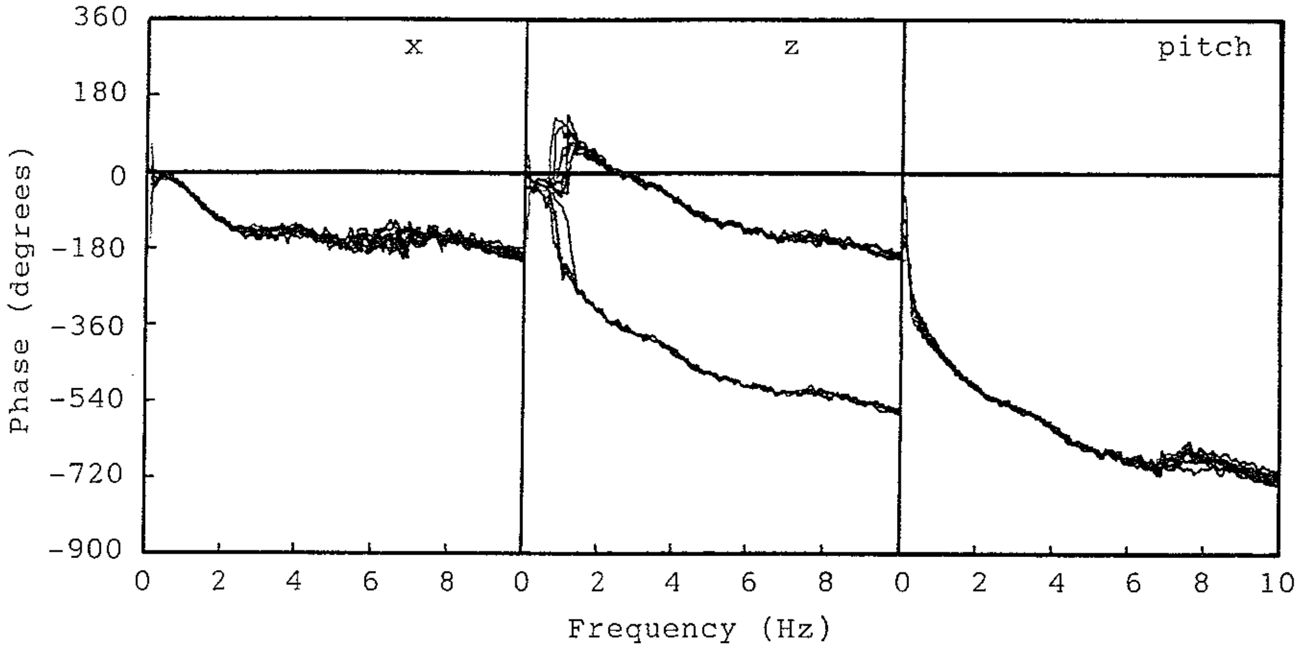


Figure 6.2 Phase for 3 axes of head motion for one subject in a rigid grip posture during fore-and-aft floor vibration.

The coherencies for motion in the mid-sagittal plane axes all appear to be relatively high compared with those for the other axes. This gives an indication of correlation between the floor and head vibration signals. It is seen that the transmissibilities for vertical motion at the head at about 1 Hz are low compared with those for other frequencies. The coherencies are small indicating low correlation between floor and head motion. The phase data appear to be erratic at this frequency. All this shows that uncorrelated data can result if poor coherencies and low transmissibilities occur.

6.2.3 Inter-subject variability

6.2.3.1 Introduction

The above study (Section 6.2.2) gave an indication of vibration transmission characteristics that should be expected for a standing subject and also showed the variation in response during repeat measures. This section presents data of the transmission of fore-and-aft floor vibration to the heads of many subjects while standing and holding on to a handrail with firstly, a light grip and then a rigid grip.

6.2.3.2 Apparatus

Vibration generation

The apparatus used for generating the vibration stimulus was the same as that described in Section 6.2.2.2.

Vibration measurement

The bite-bar used in this study had a sterilised tight fitting plastic tubing which the subjects held between their teeth rather than a personal dental mould used in the intra-subject study. All the other equipment and method was the same as that explained in Section 6.2.2.2.

6.2.3.3 Procedure

Subjects

Twelve fit male subjects took part in this experiment, their physical characteristics are shown in Appendix 9 and these are summarised in Table 6.1.

Table 6.1 Physical characteristics of 12 male subjects who took part in the inter-subject variability experiments.

	Age (yrs)	Weight (kg)	Stature (m)
Minimum	20	60	1.73
Maximum	41	87	1.92
Mean	28.42	74.33	1.81
Standard deviation	5.75	8.82	0.06

The subjects were given a set of written instructions (shown in Appendix 7) on the maintenance of their body and posture. Two postures were requested: a light grip posture with the subjects holding on to the handrail only in the event of becoming unstable and a rigid grip posture in which the subjects held rigidly with both hands on to the handrail in front of them. The same procedure as that for the intra-subject variability study (Section 6.2.2.3) was used for this experiment.

Experimental design

The order of presentation of the two postures was balanced across the subjects so that six subjects commenced with the light grip posture and the other six started with a rigid grip posture. Each subject was exposed twice to the same vibration stimulus: once for each posture. There was a pause of approximately 5 minutes between the two vibration exposures.

6.2.3.4 Results

Transmissibilities for translational and rotational motion of the head with fore-and-aft vibration of the floor while holding rigidly on to a handrail are shown in Figure 6.3. One main peak showing whole-body resonance is present in the fore-and-aft axis, at about 1.5 Hz. Motion in the vertical and pitch axes at the head show transmissibilities with similar characteristics: one broad peak in transmissibility over the 1 Hz to 6 Hz frequency region with significant motion above 6 Hz. Motion was present mostly in the mid-sagittal plane (x-, z- and pitch axes). A small but consistent peak exists in the roll motion transmissibility at about 1.5 Hz.

In Figure 6.4 are shown the transmissibility curves for subjects standing while holding lightly on to the handrail. Fore-and-aft vibration at the head is again the principal axis with high transmissibilities below 1 Hz.

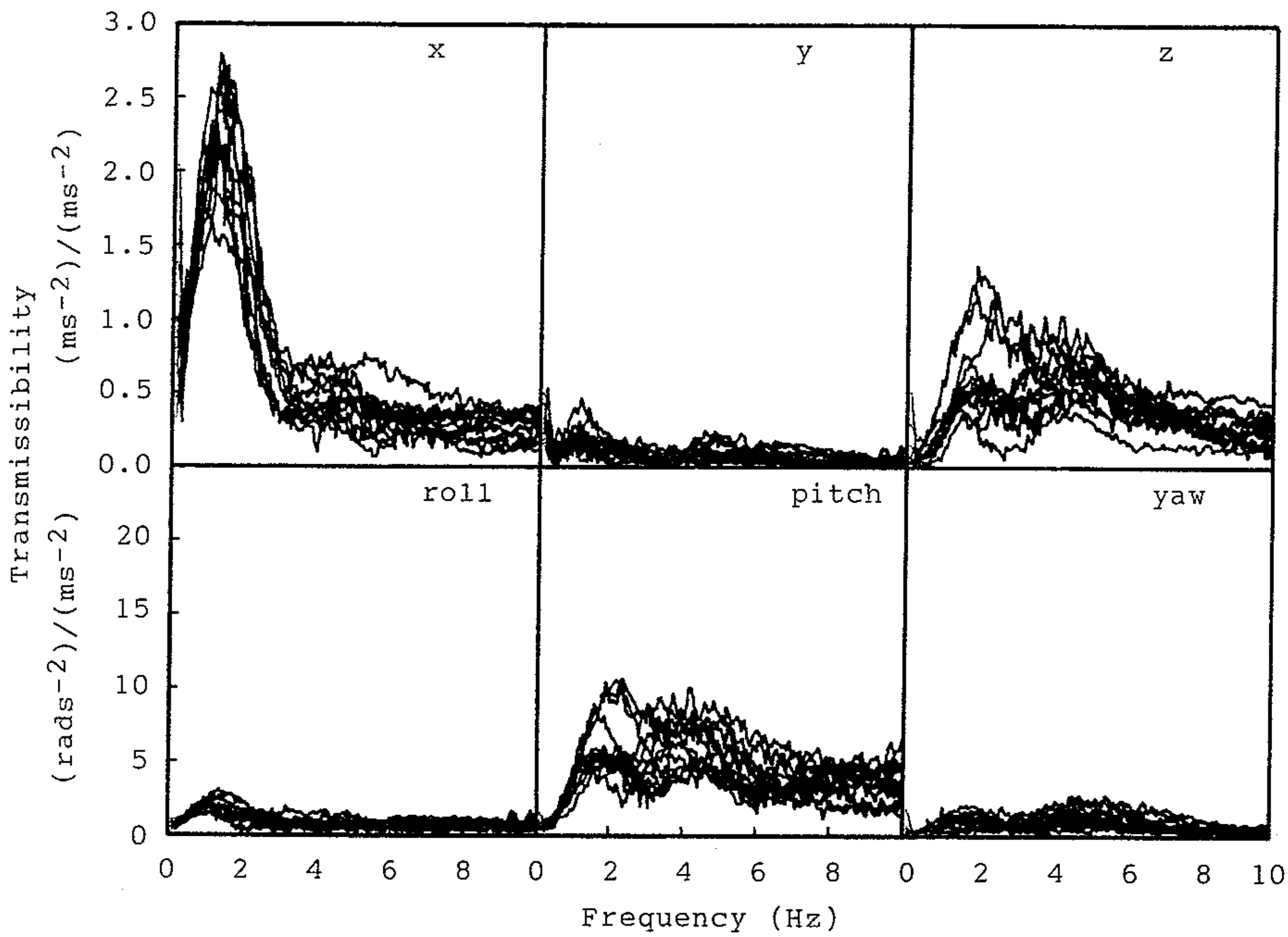


Figure 6.3 Transmissibilities for 12 subjects in a rigid grip posture during fore-and-aft floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

Transmissibilities in the vertical axis tend to show one peak at about 5 Hz with a magnitude of approximately 0.4.

Phase data were calculated for all axes at the head but since main motion at the head occurred in the mid-sagittal plane axes, phase for only these axes are presented. Figure 6.5 shows phase between fore-and-aft floor vibration and head motion for the inter-subject variability study. Data for the rigid grip posture show a high degree of repeatability with most of the curves following the general trend however, phase data for the light grip posture show a very erratic behaviour with large deviations. This is due to the relatively low transmissibility values.

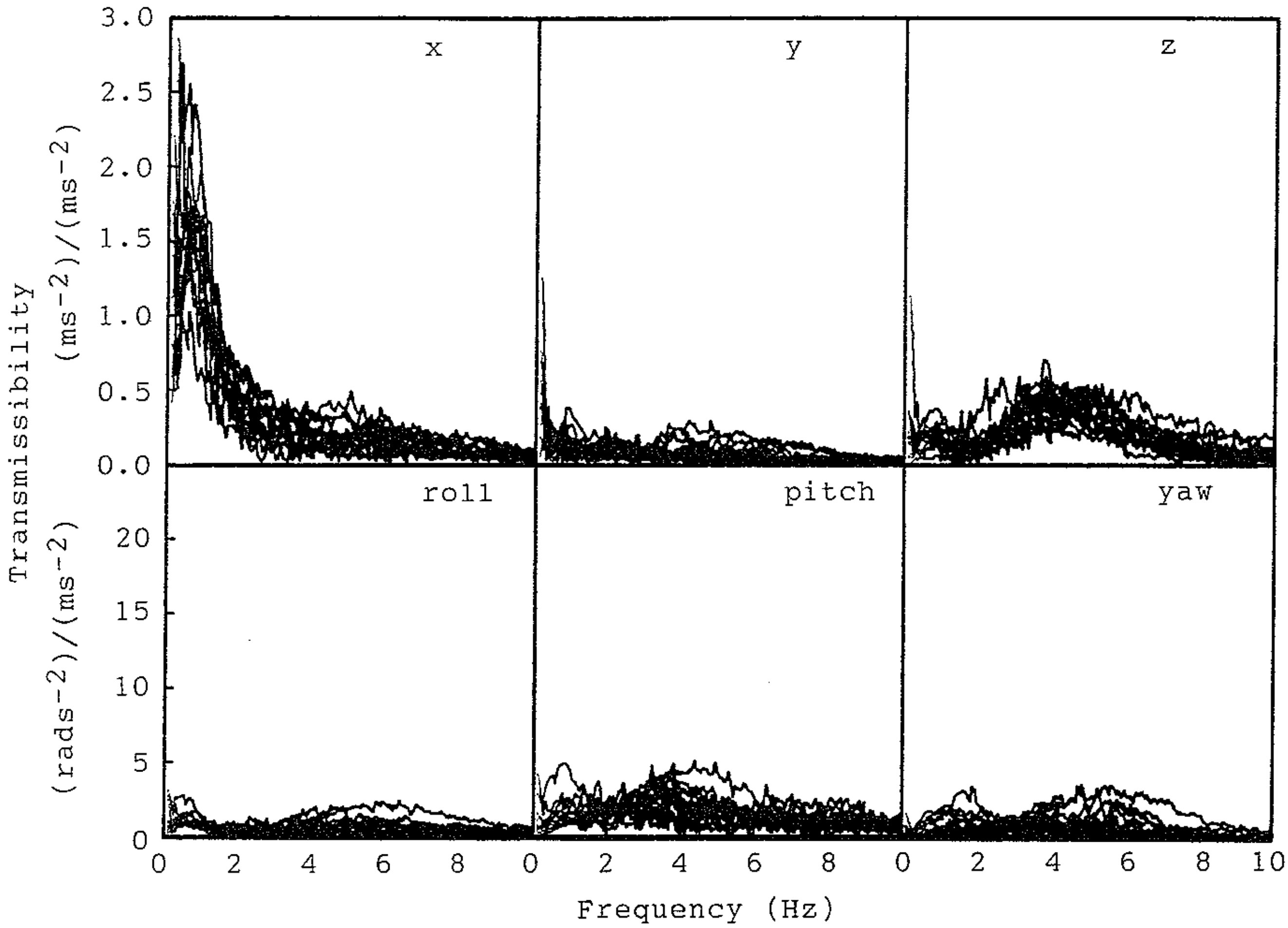


Figure 6.4 Transmissibilities for 12 subjects in a light grip posture during fore-and-aft floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

Ordinary coherencies for the two grip postures are included in Appendix 8 and give an indication of confidence in the data.

6.2.3.5 Discussion

For direct comparison, median transmissibilities of data shown in Figures 6.3 and 6.4 were calculated and are presented in Figure 6.6. It is seen that significantly more motion was transmitted to the fore-and-aft axis of the head ($p<0.01$) at frequencies above about 1 Hz when the subjects held the handrail rigidly than when holding it lightly. The situation is reversed at lower frequencies. The figure also shows less motion at the head ($p<0.01$) for

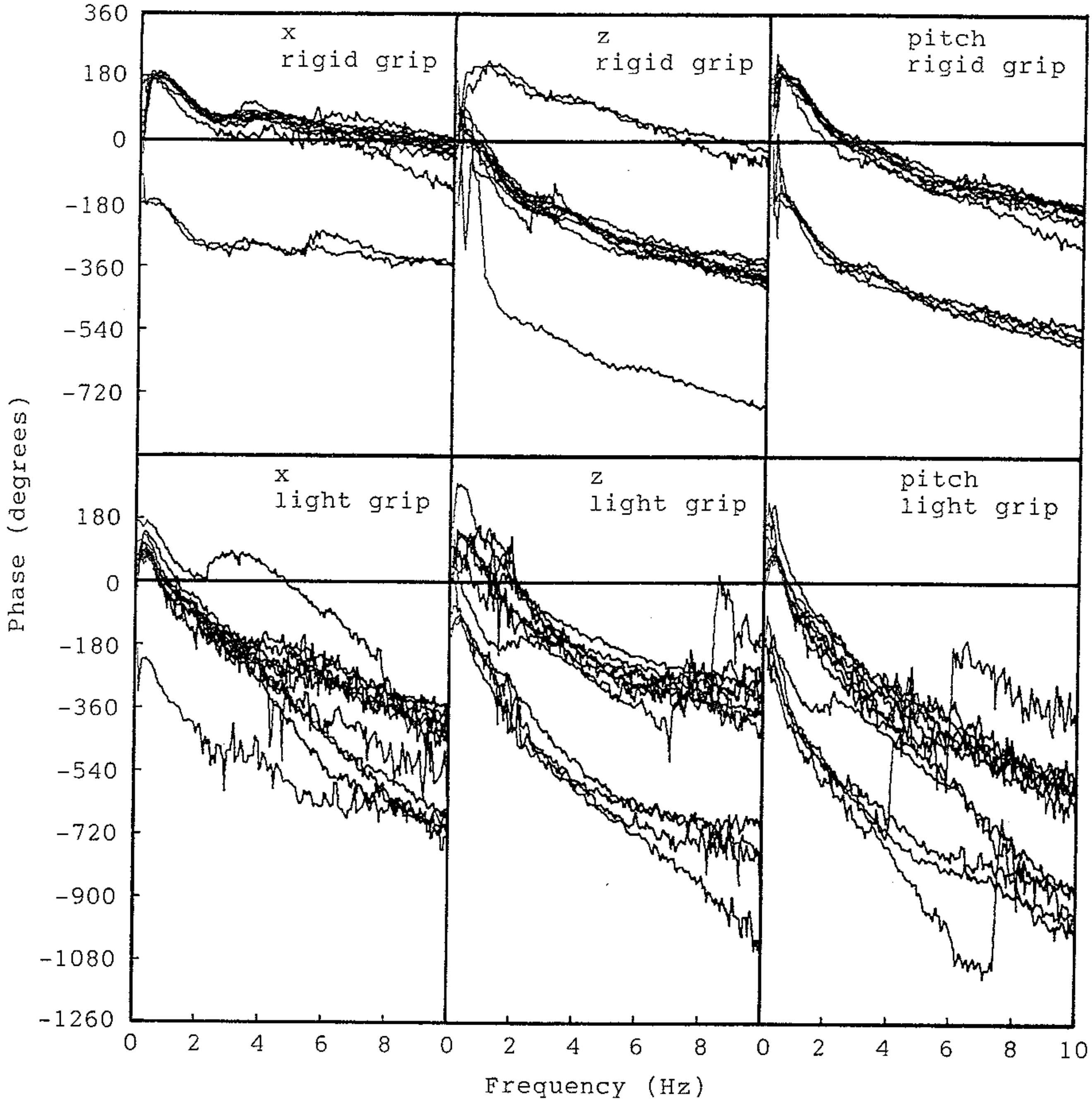


Figure 6.5 Phase for 3 axes of head motion for 12 subjects in a rigid grip and a light grip posture during fore-and-aft vibration.

the vertical and pitch axes for the subjects holding only lightly on to the handrail. It is also clear from this figure that motion at the head occurred mainly in the x-, z- and pitch axes.

The confidence of both transmissibility and phase data can be estimated by considering the appropriate coherencies. It is seen from Appendix 8 that the coherencies for motion

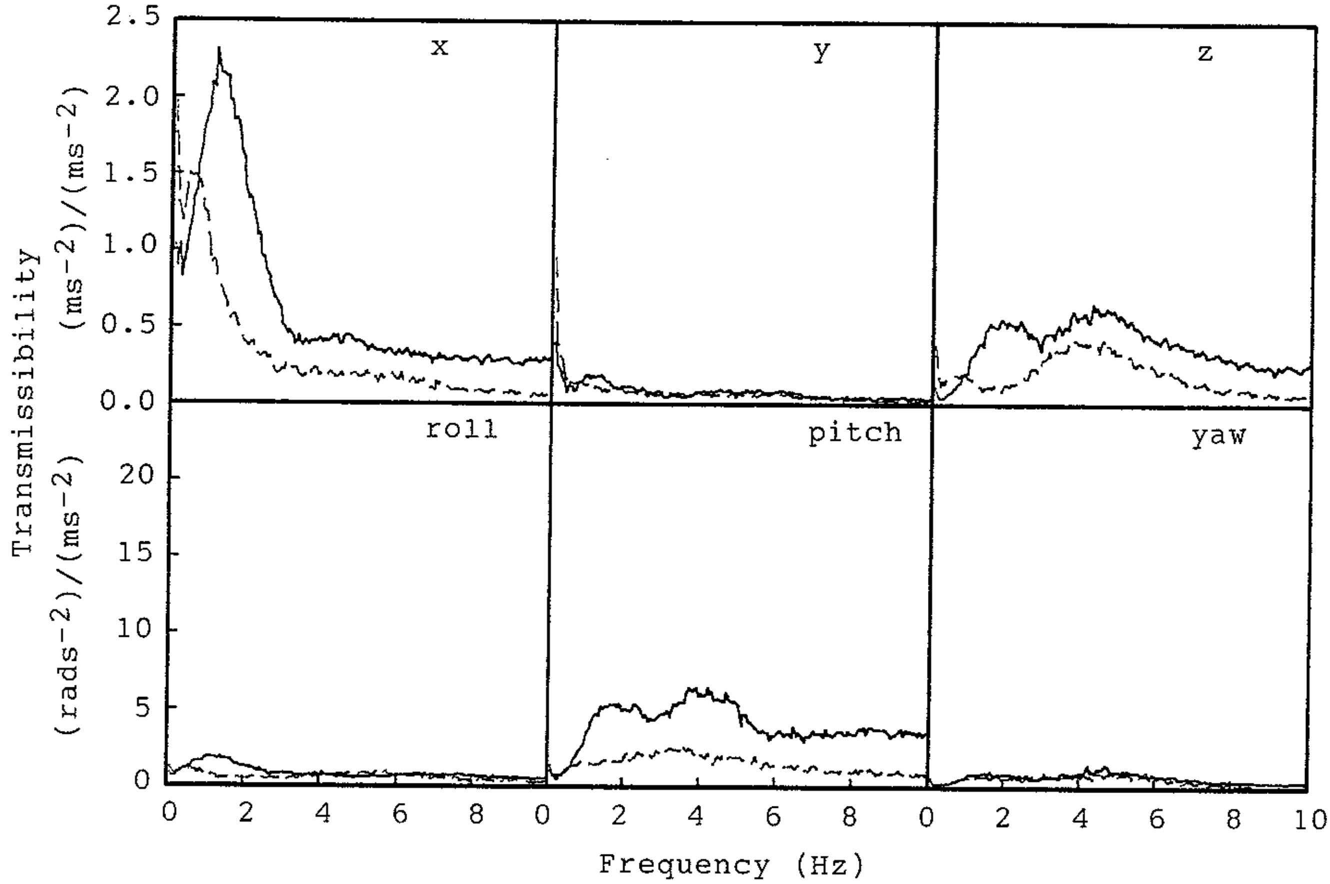


Figure 6.6 Median transmissibilities for 12 subjects in a rigid grip (———) and a light grip (- - - -) posture during fore-and-aft floor vibration.

in the mid-sagittal plane axes were relatively high for the rigid grip posture, thus genuine data were obtained. Low coherencies were calculated for all axes at the head when the subjects stood in a light grip posture, this is partly seen by the erratic behaviour of the phase data.

6.2.4 Discussion and conclusions

A search through the literature of reports dealing with the transmission of floor vibration to the head has revealed only one study in which fore-and-aft vibration was used, this was an old study by Dieckmann (1957a) (see Section 2.8.2). The study provided only the basic information with one main deficiency: the lowest frequency investigated was 1.0 Hz and a very coarse frequency resolution was used for the high frequencies. The frequencies considered were 1.0 Hz, 1.5 Hz, 2.0 Hz, 3.0 Hz, 4.0 Hz and 5.0 Hz. The transmissibilities showed just one main resonance peak, this being possibly below 1 Hz and difficult to distinguish as it appears though the transmissibility value at 1 Hz was joined to unity at 0 Hz. No other data could be found concerned with the transmission of fore-and-aft floor vibration to the head for standing subjects.

The inter-subject variability data has shown that the grip used to hold the handrail had a significant effect on motion in some axes at the head. A non-parametric Wilcoxon matched-pairs signed ranks test showed that significantly more motion occurred at the head ($p<0.01$) in the mid-sagittal plane above 1 Hz with the subjects holding the handrail rigidly than when using a light grip. This was seen in Figure 6.6 which showed the median transmissibilities for the two hand grips used. A rigid grip posture showed a distinct main body resonance at 1.2 Hz in the fore-and-aft axis whereas the peak occurred at a frequency of 0.5 Hz for the light grip posture and was of lower magnitude. Both vertical and pitch axes displayed two frequencies at which maximum transmissibility occurred, these being at approximately 2 and 4.2 Hz.

It is seen from the two figures for inter-subject variability data that the spread in transmissibility can be large; for example in Figure 6.3 (rigid grip), fore-and-aft axis at the head shows that at about 5 Hz, head motion varied between subjects by a factor of 12! The variation might be even greater for some axes e.g. vertical axis head motion at 2.7 Hz in Figure 6.3. Repeatability measures in Figure 6.1 show smaller variation than those for the twelve subjects.

A non-parametric measure of correlation (Kendall's tau) was calculated between the various body parameters (age, weight and height) and head motion. This was in an attempt to explain the large variation in transmissibility response between individuals. Some statistically significant correlations were found between the various parameters and head motion at discrete frequencies but this would have been expected with such a large range of frequencies, subjects and variables. This was found to be the case for both hand grip postures. One relatively interesting finding occurred with vertical head motion and the two body characteristics weight and height: over the 4 Hz to 9 Hz frequency range, a significant negative correlation ($p<0.05$) occurred between head motion and subject characteristics with the subjects holding on to the handrail with a rigid hand grip. However, it is seen from Table 6.2 that subject weight was significantly correlated with height at the 1% level. Therefore, a partial correlation procedure was conducted which revealed a significant correlation between vertical head motion and subject stature.

Table 6.2 Kendall's tau values for subject characteristics for twelve subjects.

	Age	Weight	Height
Age	X		
Weight	0.250	X	
Height	0.173	0.636**	X

(** = $p<0.01$)

6.3 LATERAL FLOOR VIBRATION

6.3.1 Introduction

A standing person exposed to lateral vibration of the floor can easily become unstable. The posture adopted (e.g. foot separation) and the type of support provided are known to greatly affect postural stability. This section aims to determine the nature of transmission of lateral floor vibration to the six axes of motion at the head and the effect of three different separations of the feet on transmissibility. Also investigated will be the variation in floor-to-head transmissibility during repeat vibration exposures and the variation in response between individual subjects.

6.3.2 Intra-subject variability

6.3.2.1 Introduction

This section concerns the determination of variation in transmission of lateral floor vibration to the head of a standing subject when exposed several times to the same vibration waveform. One posture of the body will be specified and used for all repeat measures. Such data would be required in explaining the variation in head motion between individuals and in determining the effect of body and experimental variables on floor-to-head transmissibility.

6.3.2.2 Apparatus

Vibration generation

The vibrator, safety frame and the vibration waveform used for this experiment were the same as those explained in Section 6.2.2.2. The acceleration magnitude of the vibration on the vibrator platform was 0.50 ms^{-2} r.m.s. with a maximum frequency of 12.5 Hz and duration of 240 seconds. The subject stood on the vibrator platform so that vibration occurred in the lateral direction.

Vibration measurement

The equipment used and the following analyses of data were the same as those described in Section 6.2.2.2.

6.3.2.3 Procedure

Subjects

A male subject (age 41 years old, weight 85 kg, height 1.87) took part in this experiment, this was the same subject as that who participated in the other intra-subject variability experiments (e.g. see Section 6.2.2). He was asked to adhere as closely as possibly to a set of written instructions on the posture of his body, legs, etc.; these instructions are included in Appendix 7. The experiment was conducted with a foot separation of 60 cm. He was instructed not to hold on to the handrail unless he was about to lose balance. The subject was asked to direct his eyes at a stationery cross approximately 8 m away and to avoid voluntary movements of the head. Throughout this experiment, the subject was provided with an emergency button which, when depressed, would stop the vibration in a controlled manner.

Experimental design

There were twelve identical vibration exposures and during each run, the subject maintained the required body posture. There was a 5 minute pause between successive runs during which the subject was asked to relax.

6.3.2.4 Results

Transmissibilities were calculated between lateral floor vibration and six axes of motion at the head; these are given in Figure 6.7 for the subject standing with a foot separation of 60 cm. Most of the motion at the head occurred in the lateral direction and this was below about 3 Hz. Motion in the other translational axes showed no particular identifiable pattern and the magnitudes were low. Rotational motion showed maximum transmissibilities of about 2 $(rads^{-2})/(ms^{-2})$ in the roll and yaw axes.

Phase was determined for all axes at the head but since the transmissibilities were low for some axes and the corresponding coherencies shown in Appendix 8 were low, erratic behaviour was seen of the phase data. So those axes which show relatively high coherencies are shown in Figure 6.8; these are for the lateral, roll and yaw axes.

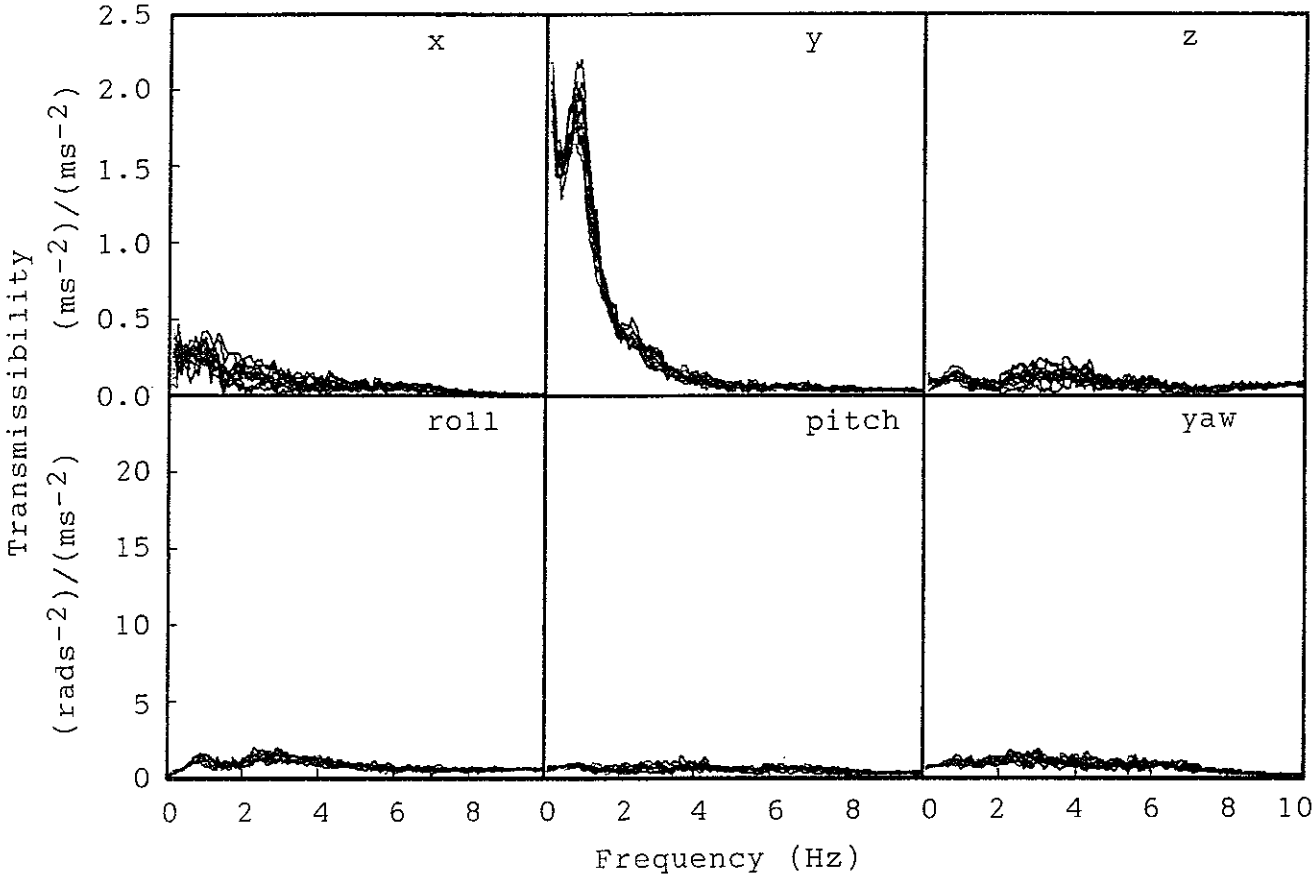


Figure 6.7 Transmissibilities for 1 subject with a foot separation of 60 cm during lateral floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

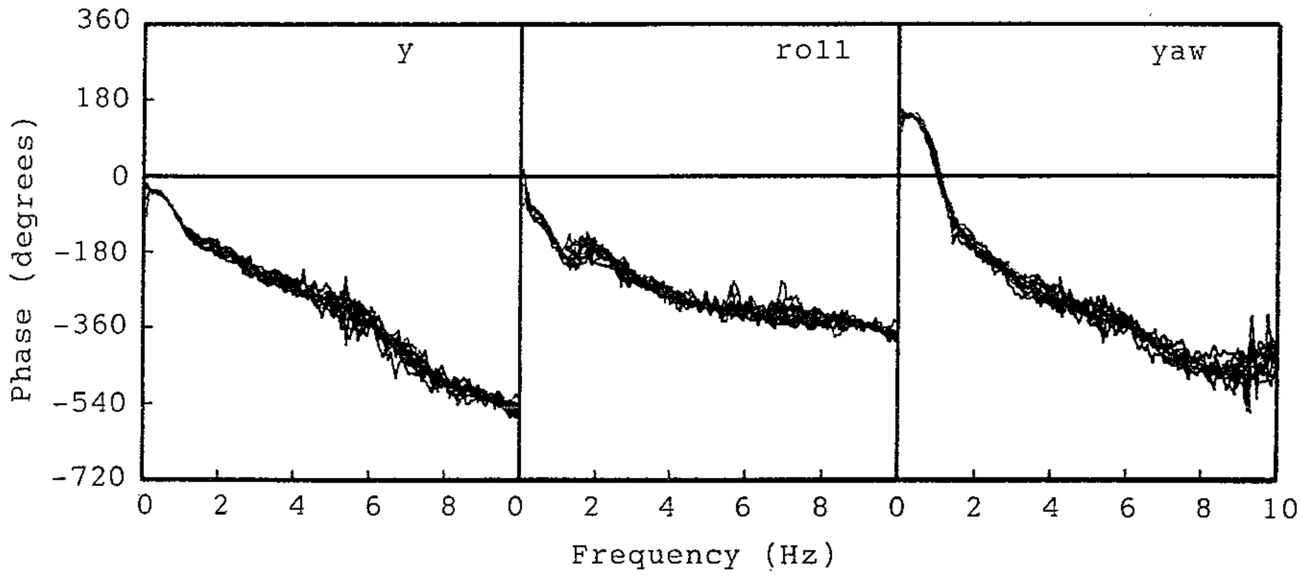


Figure 6.8 Phase for 3 axes of head motion for 1 subject with a foot separation of 60 cm during lateral floor vibration.

6.3.2.5 Discussion

A clear distinct resonance peak is seen in the lateral axis transmissibility at 0.8 Hz with an average magnitude of 1.8 and the maximum response being approximately 1.4 times the minimum response. Small but consistent resonance peaks also occurred in the vertical and roll axes. Motions in all axes apart from the fore-and-aft axis showed high coherencies (greater than 0.7) for frequencies below about 1 Hz indicating that these were probably caused by lateral vibration of the vibrator platform. Motions at higher frequencies which show low coherencies were probably self-induced and could be related to active postural feedback of the body attempting to counteract the 'disturbing' vibration at the feet.

Some interesting results are revealed by the phase data shown in Figure 6.8. Phase lags between lateral axis at the head and platform vibration show an almost linear relationship with frequency, the gradient being approximately 50° per Hz. It is seen that phase for the yaw axis begins with a phase lead of about 180°. This can be explained by considering movement of the body in the positive lateral direction, i.e. towards the left hand side. This would result in yaw motion of the head and it would tend to rotate towards the right hand side (i.e. anti-clockwise when viewed from below). The direction convention used for these analyses used the 'right hand corkscrew rule', i.e. clockwise motion about the vertical axis would correspond to positive yaw motion. Therefore, this genuine phase lead is a result of the direction convention chosen and possibly related to the centre of mass of the head being in front of the point of attachment to the neck.

6.3.3 Inter-subject variability

6.3.3.1 Introduction

During lateral vibration of the floor for standing subjects, separation of the feet is an important factor when determining postural stability. It is thought that a feet together posture would offer less postural stability than a condition in which the feet were separated by, for example, 0.5 m. This section extends the experiment for intra-subject variability (Section 6.3.2) to many subjects and three different separations of the feet. This will provide data of the effect of foot separation on the transmission of floor vibration to the head and on postural stability during lateral vibration of the floor.

6.3.3.2 Apparatus

Vibration generation

The equipment used for the generation of vibration including the vibrator and the computer-generated waveform was the same as that explained in Section 6.3.2.2. The magnitude of the vibration on the vibrator platform was 0.50 ms^{-2} r.m.s., maximum frequency of 12.5 Hz and each exposure lasted 240 seconds.

Vibration measurement

The measurement of vibration and the ensuing analyses on the data were the same as those explained in Section 6.3.2.2.

6.3.3.3 Procedure

Subjects

Twelve male subjects of varying characteristics took part in this experiment. Physical characteristics for individual subjects are shown in Appendix 9; the mean age of the subjects was 28.42 years, the mean weight was 74.33 kg and the mean height was 1.81 m (see Table 6.1 in Section 6.2.3.3).

The subjects were given written instructions about the postures they were to adopt of the body. Three leg postures were requested; these were feet together, feet 30 cm apart and feet 60 cm apart. During each run, the subjects were asked not to hold on to the handrail provided unless they felt that they were about to fall over. Other details about the procedure can be seen in Section 6.3.2.3.

Experimental design

Each subject attended the laboratory on one occasion and was exposed to lateral floor vibration with him standing in each of the three postures. The order of presentation of postures was balanced across subjects. There was a short pause of approximately 5 minutes between the vibration exposures.

6.3.3.4 Results

Transmissibilities between lateral floor vibration and the six axes of motion at the head are shown in Figure 6.9 for the subjects standing with their feet together. Transmissibilities for motion in the translational axes show that head motion occurred mainly in the lateral axis below about 2 Hz. Data above 2 Hz show transmissibilities of similar magnitudes for all three axes. Figures 6.10 and 6.11 display transmissibilities for subjects standing with foot separations of 30 cm and 60 cm respectively. From these two figures, it is again clear that at frequencies below about 2 Hz, motion in the lateral axis at the head was dominant. Only small differences can be seen in transmissibilities between the three postures.

Phase data for these transmissibilities are presented in Figure 6.12 for the y-, roll and yaw axes. The erratic nature of these data can be explained by the low

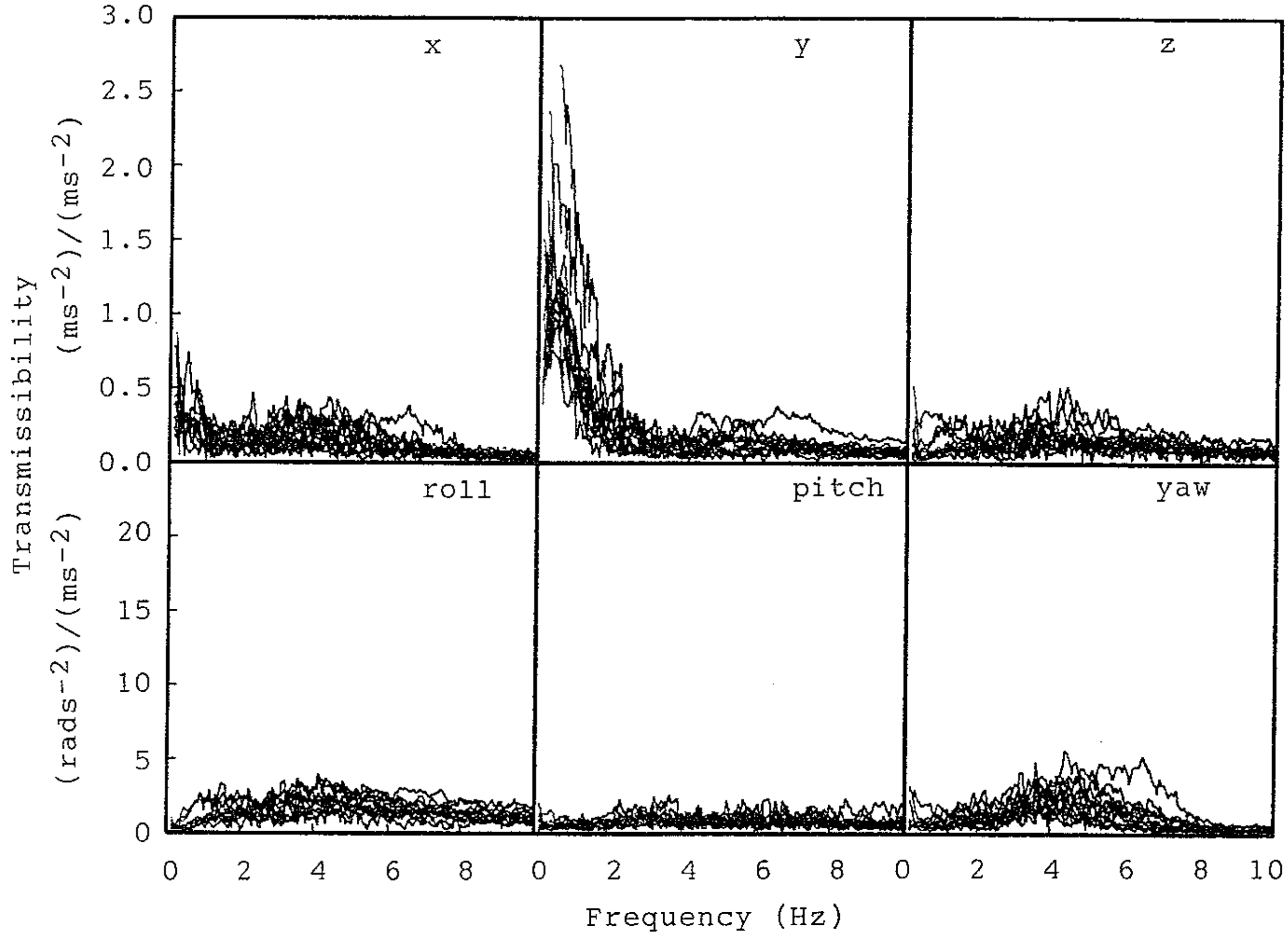


Figure 6.9 Transmissibilities for 12 subjects with feet together during lateral floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

coherencies for these and other axes as shown in Appendix 8. The coherencies can also be used to estimate the correlations between head motion and floor vibration.

6.3.3.5 Discussion

The grouped transmissibilities show only minor differences that could be attributed to changes in foot separation. However, these figures (Figures 6.9, 6.10 and 6.11) do show that the response at the head between subjects can vary by a factor of 2.3 (e.g. 60 cm foot separation, lateral head motion at 0.8 Hz) though other axes and frequencies might demonstrate greater variation. For ease of comparison of transmissibilities, Figure 6.13 shows median curves calculated from individual transmissibility data presented

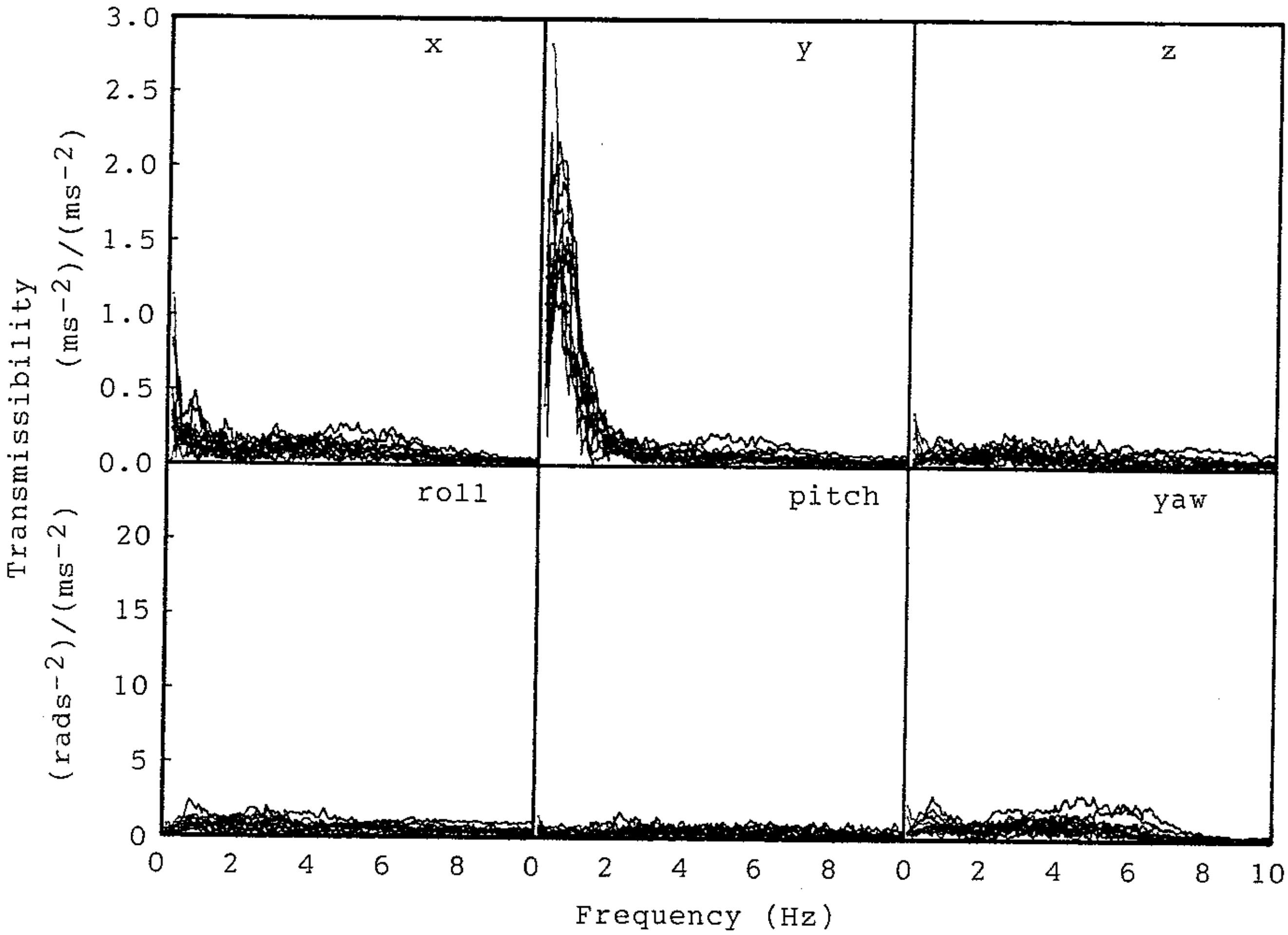


Figure 6.10 Transmissibilities for 12 subjects with a foot separation of 30 cm during lateral floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

in Figures 6.9, 6.10 and 6.11. A visual inspection shows that the main differences occurred for motion in the lateral axis at the head and these occurred at frequencies below 3 Hz. A non-parametric Wilcoxon matched-pairs signed ranks test showed that significantly more motion was transmitted to the head ($p<0.01$) in the lateral axis over the 1 Hz to 3 Hz frequency range with the subjects standing in a 60 cm foot separation posture than the other two postures. Some of the other axes also showed differences though these were small such as more roll axis head motion when standing in a feet together posture than the other two postures.

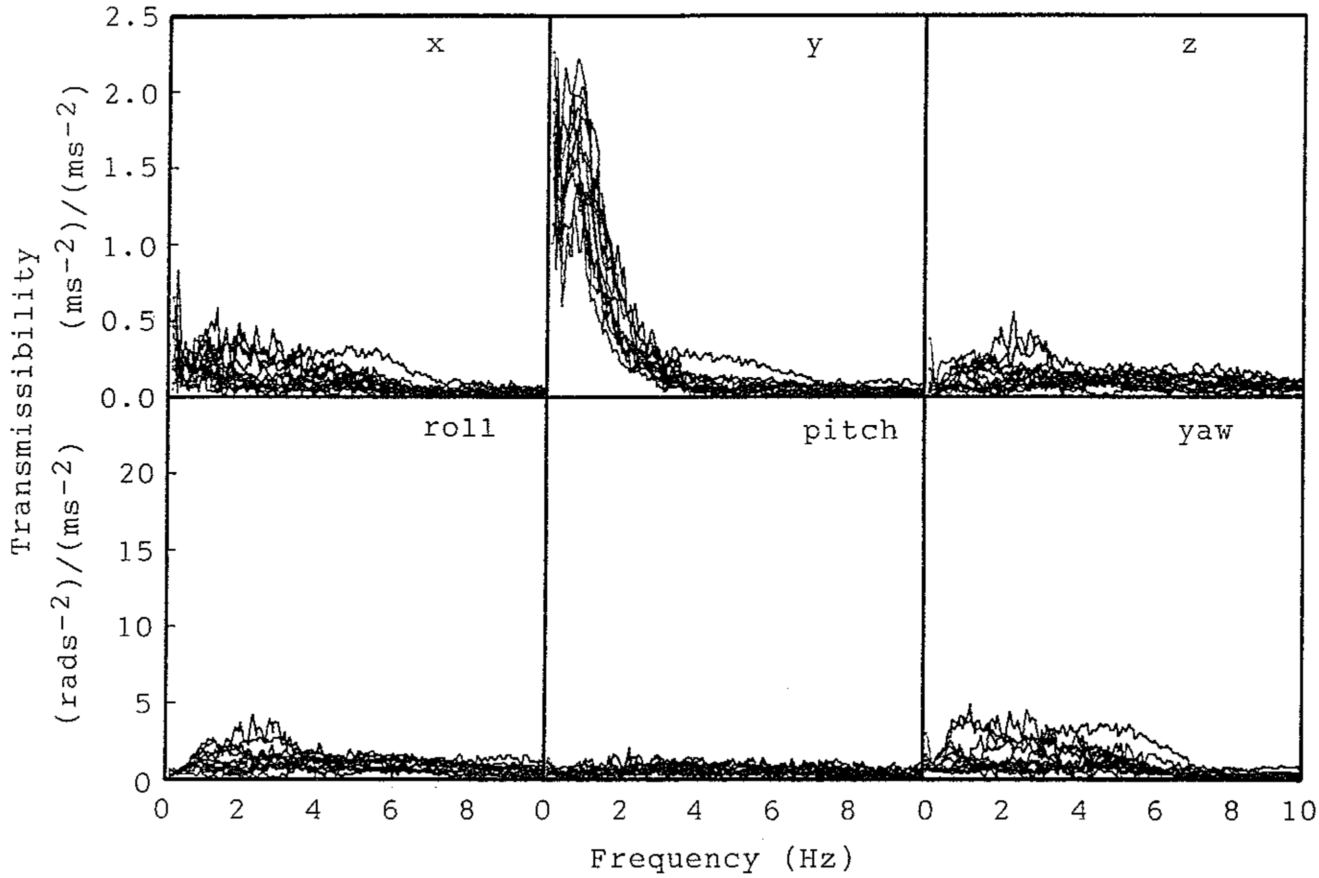


Figure 6.11 Transmissibilities for 12 subjects with a foot separation of 60 cm during lateral floor vibration. (Resolution = 0.06 Hz, degrees of freedom = 58)

Phase data for this inter-subject variability study show the main basic underlying trend but data for some subjects appear to show large sudden increases and decreases at particular frequencies. This phenomenon is associated with low coherency values at those frequencies. No immediate differences are seen in the phase that could be attributed to changes in foot separation.

