BIODYNAMIC CHARACTERIZATION OF SEATED OCCUPANT UNDER HORIZONTAL VIBRATION

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ABSTARCT

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The seated occupant responses to whole body vibration have been widely investigated, mostly under vertical vibration stimuli. The vibration environment of heavy road and off-road vehicles also comprises significant components of horizontal vibration, with magnitudes either comparable to or higher than those of the vertical vibration. It is thus desirable to investigate the seated body responses to horizontal vibration. This study concerns with characterization of the biodynamic responses in terms of apparent mass and the power absorbed by seated human occupants exposed to longitudinal and lateral vibration in the 0.5-10 Hz frequency range under automotive seating postures. The measured data revealed consistent trends in view of the factors considered, namely, the posture (back supported or unsupported), as well as the direction, magnitude, type and frequency of vibration. The results suggest strong influence of the acceleration magnitude, the back support condition and the type of whole-body vibration. The peak magnitudes of APMS and absorbed power revealed good correlation with the body mass, suggesting increased energy absorption by heavier subjects. The vibration energy absorption properties of the seated body in the low frequency range revealed highest correlation with the anthropometric factors and the magnitude of the stimulus. The data is expected to serve as a basis for developing mechanical equivalent models of the occupant for seating dynamics applications, and to enhance knowledge on the human behaviour under exposure to horizontal vibration.

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NOMENCLATURE

a_{rms}	Frequency-weighted root-mean-square (rms) acceleration (m/s^2)
$a_H(j\omega)$	Response acceleration measured at the head (m/s^2)
$a(j\omega)$	Acceleration response at the driving point (m/s^2)
a_{x_b}, a_{y_b}	Acceleration excitation at the seat base (m/s^2)
a_{x_r}, a_{y_r}	Acceleration excitation at the backrest (m/s^2)
$a_w(t)$	Frequency-weighted rms acceleration obtained by applying W_d-weighting filter defined in ISO-2631 (m/s^2)
$a_w(t_o)$	Weighted rms acceleration corresponding to an observation time t_o (m/s^2)
$(a_w)_{peak}$	Peak frequency-weighted acceleration (m/s^2)
APMS	Apparent mass (kg)
C_{Fv}	Coincident spectral density function
CSD	Cross-spectral density
CV	Statistical coefficient of variation
DPMI	Driving point mechanical impedance
$F(j\omega)$	Driving force at the driving point (N)
F_{x_b}, F_{y_b}	Force response measured at the seat base (N)
F_{x_r}, F_{y_r}	Force response measured at the backrest (N)
F-test	Statistical Fisher test
$\lvert G_{Fv}(\omega)\rvert$	Modulus of the cross-spectrum between the force and the velocity (Nms^{-1}/Hz)
$H(j\omega)$	Complex STHT
H1	Function of the pulse analyzer

j	Complex phasor $(=\sqrt{-1})$
$\overline{M}$	Mean apparent mass at each frequency (kg)
$M_{i(real)}$	real component of the apparent mass of for subject i (kg)
$M_{i(imag)}$	Imaginary component of the apparent mass of for subject i (kg)
$M(j\omega)$	Complex APMS response (kg)
M_{seat}	Complex apparent mass of the seat and its supporting structure (kg)
MSDV	Motion sickness dosage
m_o	Static mass supported by the seat (kg)
P	Power absorbed (W)
$P_{abs}(t)$	Absorbed part of the power in time domain
$P_{abs}(\omega)$	absorbed part of the power in frequency domain
P_{avg}	Average power absorbed during an exposure period T
$P_{el}(t)$	Elastic power
$P_{tr}(t)$	Instantaneous power transmitted to the body
PSD	Power spectral density
Q_{Fv}	Quadrature spectral density function
r	Correlation coefficient
r^2	Coefficient of determination
rms	Root-mean square
$S_{a_{xb}}$	Autospectral density of the acceleration excitation
$S_{F\bullet V}$	Cross-spectral density of the measured force and velocity
$S_{F_{xb}a_{xb}}$	Cross-spectral density of force F_{xb} and acceleration a_{xb}

SD, σ	Statistical standard deviation
STHT	Seat-to-head transmissibility
T	Exposure duration (s)
$v(j\omega)$	Response velocity at the driving point (m/s)
VDV	Vibration dose value
WBV	Whole-body Vibration
W_d-	Weighting filter defined in ISO-2631
$Z(j\omega)$	Complex DPMI response
ω	Angular frequency (rad/s)

CHAPTER 1

INTRODUCTION AND SCOPE OF RESEARCH

1.1 INTRODUCTION

A large number of workers are occupationally exposed to mechanical vibration, from various sources, such as moving vehicles, vibrating machines and tools, as well as buildings. Prolonged exposure to such vibration is known to cause discomfort, annoyance, and health and safety risks in extreme cases. Occupational drivers of heavy road as well as off-road vehicles are exposed to considerably large magnitudes of vibration in the relative low frequency range (lower than 20 Hz). Exposure to such low frequency and high magnitude vibration of whole-body nature has been associated with discomfort and may cause disorders of the musculoskeletal structure, such as the spine and the supporting structure. Moreover, the human driver is exposed to vibration that occurs simultaneously along the three translational and the three rotational axes. A large number of epidemiological studies have established a strong association between the back disorders among the exposed population, exposure to whole-body vibration and years of exposure [1-7].

Owing to the probable severe health and safety risks, considerable efforts are being made in two primary directions: (i) Attenuation of vibration transmitted to the occupant through enhanced vehicle ride performance and designs of effective suspension seats; and (ii) Building knowledge on transmission of vibration to and through the human body to enhance an understanding of the human response to vibration.

This dissertation research concerns the latter direction and attempts to study the human response to vibration in terms of biodynamic response characteristics of seated human subjects exposed to whole-body horizontal vibration with low frequency components. The biodynamic response characteristics of the seated human occupants exposed to vibration have been investigated in many reported studies [8-29]. The resulting sets of data have been used to identify critical frequency ranges of vibration to which the human is most sensitive, and the vibration energy or power absorbed by the human body is also exacerbated. The biodynamic responses are often characterized in two forms:

1) To-the-body response functions;
2) Through-the-body response functions.

The to-the-body functions relate the vibration motion entering the body and the human-seat interface force developed at the driving point. This force motion behaviour is expressed in terms of apparent mass, driving-point mechanical impedance or compliance. The force-motion relationship is also utilized to express the human response in terms of absorbed power. These measures have been used to develop frequency-weighting filters recommended for assessment of exposure to vibration [30, 31]. The through-the-body biodynamic responses describe the transmission of vibration to various segments of the body and thus could be used to identify resonance frequencies of different body segments [32, 33]. The seat-to-head vibration transmissibility is often used to describe the through-the-body biodynamic response. Both the biodynamic response functions have been applied to develop analytical models of the seated occupants, which could be applied for the design of seats and analyses of coupled seat-occupant system [34-37].

Although the ride vibration environment of on-road and off-road vehicles comprises significant components along all the translational axes, the vast majority of the studies focus on human response to vertical vibration alone. This is mostly attributed to the fact that majority of the heavy road vehicles and off-road vehicles transmit more significant magnitudes of vertical vibration than those along the other axes. The off-road and on-road heavy vehicles, however, also transmit considerable magnitudes of horizontal vibration. The high position of the driver in such vehicles coupled with lateral flexibility of the large diameter soft tires, specifically, causes high magnitudes of lateral vibration, in a frequency range where the human body is most sensitive [27, 29, 32, 38-49]. Despite these considerations, the human response to horizontal vibration has been addressed in a few studies only [22, 24-29, 50]. Furthermore, the majority of these studies focus on the motion sickness alone under extremely low frequency vibration.

The biodynamic response of a seated human occupant exposed to either vertical or horizontal vibration is a very complex phenomenon. A large number of factors are known to affect the response in a highly non-linear manner. These include the nature of vibration (magnitude, frequency and direction), sitting posture (erect, slouched), back support condition, seat height and geometry, etc. The reported studies have mostly considered sitting without a back support or against a vertical backrest, and a flat seat pan. The automotive seats, however, are designed with inclined pan and backrest to provide comfortable and controlled sitting posture. The biodynamic response of human occupants seated in such types of seats are exposed to horizontal vibration has not yet been explored.

This dissertation research concerns with characterization of biodynamic response characteristics of seated human occupants exposed to longitudinal and lateral vibration in the 0.5-10 Hz frequency range. These response characteristics are identified through the design of a horizontal seat vibration simulator and measurements of the force-motion relationships of seated occupants under different intensities of random vibration. The influences of sitting postures as determined by the back support conditions on the biodynamic response are further investigated. The measured force and motion data are analyzed to characterize the biodynamic response in terms of apparent mass and absorbed power.

1.2 REVIEW OF RELEVANT LITERATURE

The study of human response to vibration involves a comprehensive understanding of the nature of vehicular vibration transmitted to the occupant, synthesis of significant vibration components in the laboratory, human response measurement techniques, data analyses, seat geometry and design features, etc. The reported relevant studies on these particular aspects are systematically reviewed to develop a thorough understanding of these issues, and test and analyses methodologies, and to formulate the scope of the dissertation research. The highlights of the relevant reported studies, considered essential for the dissertation research, are discussed in the following sections.

1.2.1 VIBRATION AND THE HUMAN BODY

Human response to vibration is known to be strongly dependent upon the nature of vibration, seat design factors and individual factors. The magnitude, frequency, direction and duration of vibration exposure form the most critical factors in assessing the human responses to vibration [32, 33]. The magnitude of continuous vibration, in general, is characterized by frequency-weighted rms acceleration, given by:

$$a_{rms} = \sqrt{\frac{1}{T}\int_0^T a_w^{\,2}(t)\,dt} \qquad (1.1)$$

Where $a_w(t)$ is the frequency-weighted acceleration obtained by applying W_d- weighting filter defined in ISO-2631 [31], T is the exposure duration, and a_{rms} is the frequency-weighted root-mean-square (rms) acceleration, due to transmitted vibration.

The vibration environment of a large number of vehicles may consist of shock events, characterized by relatively high acceleration peaks. The presence/absence of such high acceleration peaks is often determined by the crest factor of vibration, computed from [6]:

$$Crest\_Factor = \frac{(a_w)_{peak}}{a_{rms}} \qquad (1.2)$$

Where $(a_w)_{peak}$ is peak frequency-weighted acceleration.

A vibration factor with crest factor exceeding a value of 9 is deemed to represent considerable shock events [32]. It has been suggested that the vibration exposure may be characterized using the running rms method, such that [31]:

$$a_w(t_0) = \sqrt{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} \left[a_w(t)\right]^2 dt} \qquad (1.3)$$

Where $a_w(t_o)$ represent the weighted rms acceleration corresponding to an observation time t_o, and τ is the integration time, usually takes as 1 second.

The vibration signals with high crest factors are also characterized by fourth power vibration dose method to obtain a vibration dose value (VDV), which is more sensitive to high magnitude events [31], such that:

$$\boldsymbol{VDV} = \left[\int_0^T (a_w(t))^4 dt \right]^{1/4} \qquad (1.4)$$

Whole-body vibration in a workplace may occur over a frequency range from below 1 Hz up to about 1000 Hz, while the major effects have been report to occur below 80 Hz [32,49,51-54]. The human body exhibits several resonances in this frequency range, such as abdominal resonance occurring in the 4-8 Hz range, and resonances of head and neck in the 20-30 Hz range [32, 52, 53]. Furthermore, the eyeball resonances have been reported to occur in the 20-90 Hz range, while the skull itself has a fundamental mode of vibration in the region of 300-400 Hz with resonances for higher modes occurring around 600-900 Hz [52,53]. Using animals in experiments as human analogy, it has been reported that the resonances of the iliac bone may be expected to occur in the 1000-2000 Hz frequency range, with collateral abdominal reactions, especially if the subject is a pregnant woman [55].

The principal resonances of the human body are presented in Figure 1.1 [53,54]. A number of studies have also identified important resonant frequencies and vibration modes of the human body under relatively low frequency vertical vibration. Table 1.1 to Table 1.3 summarize the resonant frequencies and mode shapes identified from measured driving-point mechanical impedance (DPMI) and vibration transmissibility [51, 56-59]. These studies have consistently concluded the presence of first principle mode in 4-8 Hz, which is associated with the upper torso or the spinal structure. A few studies have also identified a second important spinal deformation mode in the 10-15 Hz frequency range [12, 15-17, 29, 59-61].

Table 1.1: Resonance frequency ranges of seated human body, identified from Diving Point Mechanical Impedance (DPMI) data [58, 59].

DRIVING POINT MECHANICAL IMPEDANCE	Hz
Primary Peak	4-8 (4.5-6)
Second Peak	7-10
Third Peak	10-15
Fourth Peak	16-19

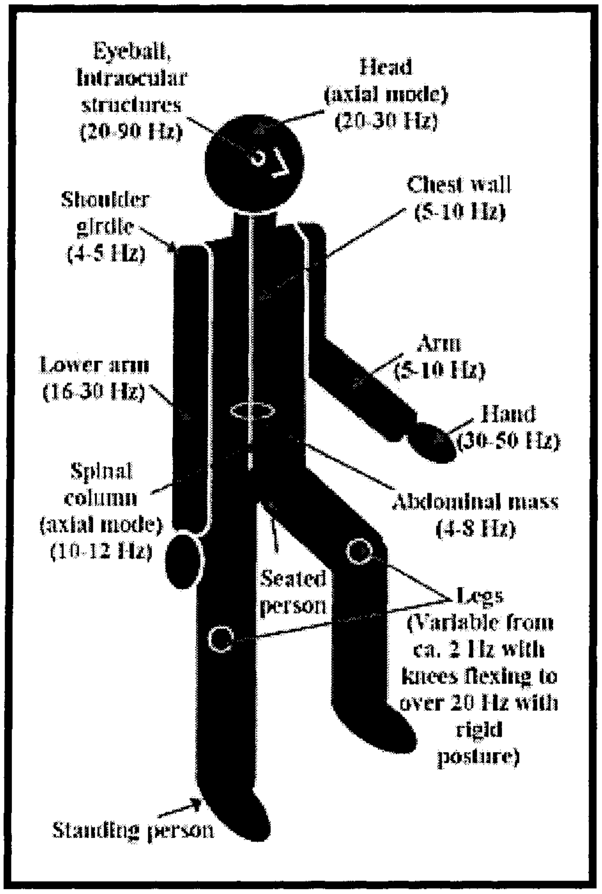


Figure 1.1: Principle resonant frequencies of the human body [53]

Table 1.2: Resonance frequency ranges of seated human body, identified from vibration transmitted to body limbs [52, 57-59].

TRANSMISSIBILITY	Hz
Chest (upper torso)	4-7
Chest wall	5-10; 50-60
Spine (seventh cervical)	4-7; 10-12; 12-20
Upper leg (thigh)	4-10; 10-15
Lower Leg	5-9
Head	2-3; 4-5.5; 20-30
Abdominal Viscera	3-6; 4-8
Shoulder	2; 4-5
Hip	1.5
Heart	4-6
Larynx	5-20
Bladder	10-18
Pelvis	10-14
Pelvic Rocking	4.5-6

Table 1.3: Vibration modes of seated human body exposed to vertical vibration [56]

MODE NO.	NATURAL FREQUENCY	BODY RELATIONSHIP	NOTE
1	1.1 Hz	Bending mode of the thoracic and cervical spine	Very Small
2	2.2 Hz	Anterior-posterior motion of the head and pelvis in opposite phase and in phase, respectively.	
3	3.4 Hz		
4	4.9 Hz	Head, spine and pelvis (entire body mode).	Principal
5	5.6 Hz	Bending mode of the lumbar and lower thoracic spine; Vertical motion of the head.	
6	8.1 Hz	Pitching modes of the pelvis with different locations of the pivot.	Second Principal
7	8.7 Hz		
8	9.3 Hz	Second visceral mode.	

It is believed that more than one vibration mode may contribute to the principal resonance in the measured biodynamic responses observed at about 4 Hz [61]. Changes in muscle tension also contribute to variations in fundamental frequencies, suggesting non-linear behaviour, which is reflected in the relatively high inter- and intra-subjects variability of the measured data [18, 62, 63]. The frequency of the principal resonance tends to be lower for the seated posture than for the standing posture, with difference being less than 1 Hz, in the 5-6 Hz frequency range [10, 12, 16, 18, 32, 52, 56, 58, 61, 63, 64]. The vertical vibration transmissibility of the lumbar vertebrae and lower spine were observed to be larger in the standing posture than in the sitting posture at frequencies around the principal resonance of the biodynamic response. At higher frequencies, the two postures, however, yield comparable magnitudes of vibration transmitted to the thoracic region, although the frequencies of the peaks were higher in the standing posture [12, 13, 16, 18, 32, 52, 64-66].

It is generally agreed that the resonant amplification of the response and dissipation of vibration energy within the human body can lead to various detrimental physiological effects on humans. It can manifest itself as increased pulse rate or respiratory rate or more seriously as complaints of spinal muscle, ano-rectal or gastro-intestinal systems [6, 63, 67, 68]. Apart from the magnitudes and frequency of vibration the human responses to vibration tend to increase with increases in the duration of exposure [7, 39, 51, 69, 70]. It has thus been suggested to define a dose measure which incorporates the exposure time factor [7, 32]. The determination of effective daily exposure duration, however, is a complex task due to considerable variation in the daily exposure duration and vibration magnitudes, which need to be considered for estimating the yearly exposure.

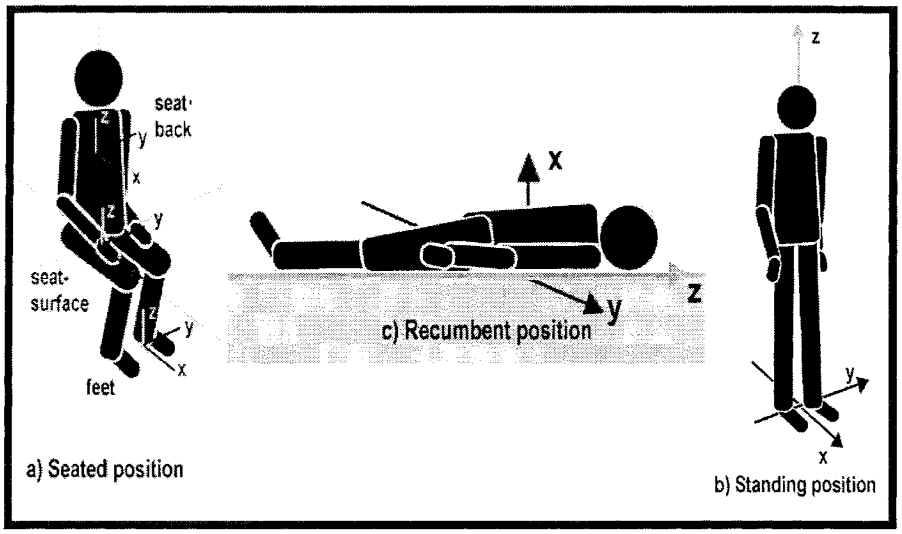


Figure 1.2: Basic Axes of the Human Body, ISO 2631 - 1: 1997

Human perception of vibration is further dependent upon the direction of vibration. A biodynamic system has been defined to study the human responses to vibration, where the point of contact is taken as the origin [31, 32]. Figure 1.2 illustrates biodynamic axis systems, for the sitting, standing and recumbent positions, where x-axis defines the back-to-front direction, y-axis as left to right, and z-axis as the foot-to-head direction. The WBV seldom occur along a single axis. Moreover, the human body may exhibit multi-axis responses even under a single-axis vibration, due to couplings caused by rotational motions of various body segments [28,35,50,56,58,71,72].