6.3.4 Discussion and conclusions

The measurements made of head motion during exposure to lateral floor vibration appear to be the only data available on floor-to-head transmissibility. Therefore, unfortunately, no comparisons with other data can be made.

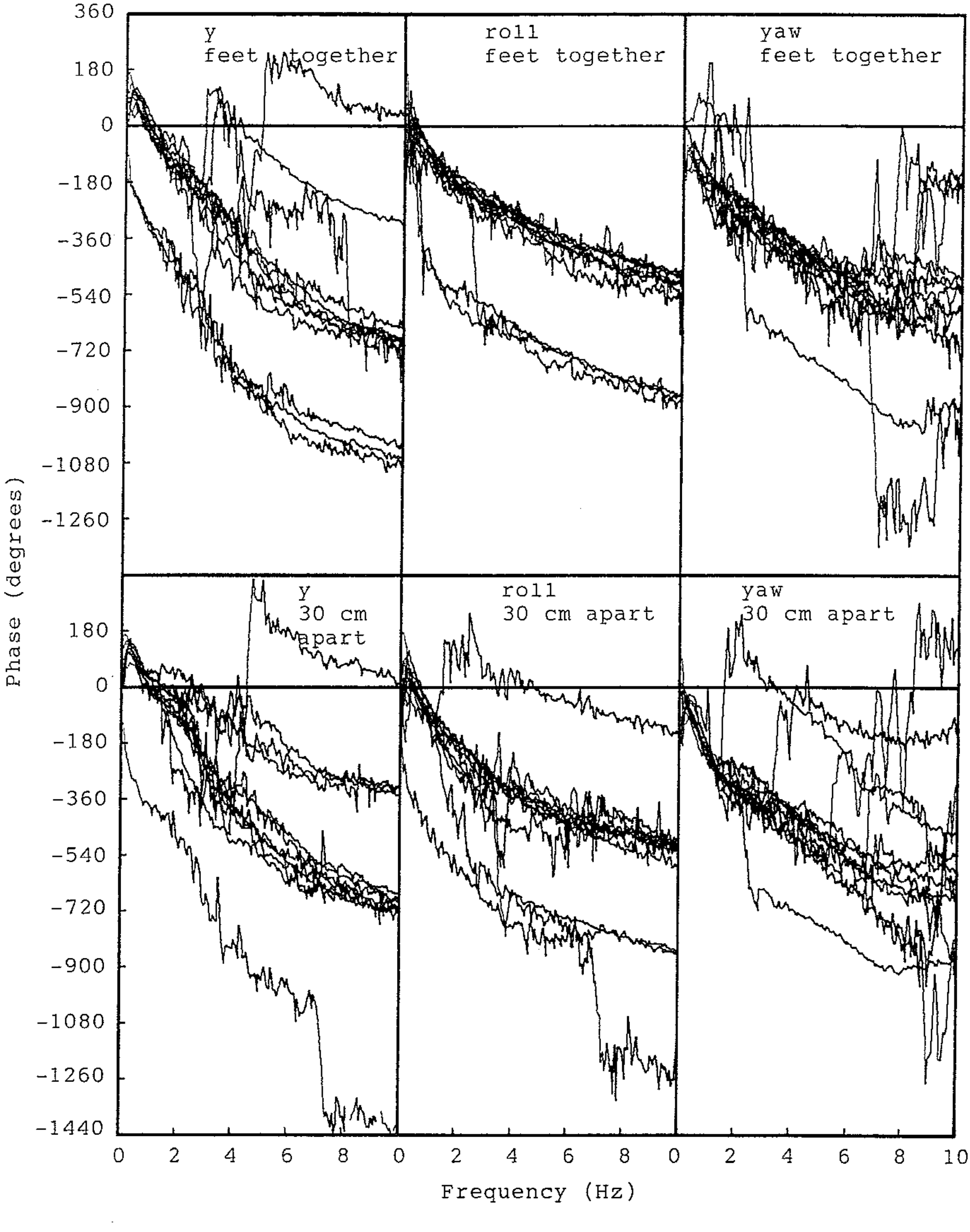
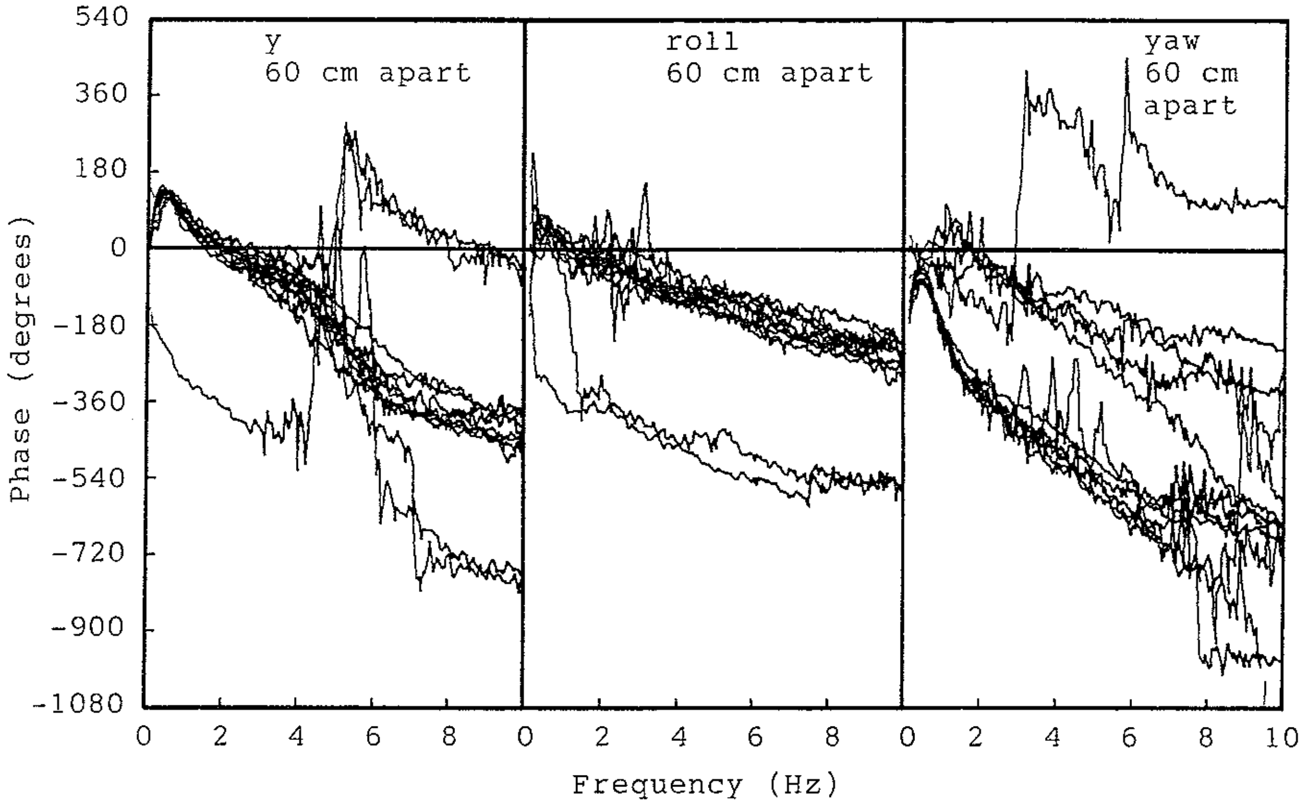


Figure 6.12 Phase for 3 axes of head motion for 12 subjects with feet together, feet 30 cm apart and feet 60 cm apart during lateral floor vibration. (Continued)



(Continued)
Figure 6.12 Phase for 3 axes of head motion for 12 subjects with feet together, feet 30 cm apart and feet 60 cm apart during lateral floor vibration.

Variability in transmissibility over repeat measures and between subjects can be seen in Figures 6.7 and 6.11 respectively for subjects standing with a foot separation of 60 cm. It was expected that intra-subject variability would be smaller than inter-subject variability measures - this clearly is seen to be the case for most axes. Transmissibilities for motion in the fore-and-aft axis for intra-subject variability data show variation in responses almost as great as those observed for inter-subject variability. Also, no particular transmissibility shape can be seen as is the case for all the other axes. These may be associated with involuntary postural movements. The three figures that show inter-subject variability (i.e. Figures 6.9, 6.10 and 6.11) appear to indicate that variability in transmissibility between subjects was lower when they stood in a 30 cm foot separation then the other two postures. Further analyses of data might be required to confirm this.

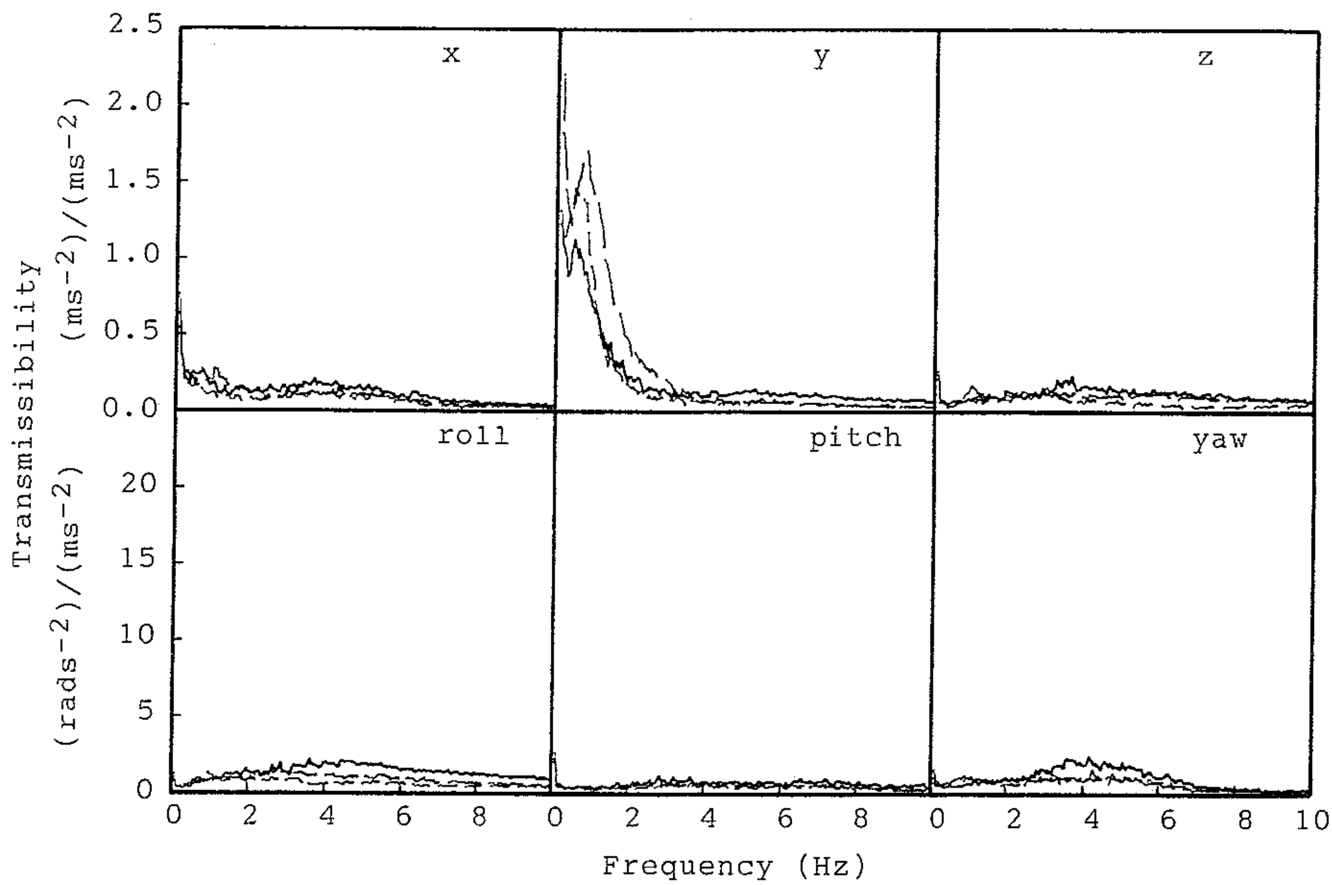


Figure 6.13 Median transmissibilities for 12 subjects with feet together (———), feet 30 cm apart (- - -) and feet 60 cm apart (— — —) during lateral floor vibration.

Some differences in transmissibility are present that can be attributed to the separation between the feet, however, the differences are small. Transmissibilities for motion in the lateral direction at the head show that for frequencies below 3 Hz, greater magnitudes of head motion occur with increasing separation of the feet. Also, the data tend to show an increase in the frequency of peak transmissibility with increasing foot separation. Significantly more motion was transmitted to the roll axis of the head ($p<0.01$) for frequencies above 3 Hz when the subjects stood with their feet together than when they stood in the other two postures.

It was seen from the phase data for both intra- and inter-subject variability studies that for most axes and subjects, erratic data resulted which were possibly due to the low coherencies. Data for one subject (intra-subject variability) appear to be 'well behaved' for the axes presented (i.e. y-, roll and yaw axes), this not being the case for the individual variability data. Also, repeatability data for the yaw axis showed a phase lead which was explained by the head moving in a negative yaw axis for very low frequencies, this was not observed for the other subjects.

All subjects found it necessary to hold on to the handrail when they stood in a feet together posture whereas only a few subjects held the rail in the other two postures. The postural stability of subjects to maintain upright appears to be related to foot separation: greater foot separation offered more stability. However, this is the case only up to a particular foot separation as 30 cm and 60 cm separations both offered similar postural stability. The horizontal position of the centre of gravity of the body might be related to postural stability in that, for a feet together posture, the body does not have to sway too much before the centre of gravity is outside the area covered by the feet.

Kendall's tau (non-parametric rank correlation coefficient) was calculated between head motion and subject characteristics to determine if any correlations could be found between the various parameters. The subject characteristics were age, height and weight while head motion was measured in all the six axes over a frequency range of up to 10 Hz (at 0.25 Hz increments). This was calculated for the three different foot separations. With so many variables and combinations, some significant correlations would be expected by chance. Overall, no pattern of correlations were seen between the subject characteristics and head motion, although both height and weight showed some significant correlations ($p<0.05$) at various frequencies with most axes of the head with the subjects standing in a feet together posture. It was found that both subject height and weight were themselves correlated at the 1% significance level.

6.4 VERTICAL FLOOR VIBRATION

6.4.1 Introduction

The exposure of standing people to vertical vibration of the floor can be seen in many situations, examples of these include escalators, lifts and some forms of transport such as buses and trains. The nature of transmission of vertical vibration to the head has been the topic of some studies and these have provided data for various postures of the body (see Section 2.8.1). Though results were presented in those studies, there have been some deficiencies in the data. These have included the lowest frequency of investigation being too high thus excluding main body resonances, frequency resolution being too coarse, no 'base line' posture for comparison and no indication of repeatability.

This section aims to provide comprehensive transmissibility data concerned with the transmission of vertical vibration from the floor to the head for standing subjects. This will include both intra- and inter-subject variabilities. The effect of three postures of the legs on floor-to-head transmissibility will be investigated.

6.4.2 Intra-subject variability

6.4.2.1 Introduction

An estimate of the repeatability of transmissibility would be required before commencing any experimentation to determine the effect of different variables (e.g. posture) and individual variability. This section concerns the determination of intra-subject variability in the transmission of vertical floor vibration to the head for a standing subject. The effect of three different postures of the legs on head motion is also investigated.

6.4.2.2 Apparatus

Vibration generation

An electro-hydraulic vibrator capable of producing vertical displacements of 1 metre was used for this experiment; it was certified safe for the exposure of human subjects to vibration. The vibrator has been described in detail in Section 3.5.2. A tubular framework was fixed to the vibrator platform for subjects to stand within; this was used for safety purposes only.

A computer-generated Gaussian random waveform was used to operate the vibrator, it had a nominally flat spectrum over the frequency range 0.1 Hz to 31.5 Hz. The vibrator stimulus was of 60 seconds duration and low-pass filtered at 31.5 Hz before being fed to the vibrator. The same vibration waveform was used for all exposures in this section and motion on the platform had an acceleration magnitude of 1.75 ms^{-2} r.m.s.

Vibration measurement

Motion of the head was monitored using a six-axis bite-bar which had six small translational piezo-resistive full-bridge Entran type EGAX±5 accelerometers located and orientated in such a manner that motion in the three translational and three rotational axes could be measured. The total mass of the bite-bar was 135 g and it has been shown elsewhere that the mass of the bite-bar had no effect on head motion (see Section 5.4.2). A personal sterilised dental mould was used for the subject to bite on. More data about the bite-bar are given in Section 3.2.

Seven channels of vibration were acquired (6 at the head and 1 at the vibrator platform) into a digital computer system PDP11-34 at a sample rate of 128 samples per second. These signals were low-pass filtered at 31.5 Hz via 48 dB/octave filters with Butterworth characteristics. All transfer functions were calculated for motion occurring on the bite-bar at mouth level and 100 mm to the left of the mid-sagittal plane of the subject. Transfer functions were calculated using the 'cross-spectral density function method' (see Section 6.2.2.2) and a frequency resolution of 0.25 Hz was used which gave 58 degrees of freedom.

6.4.2.3 Procedure

Subjects

One healthy male subject (age 41 years, weight 85 kg, height 1.87 m) participated in this intra-subject variability study. (This was the same subject as that who took part in the previous repeatability studies, see Sections 6.2.2 and 6.3.2.) The subject stood on the vibrator platform and was instructed to maintain his posture in the required manner and to look at the cross on a stationary wall in front of him approximately 1.2 m away. Instructions given to the subject are shown in Appendix 7. The distance between the subjects feet was 25 cm.

Three different postures of the legs were requested: 'legs locked', 'legs unlocked' and 'legs bent'. In the 'legs locked' posture the subject stood in a normal upright stance; in the 'legs unlocked' posture the knees were slightly forward; in the 'legs bent' posture the knees were vertically above the subject's toes. He was instructed not to make voluntary movements of the head, arms and the body during the vibration exposure. A handrail was provided for the subject to hold on to and this only in the event of him becoming unstable. The subject was provided with an emergency button which he could use in an emergency.

Experimental design

The subject attended the laboratory on three occasions, once for each posture of the legs. He was exposed to twelve identical vibration runs with him standing in each posture. There was a pause of about 5 minutes between the repeat exposures during which he was asked to relax.

6.4.2.4 Results

Figures 6.14, 6.15 and 6.16 present transmissibilities for the six axes of motion at the head for the one subject standing in three different postures of the legs during vertical floor vibration: 'legs locked', 'legs unlocked' and 'legs bent' respectively. Transmissibilities for the 'legs locked' posture show that motion of the head occurred primarily in the vertical and pitch axes with relatively smaller magnitudes of motion in the other axes. Data for the 'legs unlocked' posture are similar to the 'legs locked' posture though the transmissibilities are slightly lower. The main difference occurred when a 'legs bent' posture was adopted: motion in all axes show a resonance at about 3 Hz and magnitudes of transmissibility are much smaller for the lateral, roll and yaw axes compared with the fore-and-aft, vertical and pitch axes.

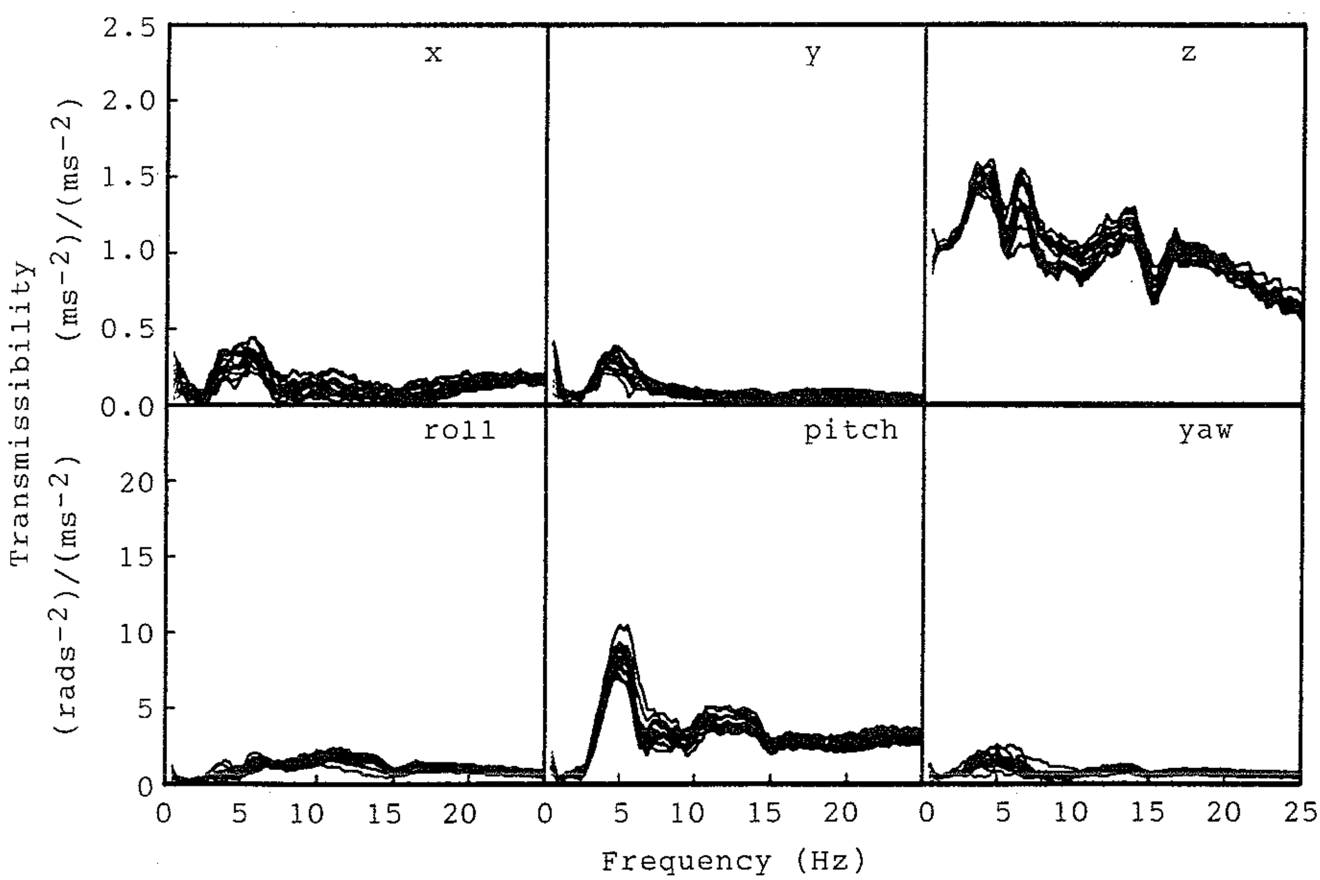


Figure 6.14 Transmissibilities for 1 subject in a 'legs locked' posture during vertical floor vibration. (Resolution = 0.25 Hz, degrees of freedom = 58)

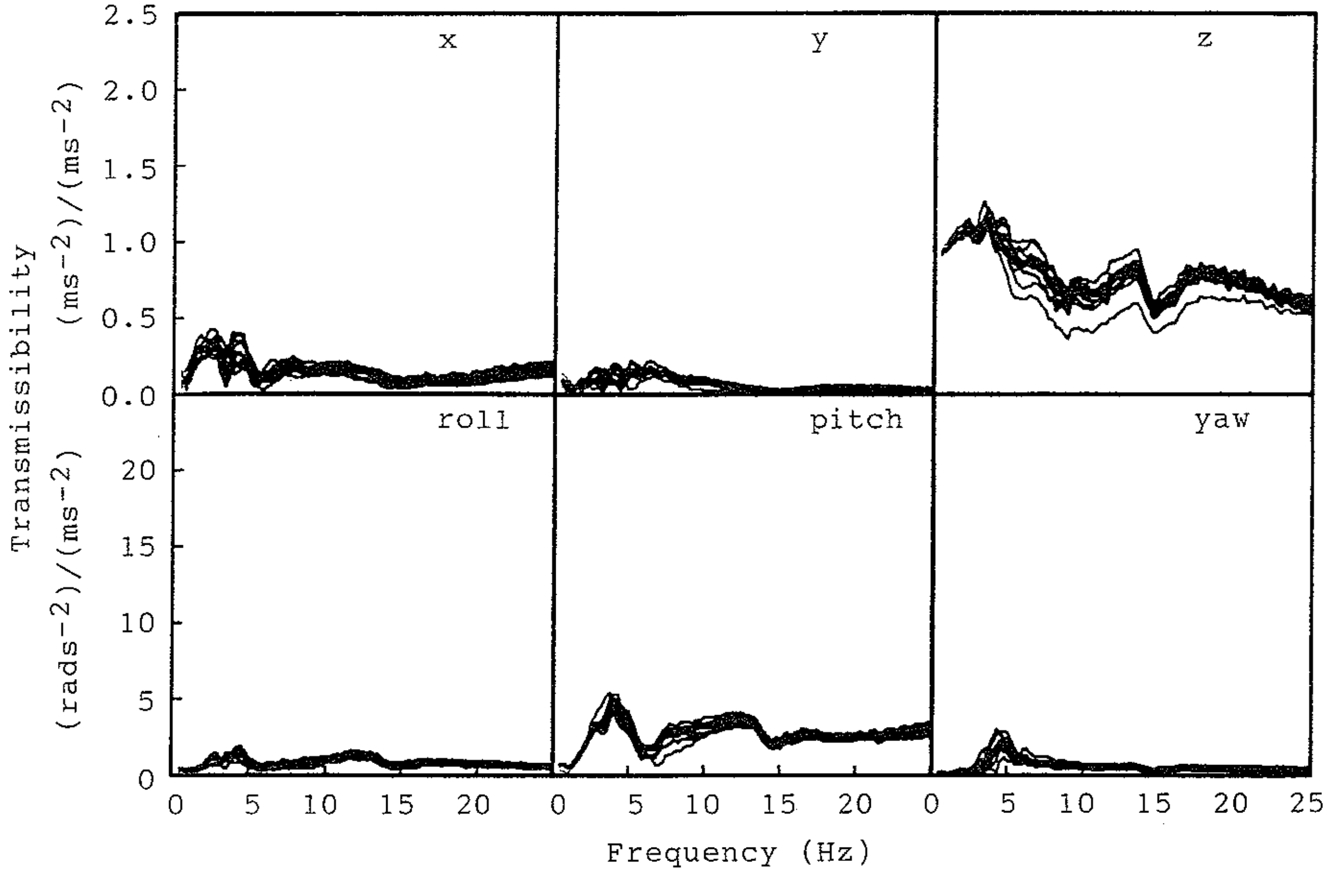


Figure 6.15 Transmissibilities for 1 subject in a 'legs unlocked' posture during vertical floor vibration. (Resolution = 0.25 Hz, degrees of freedom = 58)

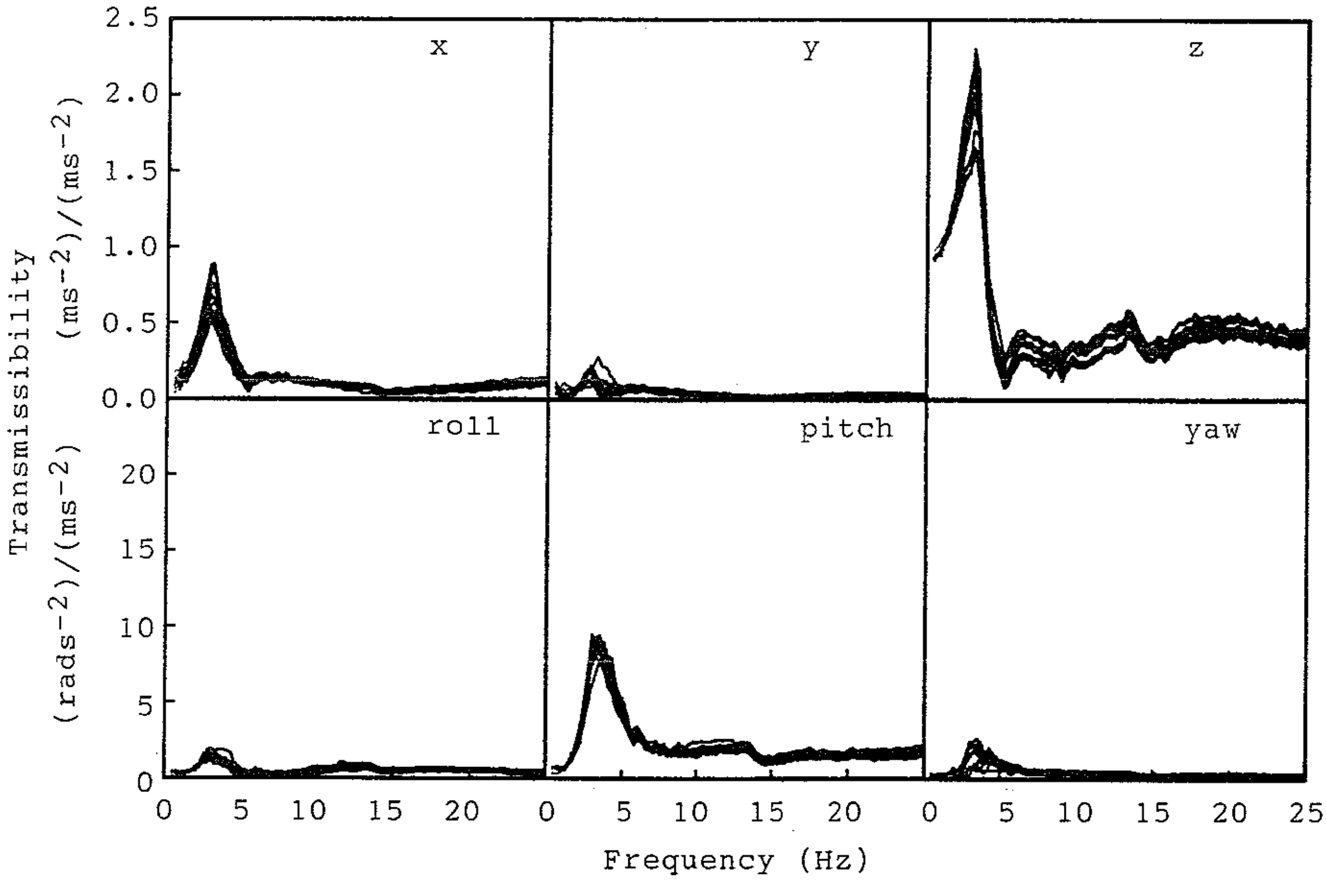


Figure 6.16 Transmissibilities for 1 subject in a 'legs bent' posture during vertical floor vibration. (Resolution = 0.25 Hz, degrees of freedom = 58)

It was seen above that, in general, higher transmissibilities were calculated for motion occurring in the mid-sagittal plane axes than the other axes. It is also seen from the coherencies for those data included in Appendix 8 that, overall, higher coherencies were calculated for motion in the mid-sagittal plane (though this might not be entirely the case for fore-and-aft motion at the head). Therefore, phase data for only the mid-sagittal plane axes are presented, these are shown in Figure 6.17 for the three postures of the legs. The rather erratic behaviour seen for phase data in the fore-and-aft axis for the subject standing in a 'legs locked' posture is thought to be associated with the low transmissibilities and coherencies at some frequencies.

6.4.2.5 Discussion

Median transmissibilities are shown in Figure 6.18 for the three postures in order to see the differences more clearly. The main axes displaying motion at the head are vertical and pitch followed by the fore-and-aft axis depending on the posture adopted. Vertical motion at the head shows that above about 3.5 Hz, a 'legs locked' posture transmitted significantly greater magnitudes of vibration than the other two postures; the 'legs bent' posture showing the lowest transmissibility. However, below about 3 Hz, the 'legs bent' posture showed higher transmissibilities than the other two postures. Similar data can be seen for pitch motion at the head. Pitch axis transmissibilities above about 8 Hz appear to be unaffected by the change in posture from a 'legs locked' to a 'legs unlocked' posture. In most of the axes, there is a slight decrease in the first resonance frequency from about 5 Hz to 3 Hz (depending on the axis) as the posture was changed from 'legs locked' to 'legs bent'.

Over most of the frequency range, a high degree of repeatability was seen between the runs with the occasional run showing different but genuine transmissibilities. An example of this is seen in the vertical transmissibilities

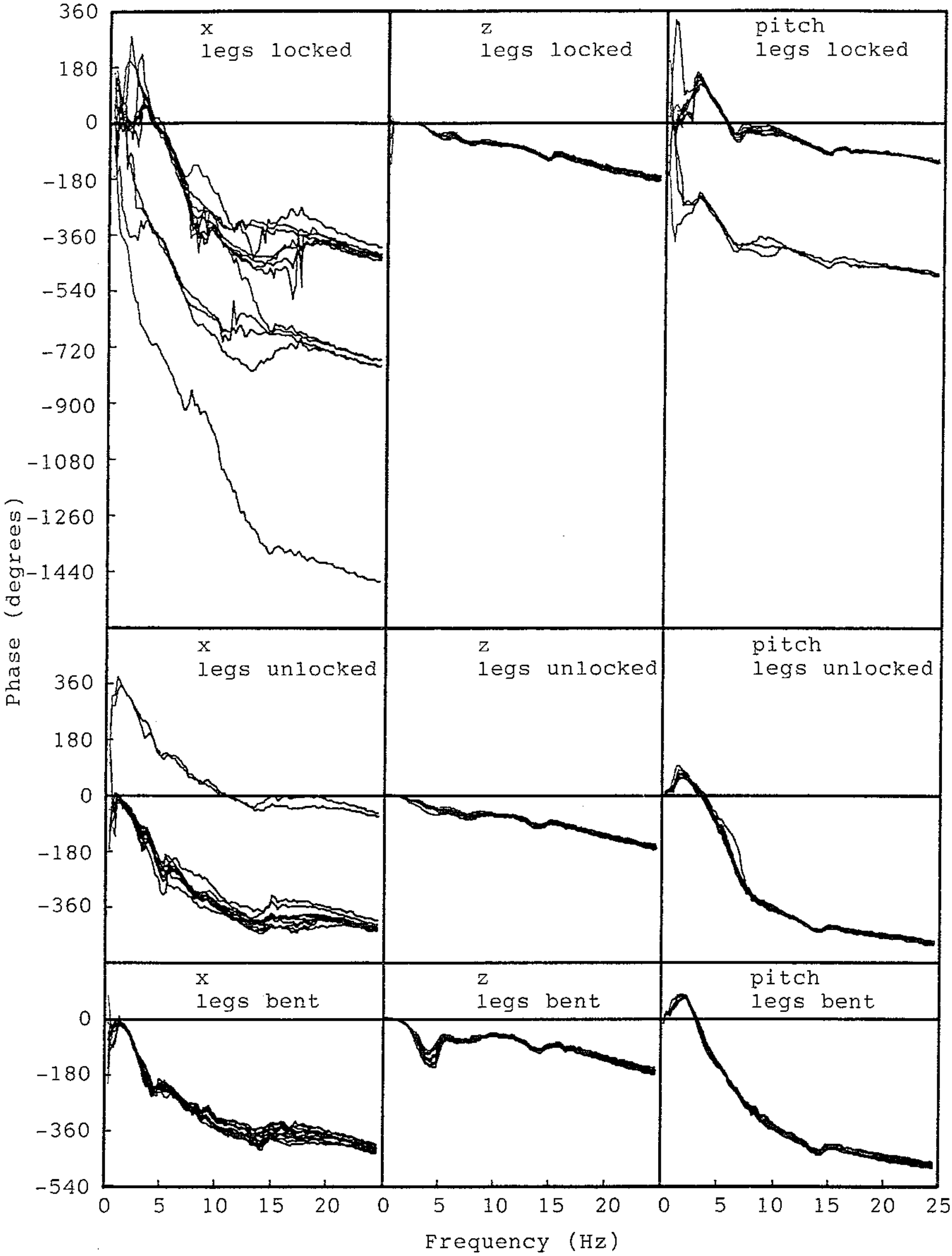


Figure 6.17 Phase for 3 axes of head motion for a subject in 'legs locked', 'legs unlocked' and 'legs bent' postures during vertical floor vibration.

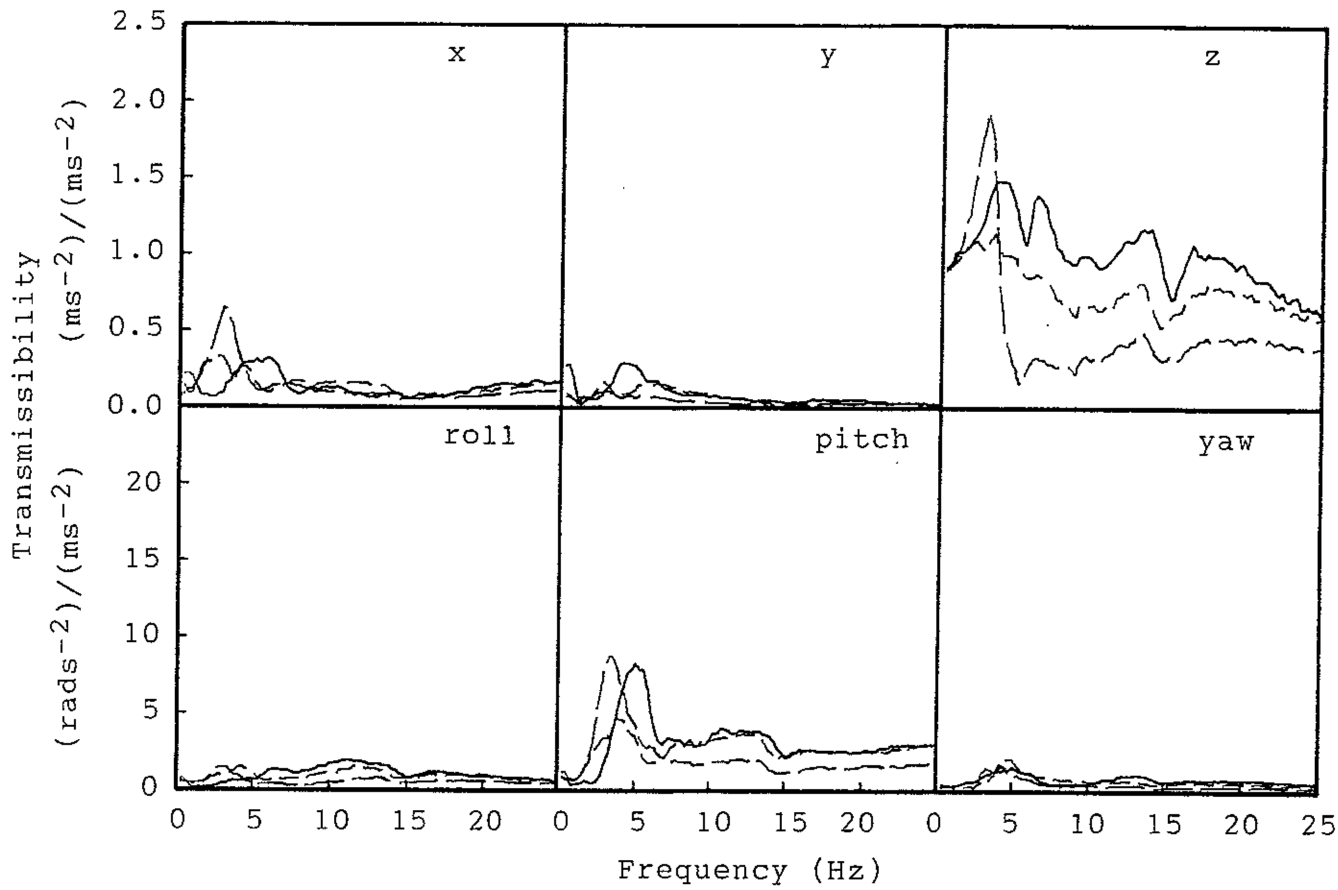


Figure 6.18 Median transmissibilities for 1 subject in 'legs locked' (————), 'legs unlocked' (- - - -) and 'legs bent' (— — —) postures during vertical floor vibration.

in Figure 6.15 with the subject standing in a 'legs unlocked' posture. It is interesting to note that the variation between the different runs is only apparent in the magnitude of the transmissibilities while the dependence on frequency remaining mainly unaffected. A high degree of repeatability is also seen in the phase data apart from those axes which show low coherence values where the transmissibilities are very small. The phase lead seen in the pitch axis at low frequencies is dependent on the convention chosen for the positive direction for the various axes. It could also be inherent in the manner the head would and does behave with respect to the input vibration.

Coherencies for these data presented in Appendix 8 show very high values for some axes and also show that the posture adopted affected the correlation between floor vibration and head motion. Data for the vertical axis at the head show an increase in incoherent motion as the posture changed from a 'legs locked', to a 'legs unlocked' posture and then to a 'legs bent' posture. Other axes show different trends.

6.4.3 Inter-subject variability

6.4.3.1 Introduction

The transmission of seat vibration to the head has been the subject of many studies. These have investigated the effects of a large number of variables such as seating conditions, individual variability, posture and head pointing angles. The transmission of floor vibration to the head has been studied by a few researchers but not to such a depth.

This study is a continuation of the previous experiment and concerns the measurement of six-axis motion at the head caused by vertical vibration of the floor. The effect of three postures of the legs on the transmissibility will be determined. Twelve subjects took part in this study to investigate inter-subject variability.

6.4.3.2 Apparatus

Vibration generation

The apparatus used for generating the vibration was the same as that used in the intra-subject variability experiment - see Section 6.4.2.2.

Vibration measurement

Head motion was measured using a six-axis bite-bar with a sterilised plastic tubing (which replaced the dental mould) for the subjects to hold between their teeth. Other equipment used for measuring and analysing the vibration signals was the same as that explained in Section 6.4.2.2.

6.4.3.3 Procedure

Subjects

Twelve male subjects took part in this study. Their mean physical characteristics were age 28.42 years, weight 74.33 kg and height 1.81 m; their individual data are shown in Appendix 9. The instructions given to subjects, the different postures of the legs and other details about experimental procedure were the same as those used for the intra-subject variability experiment explained in Section 6.4.2.3 and in Appendix 7.

Experimental design

Each subject attended the laboratory on one occasion and was exposed to the same vibration waveform three times, once for each of the three postures. The order of presentation of the postures was balanced across the subjects to minimise any effects this might have had. There was a short pause of 5 minutes between the vibration exposures.

6.4.3.4 Results

In Figure 6.19 are shown transmissibilities between vertical vibration at the floor and the six axes of motion at the head with the subjects standing in a 'legs locked' posture. The large variation in transmissibility shows the individual variability that should be expected. Lateral, roll and yaw axes show lower transmissibilities than these axes in the mid-sagittal plane, though they are not insignificant.

Translational and rotational head motion transmissibilities for the twelve subjects standing in a 'legs unlocked' posture are shown in Figure 6.20. A comparison between the transmissibilities for the two postures shows that there

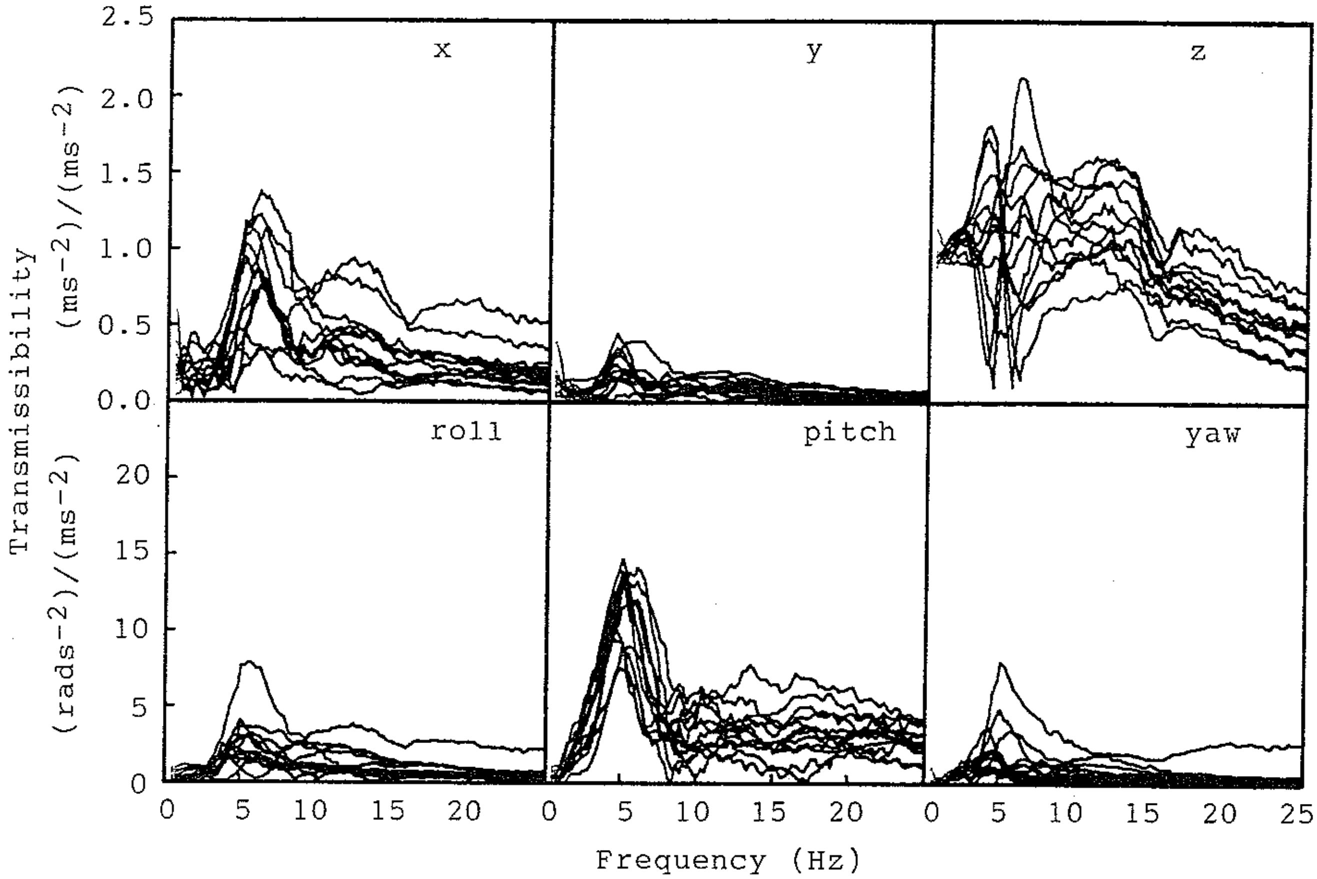


Figure 6.19 Transmissibilities for 12 subjects in a 'legs locked' posture during vertical floor vibration. (Resolution = 0.25 Hz, degrees of freedom = 58)

are only slight differences. There is a trend towards reduced motion transmitted to the head in the 'legs unlocked' posture for all six axes, though there are exceptions (e.g. pitch axis transmissibility at about 5 Hz).