1.2.2 EFFECTS OF VIBRATION

Prolonged exposure to whole-body vibration has the capacity of producing a wide variety of effects on the exposed human body. It can generate a range of subjective sensations, which are generally grouped into three categories [32, 52]:

- The threshold of perception, which is frequently related to interference with physical activity;
- The onset of unpleasant sensations, which is mainly linked to interference with comfort;
- The limits of tolerance, which is mostly shown as interference with health, by mechanical damage of the tissues and the musculo-skeletal structure.

These groups of responses also define three principal criteria for assessing the effect of vibration. A number of laboratory experiments involving both subjective and objective measures have evolved into certain guidelines to asses these effects [4, 14, 23, 29, 43, 60, 65, 67, 73-87]. It is, however, quite difficult to separate the health effects due only to vibration from those caused by other factors, such as poor posture, heavy lifting, pulling and pushing [4, 36, 88], that could yield similar health effects on the human body. All of these factors could lead to spinal injuries, abdominal and digestive problems, urinary difficulties, prostatitis, increased problem of balance, visual disorders, headaches, sleeplessness and similar symptoms [32, 84, 89, 90]. On the basis of measured response and identified resonant frequencies, a few studies have suggested a direct relationship between the vibration frequency and symptoms, which are summarized in Table 2.4 [53].

Table 1.4: Symptoms of multidirectional vibration exposure in the 1-20 Hz frequency range [53]

SYMPTOMS	FREQUENCY (HZ)
General feeling of discomfort	4-9
Head symptoms	13-20
Lower jaw symptoms	6-8
Influence on speech	13-20
"Lump in the throat"	12-16
Chest pains	5-7
Abdominal pains	4-10
Urge to urinate	10-18
Increased muscle tone	13-20
Influence on breathing movements	4-8
Muscle contractions	4-9

Other studies have identified various physiological effects of vibration [29, 32, 67, 84, 89, 90]. These include: The cardiovascular effects involving increased heart rate, cardiac output and blood pressure under vibration exposure; respiratory effects involving increased respiration rate and mechanical pumping; musculo-skeletal effects associated with deformation of bones and joints, and contraction of muscles; and endocrine and metabolic effects leading to changes in blood and urine constituents.

The data compiled by various epidemiological, subjective and biodynamic studies have identified various specific health effects of exposure to whole body vibration [2-5, 17, 36, 43, 48, 49, 56, 58, 67, 68, 80-82, 91, 92], which are briefly described below.

- Spinal column and back disorders: These are perhaps the most common diseases associated with the long-term exposure to whole-body vibration, where spine and supporting structure are believed to be especially sensitive to vertical vibration in the 4-12 Hz range. Stresses on the intervertebral discs, trunk muscles pain or inability of the neuromuscular control system to respond fast enough in a coordinated fashion are some of the effects of multiple shocks and vibration exposure [4, 36, 48, 49, 58, 63, 69, 81, 82, 82, 93]. Biodynamic experiments have shown that whole-body vibration exposure, combined with a constrained sitting posture, can put the lumbar intervertebral disc at a risk of failure or cause other spinal deformations [2, 4, 7, 12, 52]. The disc injury could be shown as a deviation of its viscoelastic properties, fluid exchange or even change in height [3, 5, 80, 91, 94].

- Digestive system diseases: The disorders of the digestive system have been widely reported in persons exposed to whole-body vibration over a long period of time, which is associated with the resonant motion of the stomach at frequencies between 4 and 6 Hz [31, 67]. Abnormalities of gastric motility (movement food during digestion), such as gastric neurosis, tachygastria, and non-ulcerative dyspepsia, are specific disorders associated with whole-body vibration [36, 52, 67, 81, 82, 92].

- Cardiovascular system effects: Prolonged exposure to whole-body vibration at frequencies below 20 Hz results in hyperventilation, increased heart rate, oxygen intake, pulmonary ventilation and respiratory rate [36, 43, 52, 69]. Damage of the capillary blood vessels structures of the body tissues and major organs can lead to internal haemorrhages of the blood vessels. Prolonged increases in blood pressure may cause premature cardiac failure and other cardio-vascular related damages, such as vein thrombosis, varicose vein formation and haemorrhoids [47, 53, 69, 81, 82].

Apart from the health effects of prolonged exposure to severe levels of whole-body vibration, the exposure is known to interfere with the sensing, decision-making, and muscular reaction abilities of the operator [36, 43, 62, 65, 73, 95, 96]. These may be attributed to the fatigue induced by movements of muscles and joints under vibration, or the reduced physical and physiological performance limits [32, 35, 41, 43, 52, 60, 63, 68, 70, 80]. Although peripheral and neurological responses of operators involved in specific tasks are quite complex, a few studies have suggested that exposure to vibration can limit human ability of perception for collecting information and neuro-muscular reaction for processing the information, and may cause fatigue leading to reduced alertness and motivation.

Some of these effects have been associated with the predominant frequencies of whole-body vibration. Exposure to low frequency vibration reduces the operator's ability in controlling the vehicle, which is reflected in the poor hand-eye coordination, foot pedal control, reaction time, visual acuity and path tracking [35, 68, 77, 97]. Perception is the process by which organisms interpret and organize information received by the sensing organs. Vibration frequently affects this perception, creating inaccuracy in the discernment of a sensory experience. Vision, for instance, is mainly affected by vibration at frequencies between 20 to 70 Hz, although the exposure to vertical vibration below 1-2 Hz causes the eyes movement to overcome the vestibulo-ocular reflex (compensatory eye movement which keeps the image fixed on the retina for any head rotations and translations) [32, 87, 95]. The excitation in the range of eye-resonance in both horizontal and vertical directions could produce the illusion of slow spot motion, generating at the same time changes in the normal proprioception (cerebral mechanism that sense the body position), altering the normal motor response [95]. Visual acuity, the ability to distinguish details and shapes, is affected by the frequency and magnitude of vibration in short time exposures to whole-body vibration, suggesting temporary threshold shift. Therefore, this could be a physiological indicator of vibration effect on humans, which decreased by approximately 23% under vertical acceleration of 0.3 g at a frequency of 3.5 Hz [77, 98]. The visual acuity may also be encouraged by the movements, which is often linked to increase contact and pitch rotation caused by high backrest seats [52, 90].

The human perception of vibration and the resulting fatigue is also dependent upon the sitting posture, which is also vibration frequency related. It has been suggested that seated occupants exposed to WBV in the 1-30 Hz frequency range experience an increased postural swing and difficulties in maintaining adequate posture [32]. Slight motions, even below the threshold for motion perception, are enough to induce postural readjustments. The visuo-motor system plays a decisive roll in controlling or readjusting the posture, when a motion is anticipated [63, 89, 99]. Such visual perception is one of the principal feedbacks of the postural control tendencies at frequencies under 0.2 Hz. Other frequency-related vibration-induced task interferences are: a) reduced compensatory tracking ability, which is impaired under vertical vibration around 3.5 Hz and horizontal vibration around 1.5 Hz; b) Reduced ability to maintain constant foot pressure, which deteriorates as a function of frequency (maximum near 3.5 Hz) and intensity of vibration; c) impaired reaction time immediately following the exposure to transverse vibration (around 3.4 Hz) leading to deteriorated visual scanning and hand-eye coordination [40, 68, 98].

The comfort effects of vibration are of primary concern in automobiles, passenger transport systems, buildings, etc. The levels of whole-body vibration in such applications are relatively low, which may not be concerned with the health and perception related effects of vibration. Considerable efforts have been made to quantify the vibration-induced comfort sensation of occupants of automobiles, passenger vehicles and buildings [29, 36, 62, 68, 73, 74, 100, 101]. It was established that the occupant discomfort is proportional to the magnitude of vibration, often expressed either frequency-weighted or unweighted rms acceleration [30-32, 35, 51, 73]. International standard ISO 2631-1 [31] provides ranges of overall total vibration magnitude and the corresponding subjective sensation of comfort, which is summarized in Table 1.5.

Table 1.5: Vibration discomfort scale proposed in ISO 2631-1 [31].

Acceleration Level (m/s^2)	**Sensation**
Less than 0.315	Not uncomfortable
0.315-0.63	A little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
Greater than 2.0	Extremely uncomfortable

The occupant's sensation of discomfort is closely related to the vibration frequency. The WBV along the vertical direction is directly transmitted through the body at frequencies below 2 Hz, suggesting mass-like behaviour of the body [53]. The motions of different body segments experience amplifications at slightly higher frequencies, which contribute to increased overall discomfort. Further increase in the vibration frequency above the resonance frequency yields increasing attenuation of vibration, and thereby reducing the discomfort sensation [29, 32, 58]. The human body is known to be quite sensitive to vertical vibration in the 4-8 Hz frequency range, and to fore-and-aft vibration at frequencies below 2 Hz. Random vibration and multiple axis vibration produce more discomfort, the human sensitively to simultaneous multidirectional vibration is considered to be approximately 18-25% higher than the uni-directional vibration [29, 32]. Furthermore the sensation of discomfort tends to increase with increasing the duration of vibration.

Exposure to vibration at frequencies near or below 1 Hz, which occurs in many forms of transport systems, has been associated with motion sickness (kinetosis). The principal symptoms of kinetosis include nausea, dizziness, vomiting, disorientation, constipation, high blood pressure, drowsiness, etc. [32, 84, 89, 90]. Unlike the health and discomfort effects, such symptoms could be felt over a short duration or shortly after exposure, but are characterized as temporal minor annoyances in most of the cases. Symptoms of kinetosis in ships has been associated with low frequency vertical vibration [83], while the same symptoms in automobile occupants have been attributed to horizontal vibration arising from acceleration, braking and cornering manoeuvres [84]. Experimental studies performed by Golding [85], Markley [86] and Stott [83] concluded that horizontal motions of the occupant is twice as nauseogenic than the vertical motion of the seated subjects. Similar findings have also been reported by Mills [87] and Turner [84]. These studies have also concluded that the symptoms are worst under exposure to vibration between 0.125 and 0.25 Hz, and only rarely occur due to vibration at frequencies above 0.75 Hz. The nauseogenic potential of motion is increased by the absence of a stable visual reference, head movements, orientation of the body with respect to the direction of the linear acceleration stimulus, the contact with low backrest, and the direction of motion [85-87]. Nauseogenicity also increases as a function of exposure time and acceleration intensity [83].

1.2.3 ASSESSMENT OF HUMAN EXPOSURE TO WHOLE-BODY VIBRATION

The human occupant's perception and sensation of vibration is directly associated with the ride vibration environment of the vehicle. A large number of subjective and objective studies have been performed on human perception of vibration in attempts to quantify vibration comfort boundaries and assessment guidelines. Considerable variations in the outcomes of these studies, attributed to variations in test conditions and individual factors pose extreme challenges in establishing generally applicable ride comfort boundaries [44]. Furthermore, a generally accepted method of assessment does not yet exist due to highly complex nature of human response to vibration. Despite the lack of generally acceptable guidelines and assessment methods, somewhat similar methods have been widely used to evaluate the human tolerance and acceptance of vibrations [44, 79]. These methods may be classified in four broad groups on the basis of the primary measurement techniques:

The first group of studies is based upon subjective ride measurements which involve evaluations by a selected sample of populations, and relatively fuzzy evaluation schemes. These studies have proven to be effective in performing relative assessments of vehicle seating environment. The second group involves repetitive shake table tests on a selected subjects sample, who are exposed to harmonic vibration of different amplitudes, at different discrete frequencies. The data derived from subjective feedbacks on their perception of vibration are used to define vibration comfort boundaries and human perception of vibration. The data shake table tests are also employed using the stimulus representing the realistic road measured vibration environment. These studies constitute the third group, and are used to evaluate the comfort and potential injury risk following either a specific or a combination of criteria. The final group of studies comprises the measurement of ride environment and vibration exposure in the vehicles under normal operating conditions. These studies involve both subjective as well as objective evaluations of ride vibration environment and human perception [32,44,52].

Although a generally acceptable criterion for objective assessment of human perception of whole-body vibration exposure does not yet exist, a number of guidelines have been proposed and standardized [36, 44, 52]. Some of these guidelines are briefly described below:

1) **Janeway's Criterion.** On the basis of subjective assessments, Janeway proposed a vertical vibration comfort criterion for automotive passengers [44, 52], which has been recommended by the Society of Automotive Engineers (Ride Vibration Manual J6a [102] for many years. The criterion is limited to vertical vibration only and suggests that the human body is more sensitive to vertical vibration in the 1-20 Hz range.

2) **International Standard ISO 2631:** Presently, the most commonly acceptable standard for evaluating human exposure to whole-body vibration is the International Standard ISO 2631-1 [31]. The standard defines the frequency-weighting functions to account for variations in human sensitivity to vibration frequency, for vibration along the three translational and three rotational axes. Its earlier version also proposed the WBV exposure limits in view of human perception, preservation of working efficiency or human fatigue, and preservation of health, in terms of magnitude of vibration in the 1-80 Hz frequency range and exposure duration [103]. The proposed guidelines and limits, however, have been criticized in many studies [14, 25, 36, 37, 41, 50, 67, 73, 74, 78].

3) **Absorbed Power**: It is a measure of the rate of vibrational energy absorbed by the human body attributed to its visco-elastic properties. The vibration energy absorbed by a seated occupant is strongly related to the magnitude and frequency of the input vibration, and the exposure duration. The criterion, initially proposed by Pradko and Lee [104], has been widely used to characterize military vehicles vibration environment [79]. The vibration energy absorbed by the human body is also considered as a significant measure for assessing the injury risk [105, 106]. A few studies have thus characterized the biodynamic responses of the seated occupants exposed to WBV in terms of the absorbed power in a few studies [11, 14, 15, 21, 25,, 107, 108].

It is essential to mention that the vast majority of the criteria have been established on the basis of different subjective and objective measures under exposure to sinusoidal vibration, which may not fully describe the human response to random vehicle vibration. Furthermore, the occupant sitting posture and conditions are not sufficiently described in these studies, to assess the suitability of the proposed limits for automotive environments.

1.2.4 VEHICLE VIBRATION ENVIRONMENT

The applications of the proposed methods and guidelines require characterization of the vibration environment of vehicles in terms of magnitudes, frequency contents and direction. Considering that the human response and perception of WBV is strongly dependent upon the nature of vibration, the characterization vibration environment forms the foremost task in such studies. A large number of analytical and experimental studies have been conducted to define the ride vibration characteristics of on-road as well as off-road vehicles [6,29,35,37,38,40,43,45,74,76,79,100,101,109-116]. The primary objectives of these studies include the assessment of ride vibration levels, design or tuning of suspension components, and sensitivity analysis under variations in design and operating factors.

Over the years, a large number of ride dynamic models have been developed to derive the vibration environment of different vehicles under specific terrain and operating conditions. These models range from a few to several degrees of freedom, and may include either linear or non-linear component characteristics [44]. The reported ride dynamic models may be classified in three categories on the basis of the degrees-of-freedom (DOF) of motion considered. The first category of models involves simplified two-DOF models of the quarter vehicle, which are effectively used to assess the vertical dynamic response alone of the suspension components [44]. The in-plane models, within the second category, are used to characterize vertical and either roll or pitch vibration of vehicles [44]. The final category comprises more comprehensive three-dimensional models, which are derived to characterize the ride vibration responses along the vertical, pitch, roll, longitudinal and lateral axes [36,44].

Alternatively, a few studies have performed extensive measurements of ride vibration environment of different vehicles under a wide range of operating conditions [6, 37, 38, 40, 43, 45, 76, 79, 101, 113-116]. Some of these studies have evolved into spectral classes of vibration of different classes of vehicles. International Standard ISO-7096 [117], ISO-5007 [118], and ISO/TR 15070-1 [119], define spectral classes of earthmoving machinery, agricultural tracks and forklift trucks, respectively. The spectral classes of vibration in these documents, however, are limited to vertical vibration alone. In a recent study, Boileau et al. [120] defined the ranges of vibration of urban buses, forklift trucks and side-walk snowploughs along the vertical, lateral, longitudinal, roll and pitch axes, while operating under a wide range of operating conditions. The results of this study clearly show that the drivers of such vehicles are also constantly exposed to comprehensive magnitudes of vibration along the lateral and longitudinal axes. The interaction of off-road vehicles with highly uneven terrains cause considerable magnitudes of WBV along the horizontal axes, while the majority of the studies on human response to vibration have been limited to vertical axis alone.

Of special preoccupation are the operators of off-road vehicles, such as agricultural tractors, forestry vehicles, movable earth vehicles, industrial tractors, scrapers, excavators, etc., who are continually exposed to severe vibration and shock motions caused by the movement of the vehicle through rough terrains. The relatively low lateral flexibility of tires coupled with high location of the operator, and presence of slope and cross-slope of the terrain, yield considerable motions along the longitudinal as well as lateral directions [6, 36, 41, 63, 112, 116, 121, 122]. Epidemiological studies have reported high incidence of disorders among the off-road vehicles drivers, being nearly 2-

4 times higher than that among the crane operators (on-road) [2]. Road vehicles also transmit appreciable magnitudes of horizontal vibration caused by steering, braking, wind loads, and interactions with the road irregularities. The intensity of transmitted vibration of different vehicles is discussed below.

Among all the off-road vehicles, the agricultural and forestry tractors have been the most widely studied group [1, 2, 5, 6, 36-38, 43, 45, 68,, 76, 96-98, 101, 106], with objectives involving mobility, ride vibration and safety. The primary focus of these studies, however, has been limited to vertical vibration, which has culminated into development of effective suspension seats [35, 36, 41, 47, 68, 68, 112, 123]. Nevertheless, the incidence of occupational diseases due to whole-body vibration exposure remains amongst the highest in such vehicle drivers [2, 36]. This could be linked to many factors including the frequent bottoming/topping of suspension seats, prolonged exposure duration, presence of high magnitudes of horizontal and rotational vibration, etc. Many studies have reported the frequency-weighted magnitudes of vibration transmitted to the driver seat in such vehicles, which are summarized in Table 1.6 [6, 18, 96, 116]. The reported data suggest that the magnitudes of transmitted vibration of tractors strongly depend upon the task, and that these vehicles cause appreciable magnitudes of vibration along the longitudinal (a_{wx}) and lateral (a_{wy}) axes. The table also summarizes the vector sum of accelerations (a_v). The addition of implements or trailers to these tractors further induces vertical pitch vibration of articulated units near 2.3 Hz [14, 36, 76, 98].

Table 1.6: Magnitudes of frequency-weighted rms accelerations due to vibration measured along the x-, y-, and z-Axis, on the seats of agricultural/forestry tractors [6,96,115,116].

OPERATION/TASK	a_{wx} (m/s^2)	a_{wy} (m/s^2)	a_{wz} (m/s^2)	a_v (m/s^2)
Tractor on-road	0.22-1.04	0.37-1.20	1.42-2.15	1.80-3.09
Tractor off-road	0.24-1.79	0.51-1.70	1.25-2.99	1.58-4.57
Tractor (road transportation-trailer)	0.30-0.60	0.40-0.50	0.50-1.00	-----
Tractor on special track without any implement	0.222-0.687	0.306-0.988	0.356-1.165	0.729-1.954
Tractor on special track carrying plough	0.215-.617	0.329-0.833	0.294-0.902	0.710-1.692
Tractor ploughing *	0.300-1.300	0.200-0.613	0.300-0.599	0.869-1.266
Tractor harrowing *	0.200-0.685	0.200-0.800	0.379-0.963	0.850-1.667
Tractor (rear mounted mower)	0.30-0.70	0.30-0.50	0.50-0.60	-----
Tractor (side mounted machine)	0.40	0.40-0.70	0.50-0.70	-----
Tractor (trailed air-blaster sprayer with engine drive)	0.30-0.90	0.20-0.90	0.30-1.30	-----
Band excavator (harrowing)	0.20-2.60	0.20-1.00	0.30-1.40	-----
Band excavator (drilling grain)	0.50-1.10	0.50-2.80	0.30-1.00	-----
Band excavator (ploughing)	0.50-1.30	0.30-1.30	040.-1.00	-----
Band excavator (low speed operations)	0.20-0.30	≈0.20	0.30-0.40	-----
Harvester-thresher	0.10-1.00	0.10-0.60	0.20-1.30	-----
Harvester for grapes	≈0.20	≈0.20	≈0.50	-----

* Data compiled from different sources

The nature of transmitted vibration is most significantly affected by the properties of the suspension and tires, apart from the vehicles weights and dimensions. A vast majority of wheeled off-road vehicles are designed without a wheel suspension. The ride behaviour of such vehicles is thus characterized by the response of a lightly damped system, where the damping arises from the tires. The road vehicles are invariably designed with a primary suspension and thus yield significantly different levels of vibration, which may be considerable dependent upon the type of vehicle. A vast majority of modern industrial vehicles employed in construction and service sectors are also designed with primary suspension in order to obtain higher speeds [36, 43, 68, 79, 96, 101, 116, 122]. Higher operating speeds, however, cause higher magnitudes of vibration along all the translational and rotational axes [43, 76, 101, 106, 122]. Table 1.7 and Table 1.8 summarize the frequency-weighted rms accelerations due to vibration transmitted along the longitudinal (*x*), lateral (*y*) and vertical (*z*) axes of various industrial and heavy road vehicles, together with the total vibration magnitudes [7, 45, 75, 112, 115, 124]. The weighted accelerations in these tables are derived upon applications of W_d- and W_k- weighting filters defined in ISO 2631-1 [31]. The results further show that the majority of vehicle cause considerable vibration along the *x*- and *y*- axes.

Table 1.7: Magnitudes of frequency weighted rms accelerations due to vibration measured along the x-, y-, and z-axis on the seats of heavy vehicles [45, 112].

Vehicle	$\mathbf{a_{wx}}$ (m/s^2)	$\mathbf{a_{wy}}$ (m/s^2)	$\mathbf{a_{wz}}$ (m/s^2)	$\mathbf{a_v}$ (m/s^2)
Tracked forestry vehicle velocity constant	0.11-1.621	0.923-0.150	0.237-0.392	0.352-0.450
Tracked forestry vehicle acceleration constant	≈ 0.254	≈ 0.121	≈ 0.398	≈ 0.560
Cargo trucks (1-2 Tons)	0.36-0.70	0.39-0.75	0.65-1.29	-----
Cargo trucks (>10 Tons)	0.20-0.42	0.20-0.24	0.42-0.70	-----
All Terrain Vehicle (cargo)	0.31-1.08	0.55-1.11	1.04-1.76	-----

Table 1.8: Magnitudes of frequency weighted rms accelerations due to vibration measured along the x-, y-, and z-axis on the seats of heavy vehicles [7,79,115,124].

Machine	a_{wx} (m/s^2)	a_{wy} (m/s^2)	a_{wz} (m/s^2)	a_v (m/s^2)
On-road passenger vehicle (smooth surface)	0.108-0.184	0.111-0.141	0.239-0.305	0.326-0.434
On-road passenger vehicle (rough surface)	0.165-0.227	0.380-0.540	0.595-0.617	0.880-1.026
Mini City Bus	0.10-0.60	0.00-0.90	0.20-0.60	-----
traddle carrier	0.02-0.013	0.19-0.27	0.30-0.36	0.41-0.55
Fork-lift truck (no specific road)	0.03-0.32	0.02-0.68	0.05-1.23	0.13-1.67
Fork-lift truck (Port-area)	0.10-0.20	≈0.10	0.20-0.40	-----
Fork-lift truck (off-road)	0.10-0.90	0.10-2.50	0.50-1.60	-----
Freighter container tractor	≈0.80	≈0.10	≈2.00	-----
Straddle Carrier	0.20-0.30	≈0.10	0.30-0.40	-----
Mobile crane *	0.00-0.63	0.03-0.90	0.00-0.60	0.26-0.80
Overhead crane *	0.08-0.14	0.05-0.09	0.02-0.20	0.10-0.34
Port Crane	0.80-1.30	≈0.10	≈0.10	-----
Dumper	0.20-0.50	0.30-0.70	0.40-1.40	0.60-1.80
Dump truck 2 Ton	0.29-1.31	0.23-1.72	0.30-1.64	-----
Garbage truck 2 Ton	0.31-1.67	0.21-1.09	0.3-1.34	-----
Garbage truck 4 Ton	0.50-094	0.56-1.98	0.37-2.45	-----
Garbage truck	≈0.10	≈0.20	0.20-0.40	-----
Industrial container truck	≈0.20	≈0.20	≈0.30	-----
Excavator	0.20-1.30	0.10-0.60	0.20-1.00	0.40-1.70
Tractor Excavator	0.20-0.70	0.10-0.60	0.20-0.80	0.40-1.60
Loader	0.20-0.80	0.30-0.70	0.30-4.10	0.70-1.70
Wheel Loader	0.20-0.90	0.30-0.80	0.60-1.50	-----
Road Grader	0.20-0.30	0.20-0.50	0.10-0.90	0.70-1.10
Band Excavator (excavating)	0.60-1.00	0.40-0.60	0.30-1.80	1.50-2.10
Band Excavator (levelling material)	0.70-1.00	0.50-0.90	0.90-1.50	1.80-2.20
Band Excavator (road transportation)	≈0.60	≈0.80	≈1.20	-----
Snowgroomer	0.40	0.30-0.40	0.60-0.90	-----

*compiled from different sources

1.2.5 NATURE OF LONGITUDINAL AND TRANSVERSAL VIBRATION IN VEHICLES

Owing to high magnitudes of transmitted vibration and their associated potential health and safety risks, a vast number of studies have been conducted to mitigate the levels of hazardous vibration and enhance understanding of the human response to vibration [2, 5, 7, 11, 14, 15, 35-37, 43, 56, 58, 67, 75, 76, 80, 91, 96, 124]. The vast majority of these studies, however, have been limited to vertical vibration alone. The reported measured data of different vehicles, summarized in Tables 1.6 to 1.8, however, suggest the presence of considerable vibration along the *x*- and *y*- axes. It may thus be worthy to further examine the nature of horizontal vibration exposure for evaluating the human response to ride vibration.

For off-road vehicles, it is generally accepted that magnitudes of longitudinal and transversal vibration are comparable to those transmitted along the vertical axis [2, 34, 46], as it is evident from the data reported for tractors in Table 1.6. On the basis of measurements performed on tractors, Kumar et al. [6] concluded that the ratio of lateral-bounce and longitudinal-bounce vibration lie in the 48% to 60% range, depending upon the operating speed and manoeuvres. Marsili et al. [96] reported that levels of vibration measured laterally could exceed the corresponding vertical vibration of the tractor during the transport operation. Many studies have reported similar levels of vibration along all three axes of tractors while performing specific tasks [53, 96, 109]. The ride vibration levels in the lateral axis increase abruptly during harrowing operation and ploughing [53, 101], while relatively higher levels of vibration are transmitted during spraying [53]. It can be thus concluded that the relative magnitudes of transmitted horizontal vibration are task-dependent.

The reported studies on WBV levels of different vehicles have been thoroughly reviewed to identify the proportion of vehicles were the rms and peak horizontal vibration values may exceed those encountered in the vertical axis [2, 36, 45, 46, 96, 125]. The results summarized in Table 1.10 suggest that for a class of construction, industrial and passenger vehicles, the levels of horizontal vibration may frequently exceed the vertical vibration levels. The table also summarizes the percentage of vehicles that could yield vibration levels with crest factor above 9, suggesting considerable shock contents. The severity of vibration and the human perception is also strongly dependent upon the frequency contents of the transmitted vibration, which would depend upon the vehicle weight and dimension, terrain properties and properties of tires and suspension [34, 40, 44, 45, 112, 113]. Table 1.9 summarizes the predominant frequencies of vibration response of wheeled off-road vehicles [57]. The results suggest that the off-road vehicle vibration mostly occur in the 0.5-5 Hz range, irrespective of the direction of vibration.

Table 1.9: Frequency ranges of predominant vibration of wheeled off-road vehicles [57].

MODE OF VIBRATION	PREDOMINANT FREQUENCY RANGE (HZ)
Bounce	2.0-3.5
Lateral	≈ 1.0
Longitudinal	2.0-4.5
Roll	0.5-4.5
Pitch	2.0-4.5

Table 1.10: Comparisons of horizontal and vertical rms vibration levels of different on- and off-road vehicles [115]

Evaluated Vehicles			% of vehicles with horizontal vibration ≥ bounce vibration		% of vehicles with peak horizontal vibration ≥ peak bounce vibration		% of vehicles with crest factors of vibration ≥ 9			Comments
Total	Type	Studies reporting peak values	X axis	Y axis	X axis	Y axis	X axis	Y axis	Z axis	
14	Dumper	0	0%	7 %	0%	0%	64%	21%	64%	Vibration magnitudes in all directions increased from asphalt to forestry road, especially in bounce mode; The peak values are large in all directions, principally in *x*- and *z*-axis.
14	Excavator	14	57%	0 %	29 %	14%	43%	57%	57%	The percentage of vehicles where the longitudinal vibration exceeds the bounce could be related to the tasks performed.
9	Loader	9	22%	22%	11%	22%	22%	23%	33%	The horizontal accelerations increased with variations in terrain conditions, while the overall rms accelerations do not show the same behaviour. The magnitudes of peaks in *z*-axis are considerably large.
6	Tractor Excavator	6	83%	17%	50%	33%	0%	0%	17%	Levels of vibration in all axes vary considerably with changes in the road surface.
24	Harvester-Thresher	0	4%	8%	-----	-----	-----	-----	-----	Lower vibration along the horizontal axes.
35	Mini City Bus	0	26%	23%	-----	-----	-----	-----	-----	The rms magnitudes of horizontal accelerations are higher than the bounce mode; the road surfaces have similar characteristics (the variations could be related to the driver). The magnitudes of peaks in *z*-axis are large.

Table 1.10: Comparisons of horizontal and vertical rms vibration levels of different on- and off-road vehicles [115]

Evaluated Vehicles			% of vehicles with horizontal vibration ≥ bounce vibration		% of vehicles with peak horizontal vibration ≥ peak bounce vibration		% of vehicles with crest factors of vibration ≥ 9			Comments
Total	Type	Studies reporting peak values	X axis	Y axis	X axis	Y axis	X axis	Y axis	Z axis	
3	Forklift Truck (on port area)	0	0%	0%	-----	-----	-----	-----	-----	
4	Forklift Truck (off road)	0	50%	25%	-----	-----	-----	-----	-----	
7	Road Grader	7	14%	14%	14%	29%	43%	14%	29%	The overall acceleration levels increased with increasing road rougher.
3	Mobile Crane	0	33%	100%	-----	-----	-----	-----	-----	The lateral acceleration is the principal contributor to the overall acceleration, and it could be related to the nature of the tasks.
2	Port Crane	0	100%	100%	-----	-----	-----	-----	-----	The nature of vibration could be related to the high position of the operator seat.
6	Wheel Loader	0	17%	17%	-----	-----	-----	-----	-----	Accelerations in all directions increased with changes in activity: The clay excavation resulted in highest for x axis, spraying the highest for z axis, and resulted in high y axis both activities.
1	Freighter containers	0	0%	0%	-----	-----	-----	-----	-----	Although the component of acceleration in longitudinal axis is lower than vertical axis, both components show with high acceleration levels.

Table 1.10: Comparisons of horizontal and vertical rms vibration levels of different on- and off-road vehicles [115]

Evaluated Vehicles			% of vehicles with horizontal vibration ≥ bounce vibration		% of vehicles with peak horizontal vibration ≥ peak bounce vibration		% of vehicles with crest factors of vibration ≥ 9			Comments
Total	Type	Studies reporting peak values	X axis	Y axis	X axis	Y axis	X axis	Y axis	Z axis	
6	Wheel Tractor Harrowing	0	0%	17%	-----	-----	-----	-----	-----	The behaviour of tractors in road shows low acceleration components in horizontal axes, but in vertical the component is the second highest depending on the tasks. The accelerations in all directions are the highest during spraying. The components in lateral and vertical axes of acceleration seem to be related when a machine is mounted in one side of the tractor.
9	Wheel Tractor Ploughing	0	67%	67%	-----	-----	-----	-----	-----	
2	Wheel Tractor with rear mounted mower	0	50%	50%	-----	-----	-----	-----	-----	
5	Wheel Tractor on road	0	0%	0%	-----	-----	-----	-----	-----	
4	Wheel Tractor /side mounted machine	0	0%	50%	-----	-----	-----	-----	-----	
10	Wheel Tractor spraying	0	30%	20%	-----	-----	-----	-----	-----	
27	Band Excavator harrowing	0	33%	22%	-----	-----	-----	-----	-----	Harrowing presents the highest components of accelerations in all the three axes; 3 of each 9 vehicles showed equal or higher levels in longitudinal than vertical direction.
8	Band Excavator excavating	4	38%	25%	0%	25%	25%	25%	0%	

Table 1.10: Comparisons of horizontal and vertical rms vibration levels of different on- and off-road vehicles [115]

Evaluated Vehicles			% of vehicles with horizontal vibration ≥ bounce vibration		% of vehicles with peak horizontal vibration ≥ peak bounce vibration		% of vehicles with crest factors of vibration ≥ 9			Comments
Total	Type	Studies reporting peak values	X axis	Y axis	X axis	Y axis	X axis	Y axis	Z axis	
7	Band Excavator drilling grain	0	100%	71%	-----	-----	-----	-----	-----	X component is higher than the Z component (80%), and even a relative high percentage of this is 50% higher in magnitude (almost the half of the vehicles); the lateral component is also high Drilling grain showed very large Y component of acceleration; Z and Y still high, but not of the intensity of the precedent tasks. Levelling material and excavation are tasks that result in medium levels of vibration in all directions; transport operation yields predominant Z- direction acceleration
3	Band Excavator levelling material	3	30%	33%	33%	0%	33%	0%	0%	
15	Band Excavator Ploughing	0	80%	60%	-----	-----	-----	-----	-----	
1	Band Excavator at road	0	0%	0%	-----	-----	-----	-----	-----	
2	Band Excavator (vineyard low speed operations)	0	0%	0%	-----	-----	-----	-----	-----	

NOTES:

Vehicles such Harvesters for grapes, Overhead cranes, industrial container trucks and straddle carriers show low acceleration component in all axes.

Vehicles such snowgroomers, show small contributions in horizontal to the overall acceleration

Table 1.11: Principal resonant frequency ranges of seated human body [32].

MODE OF VIBRATION	RESONANCE FREQUENCY (HZ)	
	FIRST RANGE	SECOND RANGE
Bounce	4.0-6.0 [56] 1.5-15.0	8.0-12.0 [56] 3.0-20.0 [64]
Lateral	1.0-2.5 [64] 2.0-4.0 [2] 0.5-2.0	6.0-11.0 [64] 5.0-7.0 [2] 4-5.5
Longitudinal	1.0-3.0 [64] 2.0-4.0 [24] 0.6-8.5	5.0-12.0 [64]
Roll	1.5-2.5	4.5-7.7
Pitch	5.0-7.0 [27] 3.0-11.0	-----
Yaw	1.7-7.0	-----

It is widely known that fundamental resonances of seated body are dependent upon sitting posture, magnitude and direction of vibration, back support condition, etc. The reported data exhibit first two resonances within certain range of frequencies, despite considerable variation in the seating and excitation condition. These ranges, identified from different studies, are summarized in Table 1.11. The results clearly show that the first two resonances of the seated human body occur at frequencies up to 20 Hz. Many studies have concluded that exposure to horizontal vibration in the 0.1- to 0.75 Hz could trigger motion sickness in roughly half the time that would be experienced under vertical vibration [83, 85, 86]. The yaw movement of the body could also cause motion sickness and reduction in the perception thresholds over 0.05-6.3 Hz frequency range [27]. Griffin [32] summarized the effects of exposure to such vibration under comfort, health, interference with activities, and motion sickness, as is shown in Table 1.12.

Table 1.12: Vibration frequency sensitivity of seated human occupants [32].

Effect of Whole-Body vibration in:	Vibration Axis					
	X	Y	Z	Roll	Pitch	Yaw
Comfort	< 3.0 3.0-6.0	1.0-2.0	4.0-8.0	< 1.0	< 1.0	< 1.0
Health	2.0-20.0 (cardiovascular system); 2.05-10.0 (respiratory system) 10.0-30.0 and below 1.25 (muscle activity)					
Interference in Activities	Low end of the range 2.0-20.0 (vision) 4.0-5.0 (steering control) 4.0-8.0 (writing process) 5.0-20.0 (speech)					
Motion Sickness	0.1-0.5	0.1-0.75	0.1-0.5	-----	-----	< 1.0 [27]

Effective primary and secondary suspensions, mostly in the form of a suspension at the seat, have been widely implemented to reduce magnitudes of the vibration experienced by the operator. The suspension seats, however, are designed to attenuate the vertical vibration alone. From review of the reported studies, it is apparent that a large number of vehicles transmit important levels of horizontal vibration. Some of the suspension seats employed to reduce the vertical component of vibration could, at the same time, increase the transverse and longitudinal components of vibration [116]. This may be attributed to the grater distance between the seat surface and the centres of rotation of the tractor chassis in pitch and roll, and to horizontal flexibility in the seat suspension mechanism and the seat cushion [34, 36, 38, 96, 114, 126]. Low natural frequency suspension seats further tend to amplify the horizontal and vertical vibration, when the suspension travel exceeds the permissible stroke [23, 34, 36, 38, 41, 96]. The resulting interactions with the end-stops that cause motions of the occupant have been reported to occur in both on-road and off-road vehicles.

1.3 HUMAN RESPONSE TO WHOLE-BODY VIBRATION

It has been suggested that the seated human occupant exposed to WBV may lead to a predicable behaviour, and may thus be considered as a mechanical as well as a biological system [32,36,52,53]. Direct measures of the biodynamic responses of the body have been characterized by transfer functions, either those where two different measurements are obtained at the same point, or those where two measures are obtained at different points, typified as transmissibility [32]. The biodynamic response of a seated human body exposed to whole-body vibration can be defined using two principal biodynamic response functions: "To the body" force-motion interrelation as a function of frequency at the human-seat interface, expressed as the driving-point mechanical impedance (DPMI) or the apparent mass (APMS); and the "through the body" response function, generally termed as seat-to-head transmissibility (STHT) for the seated occupant [32,127]. The "to the body" function also describes the energy dissipated/stored by the system, commonly known as the absorbed power [104].

The magnitude of APMS, the ratio of driving force to the acceleration, has a physical correlation equivalent to the static mass of the human body supported by the seat at very low frequencies, when the human body effectively acts as a rigid mass. Consequently, the acceleration response and the driving force at low frequencies remain in phase. In contrast, the DPMI, the ratio of driving force to velocity, tends to emphasize the response at higher excitation frequencies, while the APMS shows a peak response corresponding to primary resonant frequency [127]. The vibration transmissibility of the human body reflects the various biodynamic responses of the body, particularly those between the point at which the vibration enters the body (e.g., on a seat) and the point at which the vibration is measured on the body (e.g., on the head). The transmissibility yields considerable information nature of the vibration transmission of the biodynamic system, and the resonances of the body segments [127].