Transmissibilities of motion from the floor to head for the third posture of the legs, i.e 'legs bent', are displayed in Figure 6.21. The main difference is more apparent between the transmissibilities for this posture and the two previous leg postures in that the variation between subjects is smaller. This is clearly seen in the vertical axis transmissibilities for the three postures of the legs although the transmissibility values are also smaller for the 'legs bent' posture. (Data shown in Section 6.4.2 from an intra-subject variability experiment also showed smaller variation for a 'legs bent' posture than 'legs locked' and

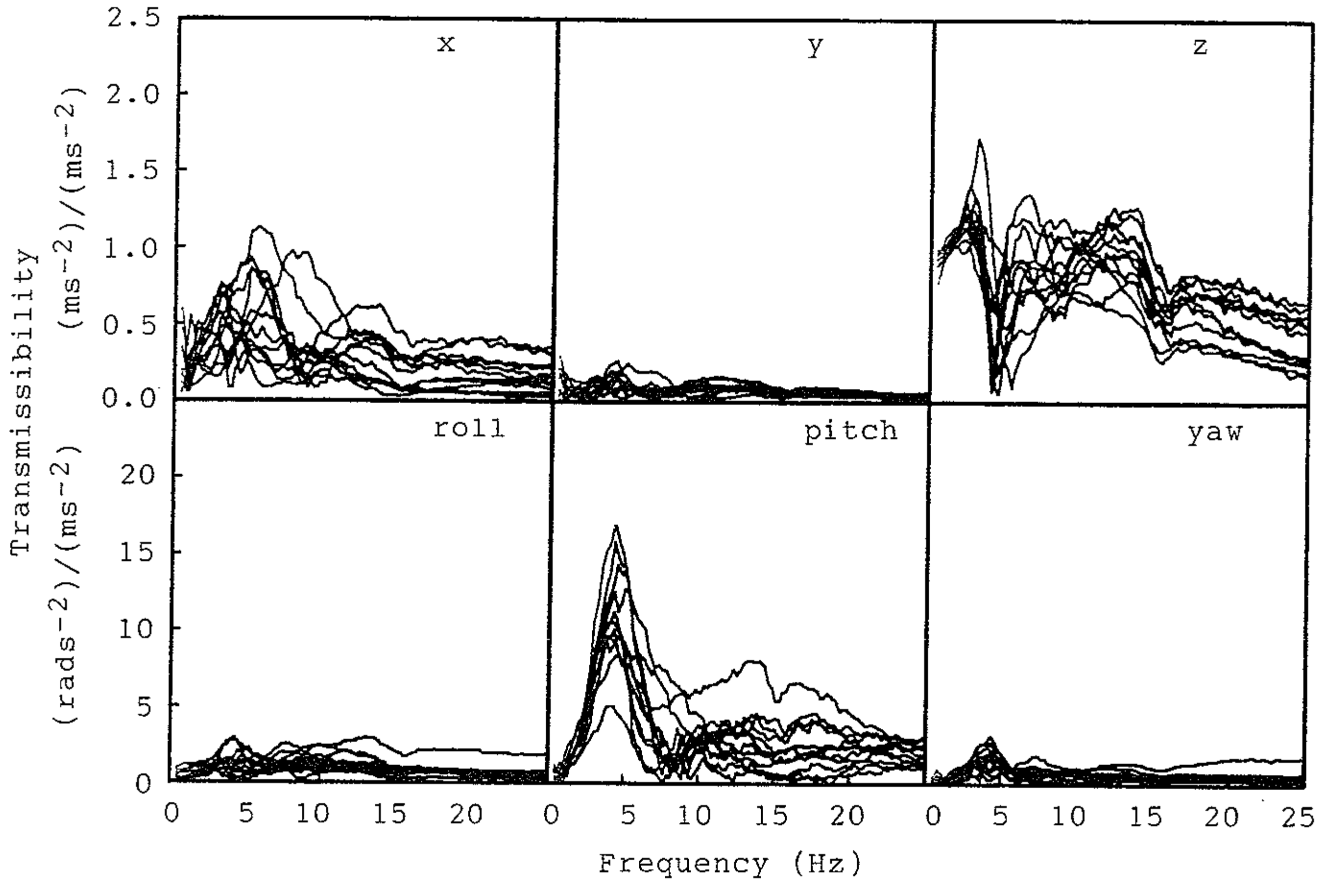


Figure 6.20 Transmissibilities for 12 subjects in a 'legs unlocked' posture during vertical floor vibration. (Resolution = 0.25 Hz, degrees of freedom = 58)

'legs unlocked' postures.) For vertical motion of the head, all the subjects produced transmissibility curves which could be summarised as having a resonance at 2.5 Hz, a point of minimum motion at 5 Hz and a second but smaller peak at 13 Hz. For the two other postures of the legs, some subjects tended to display maximum motion at the head in the vertical axis at about 5 Hz whereas others had a point of minimum motion at this frequency.

Phase data were calculated for all axes of head motion and are presented in Figure 6.22 for the mid-sagittal plane axes for the three postures of the legs. These three axes (i.e. fore-and-aft, vertical and pitch) were chosen as they demonstrated the highest transmissibilities. Coherencies for these data are included in Appendix 8. These 'ordinary coherence functions' provide an indication of the correlation between motion at the output and motion at the

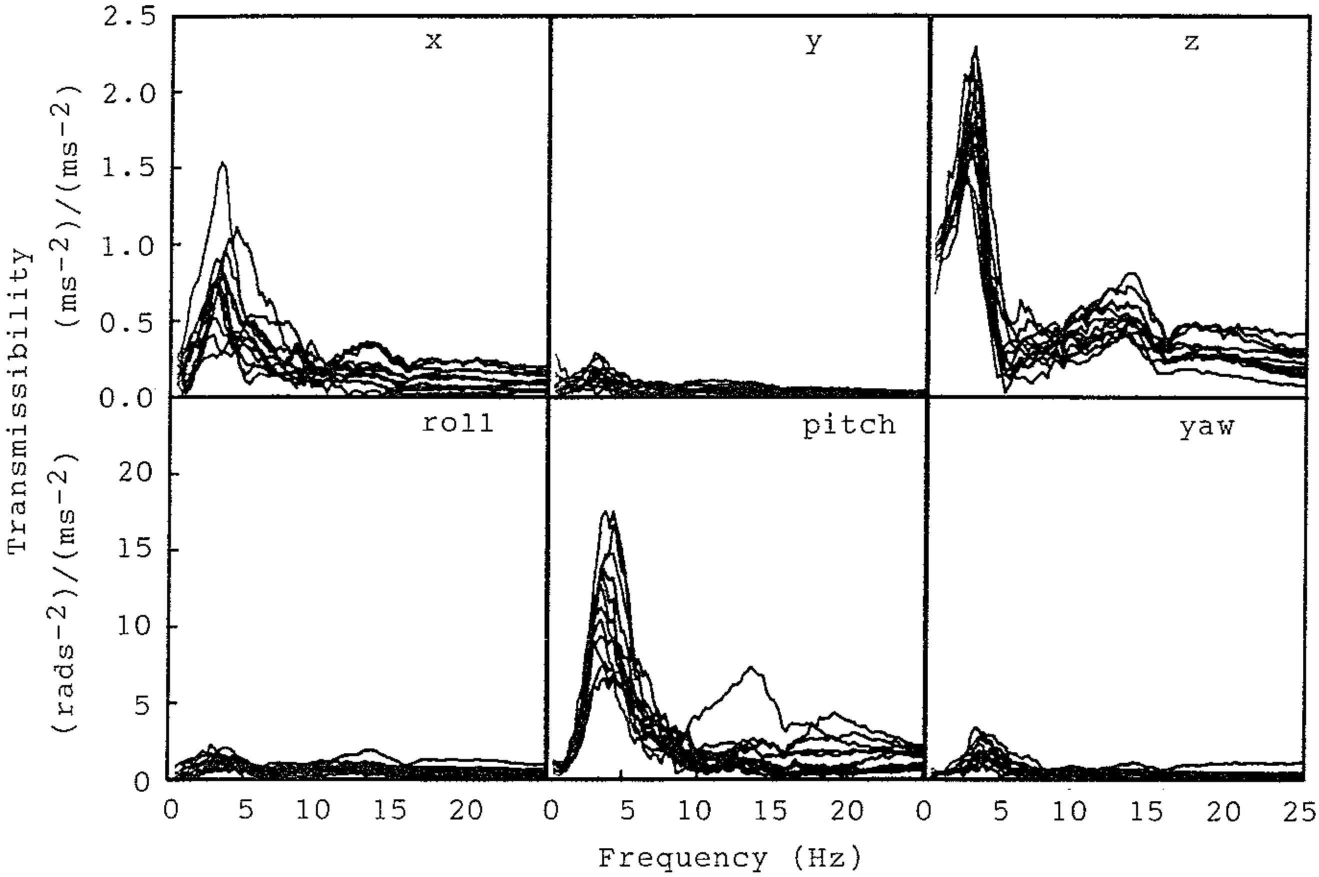


Figure 6.21 Transmissibilities for 12 subjects in a 'legs bent' posture during vertical floor vibration. (Resolution = 0.25 Hz, degrees of freedom = 58)

input. A value of unity shows that all the motion at the output (e.g. motion at the head in a particular axis) was caused by motion at the input (i.e. vertical floor vibration); this only being the case for the frequency showing the highest coherency. The erratic behaviour of the phase data at some of the frequencies is associated with low transmissibilities and low coherencies.

6.4.3.5 Discussion

For ease of comparison of transmissibilities to determine the effect of posture on the transmission of floor vibration to the head, median transmissibilities are shown in Figure 6.23 for the twelve subjects. It is seen from the transmissibilities for the fore-and-aft and pitch axes that below about 4 Hz, a 'legs bent' posture transmitted greater magnitudes of vibration to the head than the other two postures and a 'legs locked' posture transmitted the

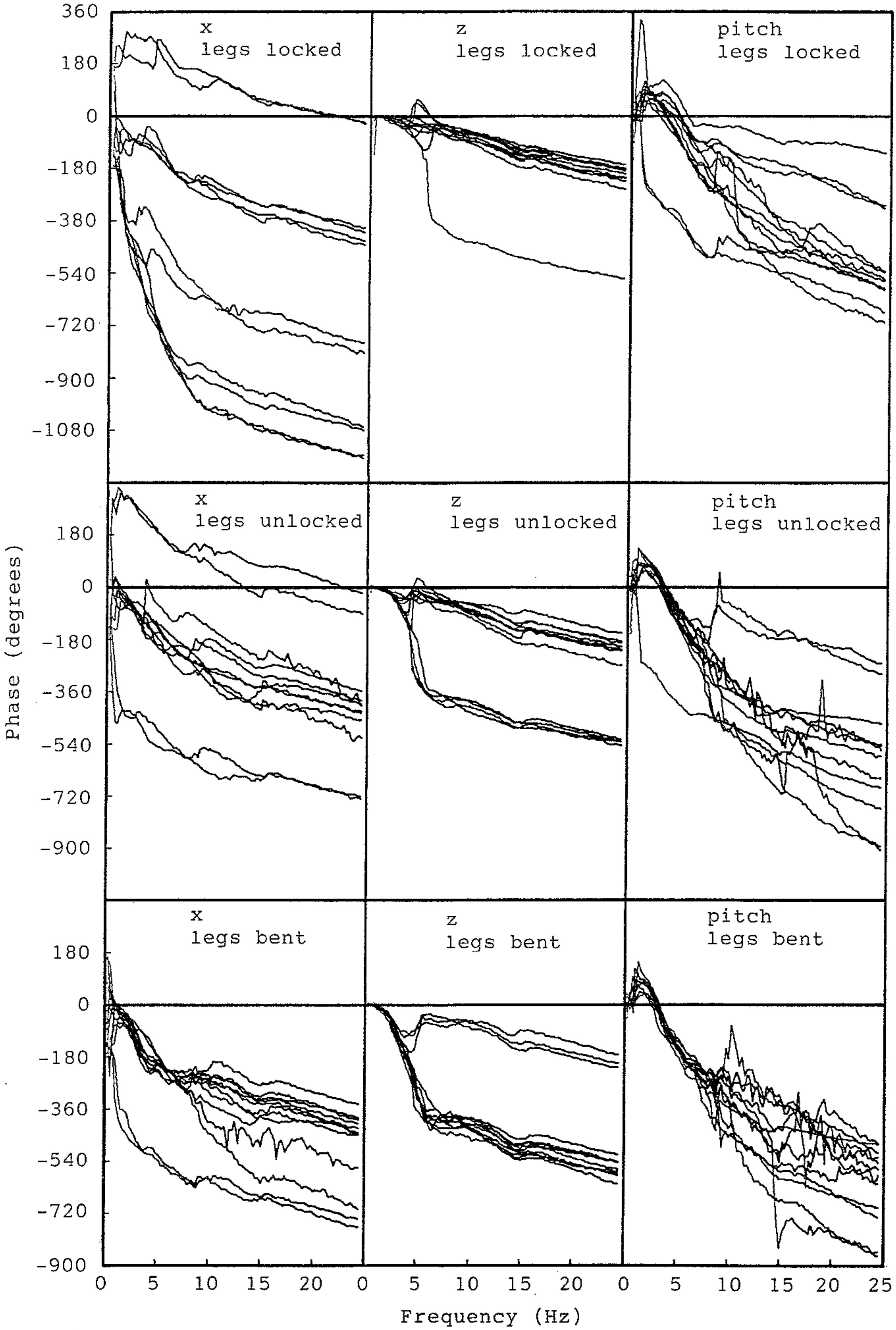


Figure 6.22 Phase for 3 axes of head motion for 12 subjects in 'legs locked', 'legs unlocked' and 'legs bent' postures during vertical floor vibration.

least motion. However, for frequencies greater than 4 Hz, the situation is reversed with the 'legs locked' posture showing the greatest transmissibilities and the 'legs bent' demonstrating the lowest transmissibilities. These differences were significant at the 1% significance level for most of the frequencies. Very similar results are seen for vertical motion transmissibilities but the cross-over frequencies vary between 3 Hz and 5 Hz depending on the postures being compared. Again, the differences are significant at the 1% level. One of the main comments the subjects made about the three postures was that a 'legs bent' was the least uncomfortable posture than the others due to the reduction in high frequency vibration at the head.

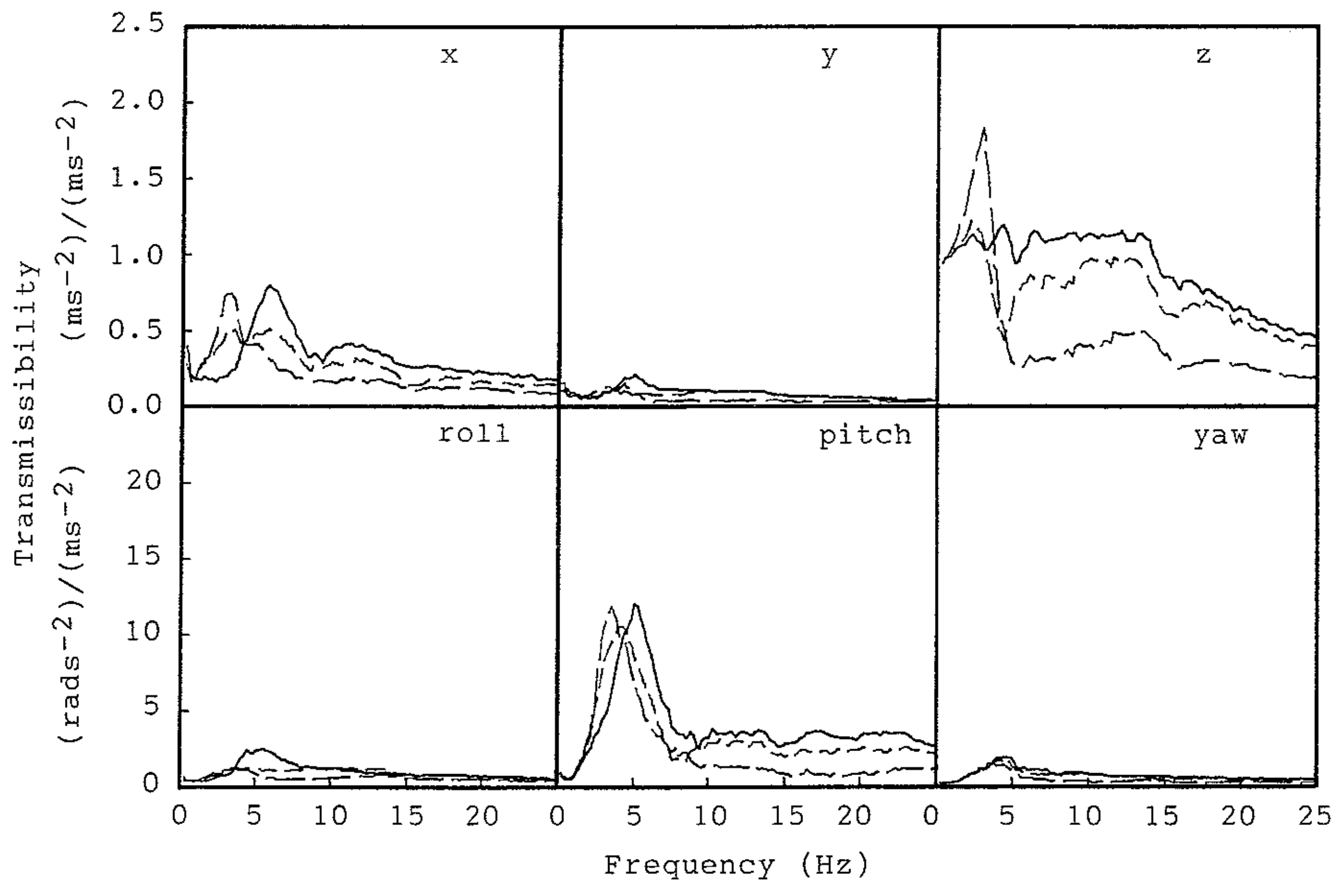


Figure 6.23 Median transmissibilities for 12 subjects in 'legs locked' (———), 'legs unlocked' (- - - -) and 'legs bent' (— — —) postures during vertical floor vibration.

It was seen from the pitch axis transmissibility curves that data for one subject deviated from others in the 'legs unlocked' and 'legs bent' posture (Figures 6.20 and 6.21 respectively). These data correspond to subject 2 (see Appendix 9) for individual subject characteristics) and a repeat experiment showed these to be genuine transmissibilities peculiar to that subject. This does show the very large variation in transmissibilities that can result between subjects. An example of this is a variation of 20:1 in the vertical axis transmissibility at 5.5 Hz for the subjects standing in a 'legs locked' posture shown in Figure 6.19.

The coherencies for these data showed low values for most axes except the vertical axis at the head. The sudden decrease in coherency seen for the vertical axis near 5 Hz is due to the transmissibilities being very low for some subjects. There is a trend in the vertical axis coherencies for the three postures of the legs: highest coherencies for the 'legs locked' posture and the lowest for the 'legs bent' posture.

Phase for the pitch axis at the head showed a slight lead at about 2 Hz for the three postures of the legs. This is possibly caused by active postural feedback of the body to counteract the forcing motion. Phase leads for this axis and similar frequencies were also seen for the intra-subject variability experiment (see Section 6.4.2.4).

6.4.4 Discussion and conclusions

Posture of the legs is obviously an important factor in the transmission of vertical vibration at the floor to the head, so this has been a variable in most of the investigations by other researchers. Coermann (1962) noticed that his subjects standing in an erect posture with 'stiff knees' produced two resonance peaks in the floor-to-head transmissibility curves for vertical motion at the head, one at 5 Hz and the other over the 12 Hz to 13 Hz frequency range. Data from this experiment are vaguely similar though distinct resonance peaks are not seen but unity transmissibility for vertical motion at the head up to about 12 Hz. In another experiment, Coermann (1962) found that when his subjects stood in a 'legs bent' posture, the first resonance peak occurred at a lower frequency and there was significant attenuation of vibration above about 2 Hz. Again, broad agreement is seen between this and his studies. Garg and Ross (1976) observed two main resonance frequencies for subjects standing in a normal stance, these were at 2 Hz and 6 Hz. This would correspond to a posture between 'legs locked' and 'legs unlocked' postures investigated for this study. A resonance peak only became clear in the 'legs unlocked' posture, this being at about 2 Hz and a broad peak over the 6 Hz to 12 Hz frequency range.

Rao et al. (1975) investigated the effect of leg posture on head motion transmissibility, the postures considered were 'standing erect with straight legs' and, the second, 'with knees bent so as to absorb the vibration'. They found that a knees bent posture showed only one resonance peak, and this was around 2 Hz to 3 Hz. Also, that vibration was greatly attenuated for frequencies above about 6 Hz. Similar conclusions can be made from the results of the present experiments.

There is only one known study in which head motion had been measured in other axes than the vertical axis, this was Kobayashi et al. (1981) where they found that at about 5 Hz, fore-and-aft axis transmissibility between vertical floor vibration was approximately unity. Data from this study showed transmissibilities of around 0.7 at about 6 Hz, this depending on the posture in which the subjects were standing.

It is seen from the transmissibilities for both intra- and inter-subject variability experiments that the variation in head motion between subjects was greater than that during repeat measures for one subject. The magnitude of spread is very much dependent on frequency, an example of this can be seen in the vertical axis transmissibility for the 'legs locked' posture for both the individual variability and repeatability studies. Also, the variation in transmissibility is different for the various axes of head motion.

Some differences were seen in head motion that could be directly attributed to the changes in posture of the legs and occurred mostly in the mid-sagittal plane axes. (Most of the motion at the head occurred in the mid-sagittal plane axes.) The data showed that there was a cross-over frequency in the vicinity of 4 Hz below which a 'legs bent' posture demonstrated the greatest head motion while least head motion occurred when standing in a 'legs locked' posture and, the situation was reversed for higher frequencies. The coherency between floor and head motion was found to deteriorate as posture changed from 'legs locked' to 'legs bent'.

A non-parametric measure of correlation (Kendall's tau) was calculated between head motion transmissibilities for the three leg postures and subject characteristics (age, weight and height), these were determined for all the axes of motion at the head. Subject age showed only a few significant correlations with head motion but these were only at specific frequencies which could be due to chance, with such a large number of frequency levels (0.25 Hz increment from 0.5 Hz to 25 Hz). No viable correlations were found between head motion in the 'legs locked' and 'legs bent' postures and subject weight and height. Significant positive correlations were observed with the subjects standing in a 'legs unlocked' posture between head motion in the fore-and-aft and pitch axes and subject weight and height. These were significant at the 5% level over the frequency range 9 Hz to 16 Hz for both axes and for both subject characteristics. Further analyses of the data using partial correlations showed height to be the important parameter.

6.5 DISCUSSION AND CONCLUSIONS

It is seen from all the experiments that variation in transmissibility between subjects was greater than that during repeat measures for a single subject. A quantitative example of this can be obtained with, for example, the variation in transmissibility response for vertical head motion during vertical floor vibration with the subjects standing in a 'legs locked' posture (i.e. Figures 6.14 and 6.19). At 6.0 Hz, the maximum response was 1.3 times greater than the minimum transmissibility for the intra-subject variability whereas the ratio was 10.7 for the inter-subject study. This example is for one frequency in one axis, greater variation might be found for transmissibilities in other axes (e.g. pitch axis head motion at 13.5 Hz with the subjects standing in a 'legs bent' posture during vertical floor vibration, see Figure 6.21). The volunteer who took part in the intra-subject variability experiments was the same person as that used for the seated subject experiments (see Chapter 5). The variation in transmissibility seen during repeat measures for this subject was typical of other subjects (see repeat measures in Section 6.4.3.5).

All data for the intra-subject variability experiments show that the twelve repeat transmissibility curves follow a particular definite underlying trend. There is small deviation from the 'average' curve for the repeat measures and all the individual peaks and troughs show through in the separate transmissibility curves. This is far from the case for the inter-subject variability data, all the subjects demonstrate a different transmissibility compared with the other subjects and when compared with the 'average' curve. This shows that each individual has their own distinct and unique 'transmissibility signature' which varies from time to time but adumbrates the general pattern and this is different compared with 'signatures' of other people.

Transmissibilities between fore-and-aft floor vibration and the six axes of motion at the head have shown that the head moves mostly in the mid-sagittal plane with significantly lower transmissibilities for the other axes. A main whole-body resonance was observed in the fore-and-aft axis at 1.2 Hz for the subjects standing with a rigid grip on the handrail and at 0.5 Hz when holding lightly. Overall, a rigid grip on the handrail resulted in significantly more motion at the head ($p<0.01$) in the mid-sagittal plane than the light grip posture. Motions in the vertical and pitch axes both showed broad resonance peaks at 2 Hz and 4 Hz.

Head motion occurred mostly below 3 Hz during lateral floor vibration for the lateral axis at the head. Transmissibilities for lateral axis head motion above 3 Hz were relatively small - of the same order as the other axes up to the maximum frequency investigated, i.e. 10 Hz. Lateral transmissibility data show that for frequencies below 1 Hz, a foot separation of 30 cm resulted in more head motion than a feet together posture while a foot separation of 60 cm transmitted greater motion to the head below 3 Hz than the other two postures. Higher transmissibilities occurred for all axes up to 10 Hz and for the lateral axis above 3 Hz when the subjects stood in a feet together posture than the other two separations of the feet. A slight increase in the frequency of the main body resonance is observed from 0.5 Hz for a feet together posture to 0.8 Hz for a foot separation of 60 cm.

A general shape of the transmissibility curves of head motion for standing subjects exposed to vertical floor vibration cannot be described since head motion is greatly affected by the posture of the legs. Overall, it can be said that head motion occurred mostly in the mid-sagittal plane axes with appreciably lower transmissibilities for the other directions, i.e. lower transmissibilities for the lateral, roll and yaw axes. The general trend in the effect of posture of the legs on head motion is that for motion in the fore-and-aft and pitch axes, a cross-over frequency appears at about 4 Hz below which a 'legs bent' posture results in the greatest transmissibilities and the least motion with a 'legs locked' posture; the case is reversed for frequencies greater than 4 Hz. There is a definite decrease in frequency of the main resonance peak as posture is changed from 'legs locked' to 'legs bent'. A cross-over region is seen to occur for vertical motion at the head: a 'legs locked' posture results in significantly more motion at the head than the other postures and a 'legs bent' shows the lowest transmissibility for frequencies greater than approximately 3 Hz to 5 Hz.

At very low frequencies (e.g. 0.25 Hz), it is seen from some figures (e.g. Figures 6.6 and 6.13) that very high transmissibilities were calculated for motion in the horizontal axes. This is thought to be associated with the accelerometers detecting the Earth's gravitational component. A horizontally pointing accelerometer will be more affected by gravity than a vertical accelerometer, this can be demonstrated as follows: assume an accelerometer is exposed to pure rotational motion and is placed at the centre of rotation. Then, the accelerometer will indicate a voltage corresponding to 9.81 ms^{-2} when its axis is in line with the Earth's gravitational field. However, if it is pointed at an angle of 6° away from the vertical, then the acceleration reading will be 9.76 ms^{-2}. This corresponds to a change of 0.51%. The same procedure can be applied to a horizontal accelerometer which will show 0 ms^{-2} with its axis horizontal and 1.02 ms^{-2} if its axis is deviated by 6° from the horizontal. Gravity is more likely to affect the signals at low frequencies than at high frequencies as greater rotations of the head would occur at low frequencies. It is worth noting that rotational signals calculated using the method employed (i.e. the difference in signals detected by two translational accelerometers) are not affected by the gravitational component since both accelerometers will be affected equally by gravity and the effect will be cancelled out when the difference in the signals is calculated.

In all the different vibration exposures and postures, apart from the rigid grip posture during fore-and-aft vibration, the subjects were instructed to hold the handrail only lightly and this only to stop themselves from falling. It was observed that all subjects used the handrail for support during fore-and-aft vibration with the light grip posture. During lateral floor vibration, all subjects found it necessary to use the handrail when standing in a feet together posture while all subjects commented that they did not have to use the handrail when standing with foot separations of 30 cm and 60 cm. During vertical vibration of the floor, postural support was generally not required but was found to be necessary for some of the large vertical displacements of the vibrator platform.

This chapter has presented new data from several experiments investigating the transmission of translational floor vibration to the head. Some comparisons have been made with previously reported results concerned with floor-to-head transmission of vibration and these have been either old studies or investigations that required confirmation, some studies (concerned mostly with vertical floor vibration) have been confirmed by these experiments. However, since only one study was found in a literature search dealing with the transmission of horizontal floor vibration to head, the data in this chapter are original and present the fundamental findings on the behaviour of the human body to such motions. Results from this chapter could provide subject matter for further experimental research in this field and help in the development of biodynamic models of the human body.

CHAPTER 7

HEAD MOTION IN A MILITARY VEHICLE

7.1 INTRODUCTION

In various studies motion has been measured simultaneously at both the seat and the head and some measure of body transmissibility has been determined. Laboratory studies have often involved a single axis of vibration so that head motion at each frequency can be expressed as a fraction of the input motion at the same frequency or as a fraction of the input motion with which it is linearly correlated. Whether it is single-axis or multi-axis motion of the seat, it can be carefully controlled in laboratory based experiments. Outside the laboratory, there is usually more than one axis of vibration at the input (usually six axes: three translational and three rotational) and additional calculations are required before the causes of head motion in any axis can be determined.

As an unrestrained head is free to move in any of the six axes of motion, the question that arises is "Which motion at the seat causes motion in which axes at the head?" The answer to such a question would be of value to designer whose aim may be to reduce head motion in a particular axis. No studies are known of where attempts have been made to provide answers to such a question.

This chapter aims to answer the above question by reporting of simultaneous measurements made of seat and head motion of a subject seated in a military vehicle during a rough cross-country ride. Spectral analyses that have not previously been used to determine the transmission of seat vibration to the head has been employed to explain the results. Data presented in this chapter have been published elsewhere (Paddan, 1985, 1986).

7.2 TRANSLATIONAL SEAT AND HEAD VIBRATION MEASUREMENTS

7.2.1 Introduction

The first stage in trying to correlate seat and head motion is to decide exactly what form the measurements should take. It is no use making head motion measures on a laboratory based single-axis motion simulator since this would result in a single-input system and only limited analyses can be conducted providing only the minimum of information. Simultaneous measurements of both seat and head motion were required and this, in an environment or vehicle which would induce significant magnitudes of vibration in all the axes. It was decided that a military vehicle traversing over rough terrain would suit the purpose.

There are six axes at the seat and the head which could be investigated. Gathering such large quantities of data would have been no easy task. Also, the next step which would have been the analyses would have been complicated. So, for this set of measurements, accelerations in only the translational axes (i.e. fore-and-aft, lateral and vertical) at the seat and the head were measured.

This section compares the various alternative methods of relating seat vibration to the head motion in a complex vibration environment and attempts to find the axes of seat motion which are responsible for the dominant movements at the head.

7.2.2 Apparatus and procedure

Vibration measurements of the seat and the head were made in an off-road tracked military Armoured Fighting Vehicle (AFV). Measurements were made in the gunner's seat while the vehicle traversed over a rough cross-country course during a run which lasted approximately 11.5 minutes. The removable backrest on the gunner's seat was not fitted for these measures. The driver was instructed to drive the vehicle in a 'normal manner'. Figure 7.1 shows the relative positions of the various seats within the vehicle. The main armament on the vehicle was locked in a rearward facing position (i.e. the same direction in which the subject faced).

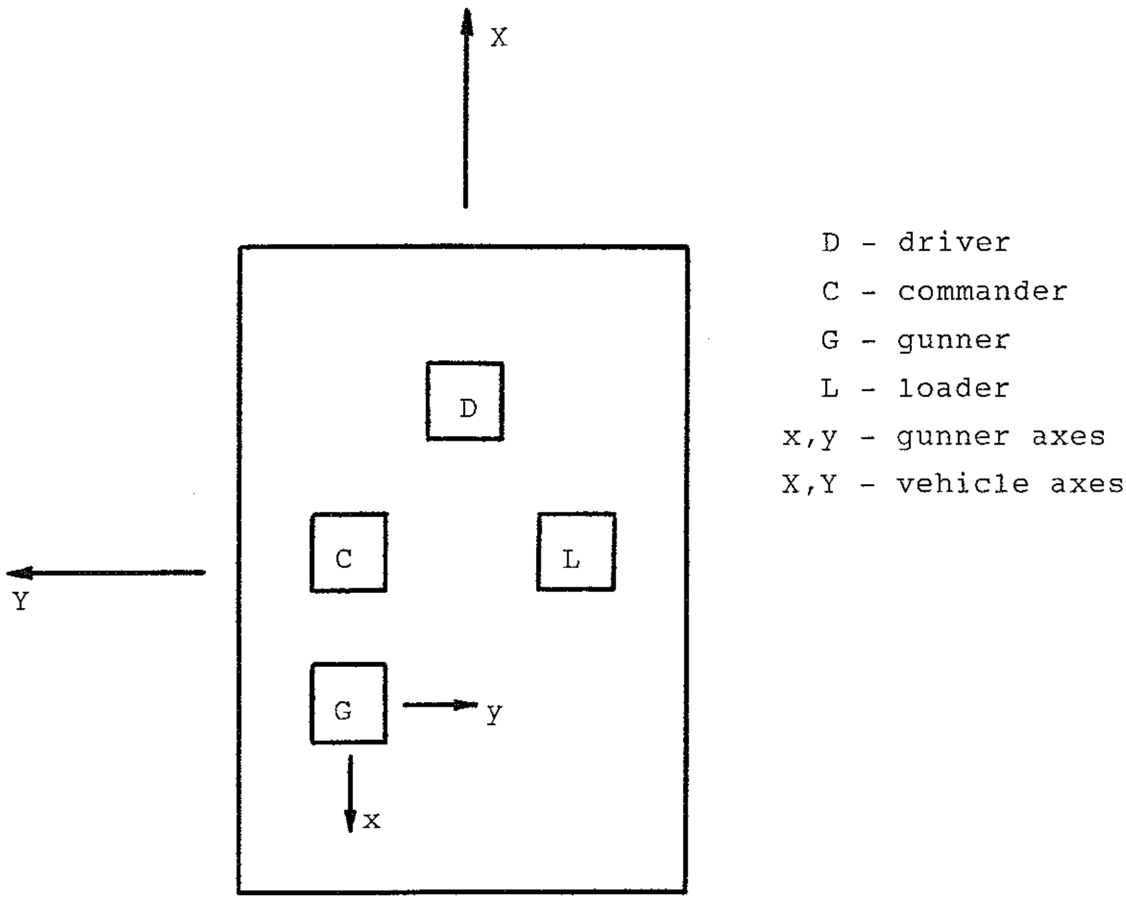


Figure 7.1 Positions of crew within the AFV.

Motion in the three translational axes at the seat was measured using a semi flexible pad containing three triaxially mounted translational piezo-resistive half-bridge Endevco type 2265-M15 accelerometers (see SAE, 1974). Head motion was measured using a bite-bar designed to monitor six axes of motion (see Section 3.2). Only translational head motion was considered in this investigation. The bite-bar weighed 135 g and had translational piezo-resistive full-bridge Entran type

EGAX±5 accelerometers. The bite-bar had a personal sterilised dental mould for the subject. The measurements reported here are for motion 100 mm to the left of the mid-sagittal plane adjacent to the mouth. The subject was instructed to maintain his line of sight towards the viewing sight and to avoid voluntary movements of the head. For safety purposes, the subject was told to spit out the bite-bar in an emergency. The subject wore an AFV crewmans helmet.

Signals from the accelerometers were passed through signal conditioning amplifiers and recorded on a 7-channel TEAC R-71 portable data cassette recorder. The data were subsequently digitised into a PDP11-34 computer system.

Subjects

A male subject of 24 years of age, weighing 77 kg and 1.79 m tall sat in the gunner's seat of the vehicle. He was a member of the University technical staff.

Analyses

Acceleration signals recorded in the vehicle were replayed and low-pass filtered at 25 Hz using 48 dB/octave anti-aliasing filters before being digitised at a sample rate of 64 samples per second. The subsequent analyses was conducted at a frequency resolution of 0.25 Hz which gave 688 degrees of freedom.

Data have been analysed using four different methods, two involving the determination of transmissibility between seat and head motion and, for the other two, the calculation of coherencies. The first set of transmissibilities were obtained using the 'power spectral density function method', the second set were calculated using the 'cross-spectral density function method'. Both ordinary coherencies and partial coherencies were calculated for all data, the latter method providing further information about the 'cause and effect' of a multi-input single-output system. These analyses are explained in detail in Chapter 4.

Further analyses were conducted to obtain the relative proportions of correlated and uncorrelated motion at the head by considering the body as a three-in one-out system. By assuming the three inputs to be $x_1(t)$, $x_2(t)$, $x_3(t)$ and output $y(t)$, four power spectra were determined of motion in various axes at the head, these being:-

i) Power spectrum of total head motion in one axis ($G_{yy}(f)$),

ii) Power spectrum of linearly correlated motion between the same seat and head axes ($\gamma^2_{x_1 y}(f)\ G_{yy}(f)$),

iii) Power spectrum of linearly correlated motion between the same seat and head axes after conditioning head motion for the other two seat axes ($\gamma^2_{x_1 y \cdot x_2 x_3}(f)\ G_{yy \cdot x_2 x_3}(f)$),

iv) Power spectrum of uncorrelated motion at the head conditioned for all the axes at the seat, i.e. noise ($G_{yy \cdot x_1 x_2 x_3}(f)$).

A full explanation of these terms is included in Appendix 2.

7.2.3 Results

Power spectral densities of the vibration measured over 11.5 minutes (688 degrees of freedom) are shown in Figure 7.2. It is seen that for motions at the seat, most of the energy is at low frequencies, with vertical motion showing the greatest energy and lateral motion the least. The overall acceleration magnitudes for the seat motions were 1.65 ms^{-2}, 1.38 ms^{-2} and 1.97 ms^{-2} r.m.s. for the x-, y- and z-axes respectively. For head motion power spectral densities, the fore-and-aft acceleration signal is greatest at frequencies below 0.4 Hz while vertical motion shows the highest energy content above 0.4 Hz. The respective overall acceleration magnitudes for x-, y- and z-axes at the head were 2.36 ms^{-2}, 1.39 ms^{-2} and 1.93 ms^{-2} r.m.s. From Figure 7.2, it is clear that high frequencies were attenuated by the body and only low frequencies were transmitted to the head.

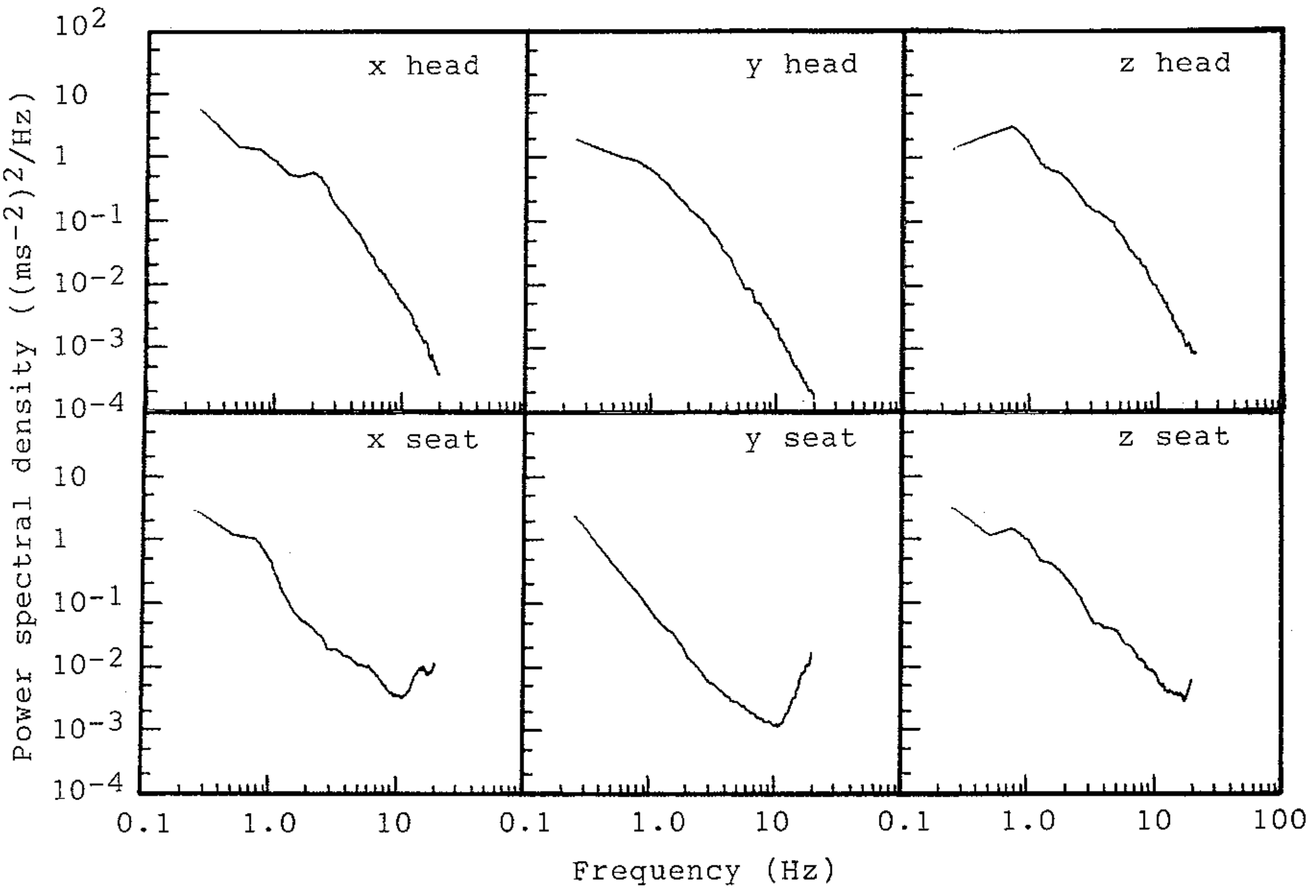


Figure 7.2 Power spectral densities of accelerations in the translational axes at the gunner's head and the seat in an AFV. (Resolution = 0.25 Hz, degrees of freedom = 688)

For direct comparison, transmissibilities between the three translational seat axes and the three head axes calculated using the 'power spectral density function method' and the 'cross-spectral density function method' are shown in Figure 7.3. The higher transmissibility curves are for the 'power spectral density function method' since this includes all of the energy content of the output signal while the 'cross-spectral density function method' takes into account only the proportion that is linearly correlated.

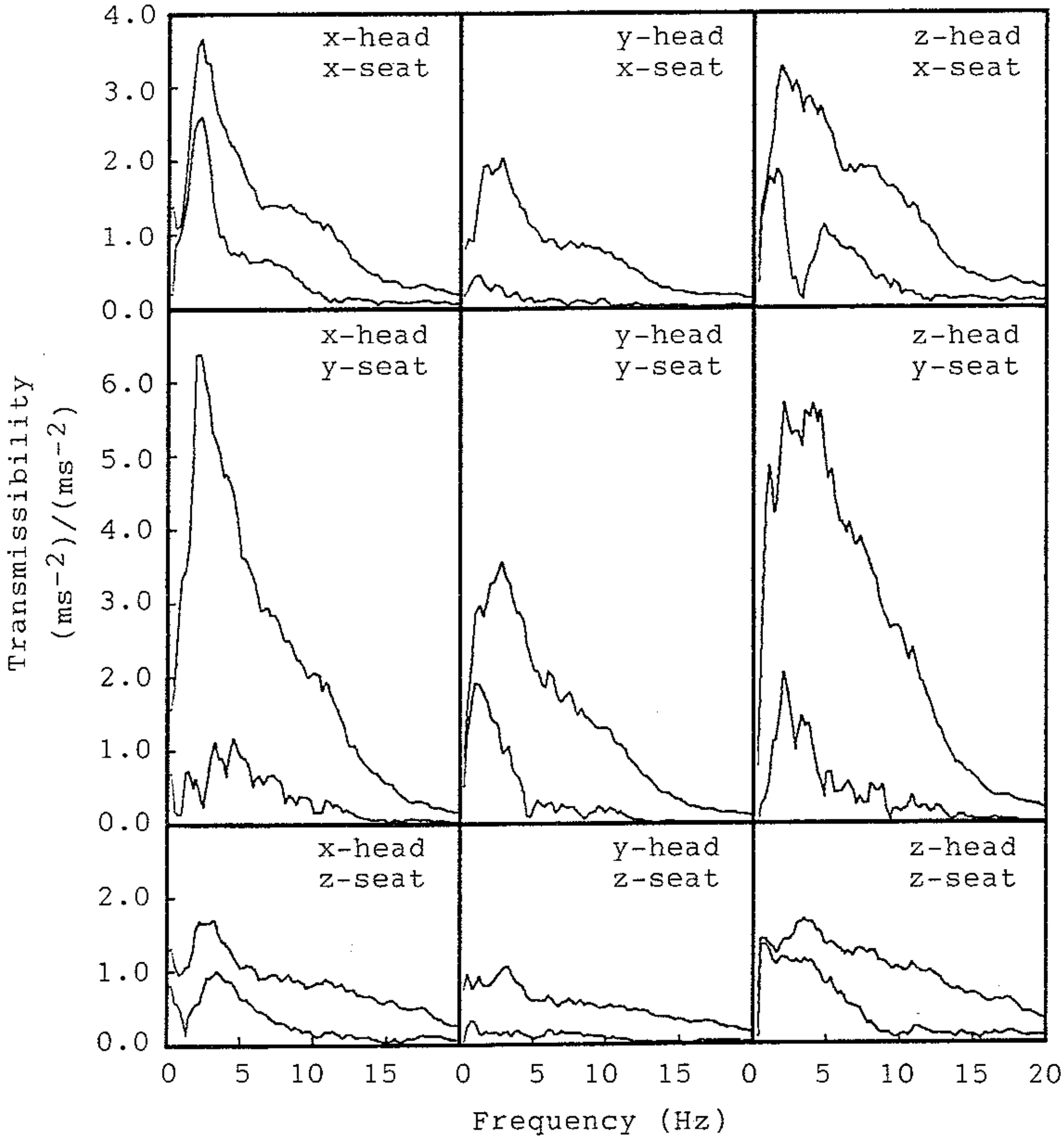


Figure 7.3 Transmissibilities between seat and head motion in the translational axes using the power (higher curve) and cross-spectral density function methods (lower curve). (Resolution = 0.25 Hz, degrees freedom = 688)

Ordinary coherencies between the three translational axes at the seat and three at the head are shown in Figure 7.4. An indication of the amount of correlation between seat and head motion is given by these figures. Transmissibilities calculated using the 'cross-spectral density function method' can be partly explained by using these coherencies. These do not exclude the effect of motion in other axes at the seat on head motion in a particular axis, e.g. the coherency between vertical seat motion and vertical head

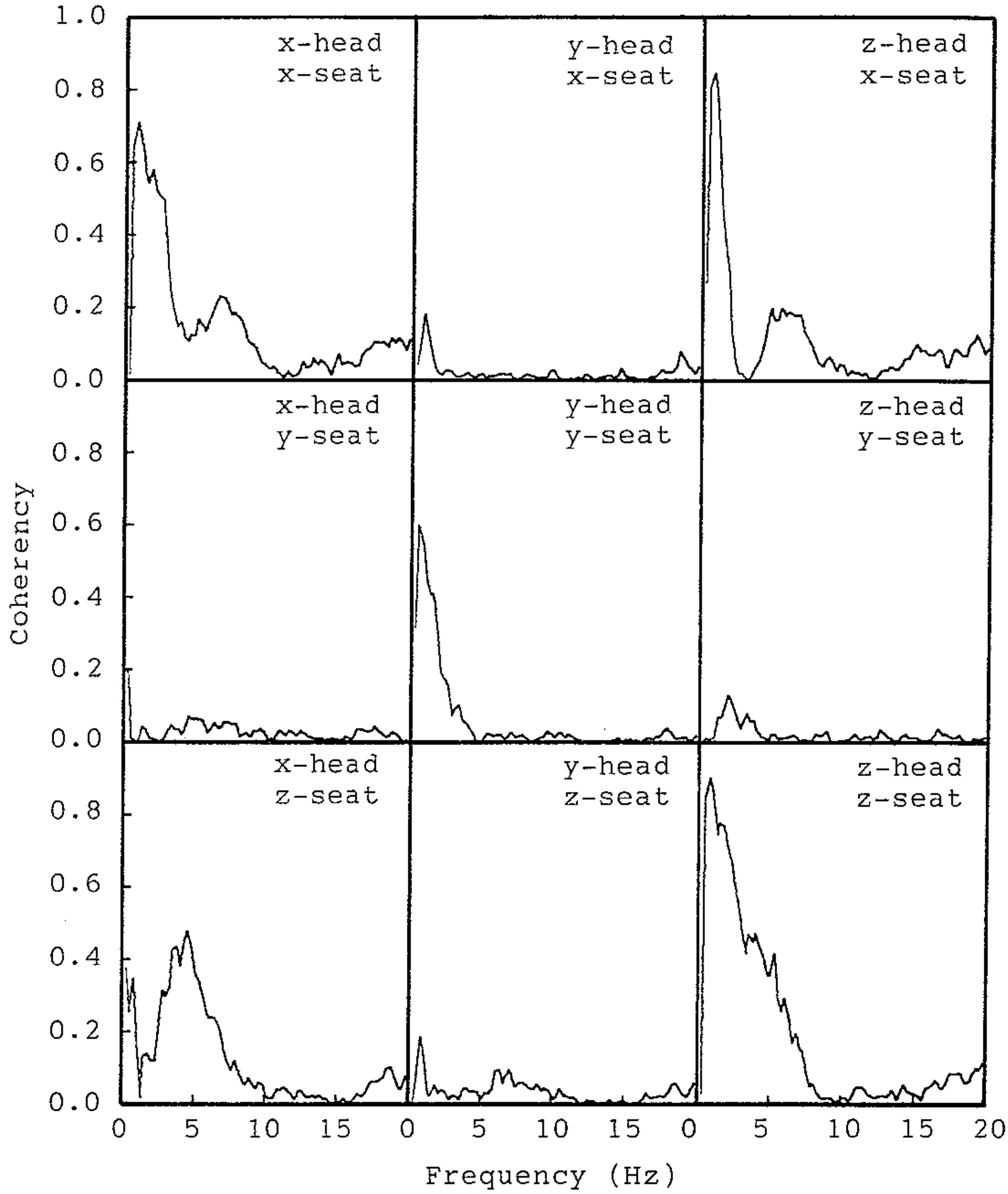


Figure 7.4 Ordinary coherency curves between translational motions at the seat and the head during an AFV ride. (Resolution = 0.25 Hz, degrees of freedom = 688)

motion will also include some of the effect fore-and-aft and lateral motion at the seat had on vertical head motion. In order to 'subtract' the effect of motion in other axes at the seat on head motion in one particular axis, partial coherencies were calculated, these are shown for the data in Figure 7.5. These can be used to determine the proportion of motion at the head in a particular axis caused directly by vibration in one axis at the seat, so Figures 7.3 and 7.5 are best considered together.