The measure of the rate at which the vibration energy is absorbed by a human, known as absorbed power, has been used to define human tolerance to vibration for very specific vehicles. This function, which is the product of the dynamic force and velocity transmitted to the human body, is believed to yield a better measure of the effects of exposure vibration and vibration magnitude compared to apparent mass. Since the amount of vibration energy (absorbed and/or exchanged between the source and the body) takes into consideration the interaction between the vibrating structure and the body, it has been suggested as a better measure of the physical stress on the body [11, 14, 15, 25, 102, 104, 105, 108, 128].

The above biodynamic response functions have been employed to characterize the human body response to vibration. These measures show considerable differences in subject masses, excitation levels, sitting postures, etc. The reported data thus show considerable differences in the APMS magnitude and phase responses, which have also been attributed to differences in experimental conditions, apart from the above-stated factors [34, 51, 57, 64, 129]. A recent study has attempted to group the data reported under vertical vibration and comparable test conditions to describe the ranges of biodynamic response of seated occupants exposed to vertical WBV. These ranges adapted in ISO-5982 [130] are considered applicable for sitting without a back support and expressed to vertical vibration. Many recent experimental studies have shown considerable effects of back support and hands position (in the lap and the steering wheel) [10, 17, 29, 33, 43, 100]. No such attempts, however, been made under exposure to horizontal vibration.

A few studies, however, have been investigated biodynamic responses of seated occupants under horizontal vibration. The associated test conditions, however, do no represent seating in a vehicular vibration environment [17, 34, 100, 125, 131]. The majority of the studies focus on assessment comfort [33, 50, 73], and sickness due to vibration on vehicles [83-87, 90, 95]. The biodynamic response functions have also been used to assess human response to horizontal excitation. Mansfield et al. [26], and Fairley et al. [22] have analyzed the biodynamic responses to horizontal vibration in terms of apparent mass, while Demić et al. [29], Tamaoki et al. [71], and Gong [65] have analyzed the through-the-body transmissibility. The power absorption under horizontal vibration has been investigated by Holmlund and Lundström [24, 25]. These studies utilize widely varying test conditions, which are discussed in the following chapters. Although these studies consider random and deterministic vibration excitations, relaxed and erected sitting posture, folded or on-lap hands position, with or without supported back, the responses under typical automotive postures involving inclined seat pan, inclined backrest and full use of backrest support, and either hands-in-lap emulating seated passengers or hands-on-steering wheel emulating drivers have not been investigated.

1.4 SCOPE OF DISSERTATION RESEARCH

Owing to significant discomfort, and health and safety effects of vehicular whole body vibration transmitted to seated human occupants, considerable efforts have been made to study the human responses to vibration and the contributing factors. The vast majority of the studies, however, have been conducted under vertical vibration. A review of the vibration environment of different road and off-road vehicles revealed that such vehicles impose significant levels of horizontal vibration. Some vehicles could yield magnitudes of horizontal vibration larger than the vertical vibration, when performing tasks. While the effects of levels of vertical vibration and the sitting posture on the biodynamics responses have been widely investigated, only limited efforts have been made to characterize such responses under horizontal vibration. These efforts have been mostly limited to the motion sickness effects, while the effects of seat design features and sitting postures have not been addressed.

The reported biodynamics responses to vertical vibration have provided considerable data on the human sensitivity to vibration, power absorption, resonances of the biological system, and the frequency-weighting of the human body. Furthermore, these studies have evolved into knowledge base on the seat design related contributory factors, such as pan and backrest inclinations, back support condition, seat height and foot-to pedal distances. Owing to the comprehensive levels of horizontal vibration and the sensation of discomfort to such vibration, it is anticipated that similar studies on biodynamic response characterization under horizontal vibration and vital for enhancing the knowledge on human response to vibration. These studies are expected to yield considerable knowledge on the role of seat design factors and sitting posture on the biodynamic response and energy absorption. Considering that only a few studies have attempted to study the biodynamic responses to horizontal vibration under varying test conditions, further studies are needed to build the datasets and knowledge base under more realistic test conditions.

It has been suggested that the vibration energy absorbed by the seated occupant could serve as a better measure for investigating the potential injury mechanism. This is attributed to the fact that unlike the APMS or DPMI, the absorbed energy strongly relies upon the severity and duration of the vibration exposure. The study of absorbed vibration energy, however, has been mostly limited to vertical vibration exposure alone. It would be desirable to undertake under horizontal vibration and representative vehicular sitting postures. The results attain would permit the studies on the effects of seated geometry, sitting posture, and the magnitudes of longitudinal and lateral vibration.

1.5 OBJECTIVES OF RESEARCH

The primary objective of this dissertation research is to contribute to the knowledge base on the seated occupant responses to horizontal vibration. The specific objectives of this thesis are formulated as follows:

1) Conduct a thorough review of reported studies on biodynamic responses of seated occupants exposed to WBV to identify more representative test conditions and methodologies.
2) Develop a Whole-body horizontal vibration simulator capable of synthesizing representative vibration, and an instrumented test seat fixture for acquiring the force-motion parameters.
3) Design the experiment to characterizing the biodynamic responses in terms of APMS and absorbed power as functions of vibration magnitude and frequency and back support condition (no support or full support).
4) Acquire the force and motion data under longitudinal and lateral random and deterministic vibration, and evaluate the biodynamic responses.
5) Investigate the inter-subject variability, and the effects of vibration magnitude and back support condition.

1.6 THESIS ORGANIZATION

The present dissertation is organized into six chapters, according to systematic development of the preceding objectives. The general knowledge about vehicle-human interface, principally on the effects of this interaction, and the justification of the analysis under horizontal vibration components is presented in chapter 1.

Chapter 2 presents a thorough review of the reported studies on the biodynamic responses in terms of the measures and test conditions considered. The reported studies are discussed in view of the needs for consideration of the automotive seating environment.

The designs of the horizontal vibration simulator and the test seat are briefly described in Chapter 3. The experiment design involving the synthesis of selected vibration excitations, instrumentation, data acquisition and analyses, is described along with the measurement methodology.

In chapter 4, the measured data are analyzed to highlight the inter- and intra-subjects variabilities. The mean values and ranges of the measured biodynamic responses are presented, and results are discussed to highlight the effects of nature of vibration and back support condition on APMS response.

The biodynamic responses are analyzed to derive the absorbed energy in Chapter 5. The results are discussed to enhance an understanding of the vibration energy dissipation properties of the human occupant, and the effects of vibration magnitude and sitting posture.

The major highlights and contributions of the study together with the conclusions and recommendations for further work are presented in Chapter 6.

CHAPTER 2

WHOLE -BODY BIODYNAMICS: SEATED OCCUPANT RESPONSE TO VIBRATION

2.1 INTRODUCTION

Biodynamic responses of seated human occupant exposed to vibration have been widely characterized to define frequency-weightings for assessment of exposure, identify human sensitivity and perception of vibration, and to develop seated body models [127, 129]. The biodynamic response of the human body exposed to vibration have been invariably characterized through measurement of force-motion relationship at the point of entry of vibration (referred to as 'to-the-body function'), and transmission of vibration to different body segments (referred to as 'through-the-body function'). Considering that the human body is a complex biological system, the 'to-the-body' response function is conveniently characterized through non-invasive measurements at the driving point alone. The vast majority of the reported studies on biodynamic response to WBV have considered vibration along the vertical axis alone [8-10, 17, 21, 34, 129]. The biodynamic responses of seated occupants exposed to horizontal vibration have also been reported in a few studies [22-28, 71, 79], while majority of these have been performed to study the motion sickness effects. Furthermore, the test conditions considered do not represent automotive seating conditions, such as sitting posture and nature of vibration exposure. On the basis of the reported biodynamics studies, it has been established that the human response to vertical vibration is strongly dependent upon frequency and magnitude of vibration, as well as various occupant and seat related parameters, such are seat design factors, postural support, and individual's weight and body built [17, 53, 125]. It has also been suggested that the majority of the studies have been performed under conditions that do not realistically represent automotive seating, namely relatively high levels of vibration, consideration of either no back support or support against a vertical back [34, 98]. On the basis of a synthesis of reported data acquired under more representative and comparable condition, the International Standards Organization has defined range of idealized values of driving-point mechanical impedance of seated occupants without a back support exposed to vertical vibration [130].

In this chapter, the reported studies on biodynamic responses under vertical vibration are thoroughly reviewed to enhance an understanding of the test and data analyses methodology, and the effects of various intrinsic and extrinsic factors. The reported studies on the response to horizontal vibrations are further reviewed in terms of their objectives and findings, and test conditions involved.

2.2 BIODYNAMIC RESPONSE OF THE HUMAN BODY

The biodynamic response of a seated human body exposed to whole-body vibration can be defined using three different biodynamic response functions. Two of these functions describe "to the body" force-motion interrelation at the human-seat interface as a function of the frequency, referred to as the driving-point mechanical impedance (DPMI) and the apparent mass (APMS). The DPMI relates the driving force and resulting velocity response at the driving point (the seat-buttocks interface), and is given by [127]:

$$Z(j\omega) = \frac{F(j\omega)}{v(j\omega)} \qquad (2.1)$$

where $Z(j\omega)$ is the Complex DPMI response, and $F(j\omega)$ and $v(j\omega)$ are the driving force and response velocity at the driving point, respectively. ω is the angular frequency in rad/s and $j = \sqrt{-1}$ is the complex phasor.

The apparent mass (APMS) response, in a similar manner, relates the driving force to the resulting acceleration response, and is given by [129]:

$$M(j\omega) = \frac{F(j\omega)}{a(j\omega)} \tag{2.2}$$

where $M(j\omega)$ is the Complex APMS response and $a(j\omega)$ is the acceleration response at the driving point.

The magnitude of APMS offers a simple physical interpretation as it is equal to the static mass of the human body supported by the seat at very low frequencies, when the human body resembles that of a rigid mass. The above two functions are frequently used interchangeably, due to their direct relationship given by:

$$Z(j\omega) = j\omega M(j\omega) \tag{2.3}$$

The DPMI thus tends to emphasize the response at higher excitation frequencies, while the APMS shows a peak response corresponding to the primary resonant frequency. From the definitions, it is apparent that DPMI leads the APMS by a constant 90° phase angle. The biodynamic response characteristics of seated occupants exposed to WBV can also be expressed in terms of seat-to-head transmissibility (STHT), which is termed as 'through-the-body' response function. Unlike the force-motion relationship at the driving-point, the STHT function describes the transmission of vibration through the seated body. The STHT response function is expressed as [127]:

$$H(j\omega) = \frac{a_H(j\omega)}{a(j\omega)} \tag{2.4}$$

where $H(j\omega)$ is the Complex STHT, and $a_H(j\omega)$ is the response acceleration measured at the head of seated occupant.

It has been suggested that the apparent mass has more similarities with the seat-to-head transmissibility rather than the mechanical impedance [129]. At low frequencies, the motion at the human-seat interface is transmitted directly to the head [127]. There is a dependency of the transmissibility on the magnitude of excitation; the peak and the corresponding frequency tend to decrease with increasing input level, suggesting the softening of the body. Relatively few data sets are available on the seat-to-head transmissibility, in contrast with the data on mechanical impedance or apparent mass. Through analysis of a single-DOF occupant model, it has been that the STHT function is identical to the normalized APMS function, such that:

$$H(j\omega) = \frac{M(j\omega)}{m_o} \tag{2.5}$$

where m_o is the static mass supported by the seat.

Apart from the above three functions, the force-motion data have also been applied to derive the magnitudes of vibration power absorbed/dissipated by the seated occupant. The average power absorbed by the body P_{avg}, during an exposure period T can be expressed as [105]:

$$P_{avg} = \frac{1}{T}\int_0^T F(t) \bullet v(t) dt \tag{2.6}$$

Under whole-body random vibration, the absorbed power is related to the cross-spectrum of the force and velocity [105, 106]. The real component of the cross-spectrum relates to the energy absorption, while the stored energy is related to the imaginary component. The energy absorbed by the seated body under WBV can thus derived from:

$$P(\omega) = \mathrm{Re}\,al[S_{F \bullet V}] \tag{2.7}$$

where P is the power absorbed and $S_{F \bullet V}$ is the cross-spectrum of the measured force and velocity.

The above three functions have been widely used to characterize the biodynamic responses of the seated human subjects exposed to WBV. The reported studies on biodynamic responses to both vertical and horizontal vibration are reviewed in the following section together with the experimental conditions employed. The reviews are limited to studies involving force-motion relations at the driving point, as these would be most relevant to the dissertation research.

2.3 BIODYNAMIC RESPONSE TO VERTICAL VIBRATION

The biodynamic response characteristics of seated human occupants exposed to vertical vibration have been widely investigated using significantly different test conditions in terms of excitation levels, number of subjects, frequency range and sitting posture. The measured responses show considerable differences due to variations in test conditions and contributions due to various individual factors related to occupant mass and build. The test conditions employed in studies reported prior to 1997 have been summarized by Boileau and Wu [34, 129]. The range of test conditions and objectives of various studies, including the more recent ones, are summarized in Table 2.1.

Table 2.1: Summary of reported studies on vertical biodynamic responses of seated human body

AUTHORS	SUBJECTS		EXCITATION			POSTURE	REPORTED FUNCTIONS
	Sample size and gender	Mass (kg)	Type	Level	Frequency Range (Hz)		
Coerman (1962) [34]	8 Males	70-99	Sine	0.1 g 0.2 g 0.3 g	1-20	Standing; Sitting with feet not supported, no backrest	DPMI magnitude and phase, STHT magnitude
Coerman (1962) [34]	1	84	Sine	<5	<20	---	STHT magnitude
Edwards and Lange (1964) [34]	2 Males	77 and 84	Sine	0.2-0.5 g	1-20	Supine Lateral Standing	Individual DPMI
Vogt et al. (1968) [34]	10 Males	79 (mean)	Sine	0.5 g increasing gravity of 1g, 2g, 3g	2-15	Erect sitting loosely restrained feet supported, but not vibrated	DPMI magnitude and phase, STHT magnitude
Suggs et al. (1969) [34, 129]	11 Males	58-90	Sine	0.10 in peak-peak	1.75-10	Sitting upright, hands in lap, feet supported and no backrest	DPMI magnitude and phase
Miwa et al. (1975) [12]	5 Males	50-76	Sine	0.1 g rms	3-200	Standing Kneeling Sitting erect/relaxed, feet not vibrated	DPMI magnitude and phase
Griffin et al. (1978) [34]	56 Males, 28 females, 28 Children	---	Sine	1 m/s^2 rms	4 and 16	Sitting, increasing height of footrest	STHT magnitude and phase
Griffin et al. (1978) [34]	18 Males 18 females	---	Sine	1 m/s^2 rms	1-100	Sitting, increasing height of footrest	STHT magnitude and phase
Griffin et al. (1978) [34]	1 Male	68	Swept sine Discrete sine	1 m/s^2 rms	1-100	Sitting, increasing height of footrest	STHT magnitude and phase

Table 2.1: Summary of reported studies on vertical biodynamic responses of seated human body

AUTHORS	SUBJECTS		EXCITATION			POSTURE	REPORTED FUNCTIONS
	Sample size and gender	Mass (kg)	Type	Level	Frequency Range (Hz)		
Mertens (1978) [34]	6Males 3 females	57-90	Sine	0.4 g rms increasing gravity of 1g, 2g, 3g and 4g	2-20	Upright sitting with feet not supported	DPMI magnitude and phase, STHT magnitude and phase
Sandover (1982) [34, 129]	6	52.7-87.2	Random	1.2, 2.3 m/s^2 rms	1-25	Sitting erect with various positions of feet and arms	APMS magnitude and phase
Donati and Bonthoux (1983) [34, 129]	15 Males	49-74	Sine sweep Broad band Random	1.6 m/s^2 rms	1-10	Sitting erect, feed supported, hands on steering wheels	DPMI magnitude and phase
Fairley and Griffin (1983) [34, 129]	1 Male	63	Random	1 m/s^2 rms	0.25-20	No backrest, feet supported/not supported, Soft/hard seat	APMS magnitude and phase
Fairley and Griffin (1986) [34, 129]	8 Males	57-85	Random	1 m/s^2 rms	0.25-20	Normal Posture, feet supported and vibrated	Individual APMS magnitude and phase
Hinz and Seidel (1987) [34, 129]	4 Males	56-83	Sine	1.5 and 3.0 m/s^2 rms	2-12	Moderately erect sitting	DPMI magnitude and phase, STHT magnitude and phase
Paddan and Griffin (1988) [34]	12 Males	58-81	Gaussian Random	1.75 m/s^2 rms	Up to 25	Sitting with backrest Sitting without backrest	STHT magnitude
Fairley and Griffin (1989) [8a]	8 Males	57-85	Random	0.25, 0.5, 1.0 2.0 m/s^2 rms	Up to 20	Normal Upright erect Upright tense Upright back supported	APMS magnitude APMS magnitude and phase for one subject only

Table 2.1: Summary of reported studies on vertical biodynamic responses of seated human body

AUTHORS	SUBJECTS		EXCITATION			POSTURE	REPORTED FUNCTIONS
	Sample size and gender	Mass (kg)	Type	Level	Frequency Range (Hz)		
Fairley and Griffin (1989) [8b]	24 Males / 24 females/ 12 children	---	Random	1.0 m/s^2 rms	Up to 20	Sitting upright, no backrest, footrest vibrating, hands in lap	APMS magnitude and phase
Smith (1993) [34]	3 Males / 2 females	64-86	Sine Quasi random	1 and 2 m/s^2 rms	3-21	sitting upright with back support and constrain	DPMI magnitude
Holmlund et al. (1995) [9]	15 Males / 15 females	57-92 54-93	Discrete sine	0.5, 0.7, 1.0, 1.4 m/s^2 rms	2-100	Relaxed upper body Erect upper body	DPMI magnitude and phase,
Lundström et al. (1995) [128]	15 Males / 15 females	57-92 54-93	Discrete sine	0.5, 0.7, 1.0, 1.4 m/s^2 rms	2-100	Relaxed upper body Erect upper body	Absorbed power
Seidel (1996) [129]	37 Males	49-103	Random Spectra	0.7, 1.0, 1.4 m/s^2	0-20	Hard seat without backrest, Feet supported and vibrated	DPMI magnitude
	11 Males	60-70	Off-road machinery	<1.4 m/s^2	0.5-20	---	
	14 Males	70-80					
Boileau and Rakheja (1997) [10]	6 Males	69.6-80.9	Sine sweep Random	1.0- 2.0 m/s^2 rms	0.5-10	Erect sitting, Sitting with back support, Hands in lap	DPMI magnitude and phase
Zimmerman and Cook (1997) [58]	30 ---	77.6	Sine	1 m/s^2	4.5-16	Sitting upright without back support	Seat to trunk and seat to head transmissibility
Hinz et al. (1997) [23]	37 Males	49-103	3 spectral classes according to ISO 7096			Back supported, varying knees and ankles angles, hands on steering wheel	Seat to trunk and seat to head transmissibility
Lundström and Holmlund (1998) [25]	15 Males/ 15 females	54-93	Discrete Sine	0.25-1.4 m/s^2 rms	2-80	Sitting relaxed Sitting erect	Absorbed power

Table 2.1: Summary of reported studies on vertical biodynamic responses of seated human body