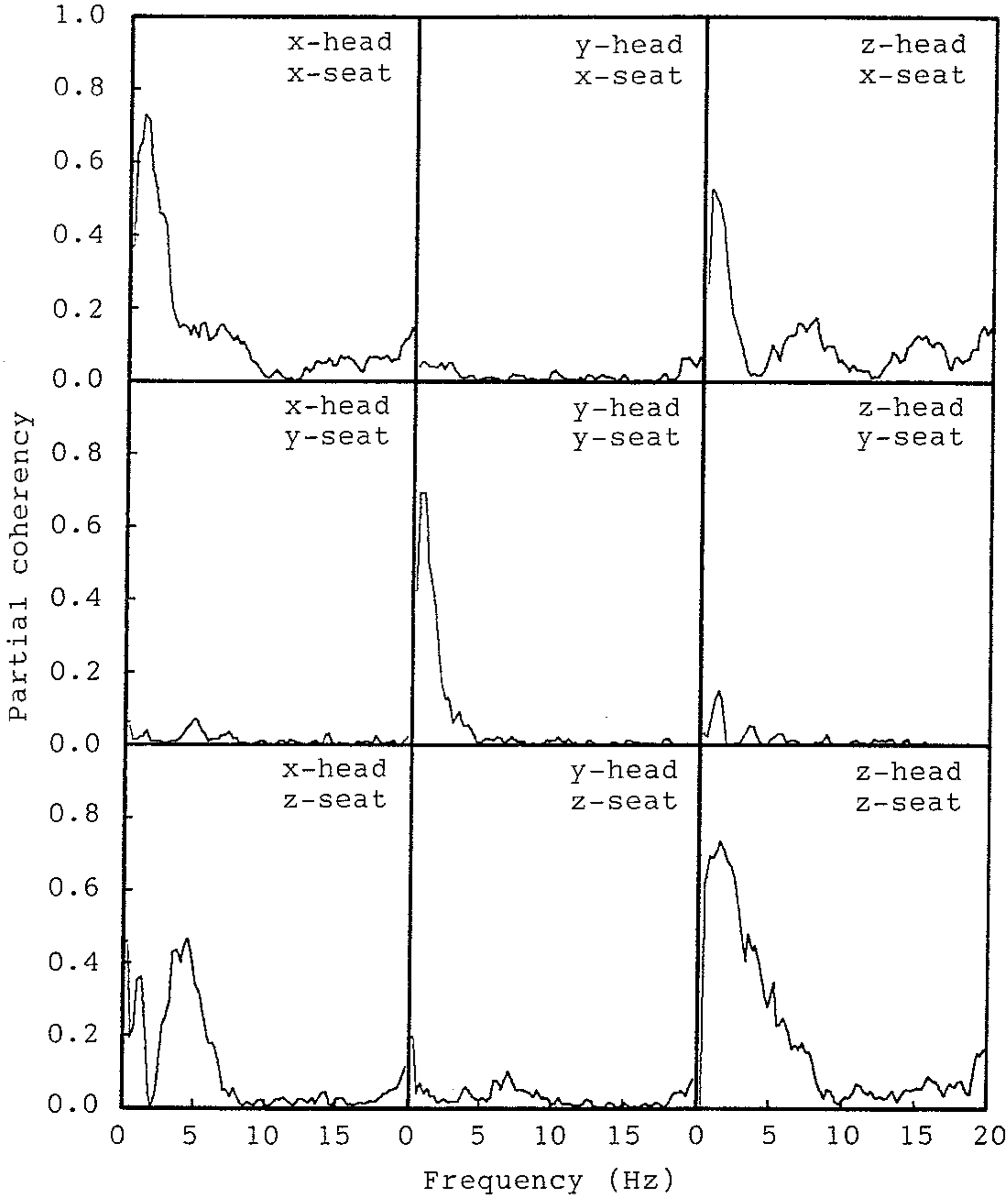


Figure 7.5 Partial coherency curves between translational motions at the seat and the head during an AFV ride. (Resolution = 0.25 Hz, degrees of freedom = 688)

7.2.4 Discussion

Direct comparisons between the transmissibilities using the two different methods can be made by comparing transmissibilities shown in Figure 7.3. Consider the transmissibilities between x-seat and x-head: they are approximately of the same shape and magnitude indicating that, for this axis, most of the motion at the head is linearly correlated with seat motion. A completely different result emerges from the transmissibilities between y-seat and x-head: the large difference between the two methods suggests that only a small amount of x-head motion is linearly correlated with y-seat motion. The proportion of head motion not linearly correlated may be partly due to cross-axis coupling and due to voluntary movements of the head. Transmissibility curves between z-seat and x-head indicate that correlation between the axes is high. From these three comparisons, x-seat and/or z-seat axes appear to be the dominant causes of x-axis motion at the head.

Comparisons between the two methods for y-axis head motion and x-, y- and z-axis seat motion show that most of the lateral motion at the head is linearly correlated with y-axis seat motion, so most of the lateral head motion was caused by lateral seat motion.

Almost the same reasoning as that for x-axis head motion can be applied to the transmissibilities between z-axis head motion and translational seat motions. Vertical motion at the head is mostly caused by x-axis and/or z-axis seat motion. Cross-axis coupling is again seen.

Ordinary coherencies for these data shown in Figure 7.4 give an indication of the correlation between seat and head motion for the various axes. Data in Figure 7.5 provide further evidence of the coherencies and these data are free from effects of other axes. An example of the difference between the ordinary and partial coherencies can be seen by comparing, say coherencies between vertical head motion caused by fore-and-aft seat vibration. Ordinary coherencies show a value of about 0.78 at 1 Hz and approximately 0.17 at 5 Hz; partial coherencies show the 'better' approximations and these as 0.50 at 1 Hz and 0.08 at 5 Hz. Therefore, although ordinary coherencies provide reasonable data for single-input systems (and as a first approximation for a multi-input system), partial coherencies would be required for a detailed explanation.

Consider the three partial coherencies between x-axis head motion and translational seat motions: x-seat, x-head shows a large value in the 1 Hz region compared with the coherencies between y-seat, x-head and between z-seat, x-head. This indicates that the transmissibility curve for x-seat, x-head in Figure 7.3 near this frequency is mostly caused by x-axis seat motion. The same logic applies to z-seat, x-head; the partial coherency near this frequency region for y-seat, x-head is comparatively low implying that x-axis head motion is mostly caused by x- and z-axis seat motion. Though the transmissibility curve for y-seat, x-head is seen to be approximately the same shape and magnitude as z-seat, x-head, the partial coherency indicates that virtually no x-axis head motion is caused by y-axis seat motion.

Comparing the partial coherencies between the various seat axes and y-axis motion at the head, it is seen that the only coherent motion is between the y-axis at the seat and the y-axis at the head, and this is only at around 0.5 Hz. This confirms the implication in Figure 7.3 that y-axis head motion is mostly caused by y-axis seat motion.

Broadly similar curves were seen for the three seat axes from the transmissibility curves between motion in the translational seat axes and z-axis motion at the head suggesting that z-axis head motion was caused by motion in all the seat axes in approximately similar proportions. The partial coherencies show different information disclosing that x- and z-axis seat motion caused vertical head motion whereas y-axis seat motion hardly affected z-axis head motion. From this, it is clear that z-axis motion at the head was a result of a combination of x- and z-axis seat motion.

Figure 7.6 shows power spectral densities of the three axes of head motion after various stages of conditioning, that is:

i) total head motion,

ii) motion linearly correlated with vibration in the same axis at the seat and no conditioning for vibration in the other axes at the seat,

iii) motion linearly correlated with vibration in the same axis at the seat after conditioning for vibration in the other two axes at the seat and,

iv) motion not correlated with vibration in any of the measured seat axes, i.e. remnant motion after conditioning for all three axes at the seat.

Considering the axes separately, spectra for the fore-and-aft axis show that noise (uncorrelated data) dominated the fore-and-aft motion at the head over all the frequency range except 0.4 Hz to 2 Hz. Over this frequency range, motion at the head in the fore-and-aft axis showed that it was likely to have been caused by fore-and-aft seat vibration near the 1.5 Hz frequency while in the lower frequency region, motion in the other axes at the seat (i.e. lateral and vertical) could well have caused motion in this axis at the head.

Power spectral densities for motion in the lateral axis at the head show that over the frequency range 0.4 Hz to 1 Hz, a high correlation existed with vibration in the lateral axis at the seat. Since the linearly correlated and the conditioned linearly correlated motion spectra over the frequency range shown are very similar, this suggests that neither fore-and-aft nor vertical axis motion at the seat caused lateral axis motion at the head. This is in agreement with the partial coherency data.

Figure 7.6 shows quantitative data whereas the coherencies are qualitative and since a similar route was used for calculating both coherencies and power spectra, similar conclusions would emerge from these data. Spectra for motion in the vertical axis only go to confirm the previously discussed results - over the frequency range

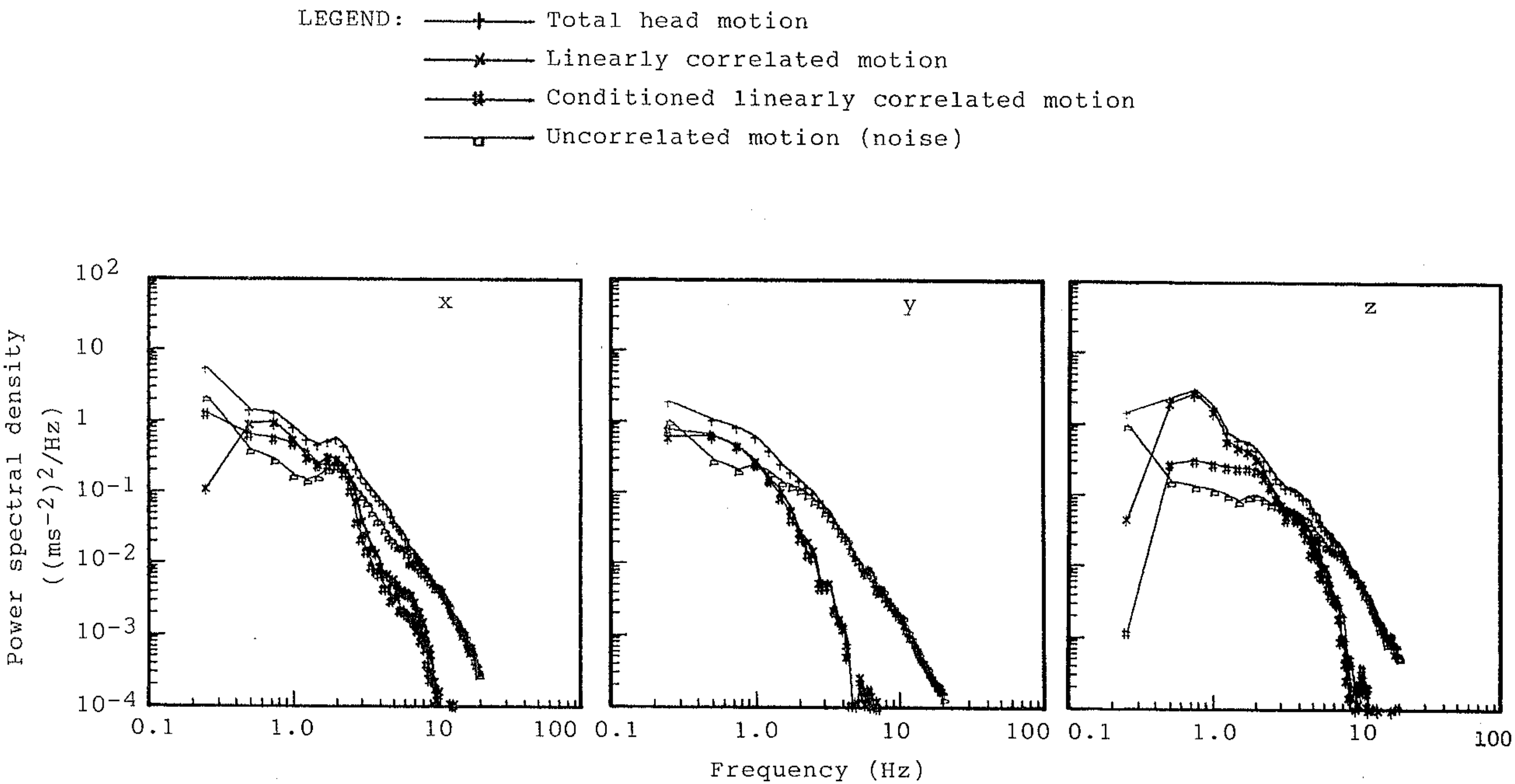


Figure 7.6 Various power spectral densities of seat and head motion in the translational axes. (Resolution = 0.25 Hz, degrees of freedom = 688)

0.5 Hz to 3 Hz, vertical motion at the head was caused mostly by a combination of fore-and-aft and vertical vibration at the seat. Once again, it is seen that noise dominates head motion above about 4 Hz.

In these data, it is seen that the remnant spectra have dominated some of the motion at the head. This noise spectrum is left over after the effect of seat vibration in the fore-and-aft, lateral and vertical axes has been subtracted from head motion. Vibrations in the rotational axes (roll, pitch and yaw) at the seat were not measured and these might have had an effect on the remnant spectra. Ideally, vibration in the rotational axes should be measured and accounted for in calculating the noise spectra. Then the noise spectrum would be better approximation of the uncorrelated vibration; this would include voluntary movements of the head caused by the subject.

So, finally it has been shown that fore-and-aft and vertical motion at the head was mostly caused by a combination of fore-and-aft and vertical vibration at the seat. Head motion in the lateral axis was caused mostly by lateral vibration at the seat.

7.3 SEAT AND HEAD VIBRATION MEASUREMENTS IN ONE PLANE

7.3.1 Introduction

The previous section involved the simultaneous measurement of translational vibrations at the seat and the head to establish the possible 'cause and effect' of vibration at the two locations. By using the different methods of analyses, it was found that fore-and-aft and vertical motion at the head was mostly caused by a combination of fore-and-aft and vertical vibration at the seat and that, lateral motion at the seat was mainly responsible for lateral motion at the head.

This section takes the topic a step further by considering motion of both the seat and the head in two different planes: the mid-sagittal plane (x-z plane) and the mid-coronal plane (y-z plane). Motion in the two translational axes and the included rotational axis was measured in each plane. Estimates are made of the proportion of head motion caused by motion in a particular axis at the seat and the amount of motion at the head that cannot be accounted for by seat motion.

7.3.2 Apparatus and procedure

Seat and head motion measurements were made of a subject seated in the gunner's seat in an off-road tracked military Armoured Fighting Vehicle traversing over a rough cross-country course. The seat had a compliant padded seat surface and no backrest. The main gun of the vehicle was locked in a backward pointing position and the subject sat facing towards the rear of the vehicle. (The relative positions of the seats within the vehicle are shown in Figure 7.1 in Section 7.2.2.)

Motion of the head was monitored using an instrumented bite-bar which the subject gripped in his teeth. Accelerations were measured using Endevco (type 2265-20) piezo-resistive translational accelerometers mounted on the bite-bar. The total weight of the bite-bar was 81 g. A SIT-BAR developed by Whitham and Griffin (1977) was modified and used to monitor vibration at the seat surface. The modified SIT-BAR had full-bridge strain gauge type translational accelerometers manufactured by Entran (type EGAX5). Accelerometers at both the seat and the head were orientated and located to measure translational and rotational accelerations in the required axes of motion.

Acceleration signals from all the accelerometers were passed through signal conditioning amplifiers and then recorded on to a portable 7 channel TEAC R-71 data cassette recorder.

Two runs were made on the cross-country course, each one lasting 8 minutes 30 seconds. In the first run, accelerations at the seat and the head were measured in the mid-sagittal plane, i.e. x-, z- and pitch axes. Motion in the mid-coronal plane axes (i.e. y-, z- and roll axes) was recorded during the second run.

The subject was instructed to maintain a normal body posture and a forward facing head position. He was asked to avoid voluntary movements of the head and not to restrain himself against the inside of the vehicle except in the event of a possible impact between his helmeted head and the vehicle.

Subjects

A male University worker took part in these measurements. He was 20 years old, height 1.73 m and weight 60 kg.

Analyses

Data were transferred on to a digital computer via 48 dB/octave anti-aliasing filters set at 25 Hz and sampled at 64 samples per second. Spectral analyses were carried out with a frequency resolution of 0.25 Hz which gave 508 degrees of freedom. Data up to only 20 Hz are considered.

Data have been analysed using similar methods to those employed in Section 7.2.2 to obtain two different transmissibilities and coherencies. These are:-

i) Transmissibility using the 'power spectral density function method',

ii) Transmissibility using the 'cross-spectral density function method',

iii) Ordinary coherency and,

iv) Partial coherency.

These various terms have been obtained for the mid-sagittal plane and the mid-coronal plane axes at the seat and the head.

Four power spectra have also been calculated for each axis of measurement at the head showing the relative proportions of correlated and uncorrelated motion at the head. (See Chapter 4 and Section 7.2.2 for further details.)

7.3.3 Results

Motion in the two planes is considered separately. Results of the different analyses are presented for the relationships between the three seat and the three head axes in each plane.

7.3.3.1 Mid-sagittal plane motion

Power spectral density functions of acceleration in the x-, z- and pitch axes at the seat and the head are shown in Figure 7.7. Fore-and-aft and vertical axes at the head display more motion than at the seat for frequencies below about 6 Hz, while the reverse is true for higher frequencies. This demonstrates that the body attenuates high frequencies. The pitch axis data show that there is a larger energy content at the head than at the seat for frequencies greater than 1 Hz. The acceleration magnitudes for these motions were 1.27 ms^{-2} r.m.s., 1.36 ms^{-2} r.m.s. and 1.78 $rads^{-2}$ r.m.s. at the seat and 1.45 ms^{-2} r.m.s., 1.69 ms^{-2} r.m.s. and 5.73 $rads^{-2}$ r.m.s. at the head in the x-, z- and pitch axes respectively.

Transmissibilities using the two spectral density function methods between the three seat and the three head axes are shown in Figure 7.8. As the 'cross-spectral density function method' takes into account only the linearly correlated proportion of the motion, it is always equal to or less than that obtained by the 'power spectral density function method'. The difference between the curves gives an indication of the amount of motion at the head that is

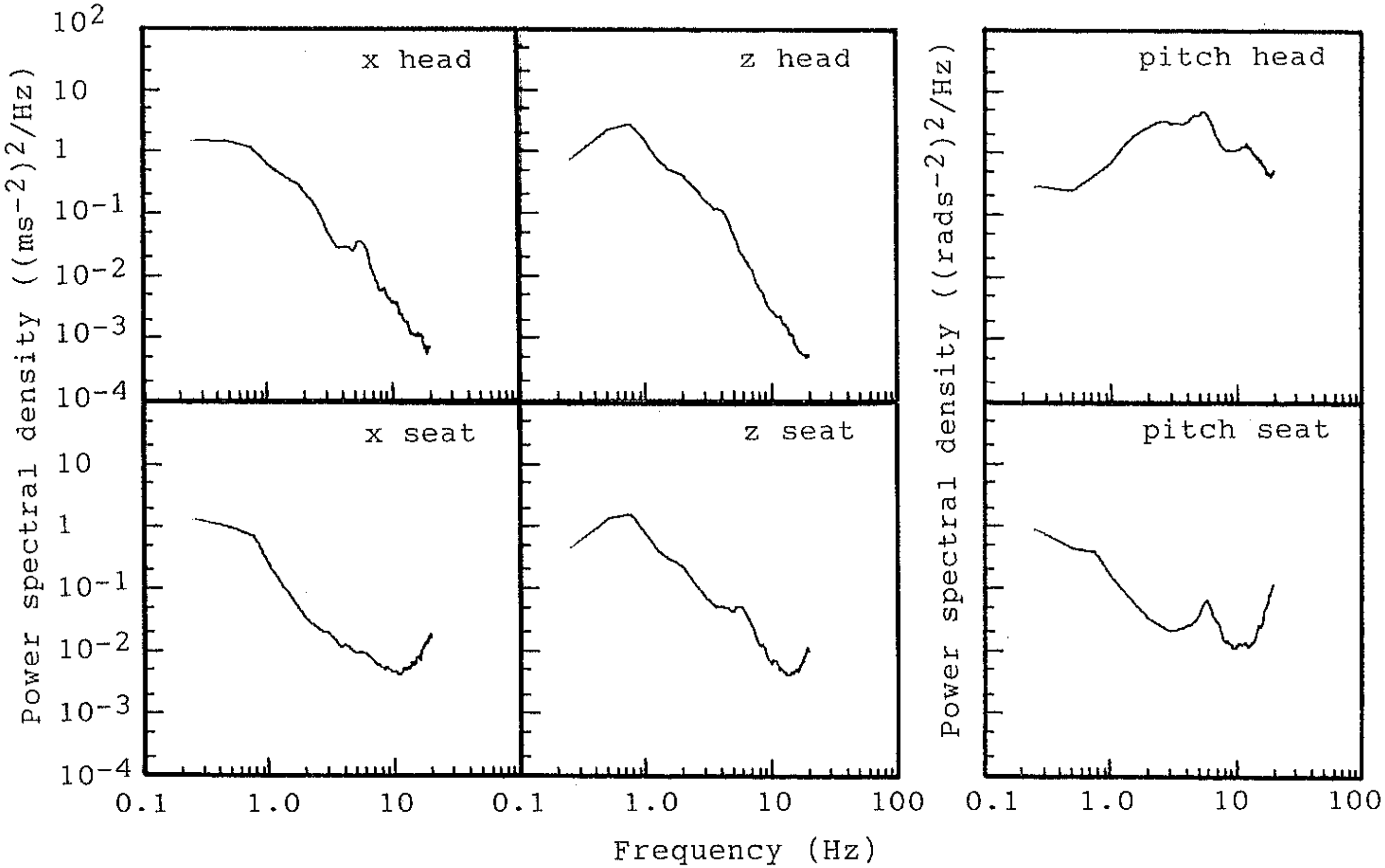


Figure 7.7 Power spectral densities of accelerations in the mid-sagittal plane at the gunner's head and the seat in an AFV. (Resolution = 0.25 Hz, degrees of freedom = 508)

not linearly correlated with the motion in the same axis at the seat. For example, consider the x-axis seat to x-axis head transmissibilities: a very large difference is seen showing that only a small amount of motion is linearly correlated between these two axes. Small differences between the z-axis seat to z-axis head transmissibilities suggest that for frequencies below about 5 Hz, most of the z-axis head motion is linearly correlated with z-axis seat motion.

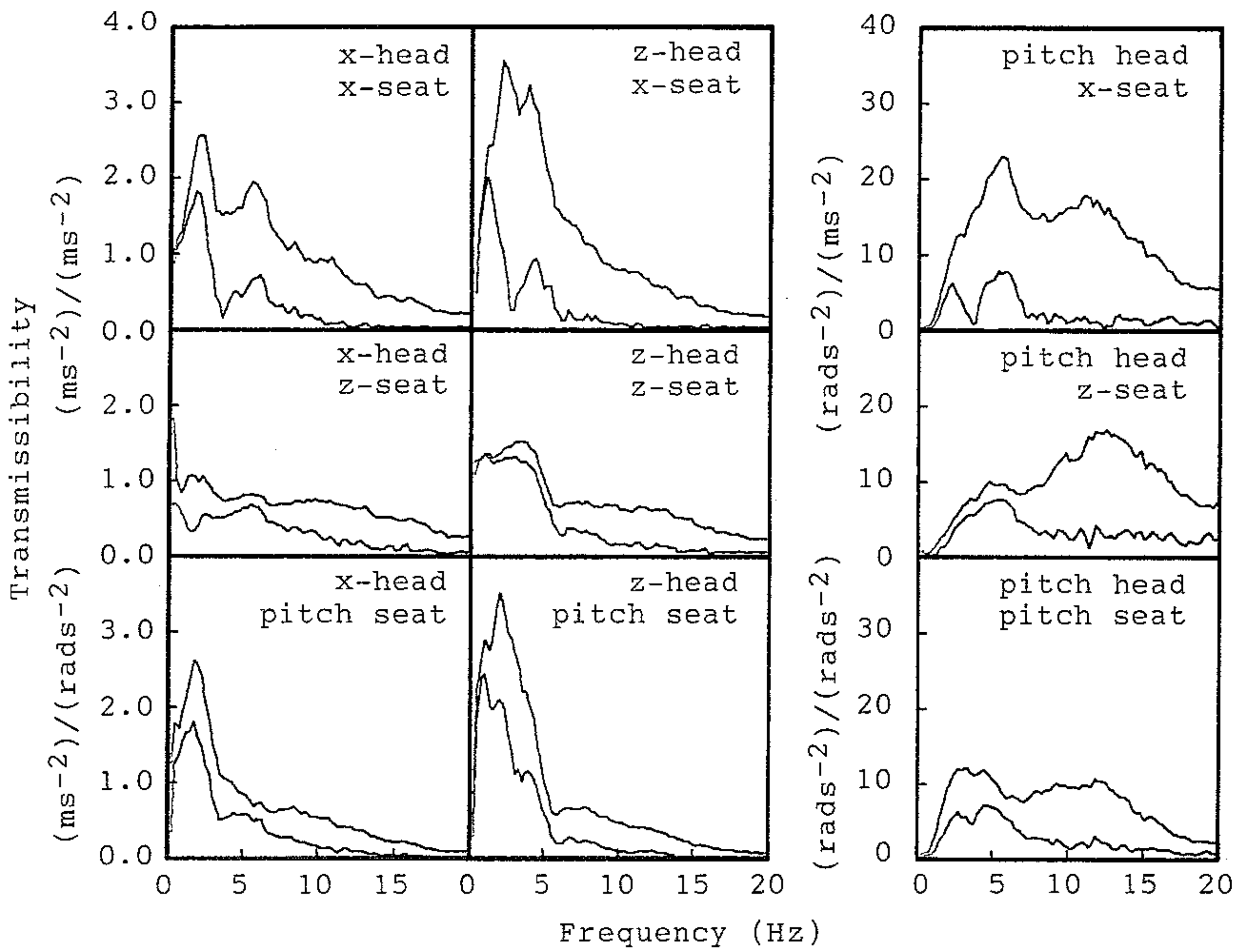


Figure 7.8 Transmissibilities between seat and head motion in the mid-sagittal plane using the power (higher curve) and cross-spectral density function methods (lower curve). (Resolution = 0.25 Hz, degrees of freedom = 508)

Ordinary and partial coherencies between the various seat and head axes are presented in Figures 7.9 and 7.10 respectively. Generally, partial coherencies are smaller than ordinary coherencies, though there may be exceptions; in all these graphs, partial coherencies are lower. The

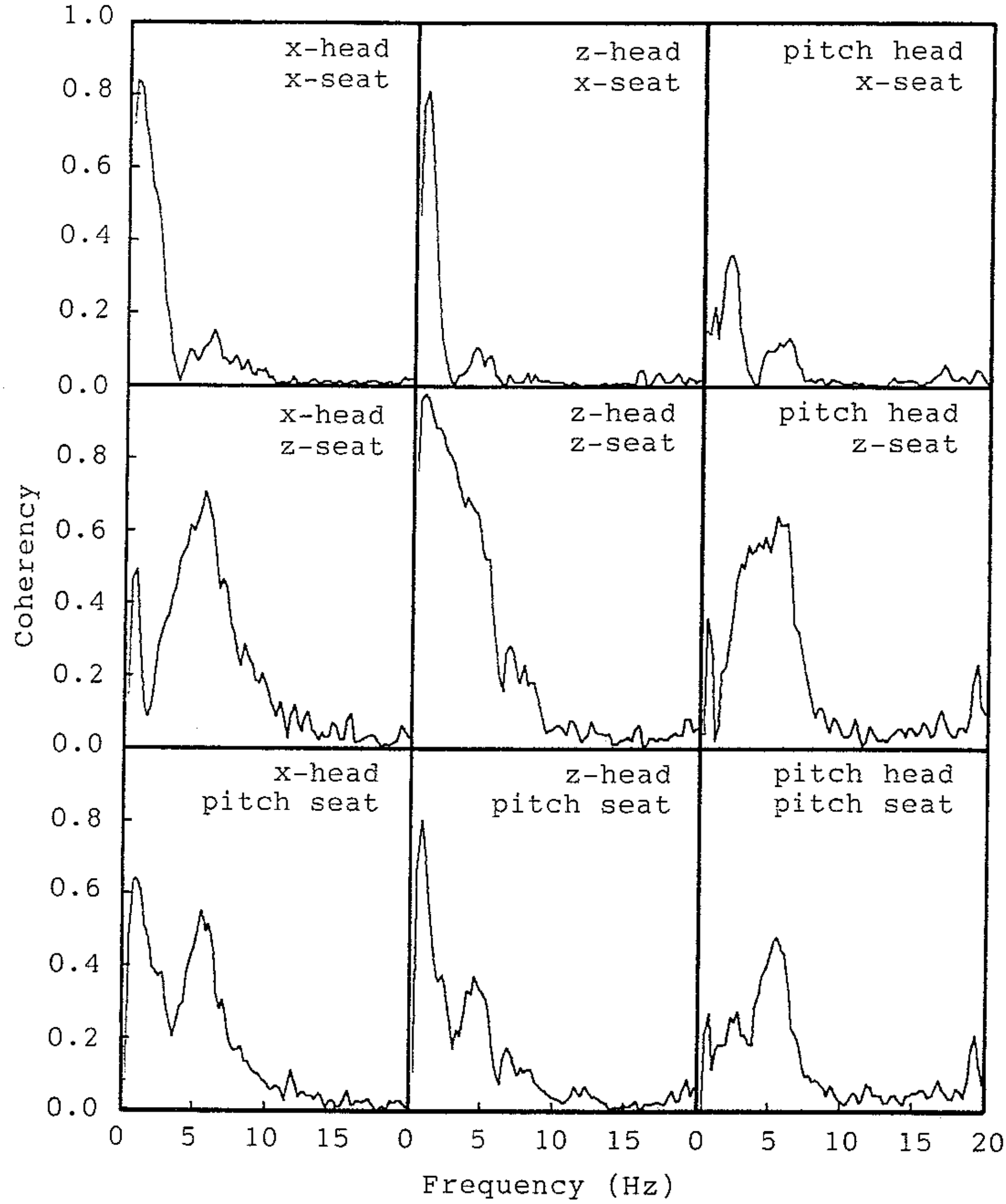


Figure 7.9 Ordinary coherency curves between motions in the mid-sagittal plane at the seat and the head during an AFV ride. (Resolution = 0.25 Hz, degrees of freedom = 508)

partial coherency is calculated after the effect of other seat axes has been subtracted from the motion at the head.

Figures 7.8 and 7.10 are considered together as the partial coherencies further explain and confirm data obtained from the transmissibilities. Fore-and-aft motion at the head below 1 Hz is mostly caused by x-axis seat motion. For frequencies higher than 2 Hz, the x-axis head motion was caused more by the z-axis seat motion the x-axis seat

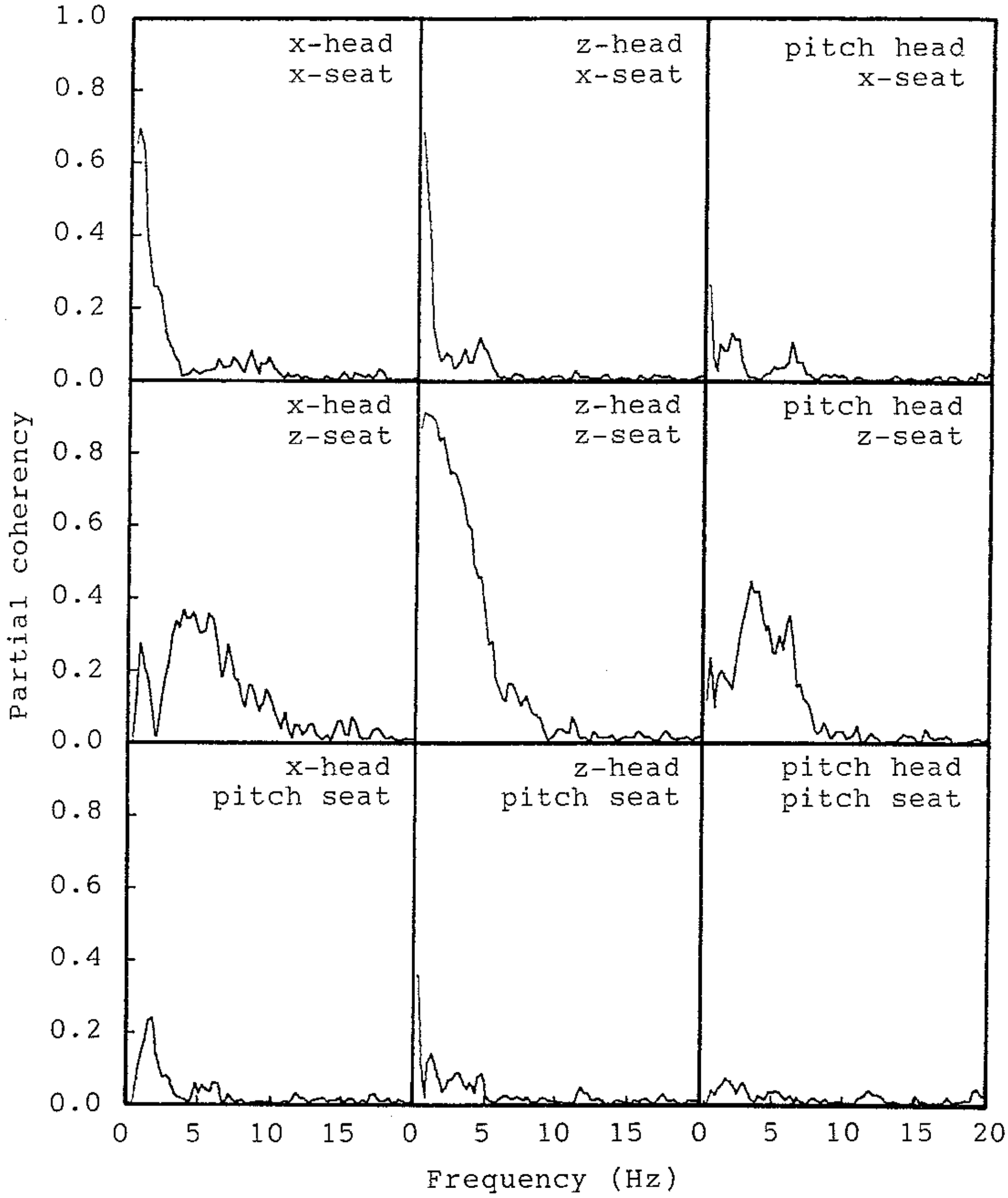


Figure 7.10 Partial coherency curves between motions in the mid-sagittal plane at the seat and the head during an AFV ride. (Resolution = 0.25 Hz, degrees of freedom = 508)

motion. Pitch axis seat motion caused virtually no fore-and-aft motion at the head. Most of the vertical motion at the head was caused by z-axis seat motion below about 3 Hz, x-axis seat motion having a small effect at very low frequencies while pitch axis seat motion again had no effect. Pitch motion at the head was caused mostly by z-axis seat motion with x-axis and pitch axis seat motion making no contribution.

In Figure 7.11 are shown four power spectra of motion for each axis with differing proportions of correlated and uncorrelated energy. Consider fore-and-aft motion at the head, the higher curve is the power spectrum of the total x-axis head motion. The linearly correlated head motion spectra with no conditioning for motion in other seat axes are higher than those which have been conditioned as they contain motion which is also correlated with motion in other seat axes. The curve corresponding to conditioned data shows that below about 1 Hz, some to the x-axis head motion is linearly correlated with x-axis seat motion; noise (motion uncorrelated with x-axis, z-axis and/or pitch seat motion) dominates x-axis head motion above 1 Hz. For z-axis head motion, a large portion of the motion is linearly correlated with z-axis seat motion below about 3 Hz after conditioning for the other two inputs. Data for pitch motion at the head show that nearly all the motion in this axis is dominated by noise, i.e. not linearly correlated with motion in the three mid-sagittal plane axes at the seat. These confirm the results obtained from transmissibility and partial coherency data.

7.3.3.2 Mid-coronal plane motion

Six power spectra shown in Figure 7.12 are of acceleration measured at the head and the seat in the y-, z- and roll axes. Larger high frequency content is seen for y-axis and z-axis seat motion than in the corresponding axes at the head. The acceleration magnitudes for motion in the y-, z- and roll axes were 1.62 ms^{-2} r.m.s., 1.37 ms^{-2} r.m.s. and 2.75 $rads^{-2}$ r.m.s. for seat motion and 1.28 ms^{-2} r.m.s., 1.82 ms^{-2} r.m.s. and 3.00 $rads^{-2}$ r.m.s. for head motion. (The similarity in the acceleration magnitudes and the power spectra for z-axis seat motion measured in the two runs shows a high degree of repeatability.)

Transmissibilities between seat and head motion for the three axes are presented in Figure 7.13. A very large difference is observed between the transmissibilities calculated using the two spectral density function methods

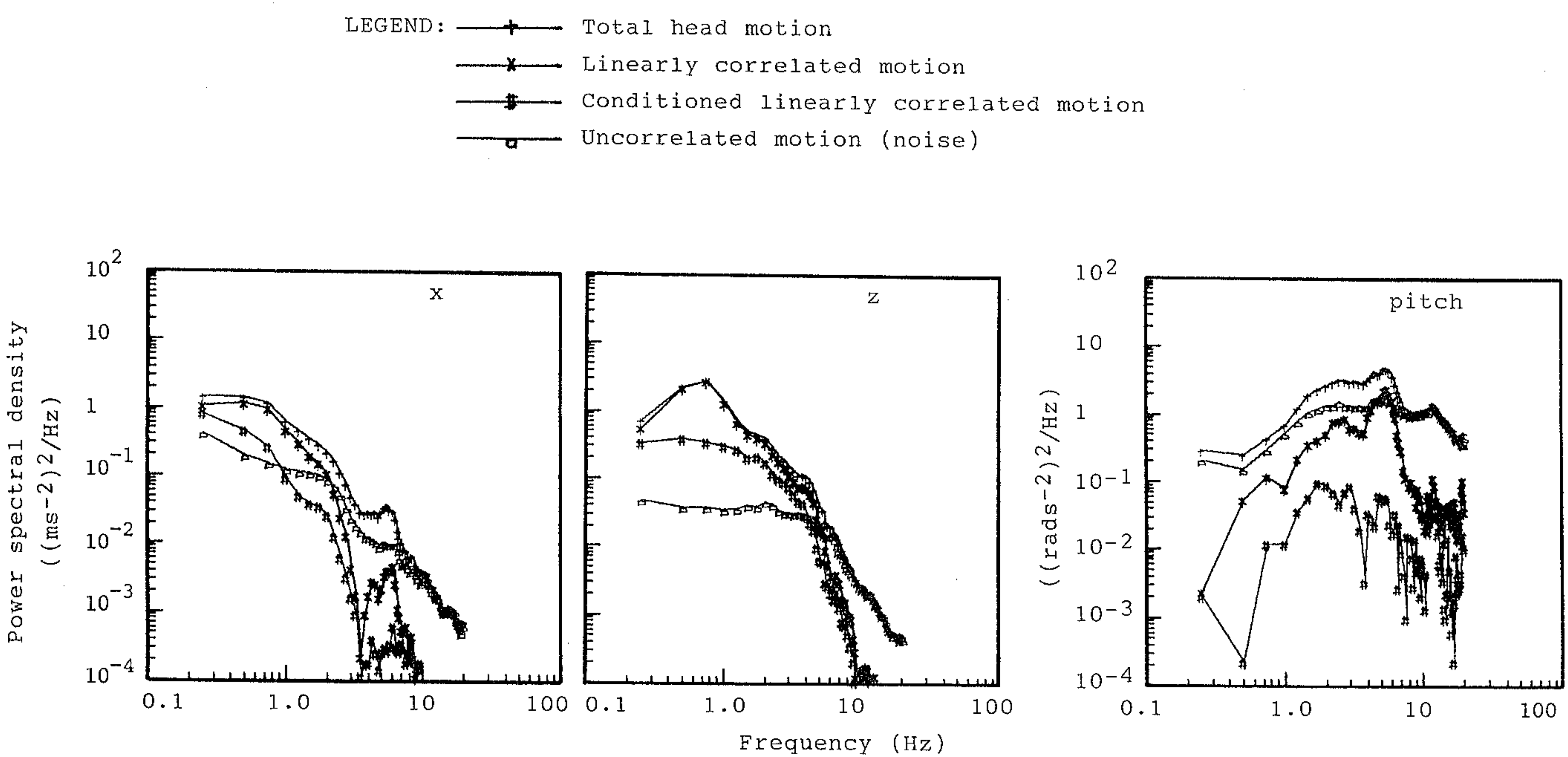


Figure 7.11 Various power spectral densities of seat and head motion in the mid-sagittal plane. (Resolution = 0.25 Hz, degrees of freedom = 508)

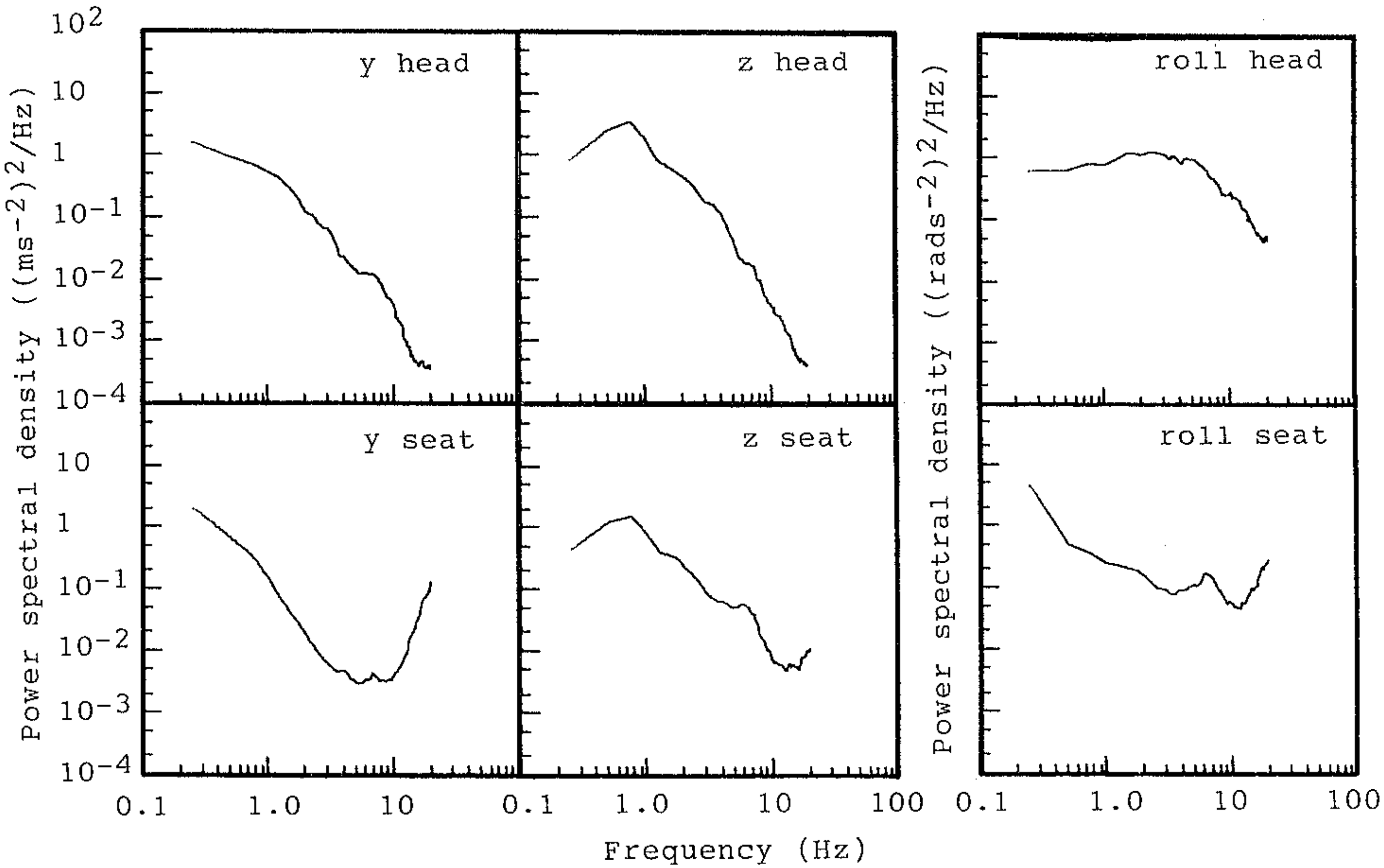


Figure 7.12 Power spectral densities of accelerations in the mid-coronal plane at the gunner's head and the seat in an AFV. (Resolution = 0.25, degrees of freedom = 508)

for y-axis seat vibration to z-axis head motion. The 'power spectral density function method' (higher curve) considers all the motion in the y-axis at the seat and the z-axis at the head. As z-axis head motion was of much larger magnitude than y-axis seat motion, a ratio of the energies results in large transmissibility values. The 'cross-spectral density function method' takes into account only the linearly correlated motion between the z-axis at the head and the y-axis at the seat, which (as is seen in the coherencies, Figures 7.14 and 7.15) is small and so produces a lower transmissibility curve.

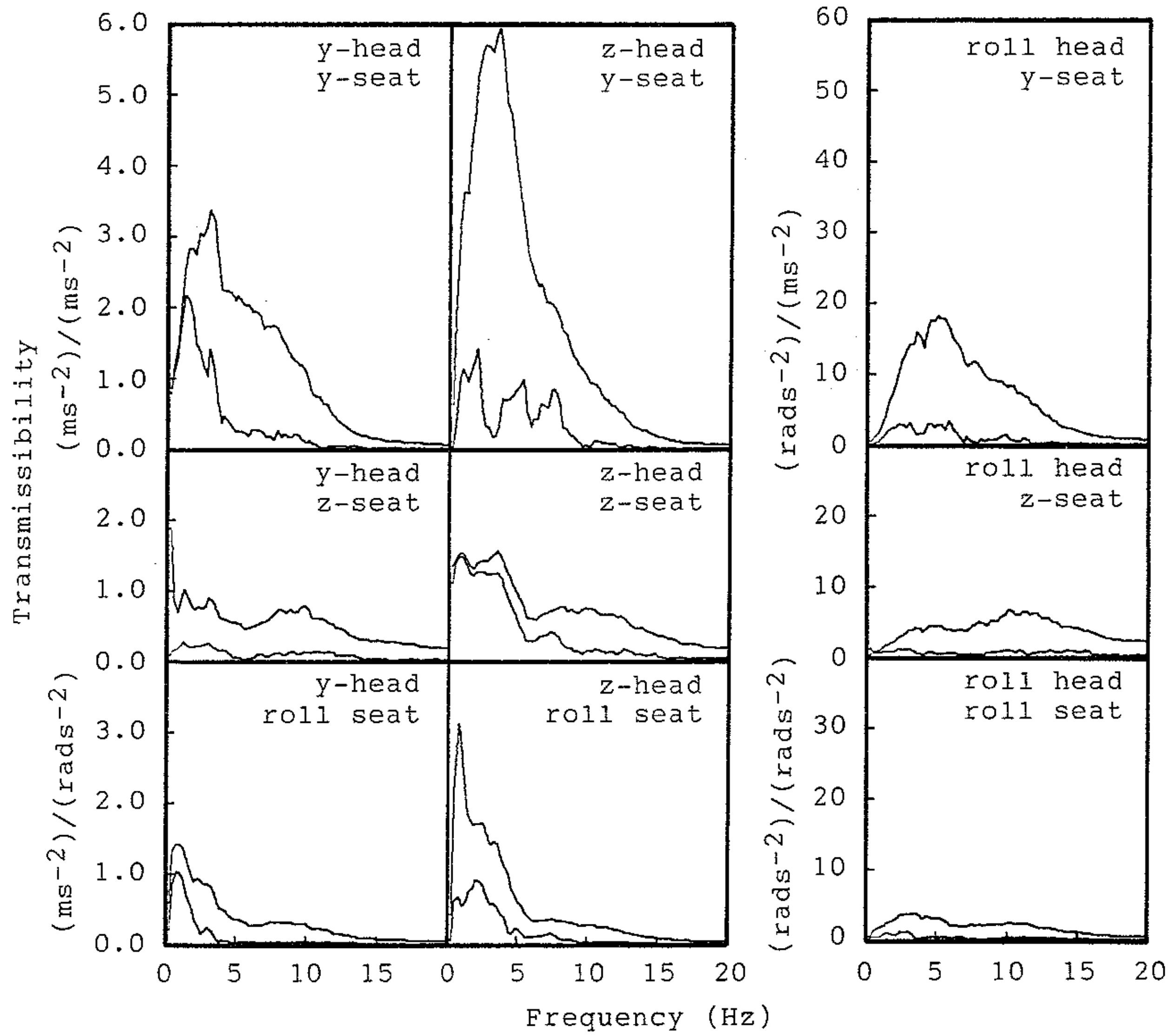


Figure 7.13 Transmissibilities between seat and head motion in the mid-coronal plane using the power (higher curve) and cross-spectral density function methods (lower curve). (Resolution = 0.25 Hz, degrees of freedom = 508)

The ordinary and partial coherencies for the three axes are shown in Figures 7.14 and 7.15 respectively. Lateral head motion is seen mainly to be caused by y-axis seat motion for frequencies below about 2 Hz. The high partial (and ordinary) coherency between z-axis seat and z-axis head motion suggests that below 5 Hz, most of the vertical motion at the head was caused by vertical seat motion. Vertical seat motion had a larger effect on roll head motion at very low frequencies than the other two seat axes. These data show that roll axis motion at the seat had virtually no effect on head motion in the mid-coronal plane (i.e. lateral, vertical and roll axes).

Power spectra showing various degrees of correlation are presented in Figure 7.16. Lateral axis power spectra show that below 2 Hz, y-axis head motion is mostly correlated with y-axis seat motion while at higher frequencies, noise dominates the motion. Vertical motion at the head is well correlated with vertical motion at the seat for frequencies below about 4 Hz before noise dominates the motion. Roll motion spectra show that there is no correlation between roll axis seat and roll axis head motion.

7.3.4 Discussion

The similarity in the transmissibilities and coherencies for z-axis seat and z-axis head motion between the studies in the two planes shows that the measurements can be repeated with reasonable accuracy.

In the mid-coronal plane, the three correlated z-axis seat to z-axis head power spectra are all high below about 4 Hz, specifically the conditioned spectrum. This was not seen to be the case for measurements in the mid-sagittal plane (see Section 7.3.3.1). The total motion spectrum and the linearly correlated spectrum with no conditioning for other axes are very similar for both sets of measurements. The conditioned spectrum for z-axis seat to z-axis head motion in the mid-sagittal plane is lower than that in the mid-coronal plane because, in the former case one of the

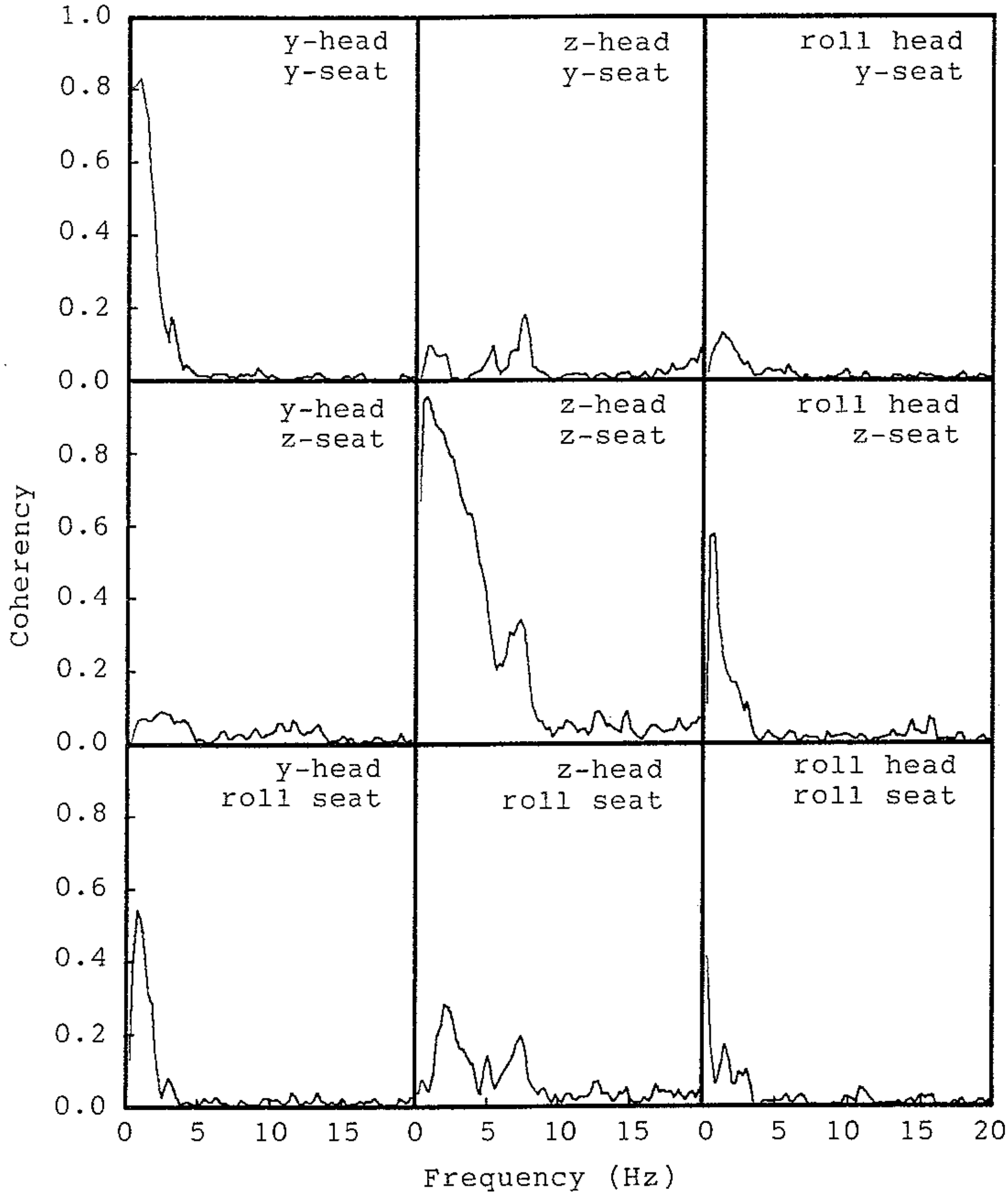


Figure 7.14 Ordinary coherency curves between motions in the mid-coronal plane at the set and the head during an AFV ride. (Resolution = 0.25 Hz, degrees of freedom = 508)

other seat axes which was monitored and conditioned affected the z-axis head motion (i.e. the x-axis seat motion). So, subtracting the effect of this axis previously resulted in a lower conditioned spectrum. The transmissibilities and coherencies showed that neither y-axis seat nor roll axis seat motion had any appreciable effect on z-axis head motion, therefore, the power spectrum remained almost unaffected.

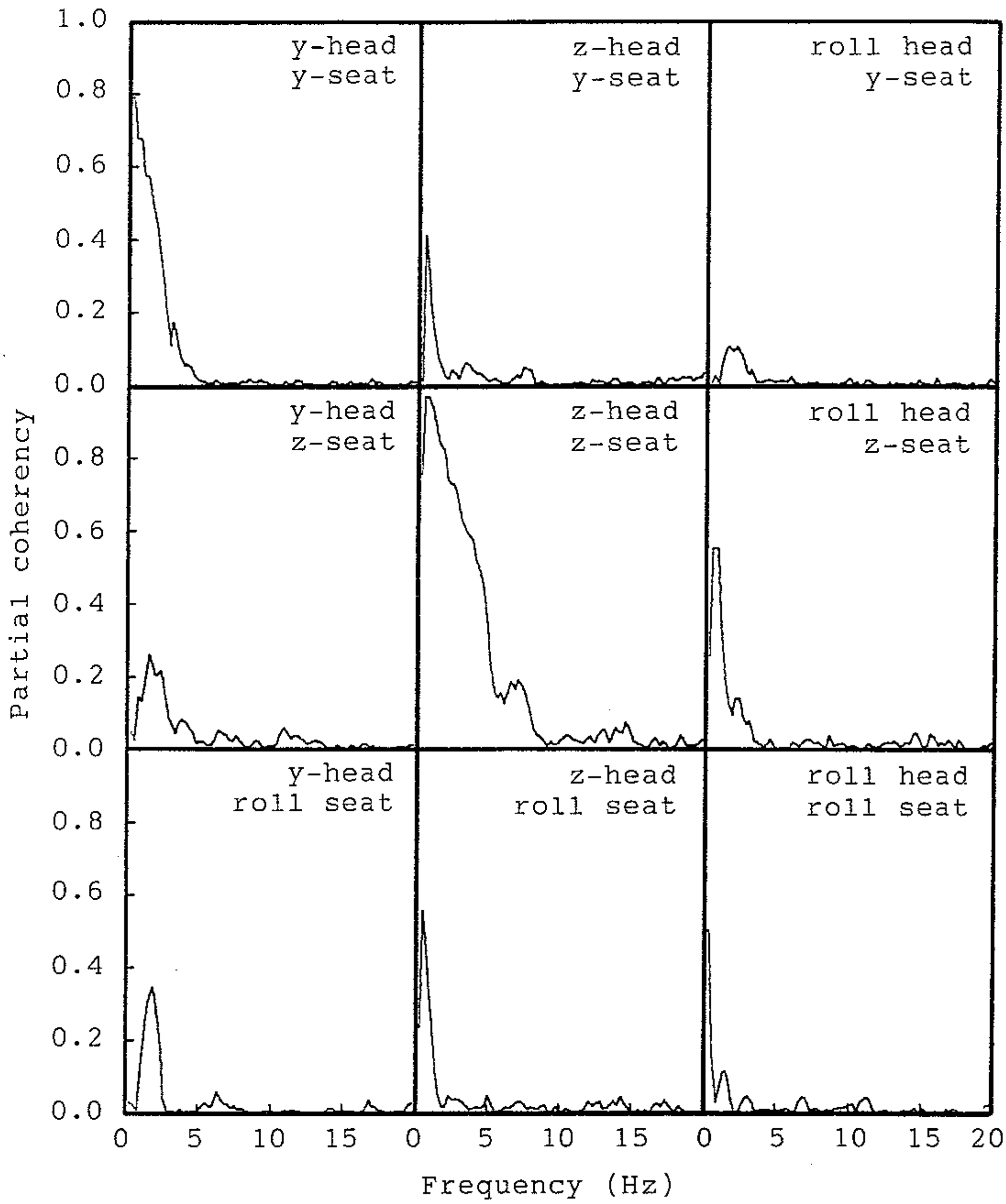


Figure 7.15 Partial coherency curves between motions in the mid-coronal plane at the seat and the head during an AFV ride. (Resolution = 0.25 Hz, degrees of freedom = 508)

The analysis can be taken a step further by considering the relation between z-axis seat and z-axis head motion for motion in both planes, and considering just the conditioned and noise power spectra. Since it has been established that y-, roll nor pitch axis seat motion had much effect on z-axis head motion, the two spectra can be taken as being "conditioned" (mid-sagittal plane) and "partially conditioned" (mid-coronal plane). Assuming that the energy content which is not correlated with x-, y-, roll or pitch

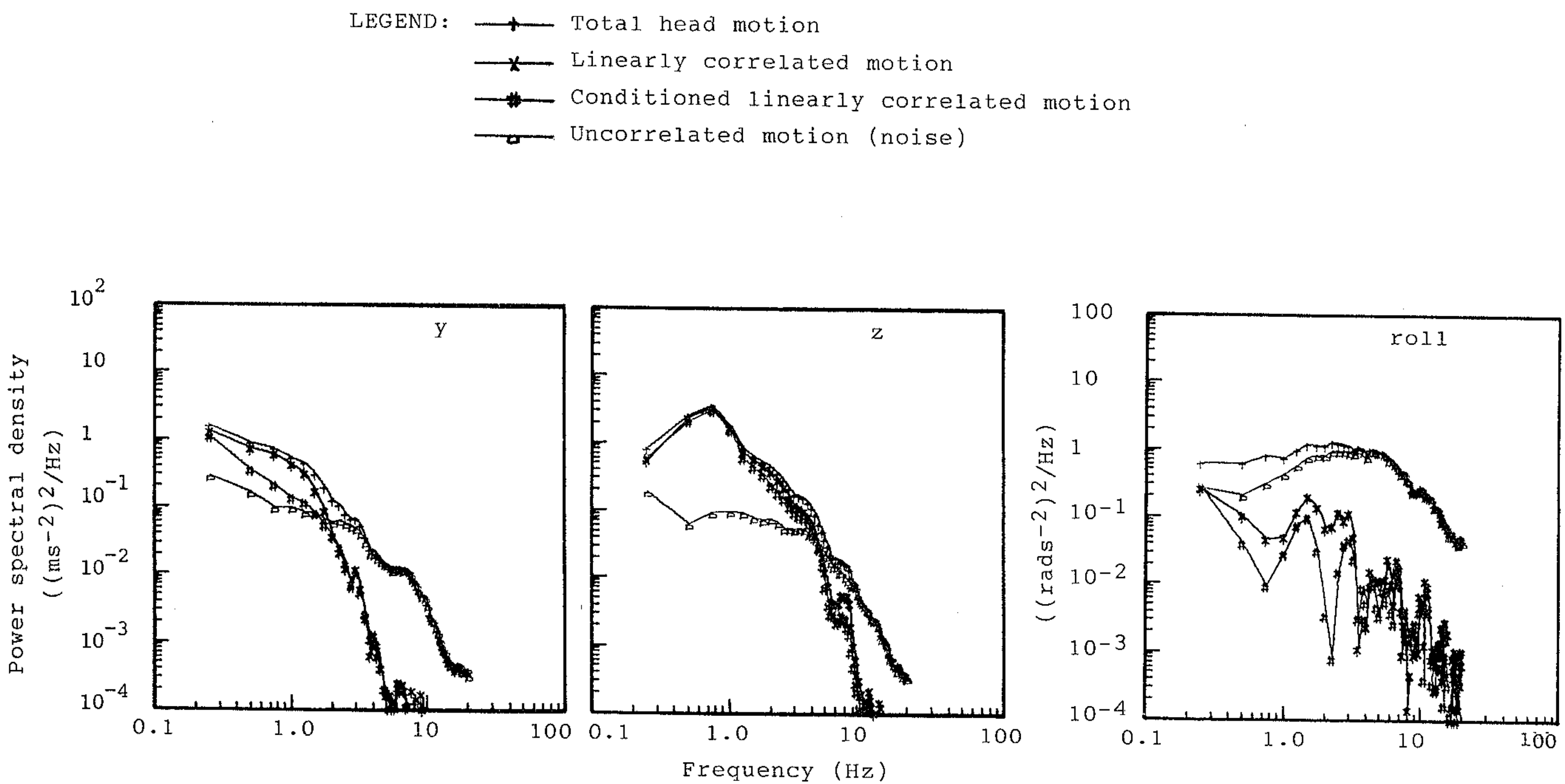


Figure 7.16 Various power spectral densities of seat and head motion in the mid-coronal plane. (Resolution = 0.25 Hz, degrees of freedom = 508)

axis motion at the seat remains constant, the difference between the two conditioned spectra and the two noise spectra should be the same. By comparing the noise spectrum for vertical head motion from Figure 7.11 (mid-sagittal plane) and Figure 7.16 (mid-coronal plane), it is seen that greater levels of noise resulted for the mid-coronal plane measurements than the mid-sagittal plane measurements. This might indicate that the noise was, to some extent correlated with fore-and-aft seat vibration and to a much lesser extent, with lateral seat vibration. Roll and pitch seat vibration may also have had an effect in generating the noise spectra, simultaneous roll and pitch measures might be required to determine the respective effects.

The results from acceleration measurements in both planes, particularly the conditioned power spectra, show the need to measure, if possible, motion in all the axes at the seat. In interpreting data, transmissibilities and partial coherencies can be used to determine the axes of seat motion that cause head motion in a particular axis. To provide further evidence, conditioned power spectra can be calculated.

7.4 DISCUSSION AND CONCLUSIONS

This section has shown that by using different and more complex analyses, a deeper and clearer understanding can be obtained about the transmission of seat vibration to the head. For instance by considering data for translational seat and head vibration only, transmissibilities obtained using the 'power spectral density function method' show that vibration in all axes at the seat caused motion in all the axes at the head. But then reanalysing the data using the 'cross-spectral density function method' together with ordinary coherency, a better and correct understanding was obtained. These formed the basis to the final conclusions but the partial coherencies and conditioned spectra were able to explain the data in more detail thus allowing finer adjustments to be made to the conclusions.

Measurement of translational seat and head vibration data showed that motion at the head in the fore-and-aft and the vertical axes was caused mostly by vibration in the fore-and-aft and vertical axes at the seat. Also that lateral vibration at the seat had the greatest effect on lateral head motion. Measurement of seat and head motion in the mid-sagittal (x-, z- and pitch axes) and the mid-coronal (y-, z- and roll axes) showed that roll and pitch vibration at the seat had virtually no effect on head motion. These also confirmed the results obtained from the translational seat and head measurements.

This section has explained the misleading results that could be obtained by analysing data for a multi-input single-output system if only superficial analyses are conducted. Therefore, for a deeper understanding of the data, further spectral analyses may be required.

CHAPTER 8

BIODYNAMIC MODELS

8.1 INTRODUCTION

Studies of models to simulate the responses of the human body to vibration are not a new subject - this is almost as old as the study of human response to vibration. Biodynamic models have ranged from basic single degree of freedom models (e.g. Coermann, 1962) to complex anatomically based models (e.g. Belytschko et al., 1976). Biodynamic models need not be restricted to whole-body vibration but other factors can also be incorporated such as the effects of impact, blast and pressure loading (von Gierke, 1964). The development of such models can provide a deeper understanding into the behaviour of the complex structure of the human body.

This chapter reviews some of the literature available on biodynamic models which respond to vibration and includes possible future modelling approaches.

8.2 A BRIEF LITERATURE REVIEW

8.2.1 Introduction

Attempts have continuously been made to model the biodynamic response of the human body and some models have been proposed. The final result from a model could be a transfer function, transmissibility or mechanical impedance and these properties are usually considered of a model to estimate the usefulness and accuracy with which it could simulate the responses of a human body. Some of the biodynamic models proposed by other researchers are discussed below.

8.2.2 Vertical axis lumped parameter models

Coermann (1962) discussed the simplest form of a model of the human body as a single degree of freedom system. Comparisons were made with experimental data obtained for a seated subject; the single degree of freedom model demonstrated, as expected, one resonance peak in the transmission of vibration to the top mass whereas the human body showed (e.g. Dieckmann, 1957a; Guignard, 1959) two or more resonance peaks depending on the posture adopted. This is an over simplification of the highly complex human body and is far from the anatomical structure of the body.

The response of a single degree of freedom model was compared with the transmissibility of a group of subjects and the response for a single subject in a study by Griffin et al. (1979). Their results showed that a one degree of freedom system might have been adequate for modelling the mean transmissibility for a group of subjects although there are some subjects who would demonstrate either greater or smaller transmissibilities than those provided by the model. Individuals with responses which can be modelled as a single degree of freedom are rarely encountered! The response of the same single degree of freedom model (i.e. natural frequency of 14 Hz and damping of 0.6 of critical) was compared to that of a single subject. It was shown that a multi degree of freedom system (possibly a three degree of freedom system) might be sufficient to provide a reasonable comparison. However, this would have been for that subject sitting in a particular posture with a specific head angle and foot position, etc. since all these factors (and more) would alter the seat-to-head transmissibility for the same subject.

The effect of position and posture was demonstrated by Frolov (1970) where seat-to-head transmissibilities were measured for a subject seated in three different body postures: normal upright, crouched and normal upright with arms pointing upwards. These are shown in Figure 8.1 with the corresponding transmissibilities. It was noticed that different resonance peaks occurred in the transmissibility curves which could be modelled as a stack of single degree of freedom systems; each unit (that is, mass, spring and damper) could be 'tuned' to respond maximally at the required frequency.

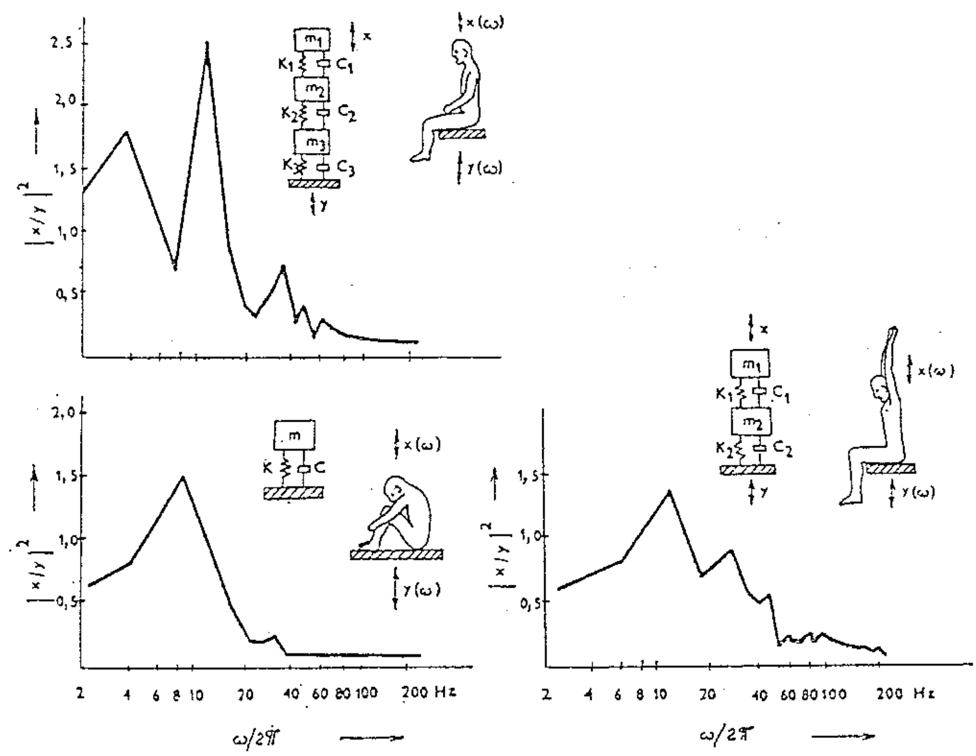


Figure 8.1 Three lumped parameter models proposed by Frolov (1970) for three different sitting postures.

The main deficiency with the above models was that the different single degree of freedom units did not represent any particular part of the body. An attempt was made by Payne and Band (1971) to calculate the responses of a four degree of freedom model with each single degree of freedom unit representing a part of the human body, the model proposed is shown in Figure 8.2. Values for the different parameters were calculated from experimental data available on the properties of the different parts of the human body. The procedure adopted in evaluating a particular model was to vary the unknown values (those not available from other experimental data) until the response of the model represented that obtained experimentally. Mechanical impedance of the model was compared with that obtained from experiments and though data were not presented graphically for transmissibilities, good agreement with the model was reported. (A non-linear model was later developed but graphical comparisons were not made.)

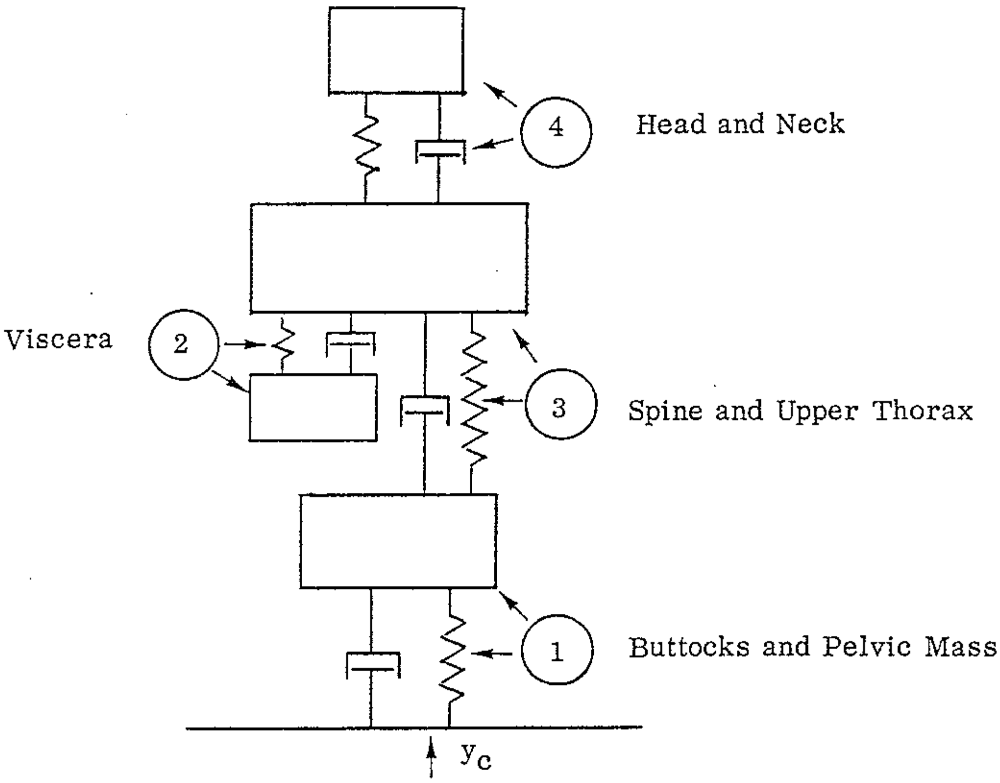


Figure 8.2 A four degree of freedom model of a seated person proposed by Payne and Band (1971).

A multi degree of freedom model of the seated human body was presented by Mertens (1978), this is shown in Figure 8.3 and comprises two models: a single degree of freedom model and a four degree of freedom model. The individual parameters of the model represent different parts of the body and values for the mass and spring elements were used from either anthro-dynamic data or determined by calculation from the resonance frequencies of the different body parts. Both transmissibility and impedance were calculated for the model and these were compared with mean experimental data from nine subjects for four increased static accelerations (i.e. +1g, +2g, +3g and +4g).

Measured and calculated transmissibility data are shown in Figure 8.4 for the four increasing gravity conditions. The model simulates the response of the human body with reasonable accuracy. Though the 'goodness of fit' might have been improved for a specific condition (e.g. transmissibility with a static acceleration of 1g), the accuracy with which impedance response and phase data were simulated might have deteriorated.

The models discussed above have been those with linear elements and producing linear responses. It has been shown elsewhere (e.g. Payne and Band, 1971) that the mechanical impedance of the human body might be non-linear thus requiring the development of a non-linear model. Such models have been proposed and the responses compared with experimental data with varying degrees of success (e.g. Wittmann and Phillips, 1969; Hopkins, 1970).

A complex multi degree of freedom lumped-parameter model for the human body shown in Figure 8.5 was suggested by Muksian (1970) and later reported with modifications by Muksian and Nash (1974). This anatomical representation of a seated body has both linear and non-linear (cubic) elements, an example of this is the ballistocardiographic force exerted by the 'thorax' element which was modelled as:

Force F = 0.024 f lb

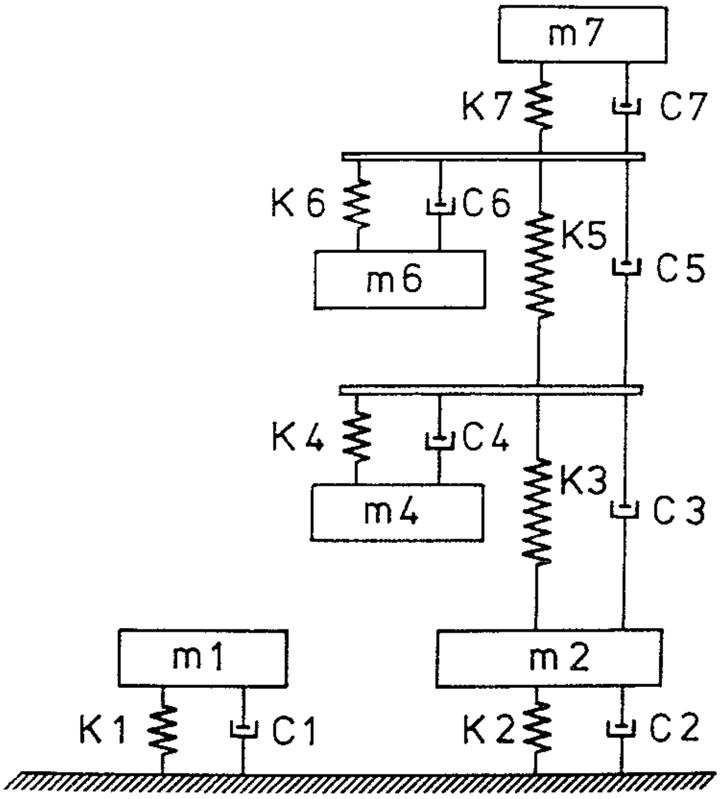
where f is given by:

$$f = \frac{2.5\, f_1 + 75}{60} \text{ Hz} \qquad 0 \leq f_1 \leq 10$$

$$f = \frac{-4\, f_1 + 40}{60} \text{ Hz} \qquad 10 < f_1 \leq 15$$

$$f = 1.33 \text{ Hz} \qquad f > 15$$

where f_1 is the frequency of seat motion (i.e. pelvis mass m_7 in Figure 8.5). Coulomb friction forces were also



Model parts

M1 Mass K1 Spring C1 Damper	of the legs, resting on the seat
M2 Mass K2 Spring C2 Damper	of the buttocks
K3 Spring C3 Damper	of the spine from L1 to S1
K5 Spring C5 Damper	of the spine from T1 to T12
K7 Spring C7 Damper	of the spine from C1 to C7
M4 Mass K4 Spring C4 Damper	of the abdominal system
M6 Mass K6 Spring C6 Damper	of the chest system

M7 Mass of the head

Figure 8.3 A multi degree of freedom model of an upright seated person proposed by Mertens (1978).

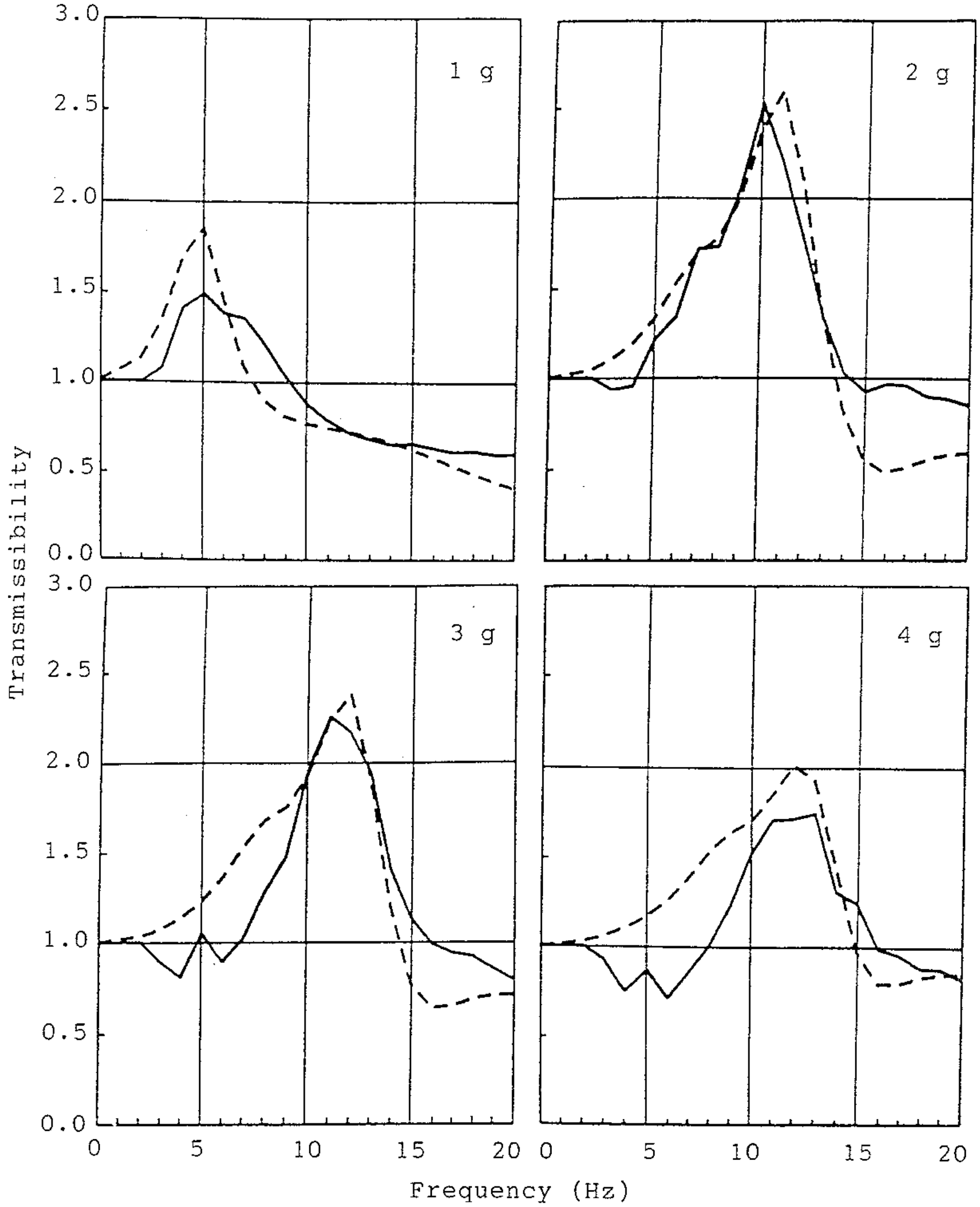


Figure 8.4 Comparison of measured (———) and predicted (- - - -) transmissibilities between vertical seat and head motion for four static accelerations using a model proposed by Mertens (1978).

included in the model (forces F_2 and F_3 in Figure 8.5). The model was only used for sinusoidal displacements of the seat. It was shown that by using a combination of both linear and non-linear elements, the model was able to predict motions of the body at different parts ranging from the abdomen to the head, general agreement was observed between responses from the model and those obtained during experiments with subjects.

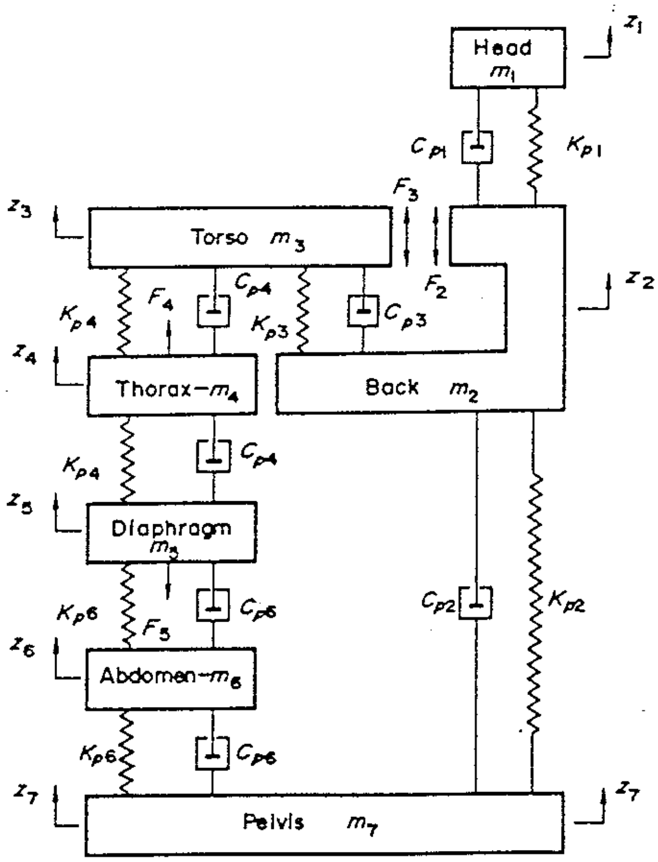


Figure 8.5 A multi degree of freedom model of a seated person proposed by Muksian and Nash (1974).

In a later report (though this was a preliminary investigation to the above study), Muksian and Nash (1976) discuss a three degree of freedom model shown in Figure 8.6 to include both frequency-dependent damping coefficients and linear spring elements. Using linear elements, it was observed that the model provided good agreement with experimental transmissibility data between seat and head motion for up to 6 Hz whereas a non-linear model showed best results for frequencies from 10 Hz to 30 Hz. For these data, the damping coefficients were modelled as:

$$\text{damping } C = 17289\, f^2\, u(f_1 - 10)$$

where: $u(f_1 - 10) = 0 \qquad f_1 < 10$

$u(f_1 - 10) = 1 \qquad f_1 \geq 10$

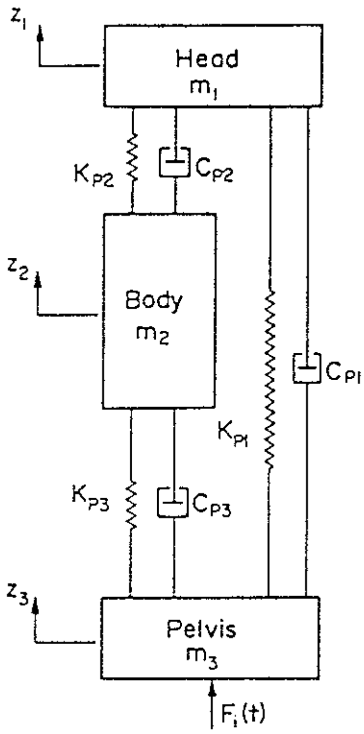
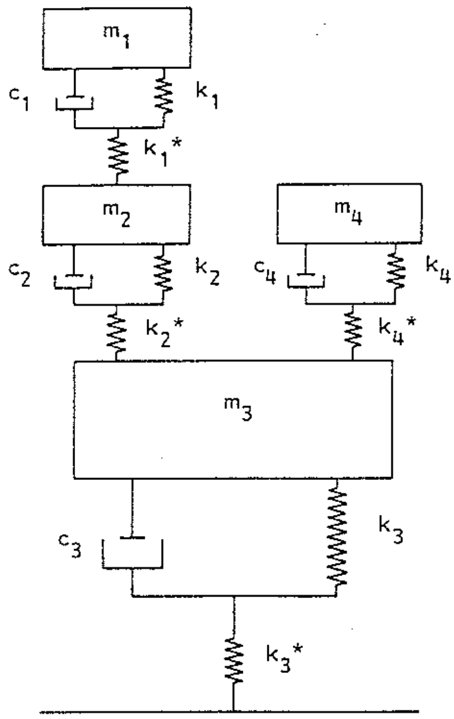


Figure 8.6 A lumped parameter model of a seated person using non-linear damping elements proposed by Muksian and Nash (1976).

The above studies have shown that a model with non-linear responses might be required to accurately predict the complex behaviour of the human body.

International Standard ISO 7962 (1987) proposed a linear four degree of freedom model shown in Figure 8.7. It is stated that "there is no direct correlation between the elements of the model and anatomical segments" and the transmissibility response of the model was determined at the top mass, m_1. The transmissibility data used for comparison were pooled together from many studies with differing experimental conditions, postures and no distinction is made between seated and standing subjects.

The experimental data presented depict an 'average' transmissibility for both seated and standing subjects. The validity and applicability of such a model is in doubt as has been noticed by Griffin (1990) that "the transmissibility of the model is virtually unchanged by the removal of the 8.24 kg 'head'".



Model parameters	
m_1	8,24 kg
m_2	8,05 kg
m_3	44,85 kg
m_4	13,86 kg
k_1	22×10^8 N.m^{-1}
k_2	$20,13 \times 10^4$ N.m^{-1}
k_3	$88,56 \times 10^3$ N.m^{-1}
k_4	$36,47 \times 10^3$ N.m^{-1}
$k_1{}^*$	36×10^7 N.m^{-1}
$k_2{}^*$	65×10^9 N.m^{-1}
$k_3{}^*$	$52,34 \times 10^4$ N.m^{-1}
$k_4{}^*$	$69,30 \times 10^3$ N.m^{-1}
c_1	748,1 N.s.m^{-1}
c_2	578,0 N.s.m^{-1}
c_3	2964,0 N.s.m^{-1}
c_4	901,8 N.s.m^{-1}

Figure 8.7 A four degree of freedom model for seated and standing persons proposed in ISO 7962 (1987).

8.2.3 Multi-axis models

Most of the biodynamic models reported in the literature have been concerned with mainly vertical motion at the seat and vertical motion at the head. It has been shown elsewhere (e.g. Griffin, 1975; Johnston, 1979) and in Chapter 5 of this thesis that appreciable magnitudes of head motion can occur in other axes at the head than just the vertical direction. A few attempts have been made to develop multi-axis models which not only predict motion at the head in more than one axis but will also respond to motions in the other axes at the input, for example, at the seat. This section reviews some of the multi-axis models reported in the literature and these can generally be categorised as either whole-body models or impact models.

A model of both the human body and a seat was proposed by Wisner et al. (1964), this is shown in Figure 8.8. The 'head', 'thorax and arms' and 'pelvis and thighs' masses are connected by springs and dampers to provide the required vibration characteristics and are also joined using pivots and linkages. These are (presumably) to include rotational pitch motion of the 'head' and the 'thorax and arms' masses. Unfortunately, no data were presented in that study using the model.

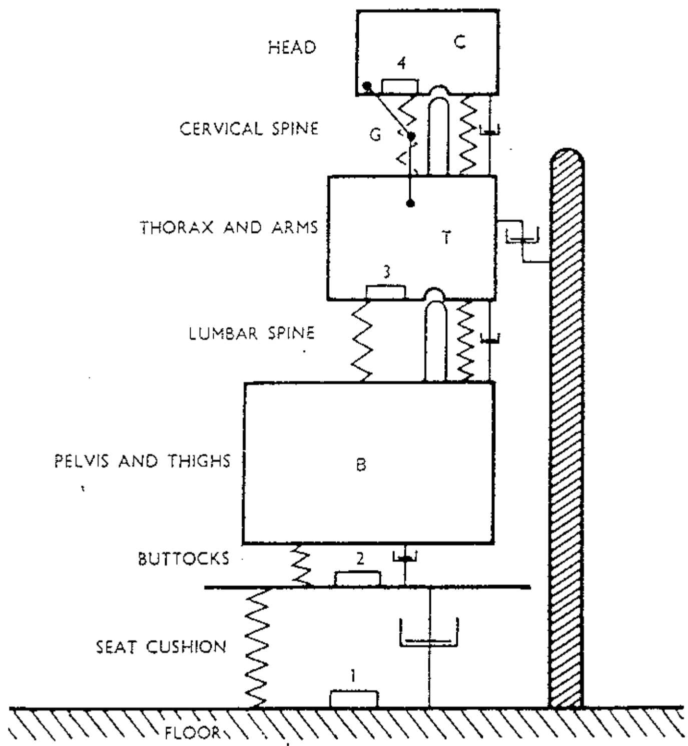


Figure 8.8 A multi-axis multi degree of freedom model proposed by Wisner et al. (1964) for the seat and the body for a seated person (adapted from Haack, 1955).

A lumped-parameter model of a seated person was presented by Meltzer (1985), this is shown in Figure 8.9. This is a model for whole-body vibration for the mid-sagittal plane. The model will respond to excitations in the fore-and-aft and the vertical directions and the results provided will be in the fore-and-aft, vertical and pitch axes. No numerical data were presented from the model.

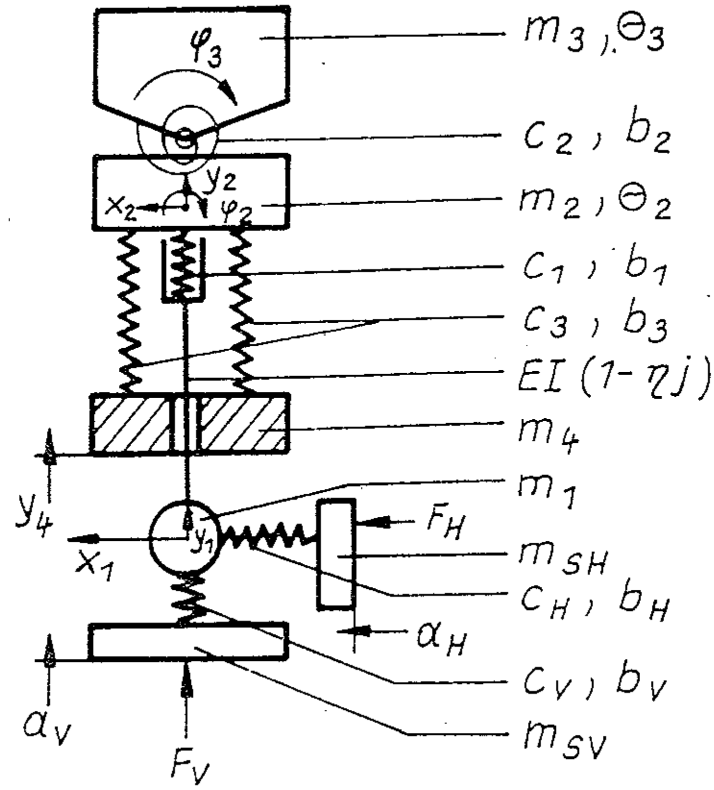


Figure 8.9 A mid-sagittal plane model for a seated person proposed by Meltzer (1985).

Melzig-Thiel and Schatte (1985) proposed a model of a seated person for the mid-sagittal plane with the different elements of the model actually representing various parts of the human body, this model is shown in Figure 8.10. (Some similarities can be seen between the two models in Figure 8.9 and 8.10). The model, which represents a driver's posture, was able to simulate the response of a seated person with reasonable accuracy when mobilities were calculated. This was the case for separate input vibration in both the fore-and-aft and vertical axes. Transmissibilities were calculated between seat vibration and head motion for both fore-and-aft and vertical seat vibration. Data obtained from the model showed some similarities with experimental data for fore-and-aft seat vibration. The model was able to simulate the biodynamic response of the head with greater accuracy for vertical vibration at the seat than for fore-and-aft seat vibration. Cross transfer functions between x-axis vibration as the input and head motion in the z-axis and for z-axis vibration as the input and x-axis motion at the head showed that the model was not able to simulate the response of the human body for these cross transfer combinations.

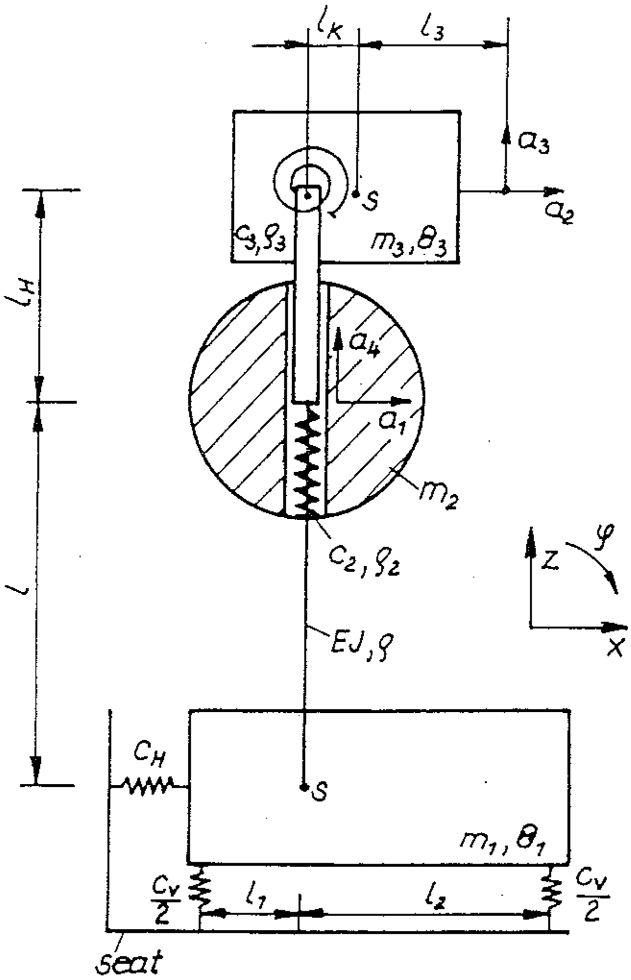


Figure 8.10 A mid-sagittal plane model for a seated person proposed by Melzig-Thiel and Schatte (1985).

There is some literature available on biodynamic models which simulate the response of a seated person when exposed to impact (e.g. Frisch and Cooper, 1978; Huston et al., 1978; Schneider and Bowman, 1978; Smith and Anderson, 1978). Experimental data on this topic are available from many sources and, generally, each study on impact models has obtained its own experimental data due to its particular requirements. The impact has been with subjects seated on a sled that is accelerated to produce a -Gx acceleration to a required velocity and suddenly bought to a halt thus producing the required impact conditions. Impact accelerations have been of the order of 15g sustained for about 60 msec (Schneider and Bowman, 1978) though higher magnitudes have also been used. Measurement of rotational motion have been made using rate gyroscopes and these data have normally been supplemented by using high speed cinematographic cameras (Ewing and Thomas, 1972). The main components of motion at the head have been translation and rotation in the mid-sagittal plane; these are the motions that have been modelled (e.g. King et al., 1979). The models, which have included highly complex three-dimensional 54 degree of freedom computer based models (Huston et al., 1978), have mainly included the head and neck system.

The biodynamic models mentioned above have not, in general been 'anatomically correct'. Indeed, any biodynamic model developed will not be 'anatomically correct' as the only 'model' that is anatomically correct will be the human body! However, there are varying degrees of anatomical correctness. Some of the basic models have considered the torso and its different constituents (e.g. ribs, vertebral column, viscera) as a single degree of freedom system. These have mainly been curve fitting exercises. A comprehensive model with a high degree of anatomical correctness of the head-spine system has been developed by Belytschko et al. (1978) which is shown in Figure 8.11. It uses separate elements for the different ribs, vertebra and the head; the inertial properties, stiffness and the coordinates of each element were based on measurements made on cadavers. Other elements used in the model included spring, beam and hydro-dynamic deformable elements; elastic properties of these were again based on cadaveric measures. This model was primarily developed for the simulation of the response of a pilot during ejection. However, the model appears to be so generally developed that there is no restriction on the vibration applied. Mechanical impedance has been calculated for the model and comparisons made with experimental data (Belytschko and Privitzer, 1979). The model has been able to simulate the mechanical impedance of the human body with acceptable accuracy. Unfortunately, no comparisons have been made with transmissibility measures of the human body.

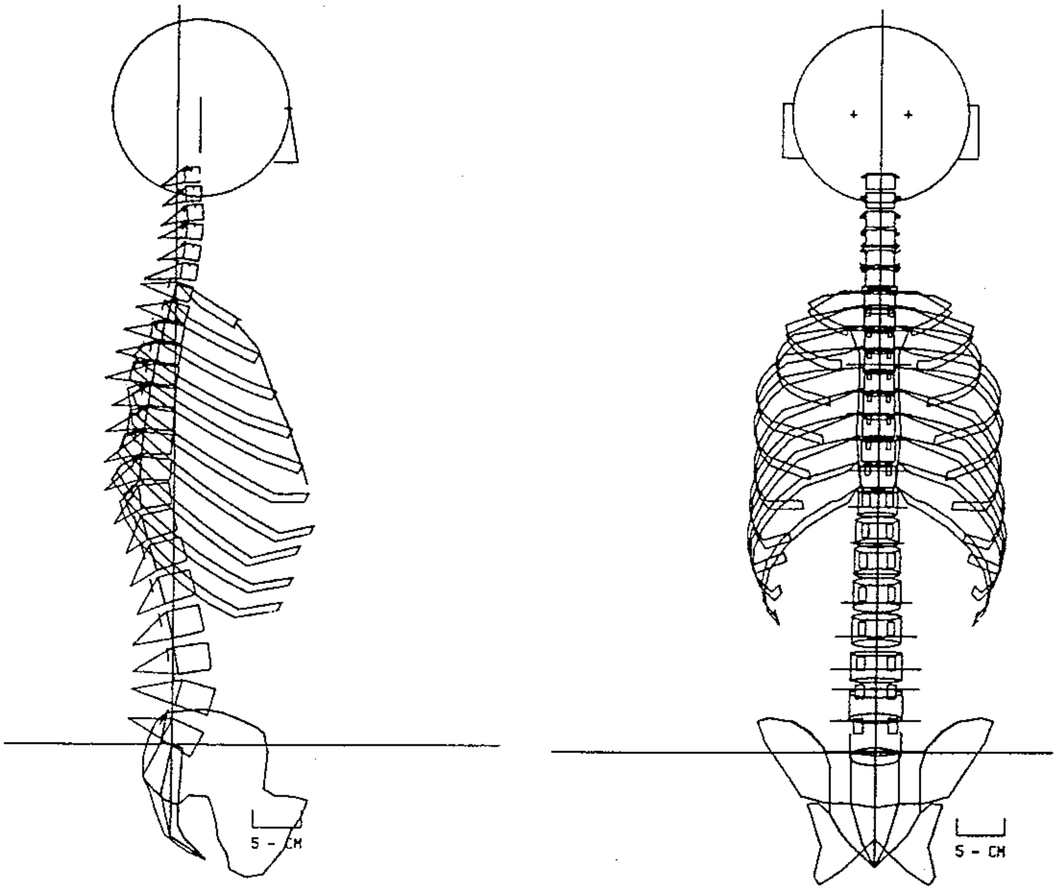


Figure 8.11 A complex anatomical model of the upper body of a seated person proposed by Belytschko et al. (1978).

Full capabilities of some of the models reviewed above have not been carried out due to possibly a shortage of experimental data.

8.3 FUTURE MODELLING APPROACHES

The lumped parameter model included in ISO 7962 (1987) was based on an average transmissibility curve obtained from a number of biodynamic studies. The experimental details and other variables such as seating condition, posture of subjects and location of measurement on the head were mostly different for all studies. Data from about 11 different reports were used in the calculation of the average transmissibility curve (see the reference list in ISO 7962 (1987)).