AUTHORS	SUBJECTS		EXCITATION			POSTURE	REPORTED FUNCTIONS
	Sample size and gender	Mass (kg)	Type	Level	Frequency Range (Hz)		
Mansfield and Griffin (1998) [11	12 Male	Mean 68.3 (SD 7.3)	Random	0.25, 0.5, 1.0, 1.5, 2.0 and 2.5 m/s^2 rms	0.2-20	Sitting upright, No backrest	Absorbed power
Kitazaki and Griffin (1998) [56]	8 ---	Mean 74.6 (SD 7.8)	Random	1.7 m/s^2 rms	0.5-35	Sitting erect Sitting normal Sitting slouched	Seat to trunk and seat to head transmissibility
Boileau and Rakheja (1998) [10]	7 Males	75.4 mean	Sine sweep Broad band random	1.0, 1.5, 2.0 m/s^2 rms	0-10	Erected sitting with back support Erected sitting without back support	DPMI magnitude and phase
Matsumoto and Griffin (1998) [61]	8 Males	63-83	Random	1.0 m/s^2 rms	0.5-20	Sitting upright, no backrest, feet hanging	APMS magnitude and phase Seat to trunk and seat to head transmissibility
ISO 5982 (2001) [130]	39 ---	51-94	Sine and random	1-2 m/s^2 rms	0.5-31.5	Synthesis of reported data under comparable conditions	DPMI magnitude and phase, STHT magnitude and phase
Nishiyama et al. (2000) [130]	9 Males/ 2 females	46-78	Sinusoidal Random	---	0-20	Automotive posture Hands on steering wheel	Transmissibility of body limbs
Smith (2000) [59]	1/1 Male/ female	75/56	----	---	---	---	DPMI magnitude Transmissibility of body limbs
Matsumoto and Griffin (2000) [12]	8 Males	63-83	Random	1.0 m/s^2 rms	0.5-20	Sitting upright, no backrest, feet hanging Standing Posture	APMS magnitude, phase and normalized Seat to trunk and seat to head transmissibility

Table 2.1: Summary of reported studies on vertical biodynamic responses of seated human body

AUTHORS	SUBJECTS		EXCITATION			POSTURE	REPORTED FUNCTIONS
	Sample size and gender	Mass (kg)	Type	Level	Frequency Range (Hz)		
Mansfield and Griffin (2000) [13]	12 Males	---	Random	0.25, 0.5, 1.0, 1.5 2.0, 2.5 m/s^2 rms	0.2-20	Sitting upright Vibrating foot support No backrest Loosely restrained	Normalized APMS and phase Seat to abdomen transmissibility
Mansfield et al. (2000 and 2001) [14 and 15]	11/13 Males/ females	54-96	Combined random and shocks	0.5, 1.0, 1.5 m/s^2 rms	2-20	Sitting upright, no back support hands in lap, feet on footrest, not moving with the seat	Normalized apparent mass Normalized absorbed power
Vibration Injury Network (2001) [132]	6 Males	70-80	White noise	0.5, 1.0, 1.5 m/s^2 rms	1-20	Seated upright, Hands on the thigh	DPMI magnitude and phase Transmissibility magnitude and phase
Lenzuni and Nataletti (2001) [107a]	12Males	---	---	0.5, 1.0, 1.5 m/s^2 rms	2-20	Sitting erect but relaxed Maximum muscle tension	Absorbed power
			Low frequency (2-7) High frequency (7-20) Sine (12) + low frequency			Sitting erect but relaxed	
Holmlund and Lundström (2001) [107b]	6 Males	69-77	Random	0.5, 1.0, 1.5 m/s^2 rms	---	----	DPMI magnitude, APMS magnitude, Seat to trunk and seat to head transmissibility
Holmlund and Lundström (2001) [28]	15 / 15 Males / females	54-93	Sinusoidal	0.25, 0.7, 1.0, 1.4 m/s^2 rms	2-100	Sitting erect	DPMI magnitude and phase
			In vehicle	50 km/h by 5 min			
Tamaoki and Yoshimura (2001) [71]	4 Males	---	Random	0.05, 0.1, 0.2, 0.3, 0.35 g's	0-20	Hands on thighs; Feet on platform	Seat to mouth and seat to forehead transmissibility

Table 2.1: Summary of reported studies on vertical biodynamic responses of seated human body'

AUTHORS	SUBJECTS		EXCITATION			POSTURE	REPORTED FUNCTIONS
	Sample size and gender	Mass (kg)	Type	Level	Frequency Range (Hz)		
Fukuda et al. (2001) [79]	1 Male	70	Vehicular vibration at different speeds and road conditions			Driving	Absorbed power
Demić et al. (2002) [29]	30	85.9 +/- 14.1	Random	0.55, 1.75, 2.25 m/s^2 rms	0.5-40	Driving posture on steering wheel Backrest position varied	STHT magnitude and phase
Nawayseh (2002) [16 and 72]	12	----	Random	0.125, 0.25, 0.625, 1.25 m/s^2 r.m.s	0.25-25	Feet Hanging Maximum thigh contact Average thigh contact Minimum thigh contact	Apparent mass and Transmissibility
Matsumoto and Griffin (2002) [18]	8 Males	63-83	Random Sine	0.35, 0.5, 0.7, 1.0, 1.4 m/s^2 rms	2-20 3.15, 4.0, 5.0, 6.3, 8.0	Upright sitting, feet on platform: Normal muscle tension; Buttocks' muscles tensed Abdomen's muscles tensed	APMS magnitude, phase and normalized Seat to trunk head transmissibility
Rakheja et al. (2002) [17, 125]	12 Males 12 females	Mean 71.2 (+/- 16.81)	White noise In vehicle, measured track of 1.07 m/s^2 rms	0.25, 0.5, 1.0, m/s^2 rms	0.2-40	Automotive seating posture: Hand on steering wheel Hands in lap	APMS magnitude and phase
Wang et al (2004) [19]	13 Males / 14 females	48-111	White noise	0.5, 1.0, m/s^2 rms	0.5-40	2 different hands positions, 3 different seat pan heights, 6 seat-dependent postures (Inclined seat pan, inclined backrest, vertical backrest, back not supported)	APMS magnitude and phase

The results summarized in table suggest that the mechanical impedance had been the most frequently used measure of the seated body biodynamic response. A few studies have also reported the STHT of the seated occupant, and vibration transmitted to different segments [23, 29, 56, 58, 59, 71, 100, 107, 132]. Different non-invasive measurement systems have been employed to measure the transmitted vibration, such as 'state-of-the-art' helmets, bite bars, infrared sensors and more sensitive contact sensors. The reported data on vibration transmissibility, however, exhibit more significant differences, which are mostly attributed to the lack of a reliable measurement system. Apart from the measurement system, the differences have also been attributed to variations in subjects' responses to specific stimulus, the differences in the soft tissues responses compared to the skull, and the differences among the experimental conditions considered [36, 52, 53].

The earlier reported studies employed relatively high magnitude harmonic vibration excitations at specific frequencies. Random vibration stimuli in a vast range of magnitudes, from 0.125 to 2.5 m/s^2 rms, have been widely used in later studies to emphasize the influence of excitation magnitude on the biodynamic response. Majority of the studies have considered an erect sitting posture with no back support, while only a few studies had been performed using back support. These studies consider contact with a vertical backrest, which does not represent automotive seating posture. A laboratory study considering automotive postures had been performed only by Rakheja et al. [17, 125]. The outcomes from these studies suggest that the biodynamic response to vertical acceleration is highly dependent on seating postures. The fundamental frequency of the seated subjects tends to shift from approximately 5 Hz to 6-7 Hz, when contact with inclined backrest is considered. It is thus generally suggested that postural changes and muscle activity affect the nature and the resonance characteristics of the biodynamic response [18, 56, 58]. The response is also affected by the subjects' body mass [17, 125]. Attempts have been made to compare the response under different postures (standing and sitting) [12]. The findings suggest that the main principal vertical resonance is the product of more than one vibration mode [61]. The input magnitude also plays an important role, in a highly complex manner as suggested by Mansfield [15]; an increase in vibration magnitude causes softening of the body.

Owing to considerable differences in test conditions (sitting posture, excitation magnitudes and frequencies, subject mass, gender, etc), the reported data tend to differ significantly. The majority of the data, however, reveal primary resonance near 5 Hz, which tends to decrease with increasing magnitude of vibration. The resonant frequency tends to increase, when an automotive sitting posture (inclined back support, and hands on steering wheel) is considered. The test conditions employed in majority of the studies (Table 2.1) do not closely relate to the vehicular seating environment in view of the vibration magnitudes and seat design features. An automotive seat with adequate seat height, inclined pan and inclined back support, is thus considered vital for this dissertation study. Furthermore, the magnitudes of vibration showed to be representative of those encountered in vehicles, which may range from 0.25 m/s^2 to 2.0 m/s^2.

2.4 BIODYNAMIC RESPONSE TO HORIZONTAL VIBRATION EXCITATION

The physical response of the human body to horizontal vibration is notably different from that to the vertical vibration: The support characteristics of the musculo-skeletal structure of the human body under vertical loading are significantly different from those under horizontal forces. The postural effects of the biodynamic responses to forces acting in the horizontal direction may thus be far more important than those under vertical vibration. Apart from the mechanical loading, the horizontal excitation tends to encourage different neuro-muscular and psychological reactions from the subject, such as stiffening of the upper body and increased pressure of the feet under high magnitude longitudinal and lateral motions. A few studies have emphasized the considerable differences in psychosomatic effects, interference in activities, perception of motion and sensation of discomfort under horizontal vibration when compared to those reported under vertical vibration [32,52,53].

From the review of literature presented in this dissertation, it is evident that majority of the studies on biodynamic responses to vibration focus on the vertical vibration. Although a large class of vehicles imposed equally difficult horizontal vibration, as described in section 1.2.5, only limited efforts have been made to study the responses to such vibration. The lack of efforts may be attributed to many factors: a large number of studies and data suggest a more direct relationship between spinal injury and the exposure to vertical vibration; more data are also available on the human comfort sensation and perception to vertical vibration; the magnitudes of vertical vibration are considerable larger than the horizontal vibration in case of majority of road vehicles; the lack of reliable measurement systems for accurate analysis of human response to horizontal vibration that predominantly occurs at far lower frequencies (< 2 Hz); the primary symptoms of horizontal vibration was believed to be motion sickness, which is of temporary nature unlike the spine injuries that may be caused by vertical vibration.

Under exposure to horizontal vibration stimuli, an array of induced mechanical responses could be found throughout the vibration frequencies. The vibration occurring below 1 Hz, tends to cause a bending motion of the upper body, although muscular action and/or additional back support help to sustain upright posture. In the 1-3 Hz frequency range, subjects encounter difficulties in maintaining a stable sitting posture due to induced motion of the upper body. At higher excitation frequencies, beyond the principal resonances of human body, the sensation of vibration converges to the point of contact of the upper body with the seat [32]. The reported studies suggest that the primary resonances of the seated occupant expressed to horizontal vibration occur in the 2-5 Hz frequency range. It is also interesting to note that the vast majority of road and off-road vehicles induce longitudinal and lateral vibration below 2 Hz, which is attributed to low frequency pitch and roll modes of the vehicle [101, 121, 122]. The magnitudes of such vibration could be considerably large, specifically for the off-road and heavy road vehicles due to relatively high location of the driver.

The exposure to horizontal vibration of seated subjects is known to affect the comfort as well as musculo-skeletal loading in an adverse manner, as is in the case of vertical vibration. The motion sickness among thee exposed individuals is perhaps the most significant symptom. The majority of the reported studies on human response to horizontal vibration thus focus on the motion sickness behaviour. Although the symptoms of motion sickness on ships have been attributed to vertical oscillations, the passengers of air and land vehicles have shown motion sickness under horizontal acceleration. Compared to responses to vertical stimuli, the kinetosis due to horizontal vibration excitation is twice nauseogenic and more easily noticeable [83-86].

The exposure to low frequency horizontal vibration induces large magnitude side-to-side and fore-and-aft displacement of the upper body, and thus directly interferes with activities to be performed by the operator. Furthermore, the exposure to such vibration could limit the human operator's abilities for sensing, decision-making, and muscular reactions. The operator uses hearing, sight, and feelings to interpret inputs and to interface with the control-instrumentation components to accomplish the required task [97]. These peripheral and neurological processes are complex involving multiple feedback paths, except for well defined circumstances in which some of the body segments reaches a physical or physiological limit of performance [19]. The impact of whole-body vibration on comfort, whether vertical or horizontal, was studied mainly by the transport industry to identify the ride comfort in vehicles, specifically the level, frequency, direction and duration of vibration that cause difficulty in performing certain operations, such as eating, reading or writing. The data obtained from those studies and many laboratory studies have contributed to defining the frequency weighting functions for assessing the vibration comfort [29,23,43,50,73,74,78,100].

The reported studies on human responses to horizontal vibration can be grouped in terms of their objectives, which directly related to the known symptoms and concerns, namely motion sickness, discomfort and biodynamic response. The methodologies associated whit these studies within each group are discussed in the following sections, together with their findings.

2.4.1 STUDIES AIMED AT MOTION SICKNESS

Vibration at frequencies of about 1 Hz and below, which occur in many forms of transport systems, may induce motion sickness (kinetosis) among the occupants leading to nausea, dizziness, vomiting, disorientation, and other inconveniences. These can influence the operator's ability to handle the vehicles and perform desired tasks in an adverse manner such symptoms could be felt shortly after or during the exposure, but they are characterized as temporal minor annoyances in most of the cases. However, some individuals could be incapacitated by motion sickness. Car sickness is believed to be caused mainly by the horizontal motion arising from acceleration, braking and cornering manoeuvres [84]. On the basis of experiments performed by Golding et al. [83, 85, 86] under representative circumstances, horizontal motion was found to be twice as nauseogenic as vertical motion, in terms of motion exposure time to reach any particular level of sickness. This relationship was also observed by Mills [87], and Turner [84].

The severity of symptoms was observed to be worst under exposure to horizontal vibration in the 0.125 and 0.25 Hz frequency range, while the symptoms rarely occur under exposure at frequencies above 0.75 Hz. The nauseogenic potential of motion is increased by the absence of a stable visual reference, head movements, orientation of the body with respect to the direction of the linear accelerative stimulus; the open eyes (comparing to blindfolded), contact with low backrest (comparing to high backrest), and by the direction of the motion relative to the gravity vector [85-87]. Moreover, the combination of other factors such as odour, ambient temperature, fatigue and exposure history increases the human susceptibility to vibration. On the other hand, restraining the upper body using harness or higher back support during exposure to fore- and-aft acceleration may reduce the susceptibility to motion sickness, due principally to a reduction of head movement [84]. Nauseogenicity also increases as a function of exposure time and acceleration intensity [83]. From the reported studies, could be synthesized that peak accelerations above 1.5 m/s^2 in the 0.1-1.0 Hz range, with variable exposure time [84].

Table 2.2: Published data in motion sickness as response to horizontal motion

AUTHORS	SUBJECT'S SAMPLE	POSTURE		EXCITATION				AXIS	REPORTED FUNCTIONS	COMMENTS
		Body Position	Back Position	Type	Level	Frequency Range (Hz)	Exposure Time			
Golding et al. (1994) [85]	26 Males, 1 Female 7 Males, 5 Females	Seated upright using harness	Padded rear head support	Sine	3.6 m/s^2 peak	0.35	≤ 30 min	Horizontal (X)	Sickness Ratings	Analysis of Variance (ANOVA) applied
Golding et al. (1994) [83]	7 Males 5 Females	Seated upright	-----	Sine	3.6 m/s^2 peak	0.205, 0.350, 0.500	≤ 30 min	X Head Body Axes	Sickness Ratings Rating of somatogravic illusion	Analysis of Variance (ANOVA) applied
Turner (1994) [84]	3256 passengers / 9 vehicles	Seated	Road coaches	Random (Vehicles)	-----	-----	38 min to 6.5 hours	X and Y Axes.	Motion Sickness Dose Values $MSDV = \left[\int a_i^{\,2} dt\right]^{1/2}$	Using a questionnaire. The measures were made on the vehicle, not on the seat
Golding et al. (1995) [86]	7 Males 5 Females	Seated Upright using Harness	Padded rear head support	Sine	3.6 m/s^2 peak	0.35, 0.50, 0.70 and 1.00	≤ 30 min	X Head Body Axes	Sickness Ratings	Analysis of Variance (ANOVA) applied
Mills (1997) [87]	36 Males	Flat Seat; in a cabin supported on a vibrating table	High flat backrest; Harness was used Low flat backrest; lap belt was used	Sine	0.7 m/s^2 rms	0.25	≤ 30 min	Fore-and aft	Motion Sickness Dose Value	-----

The reported studies on motion sickness of seated human subjects exposed to horizontal vibration are summarized in Table 2.2. Of the five studies, only one study considered the response to lateral (Y) motion. Moreover, most of the studies considered sinusoidal motions of relatively high magnitude (3.6 m/s^2) with the exception of that reported by Mills [87] under 0.7 m/s^2 rms acceleration. All the studies employed exposure to vibration at very low frequencies ranging from 0.205 Hz to 1.0 Hz. All reported studies used seats with upright back support, which may not represent the automotive sitting posture. Typical vehicular seating postures have been considered in only one study conducted in road coaches [84]. The same study also defines an objective measure of motion sickness dosage, while most of the other studies utilize subjective sickness rating. The motion sickness dosage (MSDV) has also been used by Mills [87], and is given by:

$$MSDV = \sqrt{\int_0^T a_w^2 dt} \qquad (2.8)$$

where a_w is the frequency-weighted acceleration along the x- and y- axes, and T is the exposure duration.

2.4.2 STUDIES AIMED AT COMFORT

It was established that the change in discomfort is directly proportional to the change in magnitude of vibration and exposure time [32]. International standard ISO 2631-1 [31] provides approximate values for comfort reaction or seating under exposure to vibration level (see Table 1.5). Besides, the discomfort is closely related to the vibration frequency: at low frequencies, 1-2 Hz, horizontal seat motion is most easily transmitted to the upper body members; at slightly higher frequencies the sensation is more likely confined to the body region close to the vibration source. If the frequency is increased further, the body provides an increasing attenuation of vibration reducing the discomfort [32]. In addition, human beings are very sensitive to vertical and fore-and-aft random vibration at frequencies below 1 Hz, and they are least sensitive at frequencies above 5 Hz [29].

Most of the studies on comfort sensation of horizontal vibration have been directed towards defining the equivalent contours, which are based upon subjective sensation under controlled magnitude and frequency of the stimuli. Experimental conditions employed in the studies are summarized in Table 2.3. The reported studies have been employed different levels of horizontal vibration; harmonic vibration of 0.3-1.25 m/s^2 rms magnitude in the 0.5 to 80 Hz frequency range, and 0.5-1.5 m/s^2 frequency-weighted rms acceleration in the 2-20 Hz range. The hand position ranges from hands in lap, hands on a keyboard to hands on a steering wheel

Griefahn and Bröde [73] proposed comfort contours for vertical and horizontal vibration exposure, with differences that suggest weighting factors provided in ISO 2631 underestimate the vibration effects. Their subsequent study [50] suggested that this upshot is true only for multidirectional vibration exposure, as the sensitivity to multi-axis vibration differs from that to the single-axis vibration. Demić et al. [29] proposed comfort contours under uni-directional horizontal excitation, using random vibration stimuli in the 0.5-40 Hz between equivalent comfort and multi-axis WBV.