A search was made through the literature of the number of studies reporting on 'average' transmissibility curves obtained from experimental data. In collecting the average transmissibility curves, the effect of different variables was not distinguished (such as posture, effect of backrest, head angle, vibration magnitude). Data from 37 experiments were collected (with assistance from Messenger (1990)) and these individual curves are shown in Figure 8.12. (Some investigators covered a smaller frequency range than shown in Figure 8.12, these curves can be seen as 'falling short' of the full frequency range.) Studies used in the preparation of these curves were not only greater in number than those used for the curve included in ISO 7962 (1987) but includes more recent experimentation such as the data presented in Chapter 5 of this thesis. Figure 8.12 shows that a very wide range of transmissibilities can occur between experiments and, as these are average curves, individual data would show even greater variability. Mean and range of transmissibilities shown in Figure 8.12 are included in Figure 8.13. This figure shows that in the calculation of the mean curve, data which varied by as much as 700% were used from many different studies. If these curves were to be used for the development of a biodynamic model, then it shows the range of responses that could be accepted from the model. The biodynamic model could be tuned to mimic the mean transmissibility curve.

It is important to know the different parameters that affect transmissibility and possibly, the effect of these when developing models of the human body. It has been shown in Chapter 5 that posture, which is just one of the many variables that influence transmissibility, has possibly the greatest effect and different postures (ranging from slouched to erect) can completely dictate the shape of the transmissibility curve. Experimental data presented in Chapter 5 concerned with transmission of translational seat vibration to the heads of seated subjects show that for translational input vibration in a particular axis, the axes in which head motion will occur can be predicted with reasonable accuracy. Furthermore, an estimate of the shape of the transmissibility curve can, to

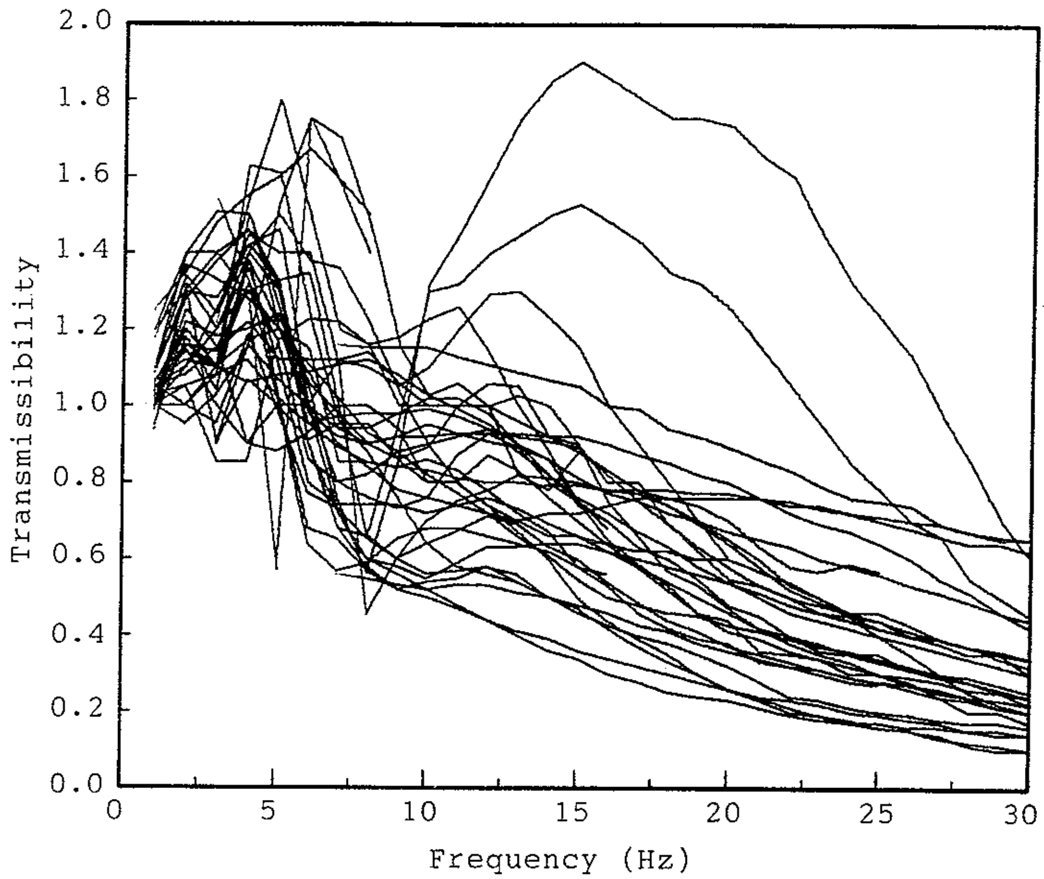


Figure 8.12 Average seat-to-head transmissibilities for vertical vibration from 37 studies involving a wide range of postures, seating conditions, head angles, etc.

some extent, be predicted although this is highly dependent on many factors including seating condition, subject posture, muscle tension and head angle. However, it can be seen from Sections 5.2 and 5.4 that for fore-and-aft and vertical vibration at the seat, motion at the head occurred mainly in the fore-and-aft, vertical and pitch axes, that is, in the mid-sagittal plane. Recent studies concerned with the transmission of pitch seat vibration to the head (Paddan, 1989, 1990) have shown that, again, dominant motions at the head were in the mid-sagittal plane. This suggests that for input vibration in the mid-sagittal plane, a biodynamic model for axes in only the mid-sagittal plane would, as a first step, provide a reasonable approximation of the response of the human body.

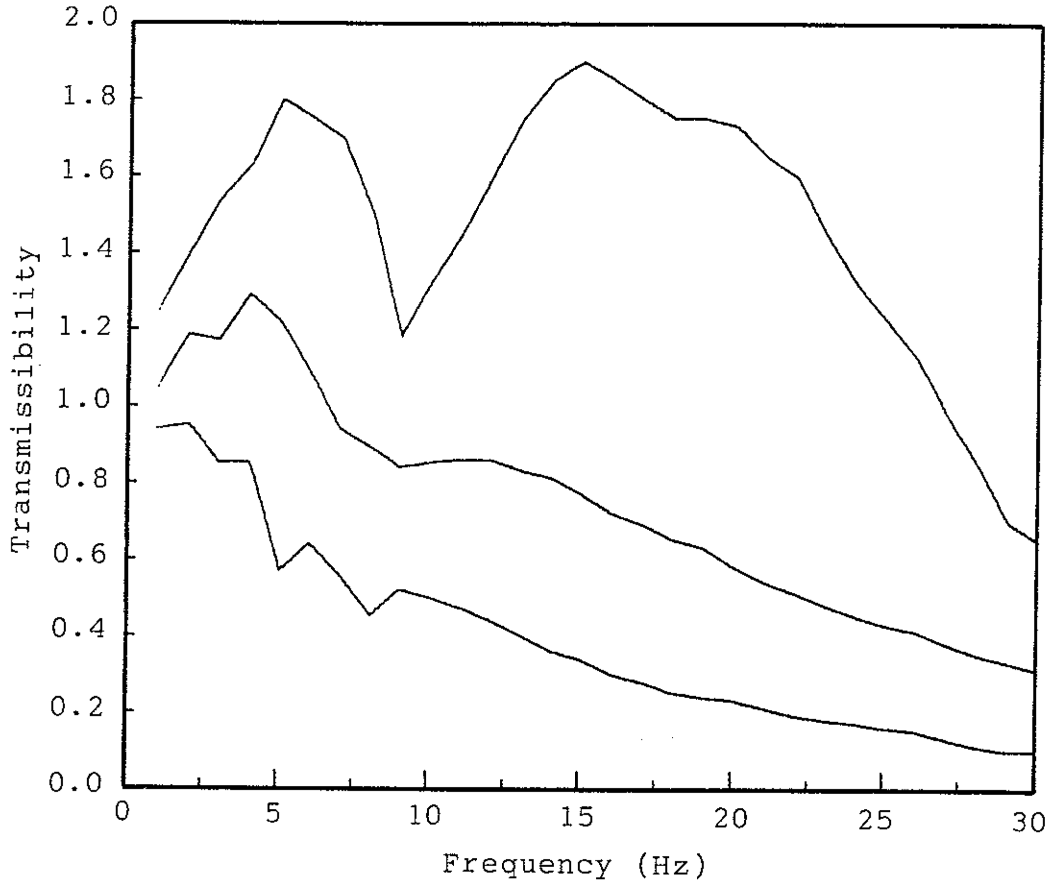


Figure 8.13 Mean and range of transmissibilities for vertical seat and head motion from 37 different studies.

The transmission of lateral vibration at the seat is rather more complex since the human body is not symmetric about the y-z plane as it was in the mid-sagittal plane. It was shown in Section 5.3 that for lateral axis seat vibration, the greatest magnitude of head motion occurred in the lateral axis with relatively smaller transmissibilities for motion in the other axes. The whole body and the head/neck system also moved in the mid-coronal plane (y-z plane); the data also showed that significant transmissibilities occurred for motion in these axes. It was also seen that transmissibilities for the yaw axis were not negligible, this is thought to be due to the centre of gravity of the head being out of line of the main roll motion of the head/neck system. Again, a recent study has shown (Paddan, 1989, 1990) that head motion for a seated subject exposed to roll vibration of the seat occurred mainly in the lateral, roll and yaw axes. There is no one common plane on the body which contains these three axes (i.e. lateral, roll and yaw axes).

8.4 DISCUSSION AND CONCLUSIONS

The studies reviewed above have been concerned with biodynamic models and the degree to which such models have been able to simulate the response of a seated person when exposed to vibration. The models discussed dealt with mainly vertical vibration at the seat. Some models were able to provide transmissibility curves that were similar to those obtained from experiments with subjects, although possibly all models would need to be tested with different conditions to determine the suitability and applicability of the models. An example of this is the highly complex model developed by Belytschko et al. (1976) which, unfortunately, was not fully exploited. There is in general a shortage of models which respond to horizontal vibration and also which determine horizontal motion at the head. Data presented in a previous section of this thesis (Chapter 5) may prove valuable in developing such models whereas sufficient experimental data may not be available for the inclusion of other variables.

Some models are available that attempt to simulate the response of the body for standing subjects (e.g. Coermann et al., 1960; Garg and Ross, 1976), but there are not as many as those available for seated subjects. This was probably due to a shortage of data for standing subjects and it is hoped that data presented in Chapter 6 might be used for such studies.

Most of the biodynamic models available have resulted in 'mere' curve fit exercises (which itself is no easy feat!). The importance of anatomically correct models should be stressed as this would allow a better understanding into the effects of vibration on various parts of the body. This should not, however, preclude the use of simple models to establish the general response of the body to vibration.

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 INTRODUCTION

This chapter summarises the findings of the experiments conducted and reported in this thesis (Chapters 5, 6 and 7). Laboratory experiments described in Chapters 5 and 6 included the determination of both intra- and inter-subject variability in the transmission of whole-body vibration to the head and the effect of various body postures on transmissibility. Data included in Chapter 7 are from experiments conducted in field conditions. Recommendations for further research are made based on the conclusions from the various experiments.

9.2 CONCLUSIONS

CONCLUSION 1

Preliminary experiments showed that bite-bar mass (158 g), bite grip and visual environment (eyes closed and eyes open) had no significant effects on the transmission of vertical seat vibration to the head of a seated subject. The variation that resulted in seat-to-head transmissibility was of the order of intra-subject variability.

CONCLUSION 2

Variability in transmissibility between individuals (inter-subject variability) was greater than that during repeat measures (intra-subject variability) for all axes of motion at the head. This was found to be the case for the three translational axes of input vibration for both seated and standing subjects.

CONCLUSION 3

When subjects were exposed to fore-and-aft seat vibration, head motion occurred principally in the mid-sagittal plane (i.e. in the fore-and-aft, vertical and pitch axes). This was the case for both 'back-on' and 'back-off' postures. Most of the motion at the head occurred below 10 Hz. One resonance peak was seen at about 3 Hz in the transmissibility curves for vertical and pitch axes of head motion for the subjects sitting in a 'back-off' posture. Significantly more motion was transmitted to the head when the subjects sat in contact with the backrest (i.e. 'back-on') and two transmissibility resonance peaks resulted at about 2 Hz and 8 Hz for motion in the mid-sagittal plane. Exposure of subjects to fore-and-aft seat vibration showed that the centre of rotation for pitch axis head motion moved closer to the mouth as the frequency of vibration increased. Average data for 31 subjects demonstrated that the centre of rotation was 11 cm behind the corner of the lips for 1 Hz and 5 cm behind the lips for a frequency of 16 Hz.

CONCLUSION 4

Head motion occurred mainly in the lateral axis during exposure to lateral seat vibration. There was no one biodynamic plane that contains the four axes showing greatest transmissibility (i.e. the fore-and-aft, lateral, roll and yaw axes). This is because the body is not symmetrical about the y-axis. Changes in body posture from 'back-on' to 'back-off' had only a small effect on head motion.

CONCLUSION 5

Exposure to vertical vibration at the seat resulted in head motion mostly in the mid-sagittal plane. Significantly greater magnitudes of head motion were measured over most of the frequency range (up to 25 Hz) for the subjects seated in a 'back-on' posture than in a 'back-off' posture. An increase in the frequency of maximum transmissibility in the vertical axis occurred from 4.5 Hz to 6.5 Hz when the subjects changed their posture from 'back-off' to 'back-on'.

CONCLUSION 6

Exposure of standing subjects to fore-and-aft floor vibration showed that head motion occurred mainly in the mid-sagittal plane. Subjects standing and holding on to a handrail with a rigid grip resulted in significantly more head motion than when holding the handrail with a light grip. Fore-and-aft motion at the head showed an increase in the frequency of maximum transmissibility from 0.5 Hz for the subjects standing with a light grip to 1.2 Hz for the rigid grip posture. The general shapes of the transmissibilities for vertical and pitch motion at the head were similar with the rigid grip posture displaying two peaks at frequencies of about 2 Hz and 4.2 Hz.

CONCLUSION 7

During exposure to lateral axis floor vibration, head motion occurred mostly in the lateral axis and below about 3 Hz. The effect of foot separation when standing and exposed to lateral floor vibration was to increase head motion over the 1 Hz to 3 Hz frequency range for foot separations of up to 60 cm. No firm conclusions can be made about the effect of foot separation on motion in the other axes at the head but there was a tendency for the feet together posture to show higher transmissibilities than the other two foot separations (i.e. 30 cm and 60 cm). Greater postural stability was offered with 30 cm and 60 cm foot separations than with the feet together.

CONCLUSION 8

During exposure to vertical floor vibration for standing subjects, motion at the head occurred mainly in the mid-sagittal plane. Transmissibilities for the fore-and-aft and pitch axes at the head showed a cross-over region around 4 Hz; the effect of standing in a 'legs bent' posture was to increase head motion for frequencies below 4 Hz compared with a 'legs locked' posture. The reverse occurred for frequencies above 4 Hz: a 'legs locked' posture resulted in the greatest head motion and least motion occurred when standing in a 'legs bent' posture. Both the fore-and-aft and pitch axis head motions showed a decrease in the resonance frequency as posture was changed from a 'legs locked' to a 'legs bent' posture. The cross-over region was not so well defined for head motion in the vertical axis but occurred around 3 Hz to 5 Hz.

CONCLUSION 9

Field measurements of motions in the mid-sagittal plane of the head showed that fore-and-aft motion at the head was mainly affected by fore-and-aft seat vibration for frequencies below about 1 Hz and vertical motion at the seat caused most of fore-and-aft axis head motion over the 3 Hz to 10 Hz frequency range. Vertical motion at the head was mostly caused by vertical vibration at the seat; the effect of fore-and-aft axis seat motion was dominant only at frequencies below 1 Hz. Seat motion in the vertical axis was responsible for pitch axis motion at the head. Pitch motion at the seat had no effect on any of the axes of head motion in the mid-sagittal plane.

CONCLUSION 10

Field measurement of seat and head motion in the mid-coronal plane showed that seat vibration in the lateral axis mainly caused lateral head motion below about 3 Hz. Vibrations in the roll axis at the seat had only a small effect on lateral axis motion at the head. The effect of lateral and roll axis seat vibration was small. Head motion in the roll axis was influenced mostly by vertical seat vibration.

9.3 RECOMMENDATIONS

RECOMMENDATION 1

In the experiments reported above for seated subjects, only two postures of the body were investigated ('back-on' and 'back-off'), but these were researched in depth. Other postural variations affect seat-to-head transmissibility which have not been so well documented should be considered in future experiments. These include body postures ranging from 'slouched' to 'erect', and the effect of seating variations such as the wearing of a harness (e.g. three, four or five point harness). When using terms such as 'slouched' and 'erect', some quantitative measure of posture should be used rather than a subjective measure. Such a procedure would provide a better insight into the variability in transmissibility between individuals.

RECOMMENDATION 2

Comprehensive data obtained from the above experiments are mostly original in that they are not available elsewhere, especially the data dealing with horizontal seat vibration. Results from the fore-and-aft seat vibration study showed the large effect that a seat backrest has on head motion; such data could be used to determine the effectiveness of providing backrests for vehicle operators (although the effect of the height of backrest may require further research for the data to be applicable in design purposes).

RECOMMENDATION 3

The frequency ranges used in the experiments reported in this thesis have been from 0.25 Hz to 16 Hz for horizontal seat vibration and 0.25 Hz to 25 Hz for vertical seat vibration; the frequency ranges for standing subject experiments were 0.06 Hz to 10 Hz for horizontal floor vibration and 0.25 Hz to 25 Hz for vertical floor vibration. It was observed that peculiar phase data resulted for very low frequencies for some axes of head motion during horizontal seat vibration. This was thought to be due to active postural feedback of the body - involuntary movement of the body to counteract motion transmitted to the head. Future experiments could include the study of the low frequency aspect of vibration using finer frequency resolutions in the analyses. The study of postural feedback at low frequencies is even more important for standing subjects as motion transmitted to the head during fore-and-aft and lateral floor vibration was below 5 Hz and mostly around 1 Hz. This might require the use of low frequency and large displacement vibrators. For such an investigation, long durations of vibration exposure would be required. One other aspect of the effect of whole-body vibration that could also be studied is postural stability. Frequencies and magnitudes that cause loss of balance and the effectiveness of handrails could form a part of an experiment. Further investigation and interpretation of phase data could possibly be encouraged by the use of better programming algorithms.

RECOMMENDATION 4

It has been shown elsewhere (e.g. Griffin et al., 1979; Wilder et al., 1982) that subject gender has an effect on the transmission of seat vibration to the head. A large proportion of the studies found in the literature concerned with biodynamics have involved only male subjects - this is only one half of the population. The data presented in this thesis were collected using male subjects. A similar study could merit investigation using both male and female subjects to determine the effect of gender on transmissibility. The effect of other subject characteristics on transmissibility should also be researched. However, it must be borne in mind that obtaining reliable data to determine the effect of subject characteristics might prove impracticable since variables such as posture and muscle tension, which are known to have a large effect on seat-to-head transmissibility, might be difficult to maintain constant between subjects.

RECOMMENDATION 5

Gravity is a force vector that will affect all translational accelerations measured using piezo-resistive accelerometers. Rotational accelerations are not affected by the Earth's gravitational force. The measurement of horizontal accelerations (that is, those axes which are perpendicular to the gravity vector) will be most affected and this is most likely to be the case at low frequencies where rotational displacements maybe large. (This might particularly be the case for experiments involving exposure to rotational motions of the body.) Future analyses of biodynamic data should calculate the effect of gravity and then subtract the proportion due to gravity from the measured translational motion signal to determine the true translational signal before the calculation of transmissibilities, etc.

RECOMMENDATION 6

A successful attempt has been made to calculate translational motion at different points on the head using the six axes of motion at one known point on the head. The procedure was conducted for only one subject and for only one posture. The procedure can be repeated for other subjects, postures and axes of input vibration to determine the different modes of vibration of the head and be used as a tool for comparison of data with other reported studies. Future experiments on biodynamics should, if possible, measure head motion in all six axes. From the preliminary data it seems that the motion of the head is almost as complex as the transmission of vibration through the body to the head!

RECOMMENDATION 7

Most of the experiments reported in this thesis for standing and seated subjects could be repeated to obtain transmissibility responses during exposure to rotational vibration of the seat or the floor. Although some experiments have been conducted by other researchers on rotational seat vibration, further data on this topic would be useful. No publications were found concerning the transmission of roll and pitch vibration from the floor to the heads of standing subjects. The main reason for this lack of data could be that equipment for producing rotational vibrations is not readily available.

RECOMMENDATION 8

All the above different methods of analysing biodynamic data should be used where input vibration occurs in more than one axis or at more than one location (e.g. at the seat surface and the backrest). This includes the following methods: 'power spectral density function method', 'cross-spectral density function method', ordinary coherencies, partial coherencies and conditioned spectra. Intermediate spectra can also be determined; this could include the spectra of the following motions for a three-in one-out system:

i) total,
ii) linearly correlated,
iii) subtract effect of input 1,
iv) subtract effect of input 2,
v) subtract effect of inputs 1 and 2, and
vi) noise, that is, subtract effect of inputs 1, 2 and 3.

RECOMMENDATION 9

Future analysis of biodynamic data could include an investigation of the effect of rotational motion at the head on the measurement of translational motion. An example of this could be the measurement of motion in the vertical and pitch axes at the head where vertical head motion would correlate with pitch axis motion at the head. (The magnitude of vertical head motion would be proportional to the distance between the point of measurement and the centre of rotation for pitch axis motion.) Vertical head motion would also correlate with roll motion at the head. Another example of this is fore-and-aft axis head motion which would correlate with motion in the pitch and yaw axes at the head.

RECOMMENDATION 10

Field data reported in this thesis have involved the measurement of three axes of vibration at the seat and three axes at the head. This involved the measurement of only half the active axes at both locations (though measurements made might have been of motions in the important axes). The ultimate task would be to monitor 6 axes of motion at the head and 6 axes of vibration at the seat. Then analyses similar to the above for a system involving six inputs and one output could be used to determine (amongst other spectra), the remnant motion (noise) at the head, that is, head motion not correlated with seat motion in any of the six axes. This could be further extended to a six-in six-out system to estimate, for example the noise which would truly be 'noise' which is not correlated with any axis of seat motion nor with any axis of head motion other than the axis containing the 'noise'. This 'noise' might be due to voluntary movement of the body, active postural control, electronic noise of the measuring apparatus, etc.

RECOMMENDATION 11

The various spectral methods mentioned above would be well suited for the analysis of field data where seat motion would normally occur in several axes. However, these methods could well be applied to laboratory based experiments involving the use of combined axis vibration. An example of this is seat vibration in both the fore-and-aft and vertical axes (both these axes are in the mid-sagittal plane). If equipment allowed, motion in a further axis could be included to simulate motion in a single plane (i.e. the pitch axis). This method of 'step-by-step' experimentation has at least two uses: (i) comparisons can be made between transmissibility data collected in field conditions and laboratory experiments. (This thesis presents data from both these environments which could be used for comparison purposes.) (ii) Laboratory data presented in this thesis concerned with single axis vibration exposures could be used to establish whether biodynamic data such as transmissibility has an additive effect. That is, to see if transmissibilities obtained for single axis vibration exposures can be added to predict the response during combined axis vibration exposures. Data included in this thesis would be ideal for such purposes.

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APPENDIX 1

VIBRATOR RESPONSE EQUALISATION

This appendix explains a procedure for equalising for the response of a vibrator.

1. Feed a broad-band signal into the vibrator and acquire the response waveform.

2. Obtain a transfer function between the input broad-band signal and the vibrator response waveform.

3. Calculate the reciprocal of the transfer function to get a weighting function.

4. Convert the weighting function into the time domain.

5. Convolve the broad-band signal from 1 or any other input time history with the weighting function.

6. Feed the weighted time history from 5 into the vibrator.

The response waveform of the vibrator after using the input signal from 6 should be the same as the broad-band signal (or any other time history) used in 5 above.

APPENDIX 2

THREE-INPUT SINGLE-OUTPUT SYSTEM

This appendix explains the method of calculation of partial coherencies and correlated conditioned spectra for a three input one output system.

Analyses for the calculation of the partial coherence function for a two-in one-out system have been discussed by Bendat and Piersol (1980). This analysis for a three-in one-out system shown in Figure A2.1 is an extension of the two-in one-out system involving the repetitive use of some basic equations.

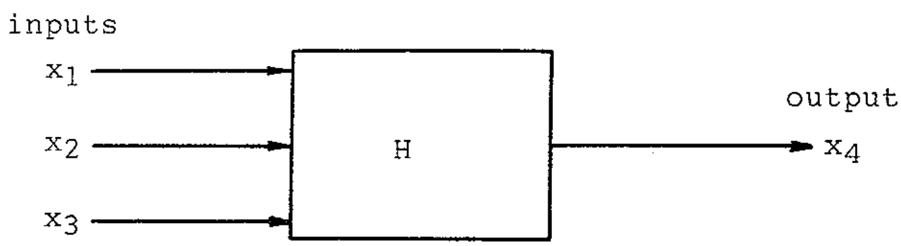

Figure A2.1 A three-in one-out system.

This system can be simplified using a decomposition technique shown in Figure A2.2 for inputs x_1 and x_2.

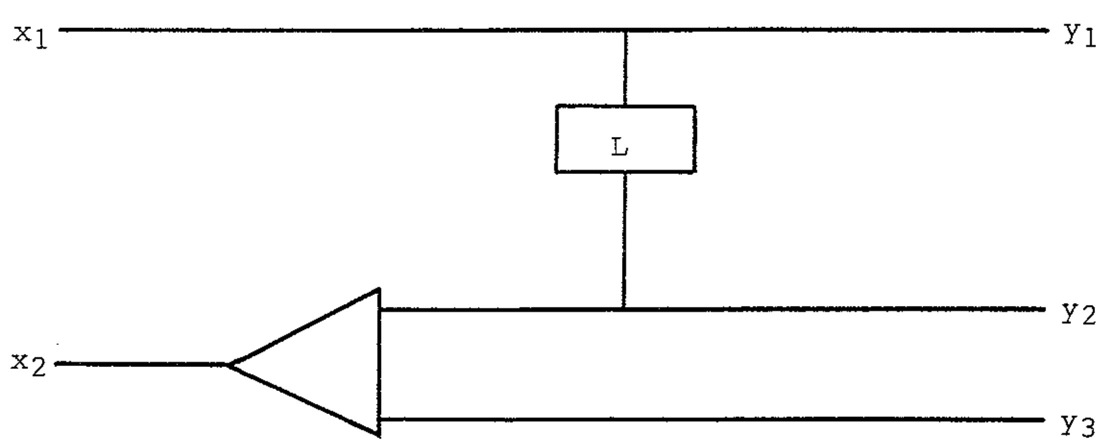

Figure A2.2 Decomposition of two signals.

Input x_2 is decomposed into two parts; y_2 which is linearly correlated with input x_1 via a linear filter L, and y_3 which is not correlated with x_1. The notation used in this analysis will be that, as y_3 has been conditioned for input x_1 (that which is left over from x_2 after subtracting the effect of x_1 from x_2), it will be written as $x_{2.1}$, i.e. input x_2 conditioned for input x_1.

The spectrum of the linearly correlated part of input x_2 is

$$Gy_2y_2 = \gamma^2 x_1x_2 \; Gx_2x_2 \tag{1}$$

using notation

$$Gx_2x_2 = G_{22} \tag{2}$$

then becomes

$$Gy_2y_2 = \gamma^2_{12} \; G_{22} \tag{3}$$

As spectra are additive,

$$\begin{aligned} G_{22} &= Gy_2y_2 + Gy_3y_3 \\ &= \gamma^2_{12} \; G_{22} + G_{22.1} \end{aligned}$$

Rearranging,

$$G_{22.1} = (1 - \gamma^2_{12}) \; G_{22} \tag{4}$$

Generalising gives,

$$\underline{G_{ii.j} = (1 - \gamma^2_{ji}) \; G_{ii}} \tag{5}$$

The partial coherency between input x_3 and output x_4 is

$$\gamma^2_{34.12} = \frac{|G_{34.12}|^2}{G_{33.12} \; G_{44.12}} \tag{6}$$

The denominator contains second conditioned spectra which can be determined by using a second conditioned spectra form of equation (5), which is

$$\underline{G_{ii.jk} = (1 - \gamma^2_{ki.j})\ G_{ii.j}} \qquad (7)$$

Hence,

$$G_{33.12} = (1 - \gamma^2_{23.1})\ G_{33.1} \qquad (8)$$

and

$$G_{44.12} = (1 - \gamma^2_{24.1})\ G_{44.1} \qquad (9)$$

To determine the single conditioned coherence function $\gamma^2_{23.1}$, consider the equation

$$\gamma^2_{23.1} = \frac{|G_{23.1}|^2}{G_{22.1}\ G_{33.1}} \qquad (10)$$

The conditioned cross spectrum in the numerator is determined by considering Fourier transforms

$$G_{23.1} = X^*_{2.1}\ X_{3.1} \qquad (11)$$

where $X^*_{2.1}$ is a conjugate of $X_{2.1}$.
Addition gives (see Figure A2.2)

$$X_2 = Y_2 + X_{2.1} \qquad (12)$$

Using linear filter L,

$$Y_2 = \left[\frac{G_{12}}{G_{11}} \right] X_1 \qquad (13)$$

Substituting and rearranging gives

$$X_{2.1} = X_2 - \left[\frac{G_{12}}{G_{11}} \right] X_1 \qquad (14)$$

Similarly for $X_{3.1}$

$$X_{3.1} = X_3 - \left[\frac{G_{13}}{G_{11}} \right] X_1 \qquad (15)$$

Then substitute for $X^*_{2.1}$ and $X_{3.1}$ into equation (11),

$$G_{23.1} = \left[X_2 - \left[\frac{G_{12}}{G_{11}} \right] X_1 \right]^* \left[X_3 - \left[\frac{G_{13}}{G_{11}} \right] X_1 \right] \qquad (16)$$

which gives

$$G_{23.1} = G_{23} - \frac{G_{21}\ G_{13}}{G_{11}} \qquad (17)$$

Equation (17) in a generalised form is

$$\underline{G_{ij.k} = G_{ij} - \frac{G_{ik}\ G_{kj}}{G_{kk}}} \qquad (18)$$

An expression is required for the numerator in equation (6), i.e. $G_{34.12}$. This can be easily obtained by using a similar derivation as that for equation (17), which gives

$$G_{34.12} = G_{34.1} - \frac{G_{24.1}\ G_{32.1}}{G_{22.1}} \qquad (19)$$

or in a more general form,

$$\underline{G_{ij.km} = G_{ij.k} - \frac{G_{mj.k}\ G_{im.k}}{G_{mm.k}}} \qquad (20)$$

The general form equations (5), (7), (18) and (20) enable the partial coherency $\gamma^2_{34.12}$ to be calculated.

Various forms of correlated and conditioned spectra can be calculated using the above analyses and these are related by

$$G_{44} = \gamma^2_{14}\, G_{44} + \gamma^2_{24.1}\, G_{44.1} + \gamma^2_{34.12}\, G_{44.12} + G_{44.123} \qquad (21)$$

where

G_{44} = power spectrum of output,

$\gamma^2_{14}\, G_{44}$ = proportion of output linearly correlated with input x_1,

$\gamma^2_{24.1}\, G_{44.1}$ = proportion of output linearly correlated with input x_2 after conditioning input x_2 and output x_4 for input x_1,

$\gamma^2_{34.12}\, G_{44.12}$ = proportion of output linearly correlated with input x_3 after conditioning input x_3 and output x_4 for inputs x_1 and x_2,

$G_{44.123}$ = power spectrum of proportion of output x_4 uncorrelated with inputs x_1, x_2 and x_3.

REFERENCE

Bendat, J.S. and Piersol, A.G. (1980) Engineering applications of correlation and spectral analysis. John Wiley and Sons.

APPENDIX 3

INSTRUCTIONS TO SUBJECTS DURING TRANSLATIONAL SEAT VIBRATION

Subjects who took part in the intra- and inter-subject variability studies on the transmission of translational seat vibration to the head were given a set of written instructions about the required postures of the body and position of the head, legs, arms, etc.

Following is a copy of the instructions:

INSTRUCTIONS TO SUBJECTS

TRANSLATIONAL VIBRATION, SEATED SUBJECTS

The aim of this experiment is to monitor the motion of the head during single axis translational seat vibration.

In order to minimise the effect of the other variables, it is important that you maintain a 'comfortable upright posture' throughout the experiment. If you are instructed to make use of the backrest, then lean but not push against the backrest. If you are instructed to keep off the backrest, then your back should be approximately 150 mm in front of the backrest. Keep your feet and legs together and your lower legs vertical. Place your hands together in your lap and avoid movements of either the arms or legs.

Just prior to the start of each run, which the experimenter will indicate, you are to place the bite-bar in your mouth and adjust your head to a normal upright forward facing position. This position is to be kept during all the runs. Keep your eyes on the cross on the opposite wall and avoid voluntary movements of the head. Ensure that a normal bite grip is kept on the bite-bar.

You are free to terminate the experiment at any time by pressing the red STOP button.

Thank you for taking part in this experiment.

APPENDIX 4

COHERENCIES FOR TRANSLATIONAL SEAT VIBRATION EXPERIMENTS

Ordinary coherencies were calculated for experiments involving the transmission of translational seat vibration to the heads of seated subjects. This appendix contains coherency data for intra- and inter-subject variability experiments. There were 12 vibrations exposures for the subject who took part in the intra-subject variability study. Twelve subjects participated in the inter-subject variability studies and 31 subjects volunteered for the centre of rotation for pitch head motion experiment. The data are included as follows:

Figure	Vibration axis	Number of subjects	Posture
A4.1	x	1	'back-on'
A4.2	x	1	'back-off'
A4.3	x	12	'back-on'
A4.4	x	12	'back-off'
A4.5	y	1	'back-on'
A4.6	y	1	'back-off'
A4.7	y	12	'back-on'
A4.8	y	12	'back-off'
A4.9	z	1	'back-on'
A4.10	z	1	'back-off'
A4.11	z	12	'back-on'
A4.12	z	12	'back-off'
A4.13	x	31	'back-on'

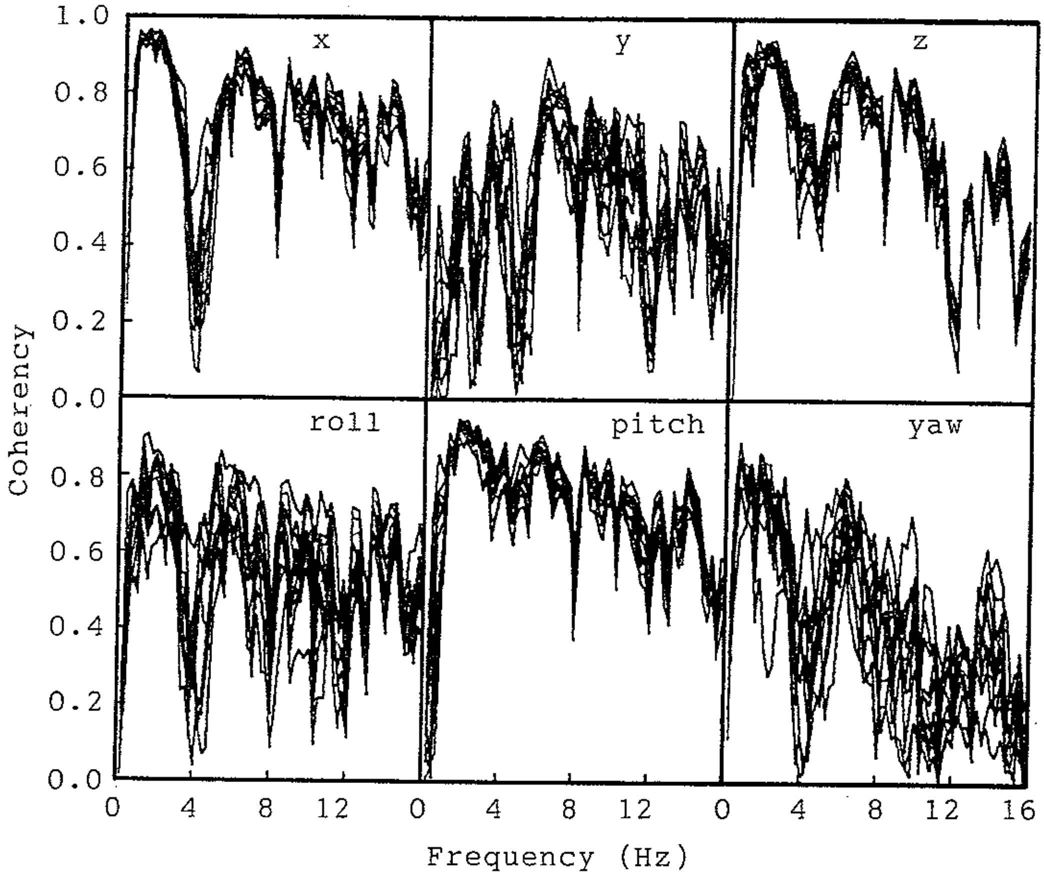

Figure A4.1 Coherencies for 1 subject in a 'back-on' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

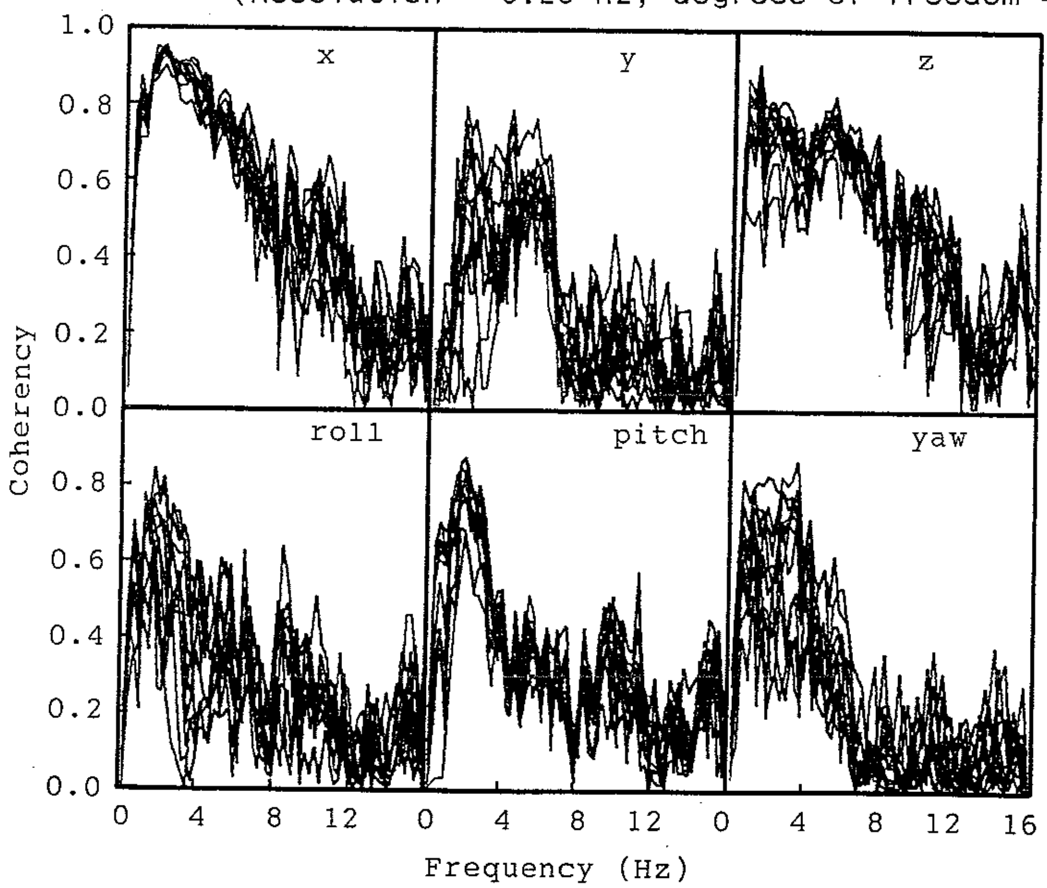

Figure A4.2 Coherencies for 1 subject in a 'back-off' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

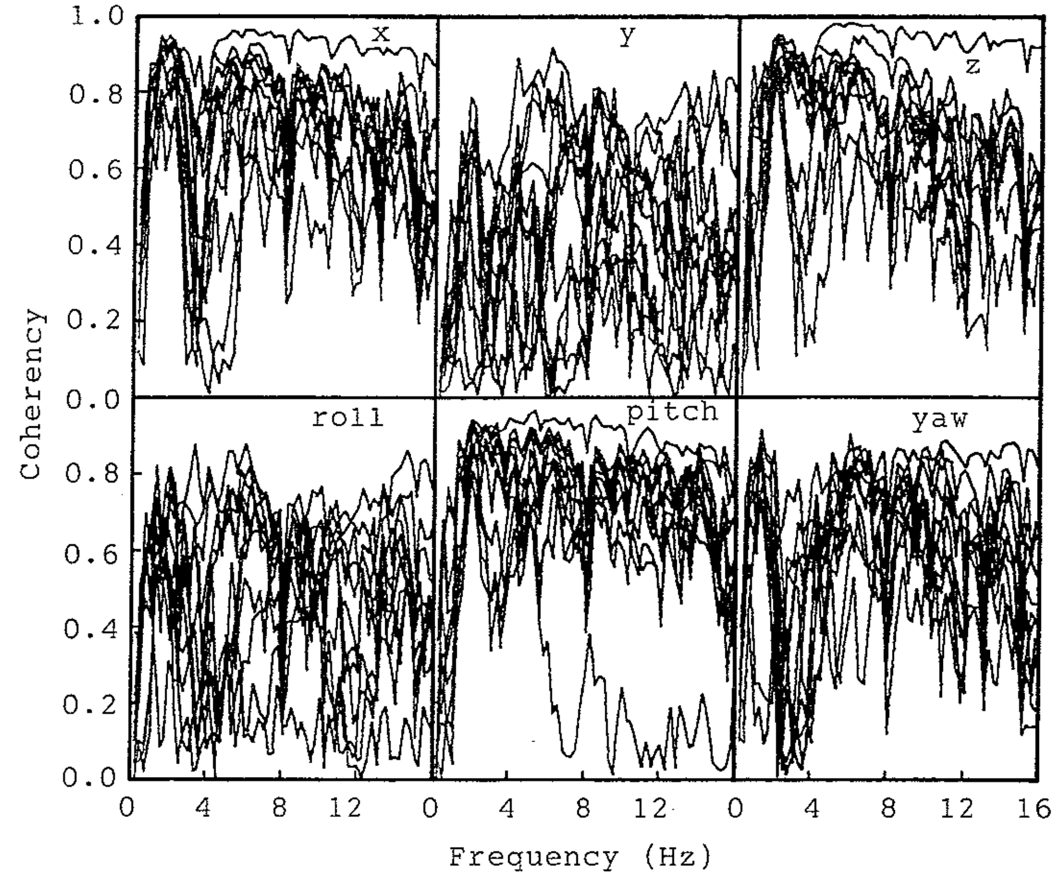

Figure A4.3 Coherencies for 12 subjects in a 'back-on' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

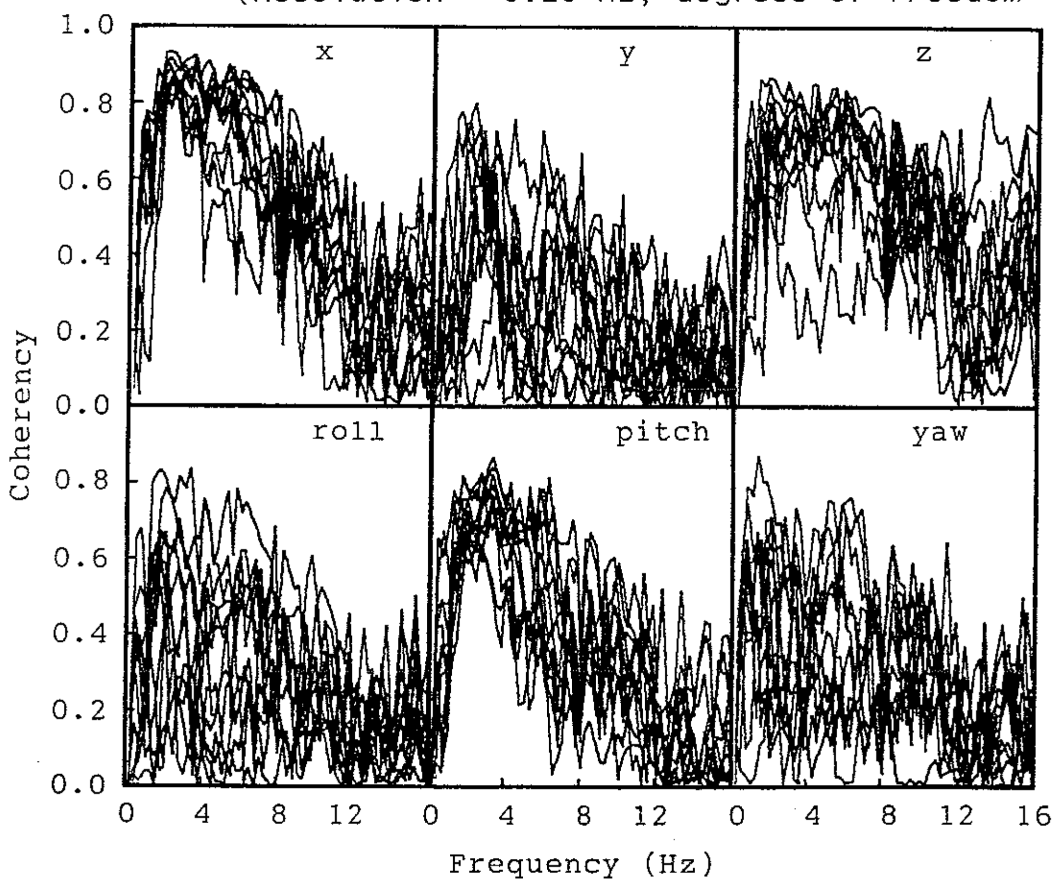

Figure A4.4 Coherencies for 12 subjects in a 'back-off' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

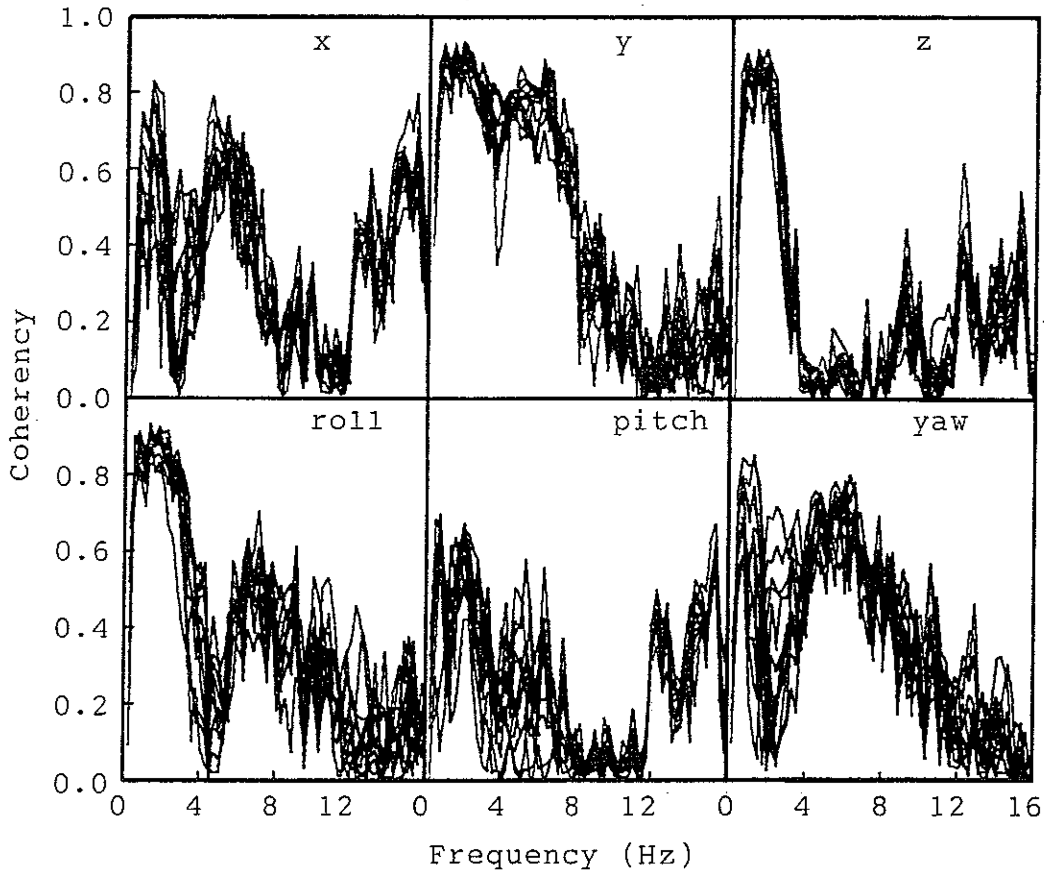

Figure A4.5 Coherencies for 1 subject in a 'back-on' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

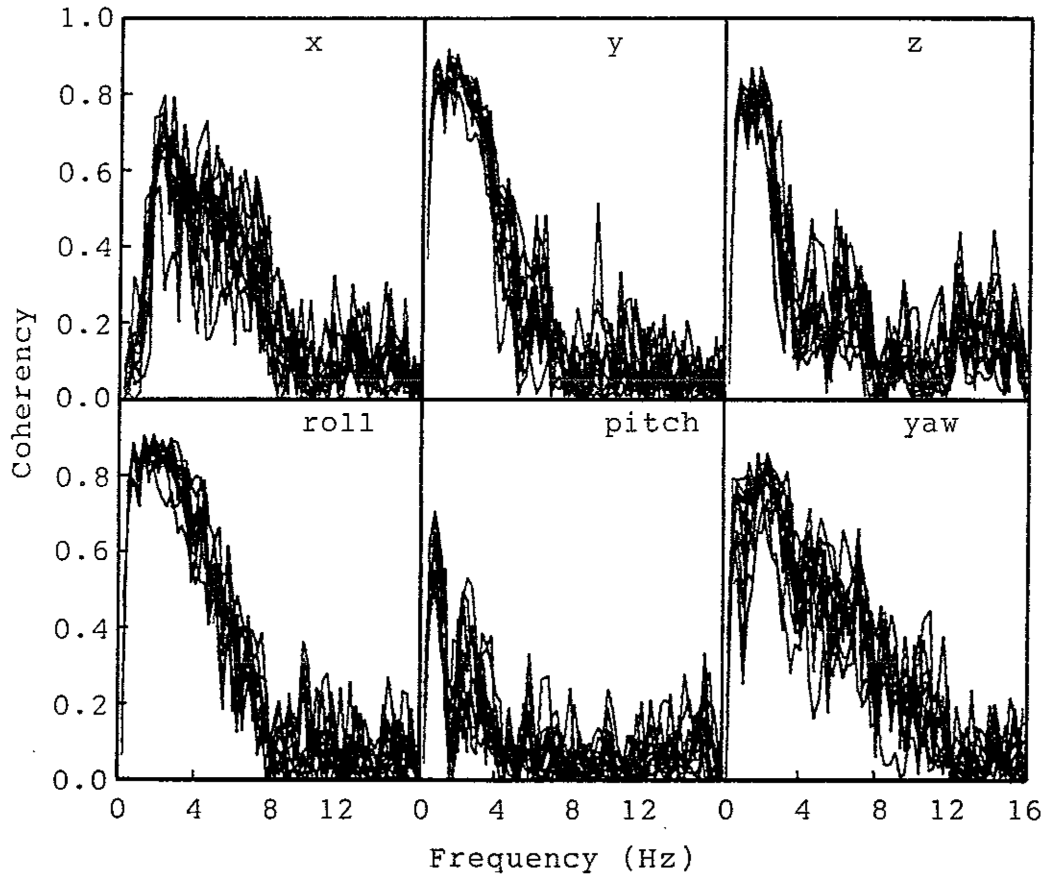

Figure A4.6 Coherencies for 1 subject in a 'back-off' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

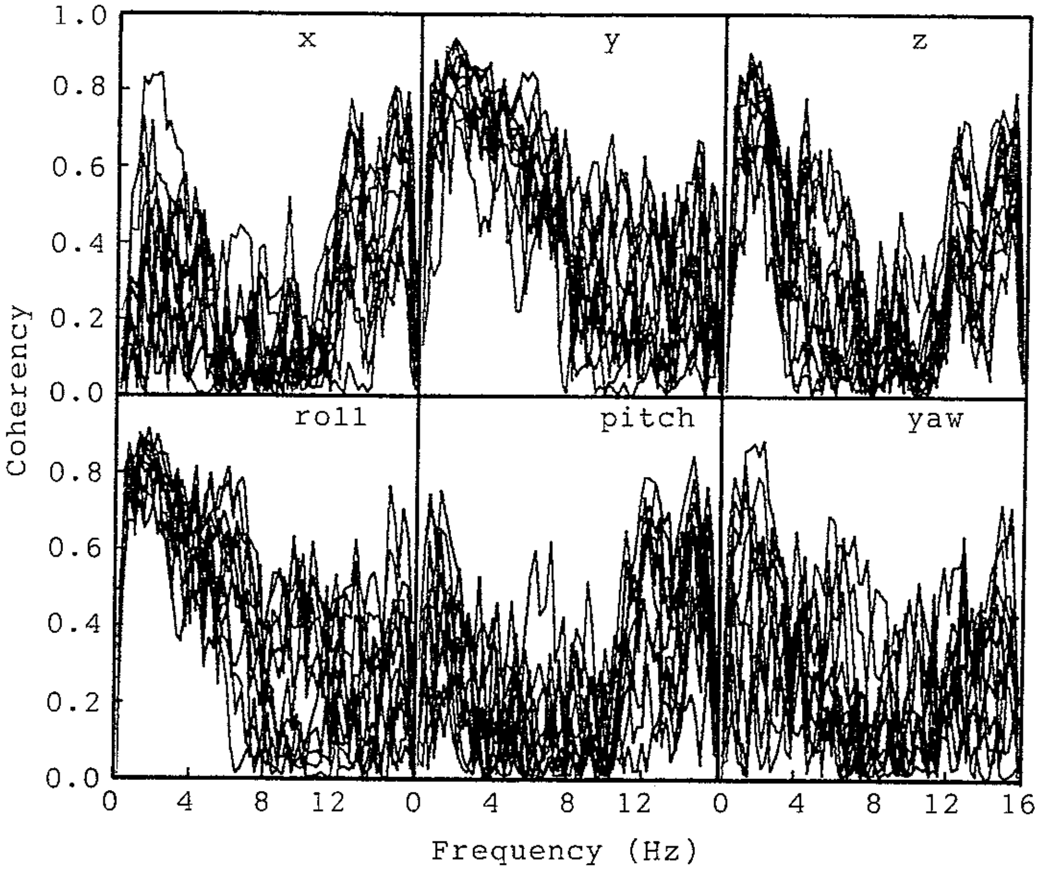

Figure A4.7 Coherencies for 12 subjects in a 'back-on' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

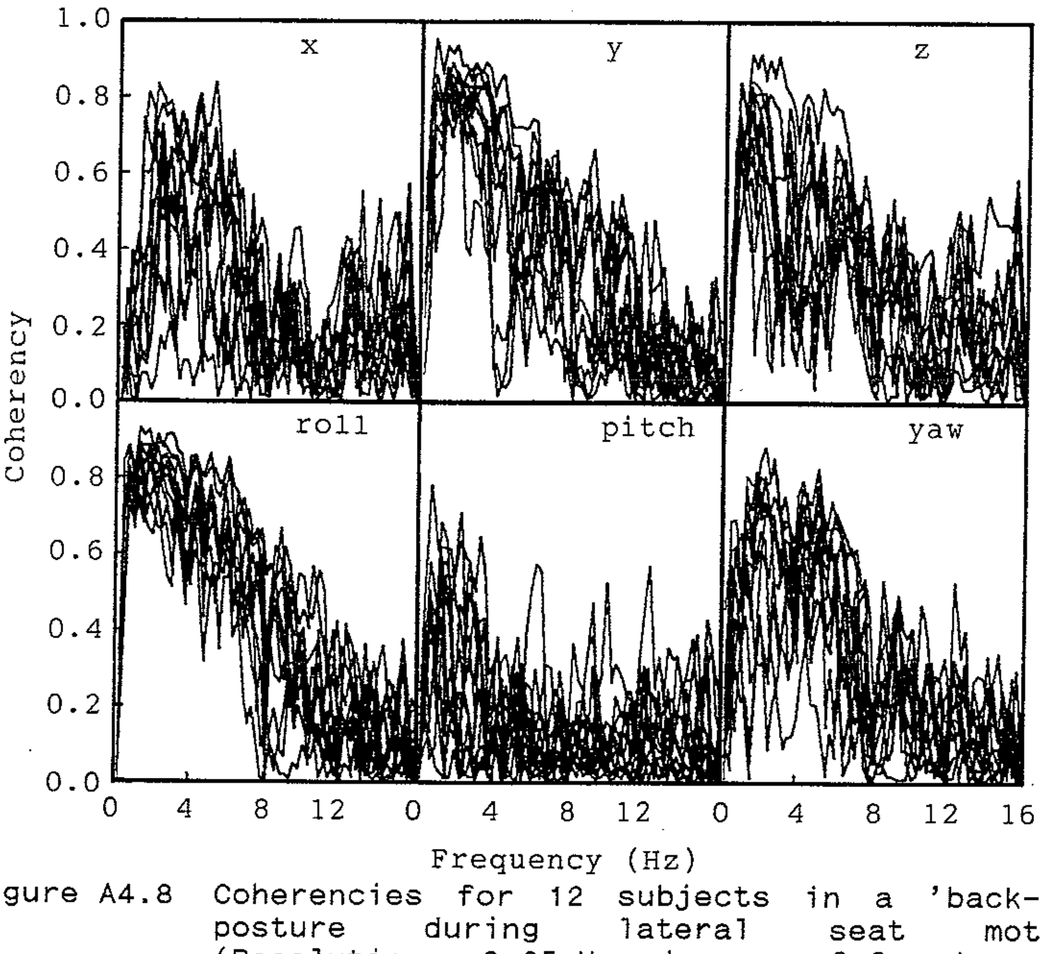

Figure A4.8 Coherencies for 12 subjects in a 'back-off' posture during lateral seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

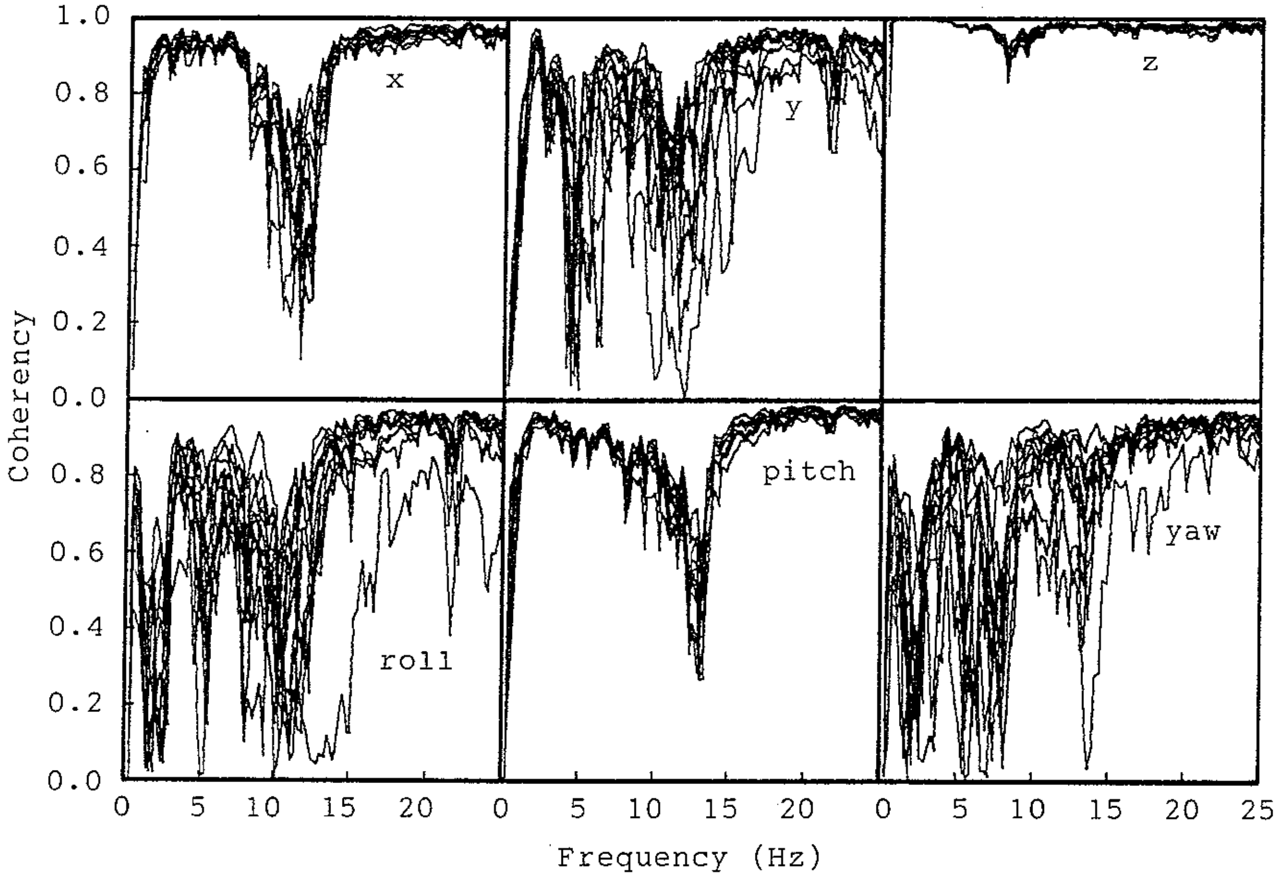

Figure A4.9 Coherencies for 1 subject in a 'back-on' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

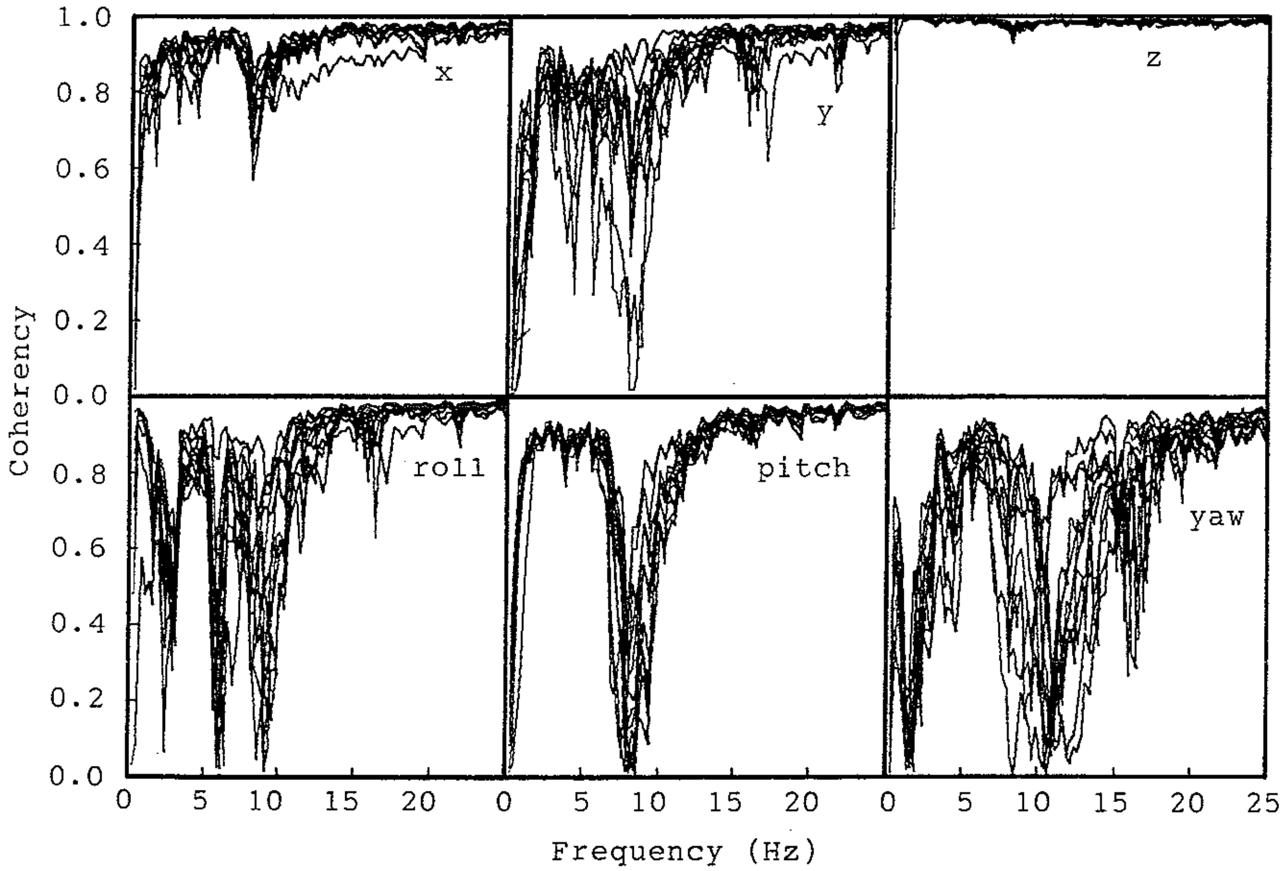

Figure A4.10 Coherencies for 1 subject in a 'back-off' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

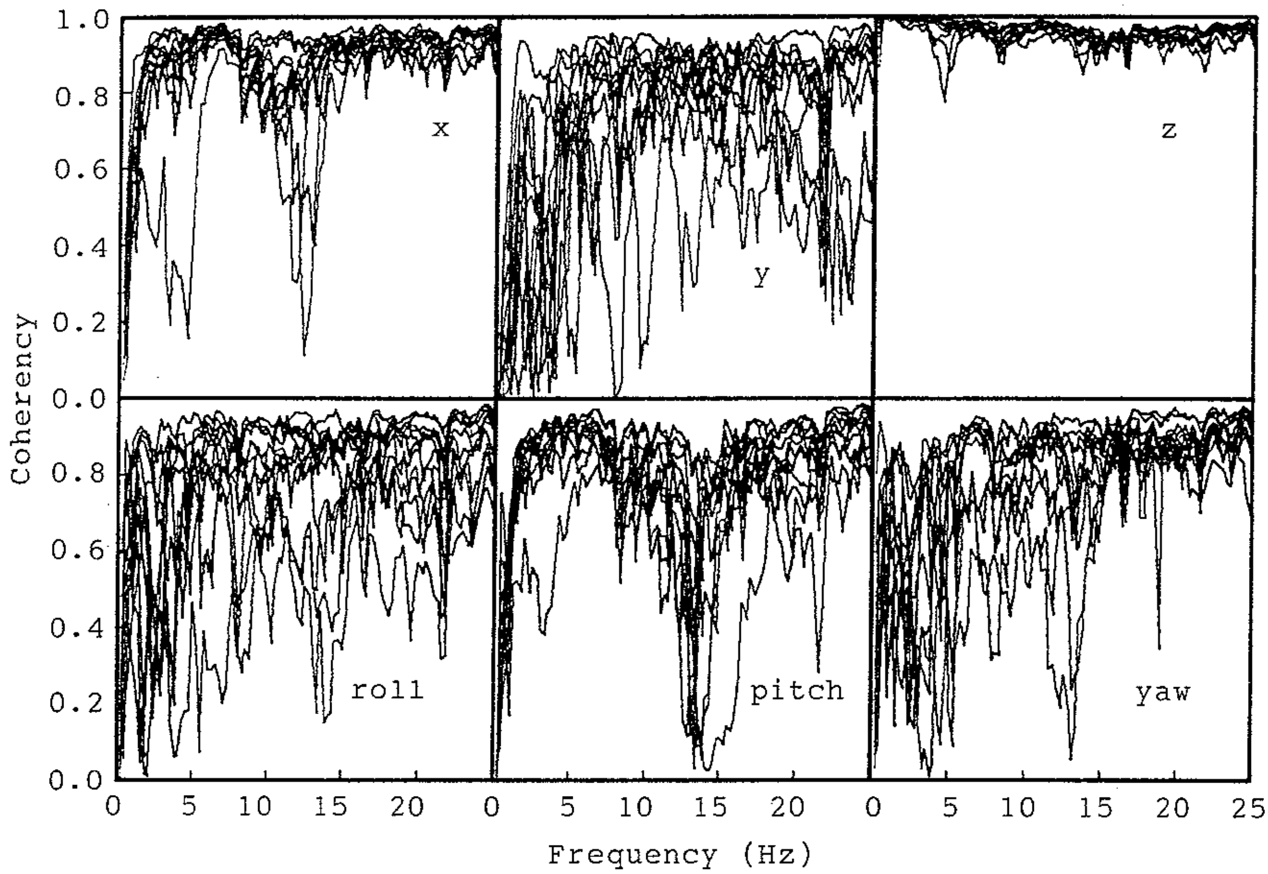

Figure A4.11 Coherencies for 12 subjects in a 'back-on' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

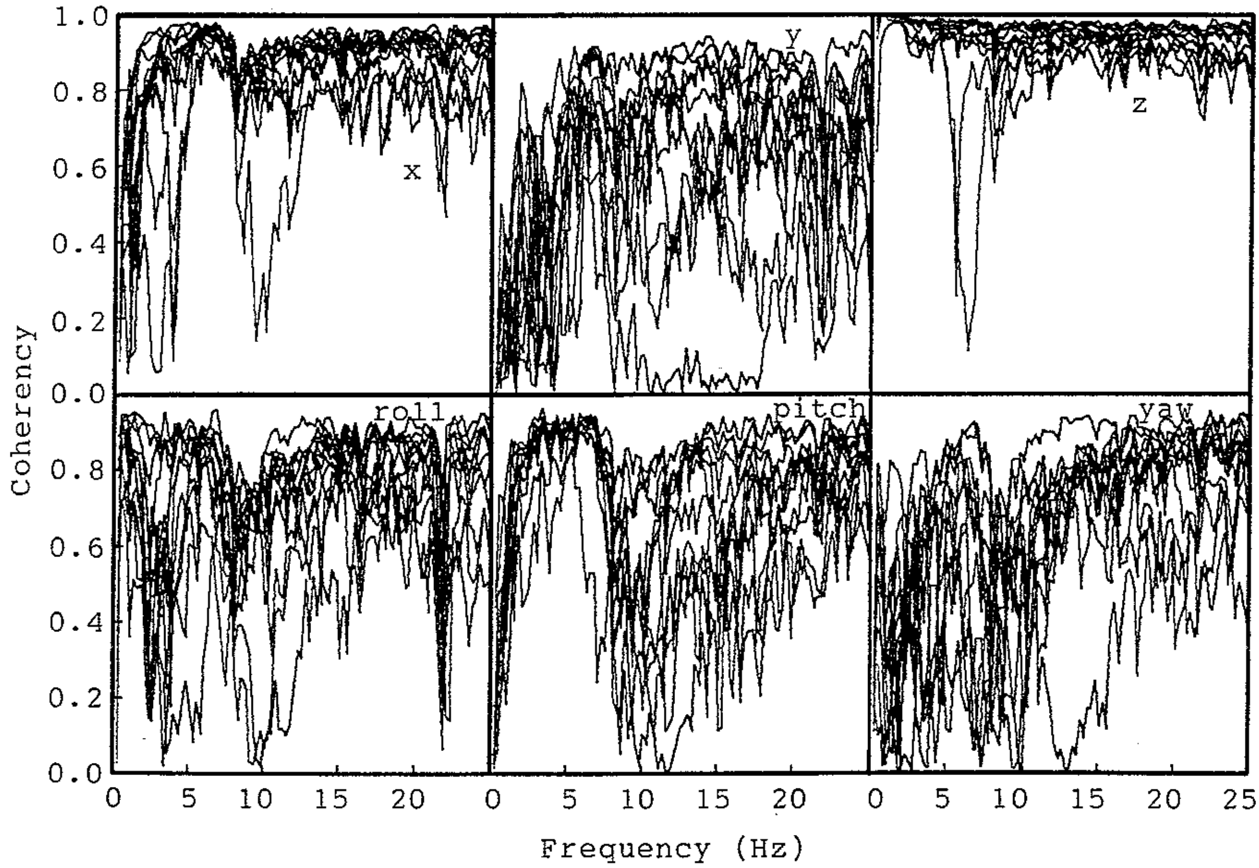

Figure A4.12 Coherencies for 12 subjects in a 'back-off' posture during vertical seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

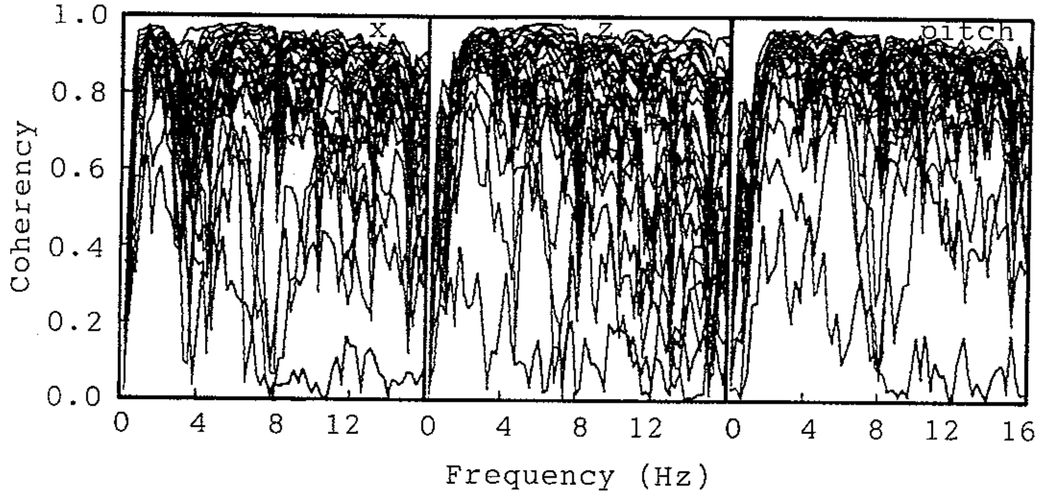

Figure A4.13 Coherencies for 31 subjects in a 'back-on' posture during fore-and-aft seat motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

APPENDIX 5

PHYSICAL CHARACTERISTICS OF SUBJECTS TAKING PART IN TRANSLATIONAL SEAT VIBRATION EXPERIMENTS

Twelve male subjects took part in the inter-subject variability experiments to determine the transmission of translational seat vibration to the head. Their following physical characteristics were measured:

i) Age: - years
ii) Weight: - clothed
iii) Height: - stature while standing
iv) Hip size: - largest circumference around the hips
v) Lower leg length: - sitting knee height
vi) Inner leg length: - crotch height

These are shown in Table A5.1.

Table A5.1 Physical characteristics of subjects who took part in the inter-subject variability experiment on head motion during translational seat motion.

Subject	Age (yrs)	Weight (kg)	Height (m)	Hip size (m)	Lower leg length (m)	Total leg (m)
1	18	62	1.77	0.94	0.59	0.85
2	34	75	1.80	0.96	0.58	0.83
3	27	59	1.65	0.89	0.54	0.76
4	26	81	1.78	1.05	0.59	0.83
5	27	58	1.73	0.92	0.54	0.77
6	29	79	1.83	1.02	0.61	0.90
7	24	71	1.79	0.99	0.55	0.81
8	23	77	1.91	0.99	0.62	0.93
9	23	79	1.84	1.01	0.57	0.81
10	24	69	1.85	1.00	0.58	0.85
11	33	72	1.75	0.99	0.57	0.75
12	25	68	1.90	0.97	0.61	0.88
Minimum	18	58	1.65	0.89	0.54	0.75
Maximum	34	81	1.91	1.05	0.62	0.93
Mean	26.08	70.83	1.80	0.98	0.58	0.83
Standard deviation	4.23	7.57	0.07	0.04	0.03	0.05

Thirty-one subjects of both sexes participated in the study to determine the centre of rotation of pitch head motion during exposure to fore-and-aft seat vibration. Their following physical characteristics were measured:

i) Age: - years

ii) Weight: - clothed

iii) Height: - stature while standing

iv) Sitting height: - seat surface to crown of the head

v) Ear-mouth x- distance: - horizontal distance between the auditory meatus and the mouth

vi) Ear-mouth z- distance: - vertical distance between the auditory meatus and the mouth

vii) Ear-shoulder distance: - vertical distance between the auditory meatus and the shoulder

viii) Ear-pelvis distance: - vertical distance between the auditory meatus and the pelvis

These are shown in Table A5.2 for all the subjects.

Table A5.2 Physical characteristics of subjects who took part in a study to determine the centre of rotation of head pitch motion during fore-and-aft seat motion. (Continued)

Subject	Gender	Age (yrs)	Weight (kg)	Height (m)	Sitting height (cm)	Ear-mouth x-distance (cm)	Ear-mouth z-distance (cm)	Ear-shoulder z-distance (cm)	Ear-pelvis z-distance (cm)
1	M	28	51	1.69	71	7	6	16	51
2	M	62	75	1.79	77	9	4	16	53
3	M	20	63	1.83	81	9	6	17	54
4	M	12	50	1.55	62	8	4	11	44
5	M	12	48	1.60	71	7	5	16	56
6	M	8	31	1.33	53	8	3	11	37
7	M	30	71	1.86	83	8	5	17	62
8	M	17	59	1.77	73	7	4	15	52
9	M	17	47	1.64	70	8	5	14	59
10	M	17	64	1.75	77	8	4	16	56
11	M	69	65	1.80	77	9	3	17	56
12	M	30	56	1.73	72	8	4	14	53
13	M	17	65	1.83	79	8	4	16	57
14	M	31	64	1.74	76	7	4	16	55
15	M	33	80	1.81	83	7	5	16	60
16	F	59	58	1.71	72	9	4	14	50
17	M	29	61	1.69	74	8	6	15	55
18	M	7	21	1.26	50	7	3	12	37
19	M	37	93	1.85	76	8	7	15	59
20	M	38	68	1.84	83	8	5	18	61
21	M	17	60	1.80	78	8	5	17	59
22	M	17	66	1.92	79	9	5	17	57

(Continued)

Table A5.2 Physical characteristics of subjects who took part in a study to determine the centre of rotation of head pitch motion during fore-and-aft seat motion.

23	M	11	42	1.52	64	7	3	13	48
24	M	44	103	1.89	83	9	5	17	61
25	M	16	66	1.80	78	8	4	17	51
26	M	31	67	1.76	77	9	6	17	57
27	M	16	51	1.77	74	8	5	16	56
28	M	16	65	1.78	72	7	5	14	52
29	M	41	63	1.64	72	9	3	15	54
30	M	13	36	1.55	64	9	6	14	46
31	F	11	37	1.49	64	7	5	14	47
Minimum		7	21	1.26	50	7	3	11	37
Maximum		69	103	1.92	83	9	7	18	62
Mean		26.00	59.55	1.71	73.0	8	4.61	15.26	53.71
Standard deviation		15.77	16.44	0.15	8	0.76	1.04	1.78	6.29

APPENDIX 6

CALCULATION OF THE SIX-AXIS MOTION OF A RIGID BODY

The aim is to calculate the acceleration of a point on a rigid body in all of the six axes of motion. This can be achieved by using nine acceleration transducers mounted at appropriate locations. Figure A6.1 shows the arrangement of nine accelerometers which can be used to calculate all the required accelerations. Four different orthogonal locations are required, and the accelerometers must be orientated so as to measure accelerations in the appropriate axes.

Assume that location 1 is the origin and that locations 2, 3 and 4 are along the x-, y- and z-axes respectively. Also, that the distance between 1 and 2 is X, the distance between 1 and 3 is Y, and the distance between 1 and 4 is Z. The three rotational accelerations can be calculated using the translational accelerations (Padgaonkar et al., 1975):

$$\text{roll, } r_x = \frac{A_{z3} - A_{z1}}{2Y} - \frac{A_{y4} - A_{y1}}{2Z}$$

$$\text{pitch, } r_y = \frac{A_{x4} - A_{x1}}{2Z} - \frac{A_{z2} - A_{z1}}{2X}$$

$$\text{yaw, } r_z = \frac{A_{y2} - A_{y1}}{2X} - \frac{A_{x3} - A_{x1}}{2Y}$$

At point 1, accelerations are then known in all the six axes of motion (x-, y-, z-, roll, pitch and yaw).

Now consider a point P on the body such that the coordinates of point P are (x_p, y_p, z_p). Translational accelerations at point P are given by the following equations:

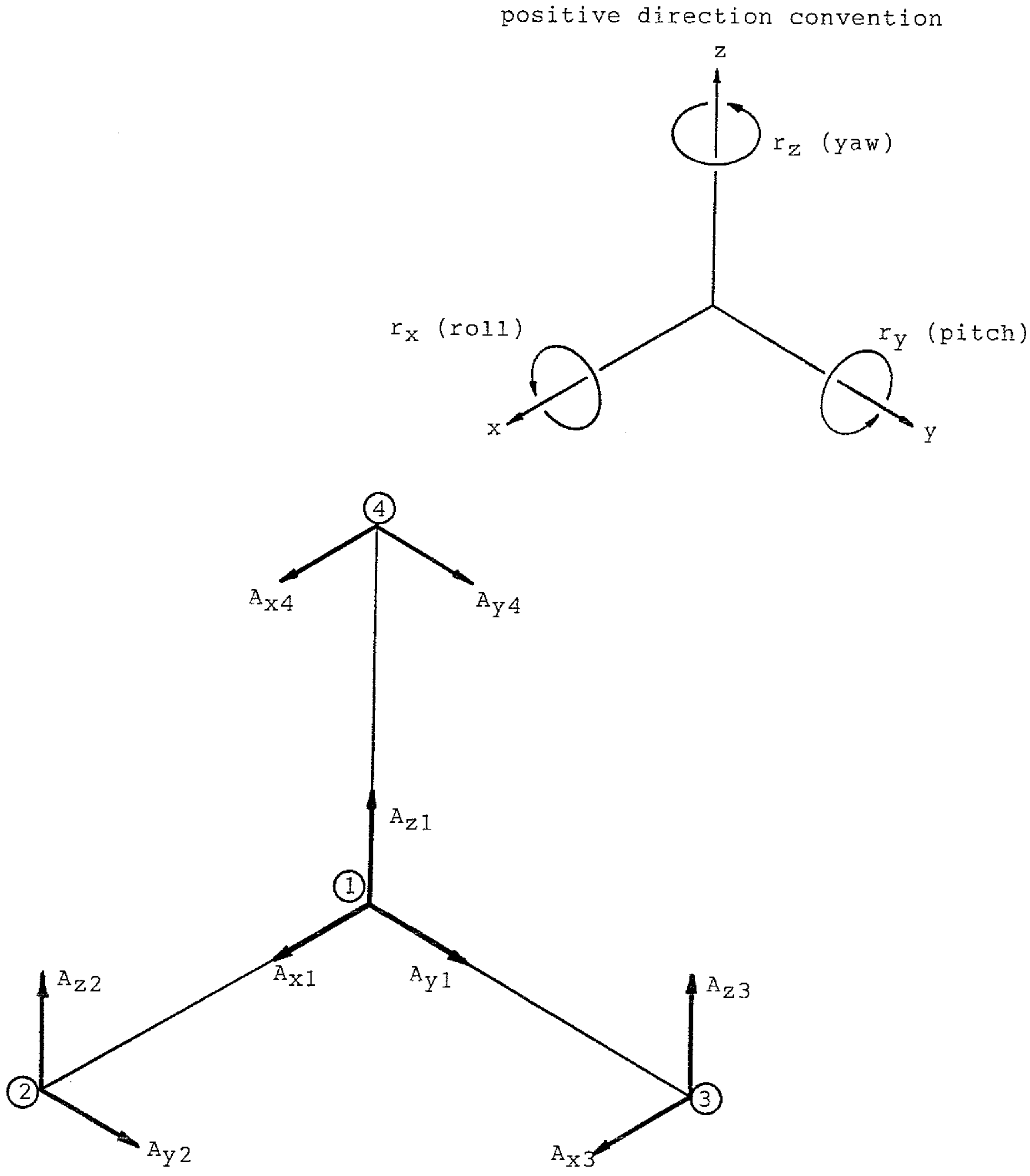

Figure A6.1 Locations and orientations of the nine-accelerometer arrangement.

$$\text{x-axis, } A_{px} = A_{x1} + z_p r_y - y_p r_z$$

$$\text{y-axis, } A_{py} = A_{y1} - z_p r_x + x_p r_z$$

$$\text{z-axis, } A_{pz} = A_{z1} + y_p r_x - x_p r_y$$

where r_x, r_y and r_z are rotational accelerations calculated above.

The nine-accelerometer arrangement can be simplified to a six-accelerometer arrangement if rotational motion of the body was to occur mainly in one axis (i.e. roll, pitch or yaw). The six-accelerometer arrangement is shown in Figure A6.2 with the different locations and orientations of the acceleration transducers. The three rotational accelerations can be calculated using the following equations:

$$\text{roll, } r_x = \frac{A_{z3} - A_{z1}}{Y}$$

$$\text{pitch, } r_y = - \frac{A_{z2} - A_{z1}}{X}$$

$$\text{yaw, } r_z = - \frac{A_{x3} - A_{x1}}{Y}$$

Translational accelerations at point P with coordinates (x_p, y_p, z_p) can be calculated using the same equations as given above for the nine-accelerometer arrangement.

REFERENCE

Padgaonkar, A.J., Krieger, K.W. and King, A.I. (1975) Measurement of angular acceleration of a rigid body using linear accelerometers. Journal of Applied Mechanics, Volume 42, Series E, Number 3, 552-556.

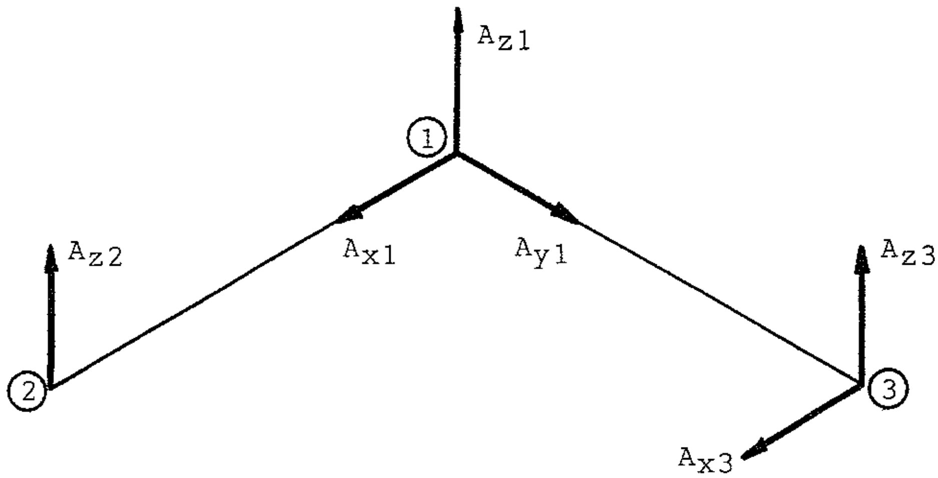

Figure A6.2 Locations and orientations of the six-accelerometer arrangement.

APPENDIX 7

INSTRUCTIONS TO SUBJECTS DURING TRANSLATIONAL FLOOR VIBRATION

Subjects who took part in the intra- and inter-subject variability experiments to determine the transmission of translational floor vibration to the head were given a set of written instructions about the required postures of the body and position of the head, legs, arms, etc.

Following is a copy of the instructions for horizontal floor vibration:

INSTRUCTIONS TO SUBJECTS

HORIZONTAL VIBRATION, STANDING SUBJECTS

The aim of this experiment is to monitor the motion of the heads of standing persons during whole-body horizontal vibration.

Vibration of the floor will be in either the fore-and-aft axis or the lateral axis. Different postures of the body will be required in each axis.

During <u>fore-and-aft</u> vibration of the floor, there will be two postures:

- i) handrail held rigidly using both hands,
- ii) handrail held lightly and then only to prevent yourself from falling.

In both postures, the separation of the feet should be 30 cm and the horizontal distance between your feet and the handrail should be about 30 cm.

During <u>lateral</u> vibration of the floor, there will be three postures:

- i) feet together,

ii) feet 30 cm apart,

iii) feet 60 cm apart.

In these three posture, the handrail can be held lightly but only to prevent yourself becoming unstable. The upper body should always be the same distance from the handrail, this being about 60 cm.

It is important that you maintain the required position and postures throughout the experiment. Keep your feet and legs in the position shown.

The experimenter will indicate the order in which these postures should be adopted. For all postures keep the upper part of your body in an upright comfortable posture. For safety purposes, you may lightly hold on to the handrail.

Just prior to the start of each run, which the experimenter will indicate, you are to place the bite-bar in your mouth and adjust your head to a normal upright forward facing position. This position is to be kept during all the runs. Keep your eyes on the cross on the opposite wall and avoid voluntary movements of the head. Ensure that a normal bite grip is kept on the bite-bar.

You are free to terminate the experiment at any time by pressing the red STOP button. Thank you for taking part in the experiment.

Following is a copy of the instructions for vertical floor vibration:

INSTRUCTIONS TO SUBJECTS

VERTICAL VIBRATION, STANDING SUBJECTS

The aim of this experiment is to monitor the motion of the heads of standing persons during whole-body vertical vibration.

It is important that you maintain the required position and postures throughout the experiment. Keep your feet and legs in the position shown. Three postures will be required:

i) 'legs locked',
ii) 'legs unlocked',
iii) 'legs bent'.

The experimenter will indicate the order in which these leg postures should be adopted. For all leg postures, keep the upper part of your body in an upright comfortable posture. For safety purposes, you may lightly hold on to the seat in front of you.

Just prior to the start of each run, which the experimenter will indicate, you are to place the bite-bar in your mouth and adjust your head to a normal upright forward facing position. This position is to be kept during all the runs. Keep your eyes on the cross on the opposite wall and avoid voluntary movements of the head. Ensure that a normal bite grip is kept on the bite-bar.

You are free to terminate the experiment at any time by pressing the red STOP button. Thank you for taking part in this experiment.

APPENDIX 8

COHERENCIES FOR TRANSLATIONAL FLOOR VIBRATION EXPERIMENTS

Ordinary coherencies were calculated for experiments involving the transmission of translational floor vibration to the heads of standing subjects. This appendix contains coherency data for intra- and inter-subject variability experiments. There were twelve vibration exposures for the subject who participated in the intra-subject variability study. Twelve subjects volunteered to take part in the inter-subject variability studies. The data are included as follows:

Figure	Vibration axis	Number of subjects	Posture
A8.1	x	1	rigid grip
A8.2	x	12	rigid grip
A8.3	x	12	light grip
A8.4	y	1	feet 60 cm apart
A8.5	y	12	feet together
A8.6	y	12	feet 30 cm apart
A8.7	y	12	feet 60 cm apart
A8.8	z	1	legs locked
A8.9	z	1	legs unlocked
A8.10	z	1	legs bent
A8.11	z	12	legs locked
A8.12	z	12	legs unlocked
A8.13	z	12	legs bent

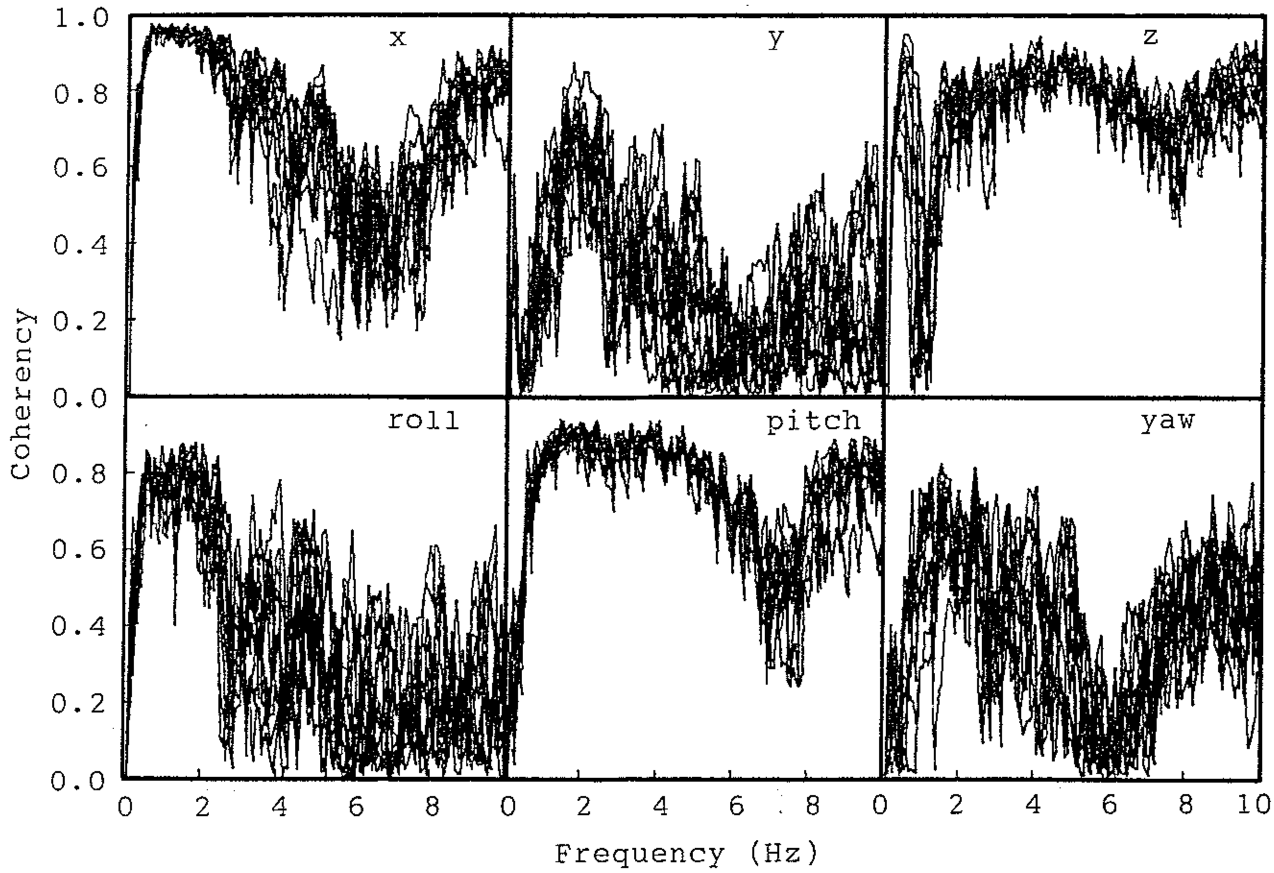

Figure A8.1 Coherencies for 1 subject in a rigid grip posture during fore-and-aft floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

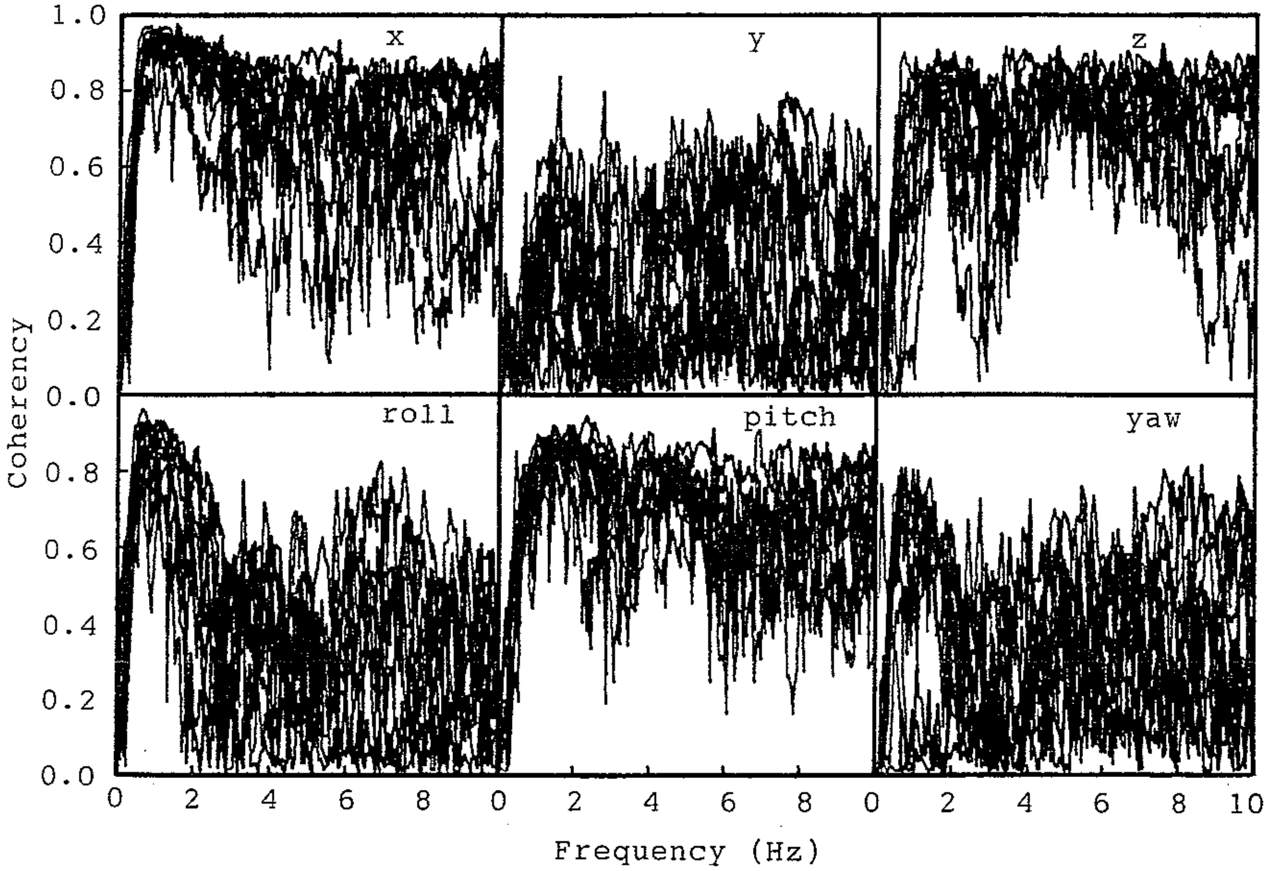

Figure A8.2 Coherencies for 12 subjects in a rigid grip posture during fore-and-aft floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

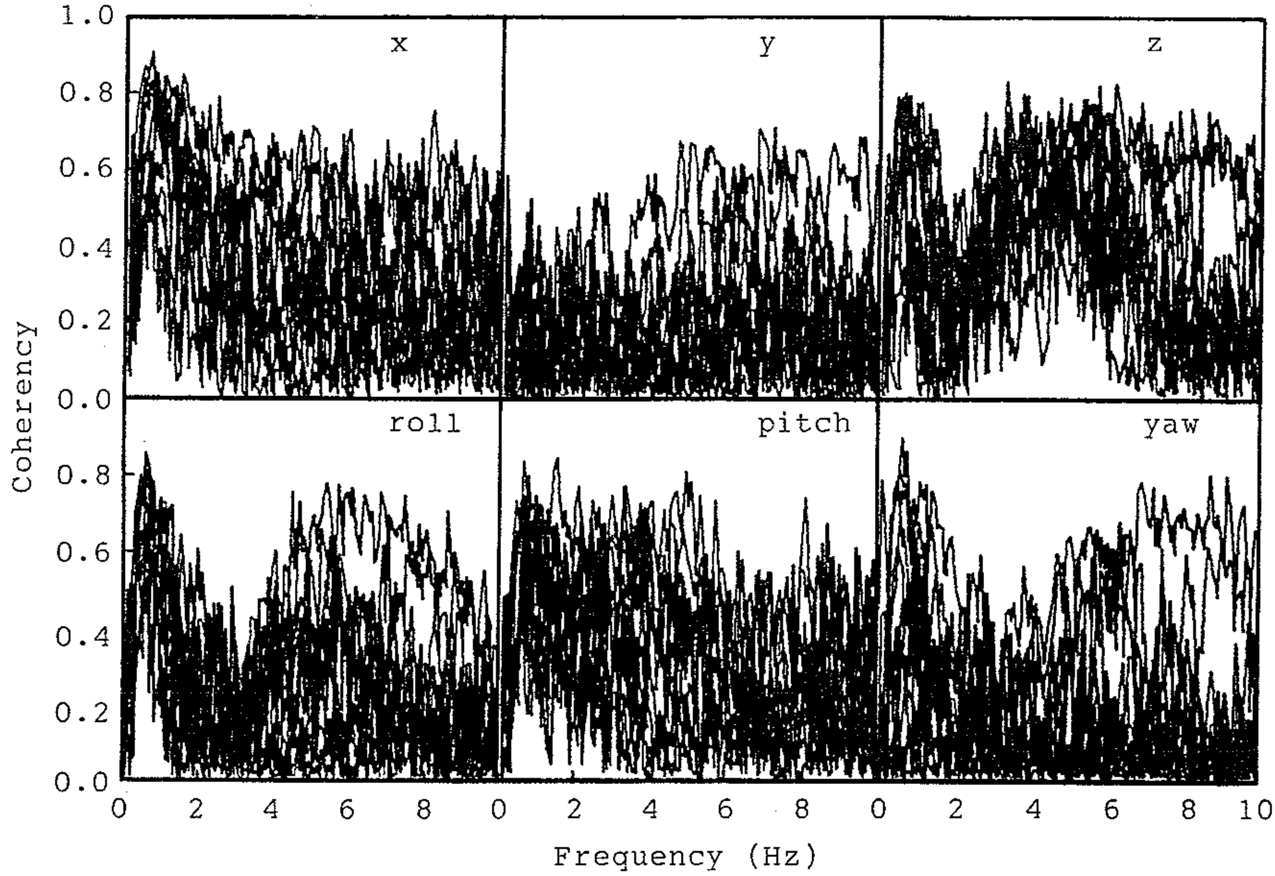

Figure A8.3 Coherencies for 12 subjects in a light grip posture during fore-and-aft floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