Table 2.3: Published data modeling comfort contours in horizontal stimuli

AUTHORS	SUBJECTS		POSTURE			EXCITATION				AXIS OF VIBRATION	REPORTED FUNCTIONS	COMMENTS
	Sample	Mass (Kg)	Body Position	Back Position	Feet Position	Type	Level	Frequency Range (Hz)	Exposure Time			
Griefahn and Bröde (1997) [73]	15 Males 11 Females	61-95 / 47-80	Seated; slightly kyphotic	No Backrest	-----	Sine	0.3, 0.6, 1.2 m/s^2 r.m.s.	0.5-80	30 s	Fore-aft (X) and lateral (Y)	Comfort Contours	18 sinusoidal reference vibrations selected (ISO/DIS 2631)
Griefahn and Bröde (1999) [50]	15 Males 11 Females	Mean 76.5 / 63.6	No harness Hands holding small keyboard	Slight Kyphotic	Onto the moving platform	Sine Vertical and Lateral	0.3, 0.6, 1.2 m/s^2 r.m.s.	1.6, 3.15, 6.3, 8.0 and 12.5	30 s.	Fore-aft, lateral	Comfort Contours	Each trial started with a single-axis sinusoidal reference motion, after a pause single or dual-axis sinusoidal test motion occurred with the same frequency.
	15 Males 16 Females	Mean 79.2 / 60.8					1.25 m/s^2 r.m.s.	1.6, 3.15, 6.3 and 12.5				
National Institute for Working Life (NIWL) (2001) [33]	11 Males 13 Females	-----	Comfor-table upright seated, hands on the lap	----	Horizontal thighs, feet positioned on a footrest, not vibrated	-----	0.5 1.0 1.5 m/s^2 r.m.s weighted	2-20	20 s	X, Y and Z direction	Subjective Ratings of Discomfort	Part of data base collected of data of human experiments and experimental data stored in a common data base
Demić et al. (2002) [29]	30 Males	85.9 +/- 14.1	Seated (Soft Seat); Hands on Steering Wheel	-----	-----	Narrow band random vibration	-----	0.5-40	75 s	Fore-and-aft and vertical	Averaged equivalent comfort curves (fore-and-aft direction)	Proposed new method to assessment of the influence of narrow band vibration on the human body.

2.4.3 STUDIES AIMED AT BIODYNAMIC RESPONSES TO HORIZONTAL VIBRATION

It has been recognized that the exposure to whole-body vibration in the horizontal plane contributes greatly to the general discomfort, motion sickness, performance rate, and to the health and safety of the exposed workers. In recent years, the focus has been diverted towards characterization of biodynamic responses of human subjects to horizontal vibration in terms of DPMI, APMS and absorbed power. The primary objective of these studies is to enhance an understanding of the human response exposure to WBV along the lateral and longitudinal axes, and to derive frequency-weighting functions for assessing the severity and risk posed by the exposure. The results attained from the studies conducted on deriving the equivalent comfort contours [29, 32, 33, 43, 50, 73, 74, 78, 100], described in section 2.4.2, had contributed to the development on the frequency-weightings defined in the most widely accepted international standard, ISO 2631-1 [31]. It is anticipated that the date attained from the objective biodynamic measures would either provide more scientific basis for the defined frequency-weighting function or yield more effective means to asses human exposure to such vibration.

The vast majority of studies on the biodynamic response of human body exposed to such motions evolved since from 1997, with the exception of a single study conducted by Fairley and Griffin [22] in 1990. The reported studies on the biodynamic response characterization under horizontal motions generally utilize the knowledge gained from the similar studies performed under vertical motions. The experimental and data analyses methods are identical to those used in vertical biodynamic responses analyses, while the nature of stimuli differs. Such studies, however, been mostly performed by two leading laboratories in the world, namely National Institute for Working Life in Sweden [24-26, 28] and the Human Factors Research Lab in United Kingdom [22, 27]. All of the reported studies employ considerably different test conditions, as has been observed in the case of vertical biodynamics, although they shore the common objective of defining the force-motion relationships.

Table 2.4, which summarizes the objectives and experimental conditions employed in reported studies on biodynamic responses of seated occupants under horizontal vibration exposure. It is evident that the reported studies have used three different types of vibration excitation: sinusoidal, white-noise random, and classes of construction vehicle excitation defined in ISO-7096 [117]. The standard ISO-7096, however, defines excitation along the vertical axis. Hinz et al. [61] employed these vertical excitations to study the transmission along the x- and y-axis, which could describe the coupling effect but not the biodynamic responses under horizontal vibration. The other studies have been considered varying magnitudes of sinusoidal vibration, ranging from 0.25 m/s^2 rms to 1.5 m/s^2 rms, and random vibration ranging from 0.5 m/s^2 rms to 2.25 m/s^2 rms. The frequencies of excitation mostly lie in the low frequency range to capture the resonance behaviour below 2 Hz. A number of studies, however, have considered frequencies above 1 and 2 Hz [24-26, 28, 107, 132], which may not represent the resonance behaviour of human occupant and the typical vehicular frequencies.

The sitting postures considered in these studies also do not represent typical automotive sitting posture. The majority of the studies employ sitting posture with not back support [24-28, 132]. Considering that motion along the longitudinal axes tends to

Table 2.4: Summary of published data on horizontal biodynamic responses of seated human body

AUTHORS	SUBJECT		POSTURE			EXCITATION				AXIS OF VIBRATION	REPORTED FUNCTIONS	COMMENTS
	Qty and gender	Mass (Kg)	Body Position	Back Position	Feet Position	Type	Level	Frequency Range (Hz)	Exposure Time			
Fairley and Griffin (1990) [22]	8 Males	57-85	Restrained seated upright, Hands on lap	No backrest Back Supported	On the vibrator table	Random	0.5, 1.0, 2.0 m/s^2 r.m.s. 1.0 m/s^2 r.m.s.	0.25-20	128 s	Fore-and aft (X) Lateral (Y)	APMS magnitude and phase	Performed four experimental conditions. Flat vertical backrest was used.
Hinz et al. (1997) [23]	37 Males	49-103	Hands on steering wheel	Back supported	Varying knees and ankles angles	3 spectral classes according to ISO 7096 (vertical axis)			67.58 ms	Seat pan-subject interface (X) and backrest-subject interface (x)	Seat to trunk and seat to head transmissibility	Two types of seats was used, both with suspension system
Holmlund and Lundström (1998) [24]	15 Males 15 Females	54-93	Seated	Relaxed / Erected (no backrest)	On the floor	Sine	0.25, 0.35, 0.5 0.7, 1.0, 1.4 m/s^2 r.m.s.	Increased from 1.13-2.5 to 31.5-80 depending on exposure level (steps of 1/6 octaves)	20 cycles at each frequency; 5 seconds pause between consecutive frequencies	Fore-and aft (X) Lateral (Y)	Normalized DPMI $Z_{norm}(f) = Z(f) / M_s$	Experimental conditions based on vibration levels and directions (X, Y and non-orthogonal).
Lundström and Holmlund (1998) [25]	15 Males 15 Females	54-93	Seated	Relaxed / Erected (no backrest)	On the floor	Sine	0.25, 0.35, 0.5 0.7, 1.0, 1.4 m/s^2 r.m.s.	1.13-80	180 s	Fore-and aft (X) Lateral (Y)	Normalized Time-Average Absorber Power $\langle P_{N_{Abs}} \rangle = \langle F(t)v(t) / m_{Sitting} \rangle$	Experimental conditions based on vibration levels and directions (horizontal and/or vertical).
Mansfield and Lundström (1999) [26]	15 Males 15 Females	Mean 75.8/ 62.0; SD 9.3/7.2	Seated; arms folded	Upright Posture, No backrest	On the floor Knee angle of 90°	Random	0.5, 1.0, 1.5 m/s^2 r.m.s.; constant X/Y 0.38 m/s^2	1.5-20	60 s	0, 22.5, 45 67.5 and 90o to the Mid-Sagital Plane	Apparent Mass $Z(j\omega) = j\omega M(j\omega)$	20 vibrations conditions. (4 acceleration magnitudes in 5 directions)

Table 2.4: Summary of published data on horizontal biodynamic responses of seated human body

AUTHORS	SUBJECT		POSTURE			EXCITATION				AXIS OF VIBRATION	REPORTED FUNCTIONS	COMMENTS
	Qty and gender	Mass (Kg)	Body Position	Back Position	Feet Position	Type	Level	Frequency Range (Hz)	Exposure Time			
Paddan and Griffin (2000) [27]	1 Male	87	comfortable upright posture Hands on lap Loosely restrained	Back supported and no supported	Feet and legs together, lower legs vertical	Random	1.0, m/s^2 r.m.s	Up to 5	120 s	Fore-and aft (X), lateral (Y) And yaw.	Transmissibility yaw seat acceleration / fore-and-aft lateral and yaw acceleration at the head	Effects of back contact, visual environment and position of centre of rotation had been investigated
	12 Males	65-87										
Vibration Injury Network (2001) [132]	6 Males	70-80	Seated (Hard Seat), Hands on the thigh	Erect, no backrest	On a Platform	White Noise	0.5, 1.0, 1.5 m/s^2 r.m.s. (according to the capacity of the vibrator)	1-20	120 seconds	Z, X and Y (at the seat); Z, X and Y (at the head)	Impedance and Transmissibility (gain and phase) $Z(j\omega)=\frac{F(j\omega)}{v(j\omega)}$	This is suggested as a reference only; it mentions also duration (120 seconds), realization of the expectrum (either around 30 or 60 seconds) and body height (between 170 and 180 cm)
Vibration Injury Network (2001) [107]	12 Males	----	Seated	Erect, relaxed Maximum muscle tension	-----	Flat Vibration Expectrum	0.5 1.0 1.5 m/s^2 r.m.s	2-20	-----	X, and Z	Absorber power (frequency and magnitude) APMS Seat to trunk and seat to head transmissibility	Spectral shape of the stimulus.
	3 Males	---		Erect, relaxed		Sine		2-7, 7-20, 12				
Holmlund and Lundström (2001) [28]	15 Males 15 Females	57-92 / 54-93	Upright Seated.	Relaxed / Erected (no back support)	Adjustable footrest	Sine (in lab)	0.25, 0.35, 0.5, 0.7, 1.0, 1.4 m/s^2 r.m.s.	1.3-25 in steps of 1/16; 25-80 in steps of 1/3 octaves	-----	X and Y	Absolute Mechanical Impedance $Z(\omega)=\frac{F(\omega)}{v(\omega)}$	The rms value for the force was determined after vector compensation for the load.
						Snow covered driving surface at 50 km/h (in vehicle)			At least 5 min			

Table 2.4: Summary of published data on horizontal biodynamic responses of seated human body

AUTHORS	SUBJECT		POSTURE			EXCITATION				AXIS OF VIBRATION	REPORTED FUNCTIONS	COMMENTS
	Qty and gender	Mass (Kg)	Body Position	Back Position	Feet Position	Type	Level	Frequency Range (Hz)	Exposure Time			
Tamaoki and Yoshimura (2001) [71]	4	-----	Wooden seat Hands on thighs	Erect posture, No support	On platform	Random Wave	0.05g, 0.1g, 0.2g, 0.3g and up to 0.35g	0-20	-----	Fore-and-aft (X), Lateral (Y) and Vertical (Z)	Transfer functions (seat-mouth and seat-forehead)	Multidirectional base excitation.
Fukuda et al. (2001) [79]	1 Male on a sedan type passenger car	70	Seated	-----	-----	3 different road surfaces	-----	-----	25 seconds (limited by the record capacity)	3 axes	Absorber Power	Analyses made according ISO 2631-1 and BS 6841
Demić et al. (2002) [29]	30 Males	85.9 +/- 14.1	Seated (Soft Seat); Hands on Steering Wheel	-----	-----	Narrow band random vibration	0.55 1.75 2.25 m/s^2 r.m.s	0.5-40	-----	Fore and aft / Fore and aft and Vertical	Seat to Head Transmissibility (STHT, magnitude and phase) $H(j\omega)=\frac{a_H(j\omega)}{a(j\omega)}$	Single and multi-axis base excitation.

excite considerable interactions between the upper body and the backrest, it is essential to study the occupant biodynamics into representative back support. While Hinz el al. [23] investigated the human response under back support conditions, the excitation were limited to vertical axis alone. Moreover, the study employed suspension seats with an objective to determine vibration transmissibility. Fairley and Griffin [22] investigated the biodynamic responses with back supported against a vertical backrest. Other reported studies do not specify the backrest condition [29, 71, 79, 107]. With the exception of two studies, all the reports consider hands in the lap posture. Demić et al. [29] investigated the seat-to-head transmissibility of occupants seated with hands on a steering wheel, whereas Mansfield and Griffin [26] examined the effects of hands folded. The results revealed significant effect of hands position.

Despite the differences in test conditions, the reported studies have generally accepted that the biodynamic responses vary with the direction and level of vibration, sitting posture and gender [22, 24-26, 29]. Under fore-and-aft excitation, the results generally revealed two notable peaks in the response. The principal mode was observed in the 2-5 Hz frequency range, while a secondary peak of lower magnitude was observed around 6-7 Hz [24, 26, 28, 29, 71]. The peak response corresponding to the principal mode increased with increasing excitation magnitude, while its frequency decreased. The magnitude and the frequency due to the second peak decreased with increase in the magnitude of stimuli. This behaviour was also observed under excitations along the lateral direction. The results reported by Tamaoki and Yoshimura [71], however, contradict the above findings. It was suggested that the magnitude of the response, as well as the principal resonance peak decrease with increasing acceleration excitations, although the principal resonance was reported to be in the similar range.

Fairley and Griffin [22], suggested the presence of a third resonance peak at a lower frequency, which was attributed to the motion of the whole of the upper body. The magnitude of the apparent mass increased under back support condition, due principally to the response at two contact locations, the platform and the backrest. The single mode of vibration that was observed may be associated with the horizontal response of the musculo-skeletal structure of the body (perhaps a response of the body at the level of the buttocks and the hips, which is out of phase with the shoulders) in the absence of the backrest support. The support against a vertical backrest appeared to have a stiffening effect of the upper body. Holmlund and Lundström [24, 25], highlighted the differences between lateral and fore-and-aft responses, in order to treat both excitations differently when assessing risk. They also identified the need to perform more studies with back support. The study further established a relationship between the absorbed power and the subject's body weight.

Mansfield, and Lundström [26], suggested that the sitting weight must not be used for normalization, as is often used for computing the normalized vertical apparent masses, as the influence of the legs on the force measurements may also vary with vibration direction. From the analyses of measurements of forces and accelerations in the orthogonal axes, it was conclude that the principle of superposition does not hold for horizontal vibration. The coupling between the motions along the different axis has also been suggested by Tamaoki and Yoshimura [71], for vertical and fore-and-aft stimuli. Paddan and Griffin [27], in a similar manner revealed coupling between yaw and lateral movements.

2.5 SUMMARY

From the reported studies, it is evident that only a few attempts have been made on characterizing the biodynamic responses of seated human subjects exposed to horizontal vibration. The reported studies have emphasized the need to perform further studies to build a more reliable data bank and to explore the role of various seat and occupant related factors. It is also evident that the majority of these studies have employed seat and postural factors that may not be representative of automotive seating. It would be thus desirable to characterize the biodynamic responses under more representative postures that would not describe the behaviour applicable for automotive seating but also contribute to the needed data base. The range of experimental conditions and test methodologies used in the reported studies helped to design the experiment and the test matrix, which is described in the following chapter.

CHAPTER 3

MEASUREMENT METHODS AND DATA ANALYSIS

3.1 INTRODUCTION

Subjective and objective methods are often used to enhance understanding of human response to vibration, specifically the comfort sensation, ride quality in case of vehicles, inconsistency in accomplishing activities, motion sickness, and other more severe musculoskeletal effects. The subjective methods are known to offer inconsistent results due to the disproportionate variations in the preferences of the individuals, although these methods have been widely used to develop comfort contours and to assess relative comfort performance of seats. The objective methods, on the other hand, yield more repeatable results. The use of objective methods, however, involves identification of variables to be measured, correlation between the measured variables and the target objective, experiment design and selection of measurement system. All of these tasks could be quite complex. Moreover, the use of human subjects during the repetitive trials on vibration generating platform may pose some ethical concerns. Alternatively, the objective methods may be applied in the field, which tend to be more expensive and yield proportionately inconsistent information due to poor repeatability owing to relatively large inter-subject variability and complexities associated with a large number of contributory factors. The objective methods often require carefully controlled test conditions to study a particular aspect of the human response to vibration. Moreover, the objective methods should be based upon non-invasive measurement methods to minimize the potential ethical concerns.

The methods for measuring the biodynamic responses of seated occupants exposed to vibration have been well established through various studies conducted on the vertical biodynamic [8-10, 13, 56, 58, 59, 61, 125] and summarized in the previous chapter. The reported methodology based on the vertical biodynamics can be directly implemented for the present study under horizontal vibration, which involves measurement of force and acceleration at the driving point. Since the vast majority of the studies consider seating without back support, the measurements have been limited to the seat pan alone [11, 16, 29, 35, 56, 73, 91]. Alternate measurement systems need to be explored to quantify the human body interactions with the back support, which closely represents the automotive seating environment.

This chapter describes the design of a test seat representative of the automotive seating, while the experiment is designed to perform measurements at both the pan and the backrest. The whole-body horizontal vibration simulator is briefly described together with the measurement and data analysis systems. The experimental methodology is also described in accordance with the protocol approved by the Human Research Ethics Committee.

3.2 SEAT AND TEST FIXTURE DESIGN

By definition, sitting is a body position in which the weight of the body is transferred to a supporting area mainly by the ischial tuberosities of the pelvis and their surrounding soft tissue. Its purpose is to remove weight from the feet and maintain a stable posture so that the muscles not directly involved with the work can relax. Considerable attempts have been made to describe ideal automotive seat geometry, to provide most comfortable and controlled posture [9, 17, 29, 35, 37, 38, 41, 43, 46, 63, 100]. The sitting posture, in general, is described by two specific postures:

- Relaxed posture assumed while sitting unsupported, in the middle of the seat pan, with the center of mass directly above ischial tuberosities. Approximately 25% of the body weight is supported by the floor, while the posture yields either straight or slightly kyphotic lumbar spine [131].
- Posterior posture with backward leaning, and center of mass behind the ischial tuberosities. The floor supports less than 25% of the body weight in this posture [131].

The relaxed posture is generally assumed in commercial vehicle seats, with high backrests and small inclination in both, seat pan and back support. The second posture relates more closely to the automotive seats geometry, with low backrest but important inclinations of the back support and the seat pan. Considering that the biodynamic responses of the seated occupants to whole-body vibration are strongly influenced by the posture and thus the seat-geometry, it was deemed essential to design a representative automotive seat for the experiments. A representative seat geometry was employed, which was previously used to perform experiments under vertical excitations. This seat was realized upon consultations with the General Motors seating group, specifically on the seating height, as well as pan and backrest inclinations. Figure 3.1 illustrates the geometry of the seat utilized for this study.

The seat pan is an aluminium rigid platform with 13 degrees of inclination with respect to the horizontal; the backrest is an aluminium support with 66 degrees of inclination with respect to horizontal. The angle between the seat pan and the backrest is 101 degrees. The truss structure was made using hollow square-section steel bars to reduce its total weight and to ensure that its fundamental resonance lies at frequencies well above the range of excitation frequencies. The rigid seat (pan and backrest) assures the direct measures of horizontal forces transmitted to the body. The total mass of the seat and its structure was measured as 38 kg.

The test seat was installed on a rigid aluminium plate, which was mounted on the vibration platform through a three-axis Kistler dynamometer to measure the forces along the x- and y- axes. Figure 3.2 presents the pictorial views of the seat mounted on the vibration platform. The backrest of the seat comprises a 12.5 mm aluminium plate installed on the tubular frame through two single-axis force sensors, which provide the measurement of forces developed due to contact with the backrest.

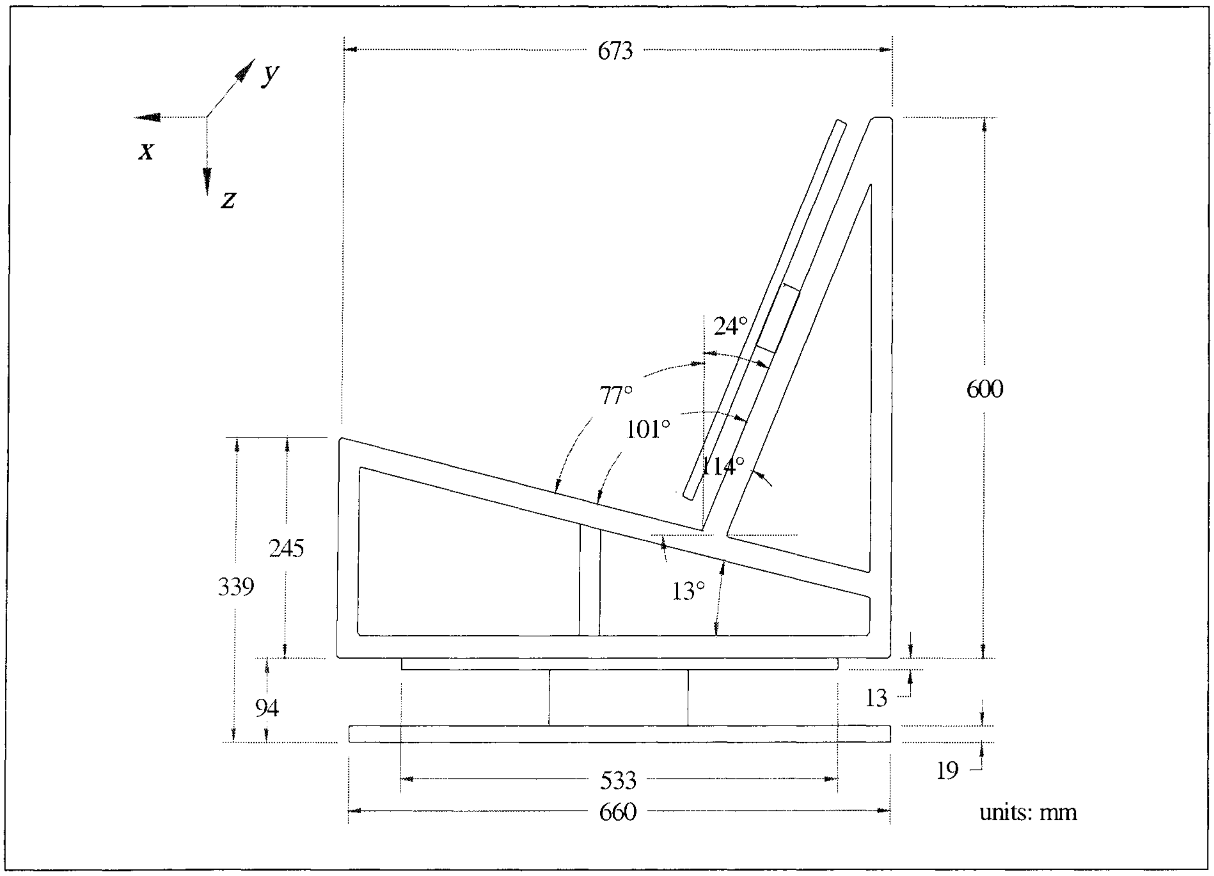


Figure 3.1 Geometry of the test seat.

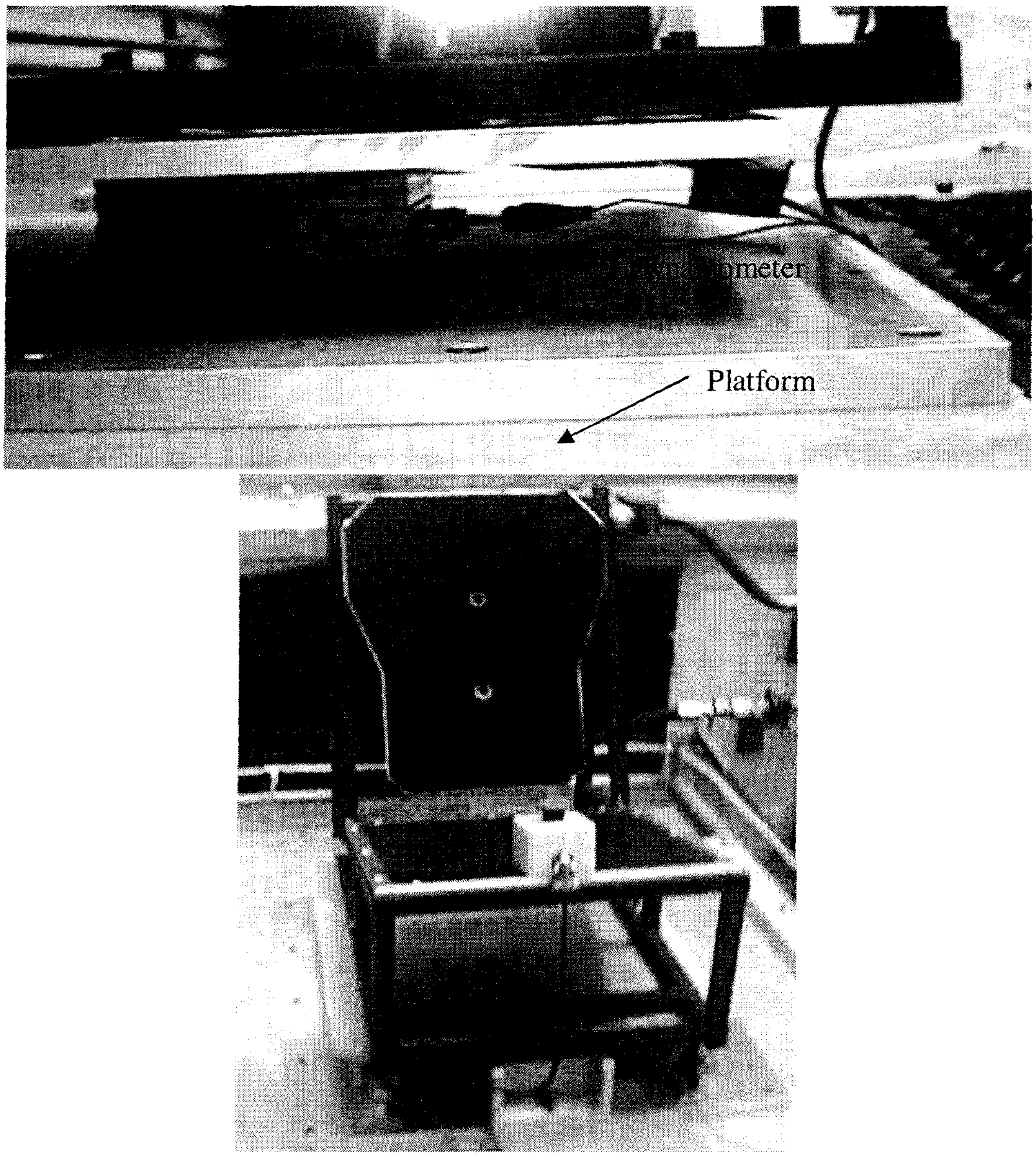


Figure 3.2 Pictorial views of the seat installed on the vibration platform.

The measurement of biodynamic responses to whole-body vibration in the laboratory involves complex challenges and many ethical concerns associated with human exposure to vibration. The low frequency nature of the whole-body vibration encountered in road and off-road vehicles generally requires high displacement vibration exciters, which could be realized using servo-hydraulic actuators. An intrinsic problem in the design of such vibration systems is that the subject may be exposed to unexpected transients, leading to potentially dangerous magnitudes of mechanical vibration or shocks. A special-purpose horizontal vibration simulator was thus designed with a number of safety control loops, while the peak magnitude of vibration and exposure duration were limited in accordance to ISO 1309-1: 1998 [69]. The safety limits were introduced to limit peak acceleration level below 0.6 g. Emergency switches were provided to both the operator and the subject to interrupt the experiment at any time.

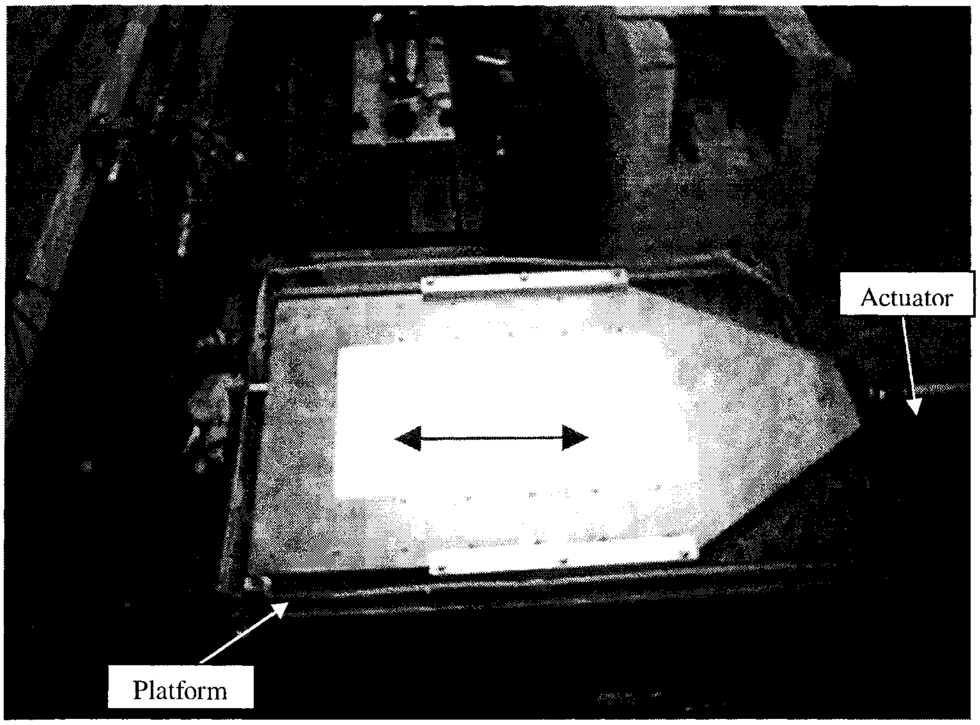


Figure 3.3: A pictorial view of the horizontal vibration simulator.

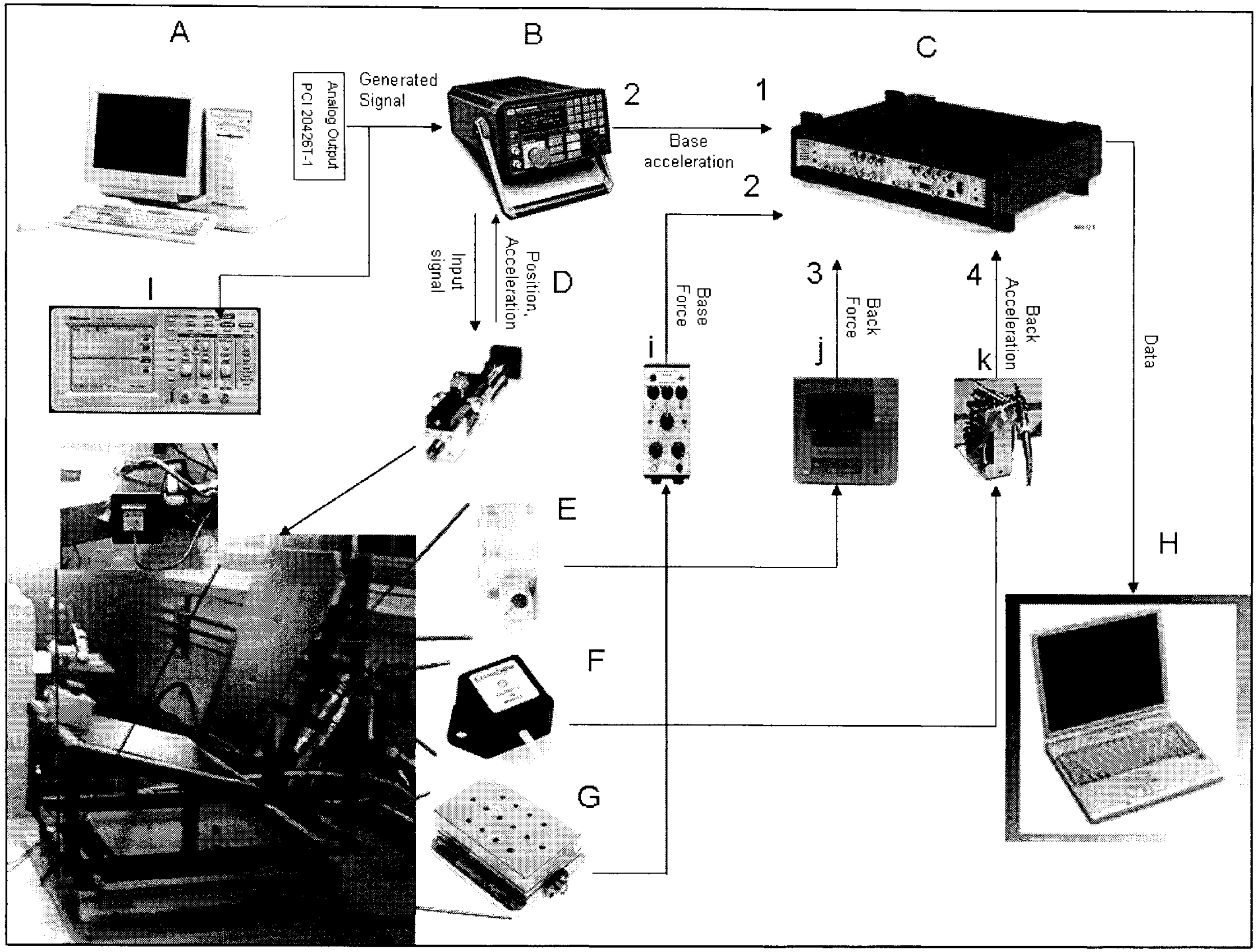
The horizontal vibration simulator designed in this study comprises a vibration platform supported on an oil film and attached to a long stroke (48 cm) hydraulic actuator through a self-aligning spherical bearing, in the horizontal plane, as illustrated in Figure 3.3. A MTS-407 servo-controller is used to operate the actuator using the displacement feedback. The controller was programmed to limit the peak acceleration, while ramp-up and ramp-down functions were used to smooth the start-up and stoppage.

The test seat was instrumented to acquire the vibration excitations and the force responses at the seat pan and the backrest. A micro-accelerometer, ADXLOSEM-1 (± 4g) was installed on the Vibraglide platform to acquire the acceleration due to vibration excitation along the x- and y-axes. Another single-axis accelerometer (Crossbow CX02LF12, ± 2g) was installed on the tubular frame of the seat backrest to measure the acceleration of vibration along an axis normal to the backrest. A three-axis Kistler dynamometer (model 9257A, range =5 kN) was installed between the seat base and the vibration platform to measure the force responses along the x- and y-axes. Two strain-gage based load cells (Omegadyne, 450 N range) were installed between the backrest plate and the seat back frame to measure the force response at the backrest along a direction normal to the backrest. A summing circuit was used to sum the load cells signals and the total signal was conditioned using a strain gage conditioner. Charge amplifiers were used to condition the signals from the dynamometer. Figure 3.4 illustrates the sensing, conditioning and acquisition components of the experimental set-up. The seat pan and the back acceleration signals were stored and analyzed using a 4-channel Brüel & Kjær analyzer, as shown in the figure.

The experimental set-up was designed to ensure safety of the subject and the experimenters. The controller was configured to provide five simultaneous safety checks through various interlocks. The safety features of the experiment are summarized below:

a. An easily accessible emergency stop was made available in the front panel of the MTS 407 Controller, which when depressed would stop the motion through the ramp-down control.

b. A displacement over-travel control was configured using the displacement feedback and the interlock within the controller.



A) Sigmawave desk top computer X86.

B) Vibration Generator: MTS 407 Controller

C) Data collector FTT BRÜEL & KJÆR Analyzer, type 3560 C

D) Acceleration transducer ADXLOSEM-1

E) Quartz-3-component dynamometer 9257A

F) Acceleration transducer CX02LF12

G) Tension/Compression load cell LCHD-100

H) Notebook C6000 Latitude Dell

i) Brüel & Kjær Charge amplifier, Type 2651

j) Condor strain indicator, model HB5-3/OUP-AT

k) Aries Instruments charge amplifier, type 8133-000-01

Figure 3.4 Measurement set-up and data acquisition.

c. An additional interlock was configured to limit the peak acceleration of the platform to +/- 0.6 g.

d. A hand-held emergency stop was made available to the test subject, which could be depressed to stop the experiment. Each subject was advised to use this switch, whenever the subject wished to discontinue the experiment or if any emergency situation was perceived.

e. An emergency stop was also placed on the Master pump control panel, which could be depressed by the experimenter to interrupt the hydraulic flows under an emergency situation.

3.3 VIBRATION EXCITATIONS AND TEST METHODOLOGY

The biodynamic response characteristics of seated occupants are frequently evaluated under harmonic as well as random white noise excitations. In the present study, harmonic as well as random excitations of different magnitudes were synthesized, while identical excitations were used along the two-axes (x and y). Considering that the horizontal vehicular vibration predominate in the low frequency range, the vibration excitations were limited to an upper frequency of 10.0 Hz. The magnitudes of harmonic and random vibration were chosen upon consideration of the daily exposure duration and the guidelines provided in the International Standard (ISO 1309-1: 1998 [69]).

A harmonic vibration signal swept in the 0.25-10 Hz frequency range at a rate of 0.038 Hz/s was synthesized in the laboratory. A constant displacement amplitude waveform could not be applied in this study, since the resulting acceleration at higher frequencies was judged to be high. A constant acceleration waveform was also considered inadequate, since it would cause too high a displacement at extremely low frequencies and too low a displacement at higher frequencies. An alternate waveform was thus synthesized to produce a constant displacement harmonic motion in the 0.25-1.0 Hz range, and constant acceleration thereafter. Three different magnitudes of excitations were synthesized to yield peak accelerations of 1.0, 1.5 and 2.0 m/s^2 at the transition frequency of 1.0 Hz. These correspond to constant peak displacement amplitudes of 25, 38 and 50.7 mm, respectively, in the 0.25 to 1.0 Hz frequency range, as illustrated in Figure 3.5. The experiments were conducted under one complete cycle involving upward (0.25 to 10.0 Hz) and downward (10.0 to 0.25 Hz) frequency sweep. The total exposure time associated with each run was 512 s.