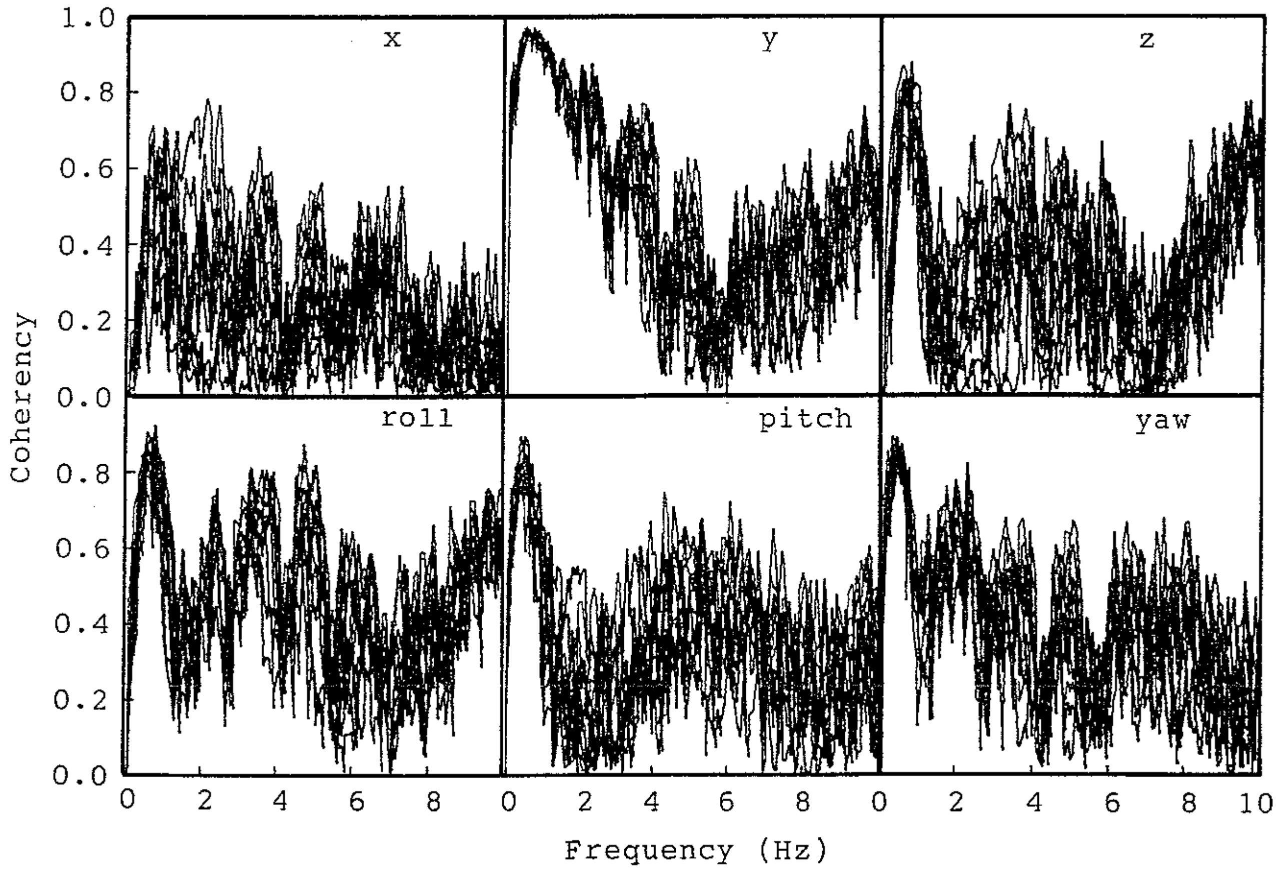

Figure A8.4 Coherencies for 1 subject with a foot separation of 60 cm during lateral floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

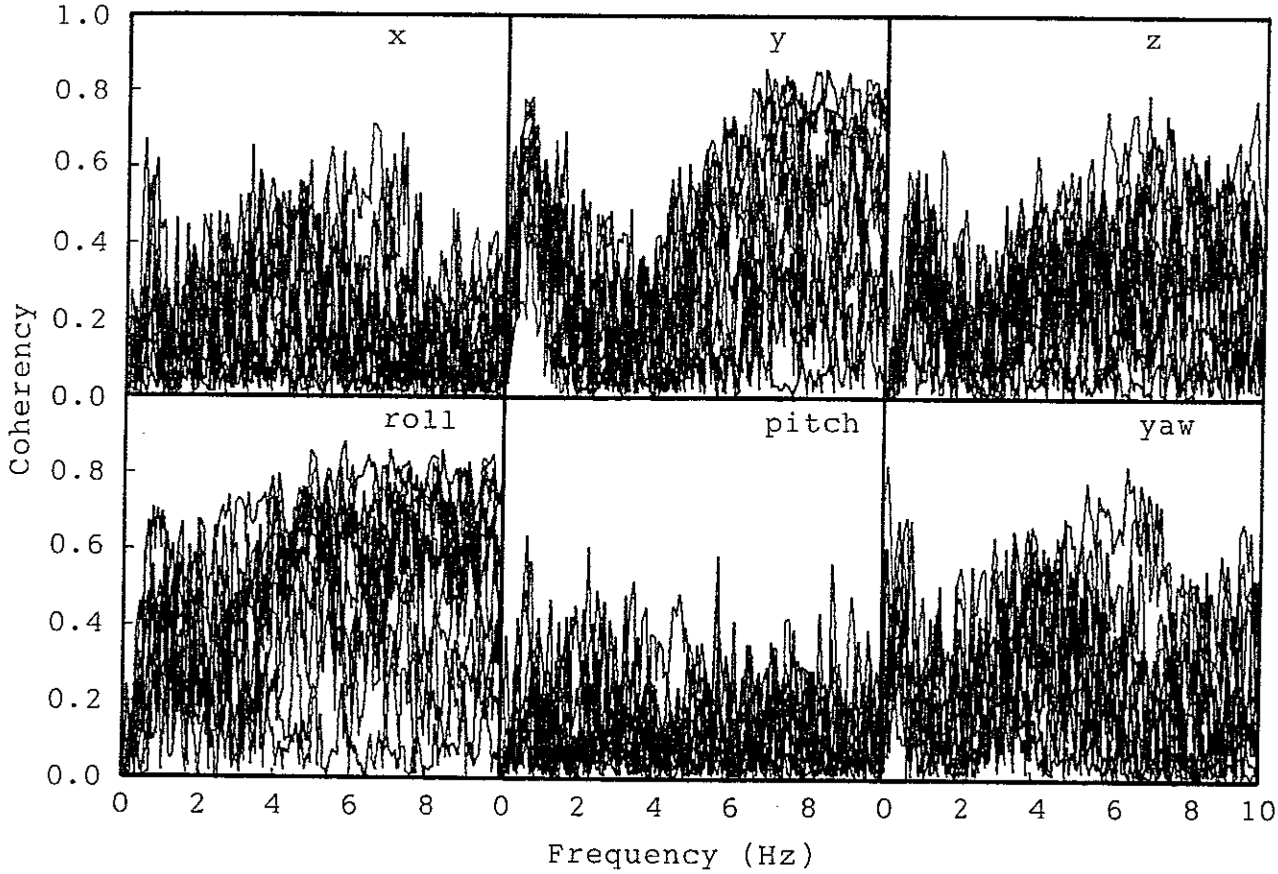

Figure A8.5 Coherencies for 12 subjects with feet together during lateral floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

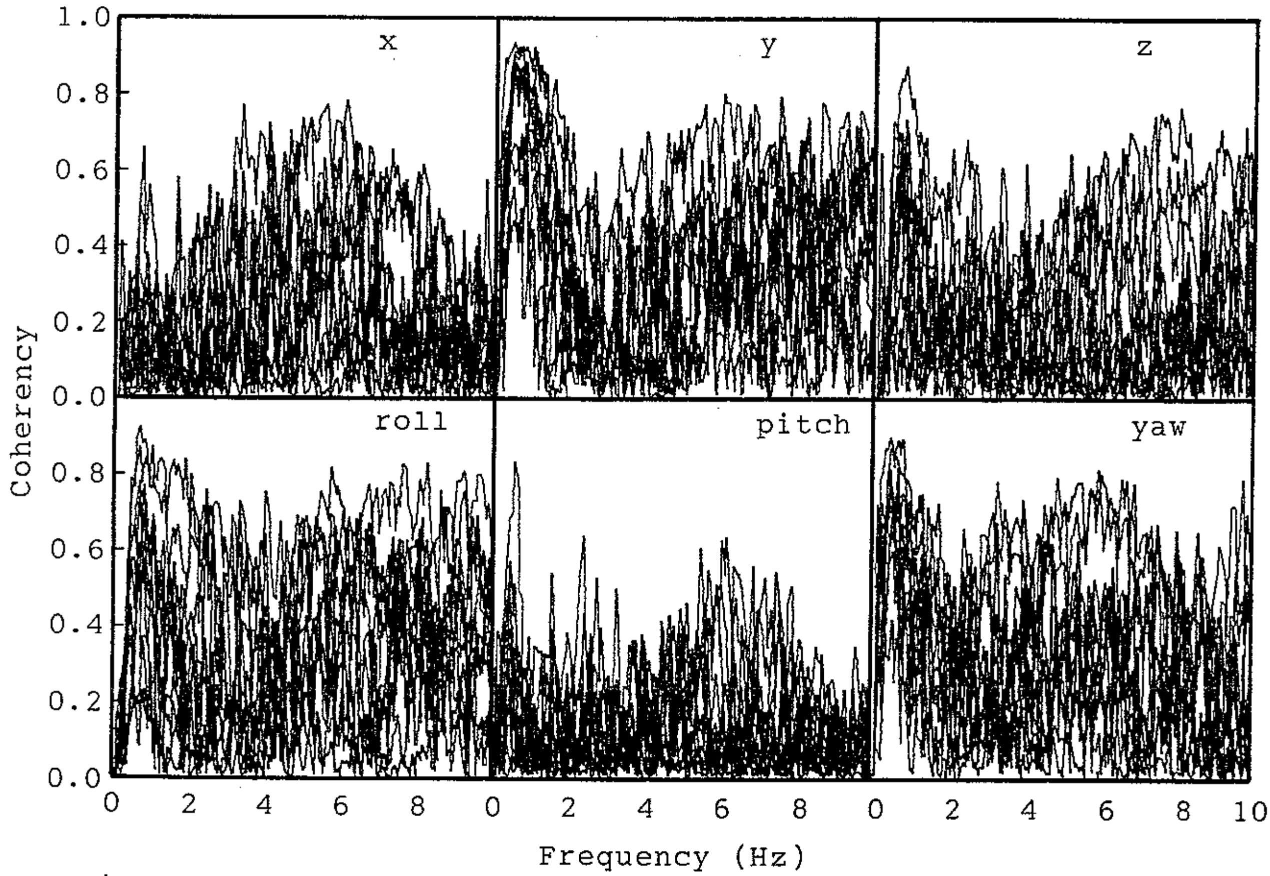

Figure A8.6 Coherencies for 12 subjects with a foot separation of 30 cm during lateral floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

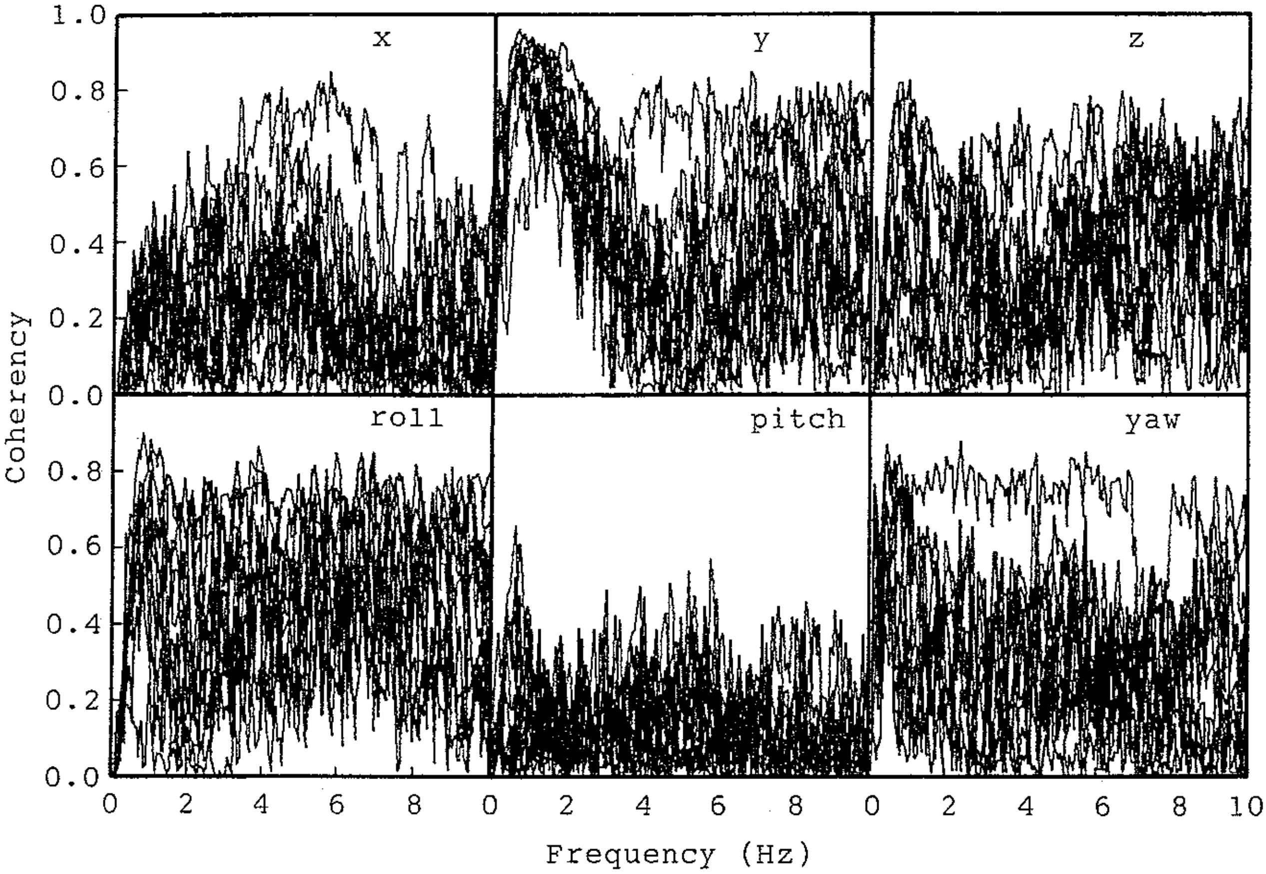

Figure A8.7 Coherencies for 12 subjects with a foot separation of 60 cm during lateral floor motion. (Resolution = 0.06 Hz, degrees of freedom = 58)

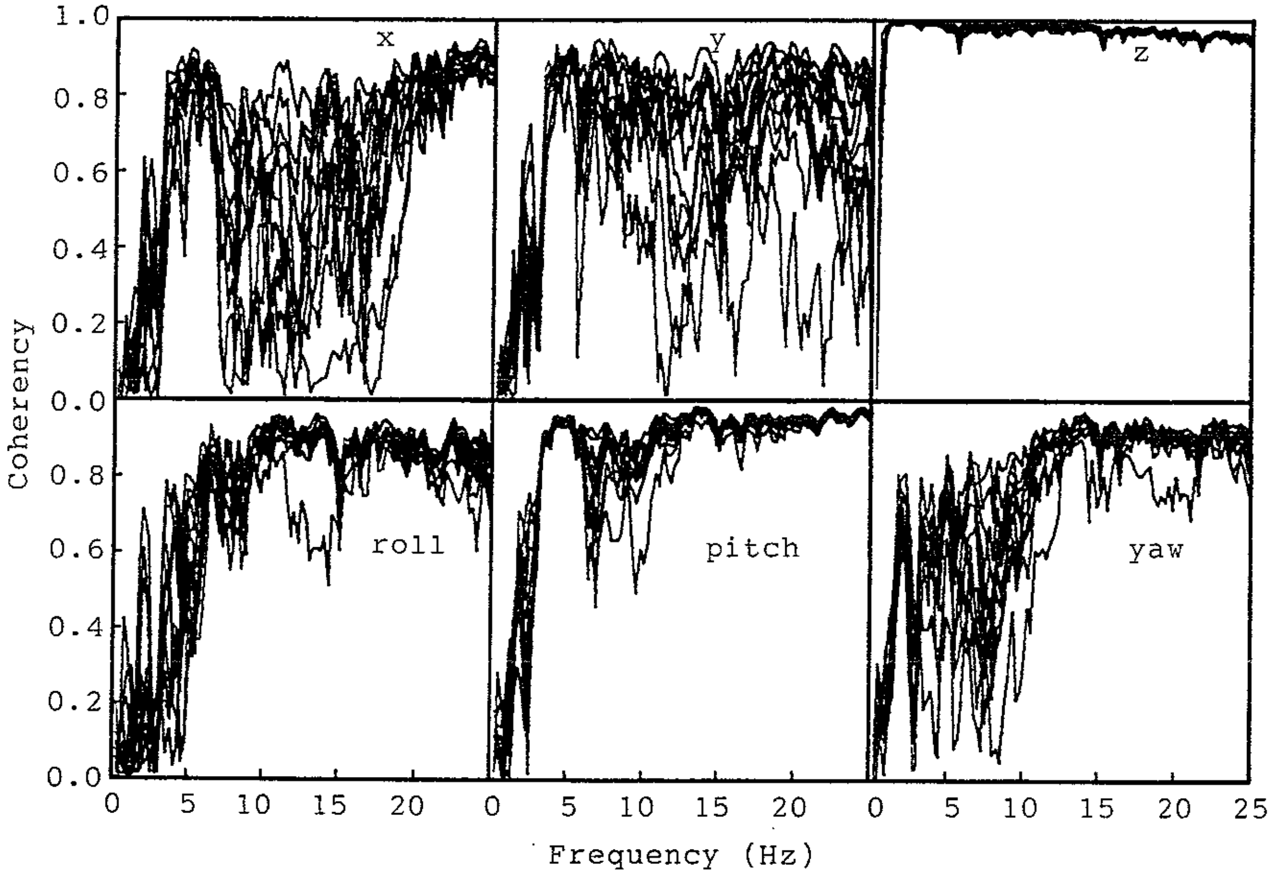

Figure A8.8 Coherencies for 1 subject in a 'legs locked' posture during vertical floor motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

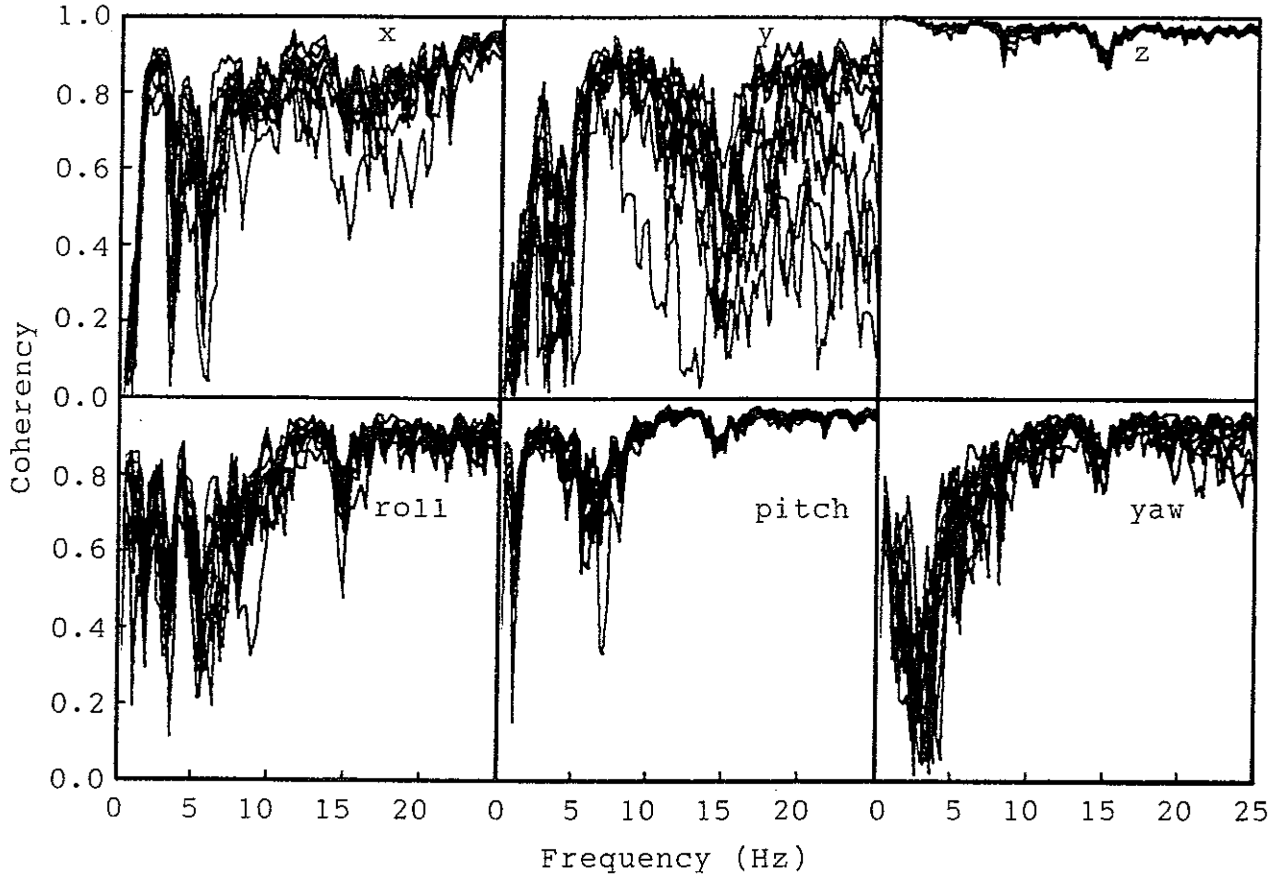

Figure A8.9 Coherencies for 1 subject in a 'legs unlocked' posture during vertical floor motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

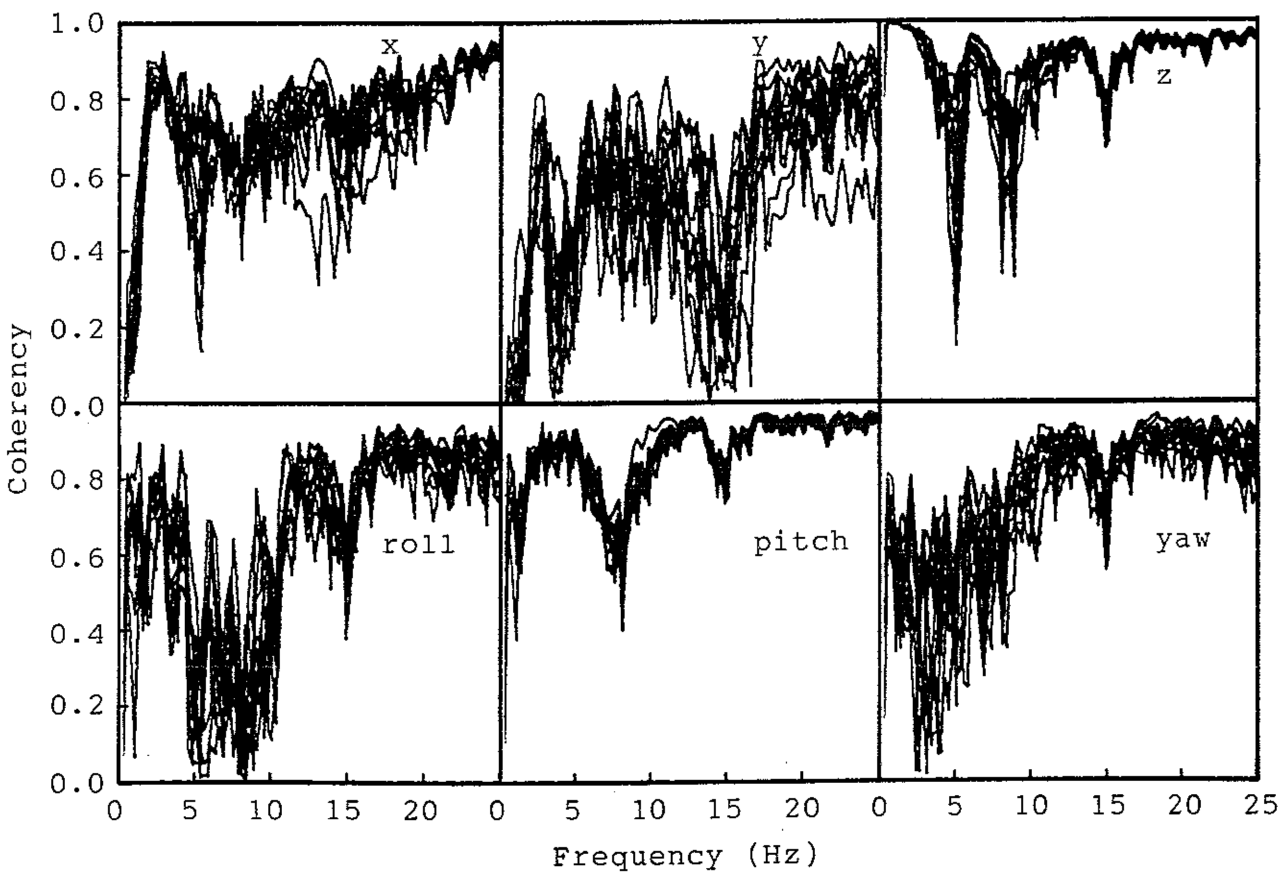

Figure A8.10 Coherencies for 1 subject in a 'legs bent' posture during vertical floor motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

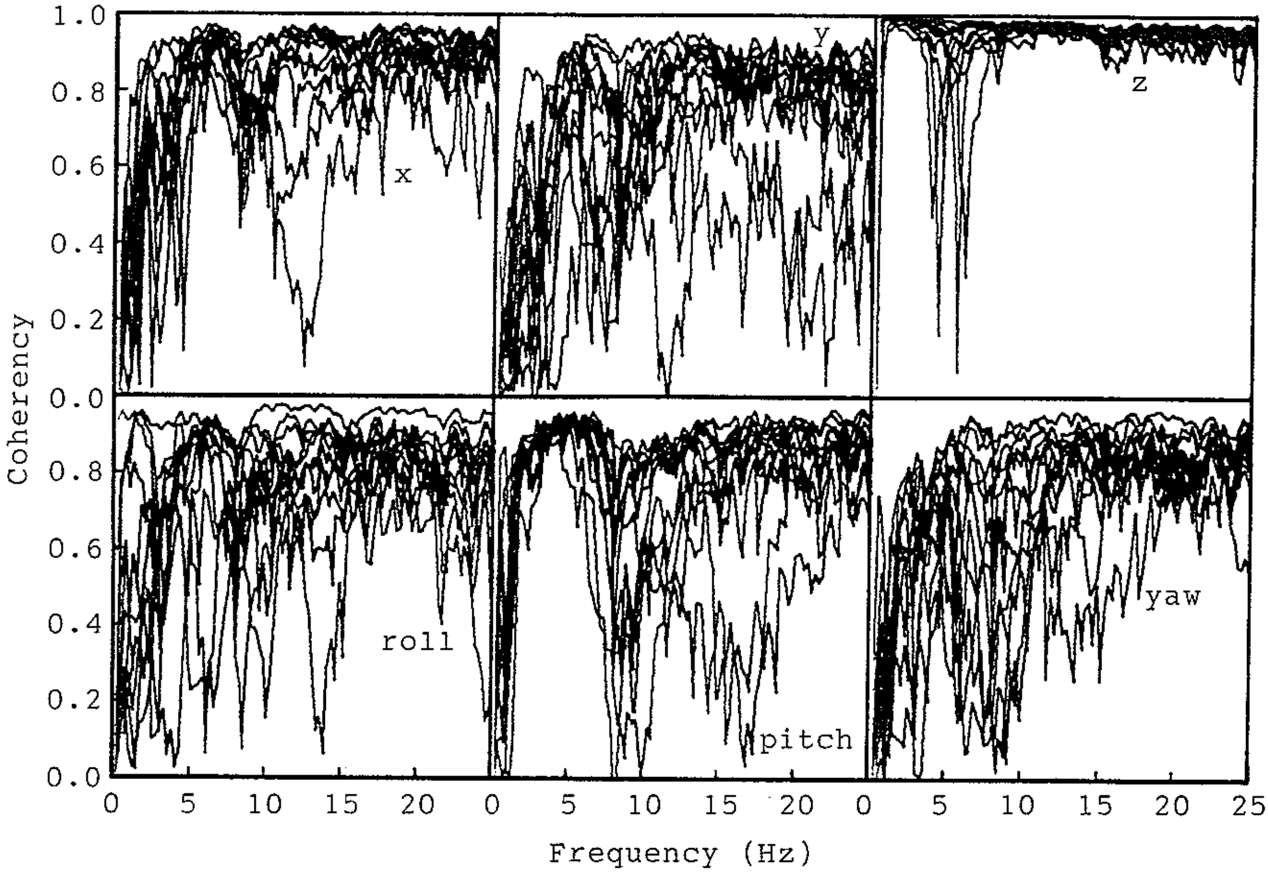

Figure A8.11 Coherencies for 12 subjects in a 'legs locked' posture during vertical floor motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

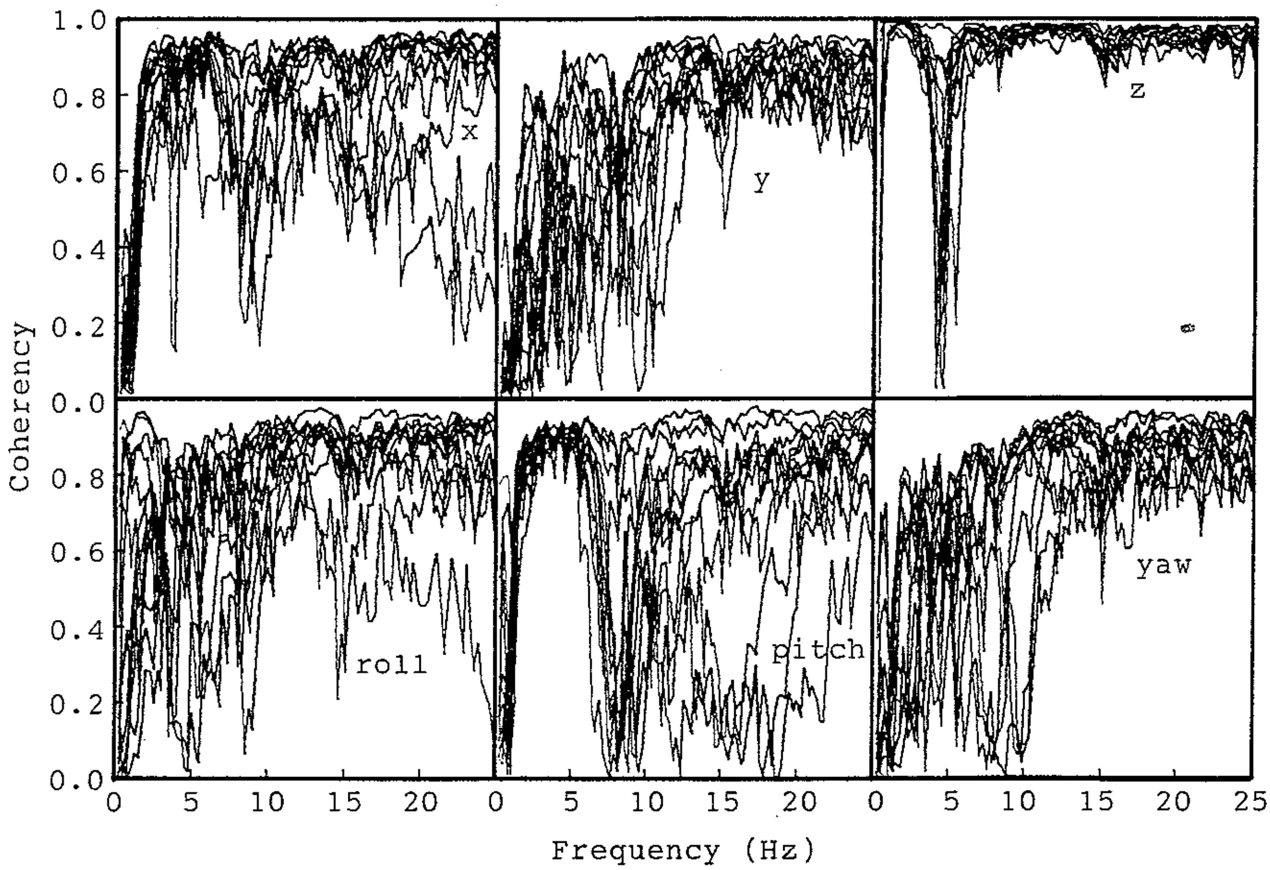

Figure A8.12 Coherencies for 12 subjects in a 'legs unlocked' posture during vertical floor motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

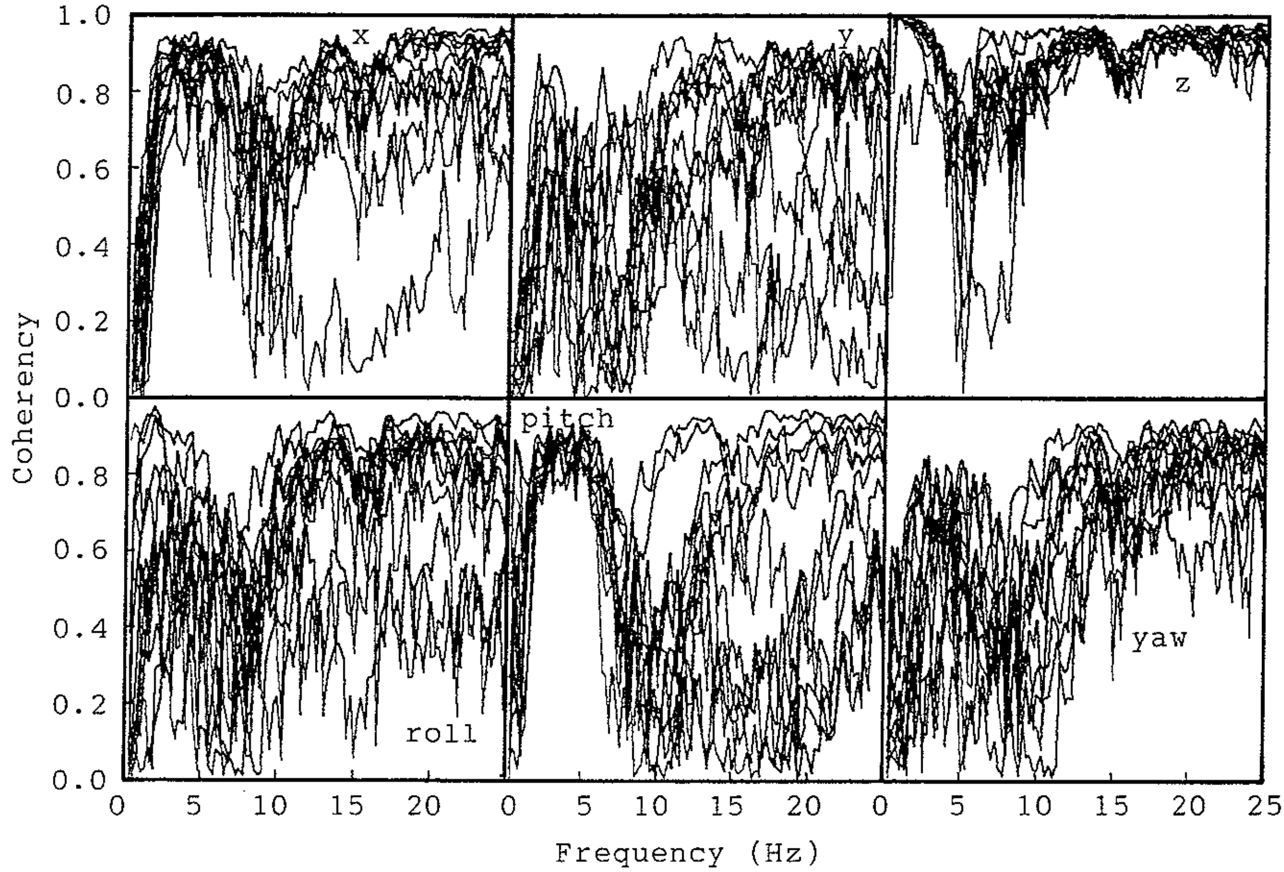

Figure A8.13 Coherencies for 12 subjects in a 'legs bent' posture during vertical floor motion. (Resolution = 0.25 Hz, degrees of freedom = 58)

APPENDIX 9

PHYSICAL CHARACTERISTICS OF SUBJECTS TAKING PART IN TRANSLATIONAL FLOOR VIBRATION EXPERIMENTS

Twelve male subjects took part in the inter-subject variability experiments to determine the transmission of translational floor vibration to the head. Their following physical characteristics were measured:

i) Age: - years
ii) Weight: - clothed
iii) Height: - stature while standing

These are shown in Table A9.1.

Table A9.1 Physical characteristics of subjects who took part in the inter-subject variability experiment on head motion during translational floor vibration.

Subject	Age (yrs)	Weight (kg)	Height (m)
1	27	87	1.89
2	31	61	1.73
3	28	73	1.84
4	25	82	1.83
5	25	72	1.74
6	29	82	1.92
7	28	69	1.77
8	20	65	1.79
9	27	80	1.84
10	38	76	1.75
11	41	85	1.87
12	22	60	1.74
Minimum	20	60	1.73
Maximum	41	87	1.92
Mean	28.42	74.33	1.81
Standard deviation	5.75	8.82	0.06

APPENDIX 10

SPECTRAL ANALYSIS INTERPRETATION

This appendix explains the reliability and interpretation of the data presented in the thesis by comparing two different procedures for calculating transmissibilities and the calculation of confidence intervals for two sets of data with varying values for coherency.

Transfer functions were calculated between seat vibration and the six axes of head motion for all translational axes of seat vibration (fore-and-aft, lateral and vertical) and for the two sitting postures ('back-on' and 'back-off'). The transfer functions are presented in Chapter 5 and the corresponding ordinary coherencies are included in Appendix 4. These data can be further interpreted to estimate the linearity of the human body in vibration transmission and the amount of noise (uncorrelated motion) in the system.

All transfer functions presented in Chapter 5 were calculated using the 'cross-spectral density function method'; this method takes into account only the linearly correlated proportion of the output motion with the input motion. The results are compared with those obtained using the 'power spectral density function method' in which case the total energy present in the output signal is taken into account. (Transmissibilities calculated using the 'power spectral density function method' will always be greater than or equal to those calculated using the 'cross-spectral density function method'.) The difference between the transmissibilities calculated using the two methods together with the corresponding coherency provides an indication of the linearity of the system, noise present in the system, correlation between input and output motions, etc. If the coherence value is unity, then the two methods will give the same results (see Chapter 4 'Analysis of head motion data').

Confidence intervals can be calculated for a transfer function to determine the reliability of the data (Bendat and Piersol, 1980). These can be calculated using the following procedure for approximately 95% confidence that the true value (Φ) lies within the interval:

$$[\Phi(1 - 2\varepsilon r) \leq \Phi \leq \Phi(1 + 2\varepsilon r)]$$

where

Φ is the true value of the modulus of the transfer function, and

εr is normalised random error.

The random error, εr, is calculated using the following equation:

$$\varepsilon r = \frac{[1 - \gamma^2_{xy}]^{1/2}}{|\gamma_{xy}| \sqrt{2n_d}}$$

where

γ_{xy} is the coherency between input x and output y, and

n_d is the number of degrees of freedom.

Two examples of the use of the above methods are considered: one in which the coherency was high and one in which the coherency was below 0.5 at some frequencies. Figure A10.1 shows transmissibilities (calculated using both the 'cross-spectral density function method' and the 'power spectral density function method'), 95% confidence intervals and coherency between vertical seat vibration and vertical head motion for a subject seated in a 'back-off' posture (see Section 5.4.3). It is seen that the coherency was above 0.95 over all the frequency range and also that the two methods of calculation of transmissibilities gave almost identical results. This implies that vertical motion at the head was almost all linearly correlated with (and caused by) vertical vibration at the seat. The confidence intervals are very 'tight' indicating the high degree of reliability of the data.

Figure A10.2 shows a low coherency between vertical seat vibration and lateral head motion for a subject seated in a 'back-on' posture (see Section 5.4.4, subject 3). Differences in transmissibilities calculated using the two spectral density methods show uncorrelated motion at the head with seat vibration, this could be due to voluntary movements of the body, nonlinearities in the system and signal noise. Even though the coherency was low at some frequencies and there were appreciable differences between transmissibilities using the two different methods, the confidence intervals again show a high degree of reliability of the data.

REFERENCE

Bendat, J.S. and Piersol, A.G. (1980) Engineering applications of correlation and spectral analysis. John Wiley and Sons. ISBN 0-471-05887-4.

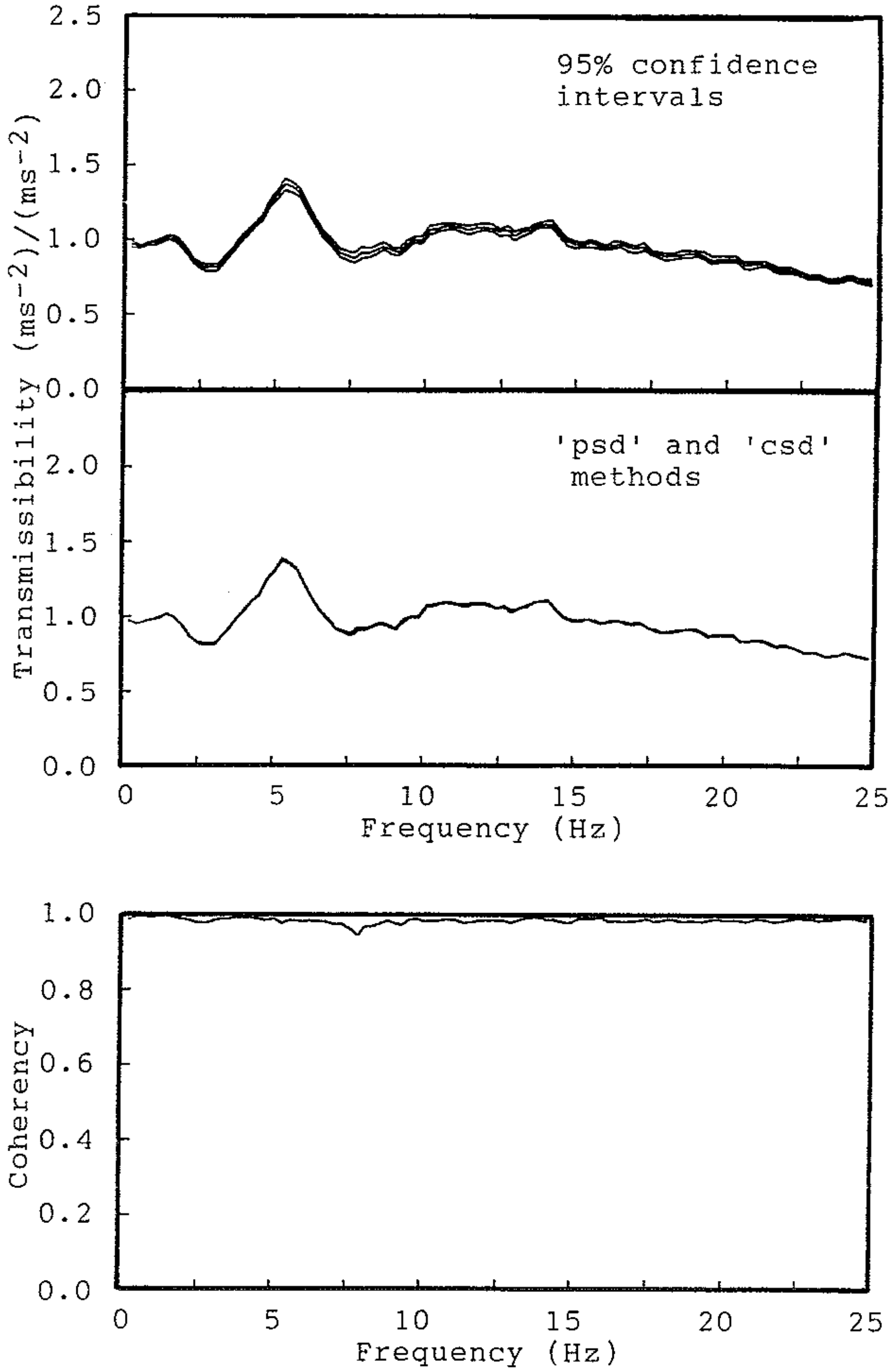

Figure A10.1 Transmissibilities and coherency between vertical seat vibration and vertical head motion for a subject seated in a 'back-off' posture. (Resolution = 0.25 Hz, degrees of freedom = 58)

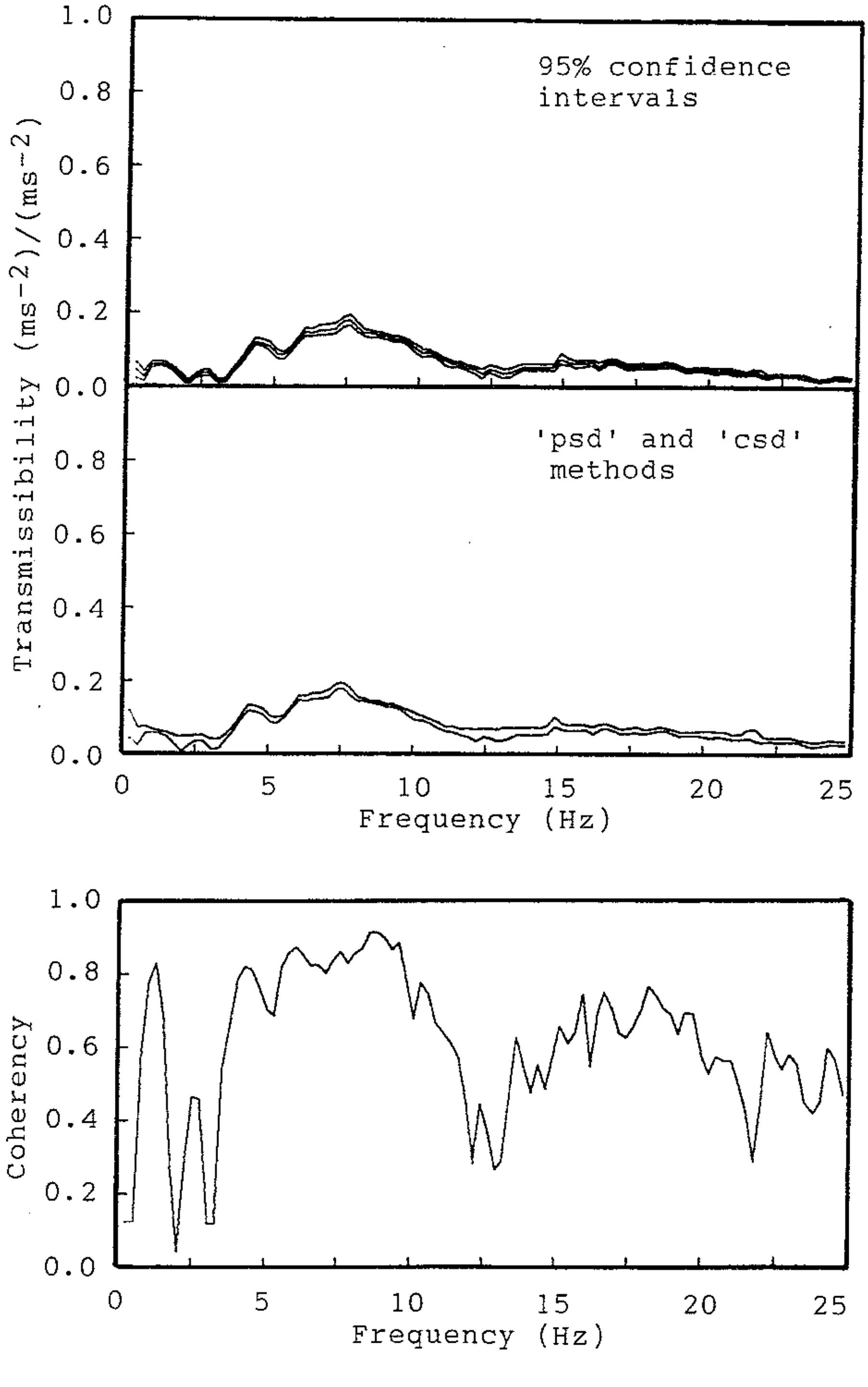

Figure A10.2 Transmissibilities and coherency between vertical seat vibration and lateral head motion for a subject seated in a 'back-on' posture. (Resolution = 0.25 Hz, degrees of freedom = 58)