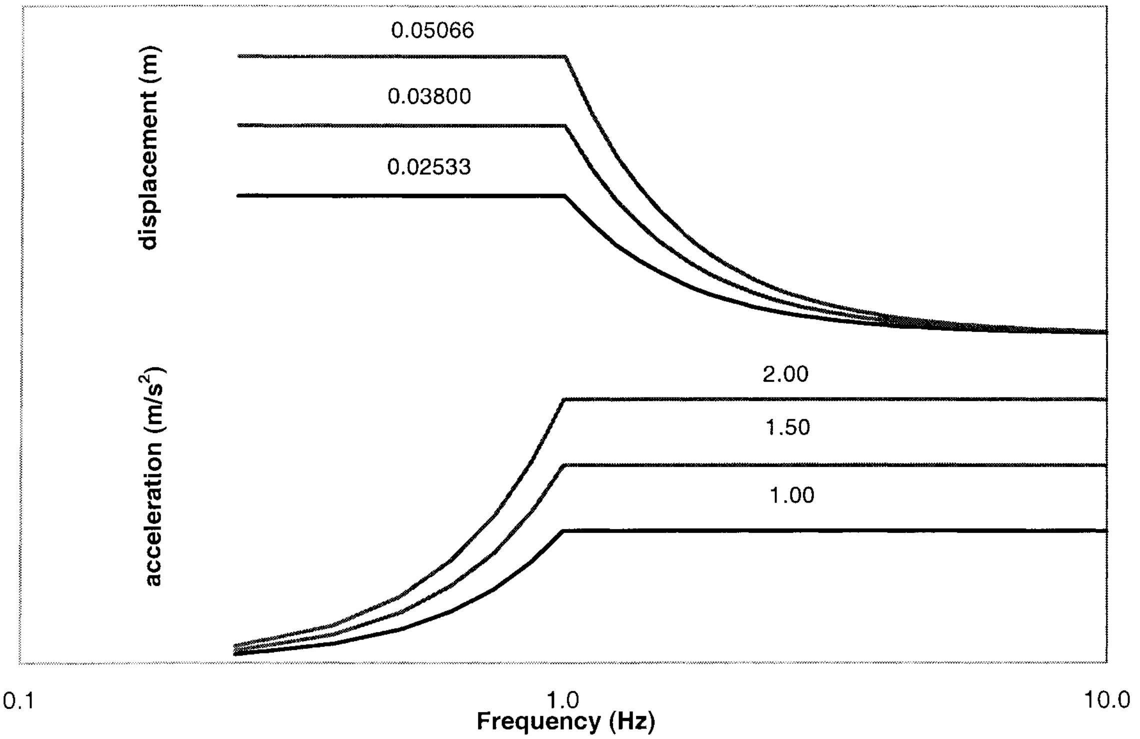


Figure 3.5 Displacement and acceleration amplitudes of swept harmonic excitations.

A white-noise random excitation signal was also synthesized to yield a nearly flat acceleration expectrum in the 0.25-10.0 Hz frequency range. The magnitude of the excitation was tuned by adjusting the controller gain. Three different controller gains were selected to attain three different magnitudes of random excitations, which were denoted by their respective overall rms acceleration values. There were selected as 0.25, 0.5 and 1.0 m/s^2 for the fore-and-aft direction. The higher magnitude, however, was limited to 0.75 m/s^2 for the lateral axis, since the subjects could not maintain a steady sitting posture under 1.0 m/s^2 rms acceleration excitation. The total exposure time of each run was set as 125 s. Figure 3.6 illustrates the power spectral density (PSD) of the acceleration excitations, which were evaluated using the pulse system.

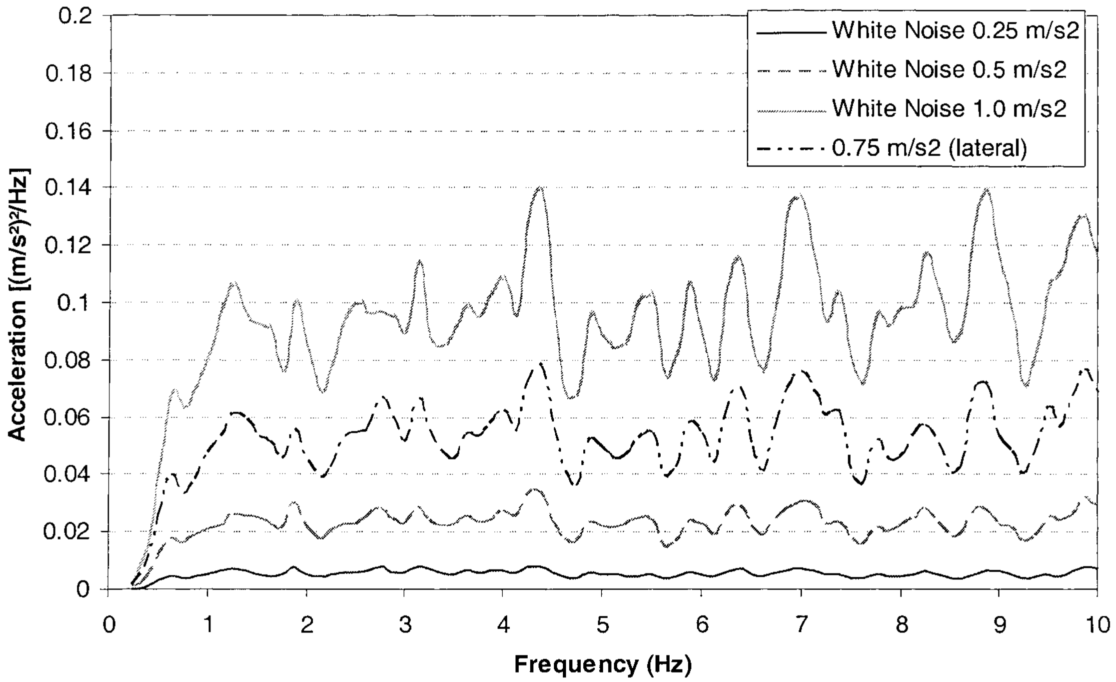


Figure 3.6 Acceleration PSD of synthesized random excitation

The characterization of biodynamic responses of the seated human body through measured force-motion relationship at the driving point necessitates that the resonances of the seat and supporting structure, and the measurement systems be higher than the upper limit of the frequency of interest. The resonant behaviour of the seat fixture and the measurement systems were thus measured under the synthesized harmonic and random excitations in the frequency band of 0 to 100 Hz. The measured force and acceleration signals at the seat pan were analyzed to compute the apparent mass of the seat and supporting structure using the H1 function of the pulse analyzer, which yields [52]:

$$M_{seat}(jw) = \frac{S_{F_{xb}a_{xb}}}{S_{a_{xb}}} \tag{3.1}$$

where M_{seat} is complex apparent mass of the seat and its supporting structure, measured under fore-and-aft excitations. $S_{F_{xb}a_{xb}}$ is the cross-spectral density of force F_{xb} and acceleration a_{xb} measured at the seat pan or the base, and $S_{a_{xb}}$ is the autospectral density of the acceleration excitation.

Figure 3.7 illustrates the magnitude of the apparent mass of the seat measured at its base subject to different excitations along the fore-and-aft (x) axis. The results show nearly constant apparent mass equal to the seat mass (38 kg) in the frequency range of interest (0.25-10 Hz), irrespective of the type of excitation. The seat and its supporting structure exhibits resonances at frequencies above 25 Hz. The apparent mass phase response was observed to be close to zero in the frequency range of interest. Figure 3.8 illustrates the apparent mass magnitude response derived from the force and acceleration measured at the backrest. The results suggest flat frequency response in the frequency range of interest, where the constant magnitude of 3 kg represents the mass of the backrest plate and the bolts. The responses under the lateral excitations were also observed to be identical. It is thus concluded the test seat can be effectively applied to capture the biodynamic responses of the seated human body in the 0.25-10 Hz frequency range.

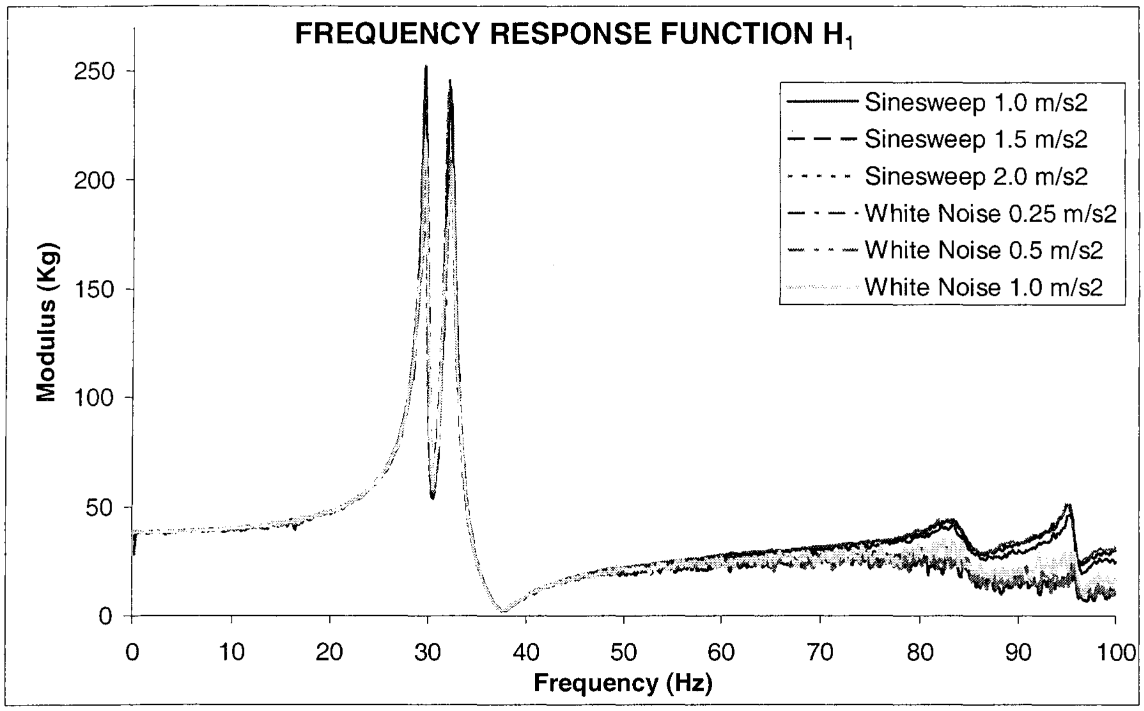


Figure 3.7 Apparent mass response of the seat pan under different excitations.

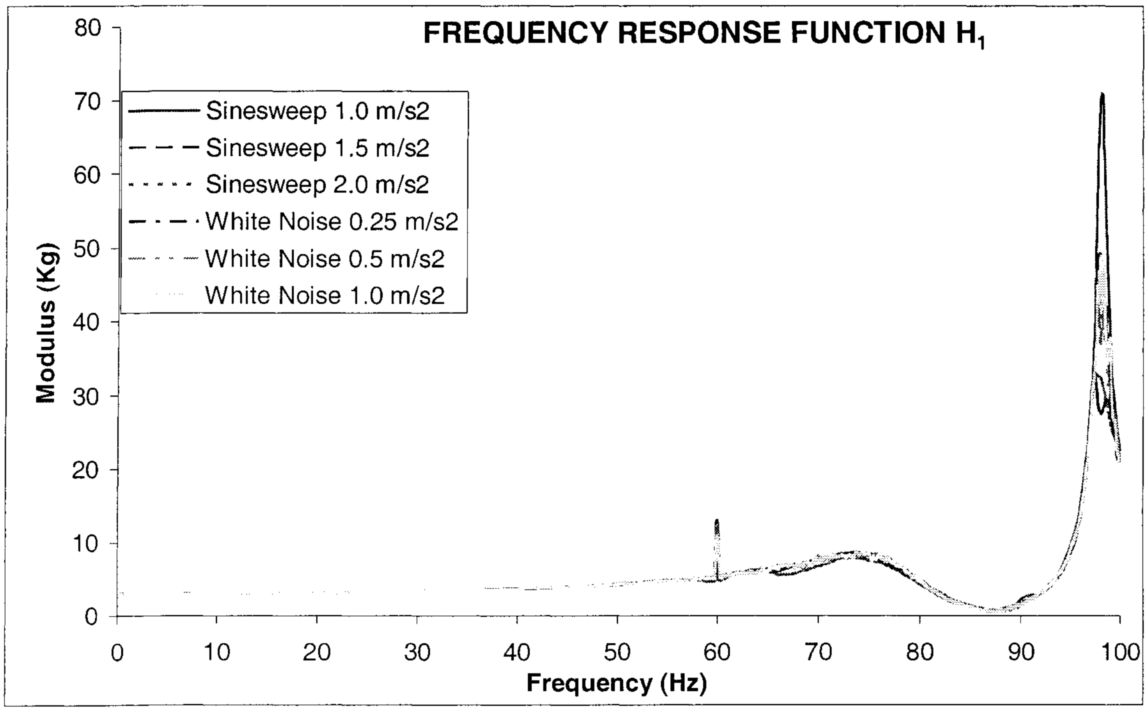


Figure 3.8 Apparent mass response of the backrest under different excitations

As the equipment operates in only one horizontal axis, the measurements under fore-and-aft (X) and lateral motions (Y) were conducted in separate sessions and achieved by rotating the seat through 90^{o}. The experiments involved a single trial for each level of sinesweep excitations and two trials under white noise excitations, for a total of 36 trials for each subject and axis, involving two postures (back supported and unsupported), and three levels each of sinusoidal and random excitations. Each subject took part in two sessions, one for each direction, of approximately 1.5 hours, including the training and briefing during the first session. The subjects were advised to relax for periods of 5-10 minutes between the successive trials.

Prior to the test, each subject was advised to assume a stable posture on the test seat with the chosen posture, such as back supported and not supported. The command signal corresponding to a selected waveform was then applied using the MTS controller and the DSP board installed within a desktop computer. The test signal was applied through a ramp-up control. The sensors signals were acquired using the 4-channel pulse analyser after a steady motion of the platform was realized. The test signals included the following (Figure 3.9):

- Force response measured at the seat base using the Kistler Dynamometer (F_{x_b} and F_{y_b})
- Acceleration excitation at the seat base using a single axis micro-accelerometer (a_{x_b}, a_{y_b})
- Force response measured at the backrest using two load cells (F_{x_r}, F_{y_r})
- Acceleration excitation at the backrest along a direction normal to the backrest (a_{x_r}, a_{y_r})

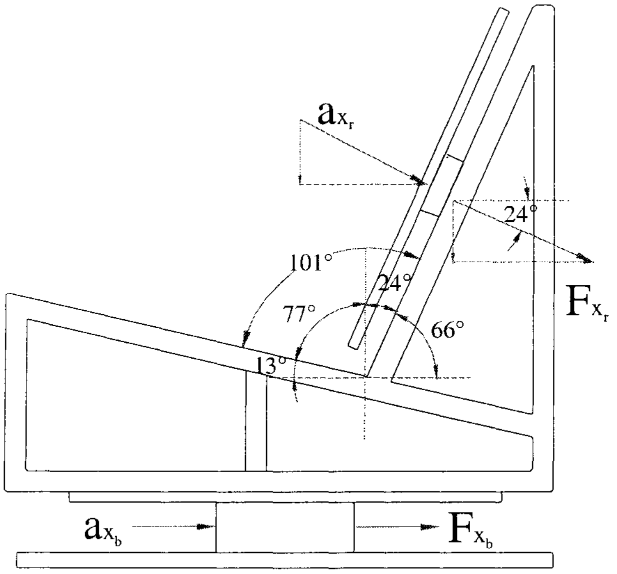


Figure 3.9 Measurement points and directions of measured acceleration and forces.

From Figure 3.9, it is evident that the backrest acceleration is related to the base acceleration through the seat geometry:

$$a_{x_r} = a_{x_b} \cos(24^o) \tag{3.2}$$

The acquired data were analyzed using the CPB (constant percentage bandwidth) and FFT (Fast Fourier Transform) analyzers of the pulse system. The bandwidth of the analyses was selected as 50 Hz. The pulse software was configured to display the following response quantities for monitoring purposes in various windows:

- The magnitude of APMS response at the seat pan corresponding to the selected test condition, which was derived from the measured seat base force and acceleration using the H_1 function.
- The magnitude of APMS response at the seat back corresponding to the selected test condition, which was derived from the measured seat back force and acceleration using the H_1 function.
- The signal to noise ratio of the seat base force and the acceleration.

- The signal to noise ratio of the seat back force and the acceleration.
- The power spectral densities of the measured forces and acceleration.
- The real part of the cross-spectrum of the seat base force and acceleration.
- The real part of the cross-spectrum of the seat back force and acceleration.

The measured APMS and cross-spectra responses were stored in terms of their real and imaginary components for further analyses. The spectral densities of the force and acceleration signals were also stored for each condition. The APMS and cross-spectra responses of the seat alone were also acquired prior to the test with each subject, and stored to perform inertial corrections of the responses of the seat with subject.

A total of 7 subjects were recruited for the study. The subjects who had prior history of back pain were not permitted to participate in the study. Each subject was asked to attend four different test sessions, two for each axis of vibration involving random and sinusoidal excitation. A test session involving random vibration included a minimum of 12 trials including 2 postures, two repeats and 3 levels of excitation. The test series involving sinusoidal vibration included a minimum of 6 trials including two postures and three levels of excitations. It should be noted that some of the trials were occasionally rejected by the experiment, when considerable differences in the responses were observed. The maximum daily exposure was estimated as 33 minutes, which conformed well with the guidelines provided in the ISO 1309-1 [69].

The test participants were chosen using an extended list of medical contra-indications based on ISO 13090-1 [69] and regular questionnaires applied in Europe [81, 82]. They were informed about the experiment and took part in a training session to familiarize them with the procedure and their tasks. After explaining the experiment to the subjects, including the test procedures, as well as the safety and emergency measures, their consents were obtained, through signing a participant consent form. A copy of the consent form is included in Appendix A, together with the summary protocol, describing proposed experiment, which was approved by the Human Research Ethics Committee of the Concordia University. Each subject was asked to wear light and comfortable clothes to ensure comparable friction between the subject back and the backrest. The experiment recorded the participant's name, address, age, weight, height, body build (light/medium/heavy) and observed physical fitness (excellent/very good/good).

The study group consisted of 7 adult male subjects, with no prior history of back pain. Table 3.1 summarizes the ranges of subjects' weight, height and age. The subjects' height varied from 1.7 to 1.83 m with mean height of 1.75 m. The mean body weight of the participants was computed as 77.11 kg, which varied from 61.2 to 88.1 kg. Table 3.2 and 3.3 present the summary of the test conditions employed in the study.

Table 3.1: Age, weight and height of the test participants.

(n=6)	Mean	SD	Min	Max
Age (years)	34.86	9.62	25	50
Weight (kg)	77.11	9.41	61.2	88.1
Height (m)	1.75	0.04	1.70	1.83

Table 3.2 Summary of body posture adopted during the experiment.

Back	Dorsum supported (Backrest used); backrest 24 degrees of inclination, with relation to the vertical. No restricted by any harness
	Dorsum unsupported (No Backrest used), Upright posture (90 degrees with relation to the horizontal); No harness used
Feet and legs	Feet supported on the vibrating platform with full contact with the surface. Thighs parallel to the plane of the seat pan.
Hands	Resting on the lap.
Description:	The posture was visually checked by the experimenter during each test run. The subjects were advised to make necessary correction, if needed, prior to application of a vibration signal. The consistency of the contact with the backrest was also monitored from the displayed force spectrum.

Table 3.3 Summary of test trials.

INPUTS	SINUSOIDAL			RANDOM		
Level	$1.0\ m/s^2$ †	$1.5\ m/s^2$ †	$1.5\ m/s^2$ †	$0.25\ m/s^2$ †† rms	$0.5\ m/s^2$ †† rms	$1.0\ m/s^2$ †† rms {$0.75\ m/s^2$} *
Trials and Postures	Seated with backrest (1)	Seated with backrest (1)	Seated with backrest (1)	Seated with backrest (1)	Seated with backrest (1)	Seated with backrest (1)
	Seated without backrest (1)	Seated without backrest (1)	Seated without backrest (1)	Seated without backrest (1)	Seated without backrest (1)	Seated without backrest (1)
Direction of excitation	FORE-AND-AFT (X)			FORE-AND-AFT (X)		
	LATERAL (Y)			LATERAL (Y)		

* The higher magnitude was limited to 0.75 m/s2 rms under lateral excitation.

† Peak magnitude. †† Overall rms level.

3.4 DATA ANALYSIS

The biodynamic responses of the body when exposed to WBV are widely measured in terms of the driving point mechanical impedance, apparent mass or absorbed power. All three quantities can be calculated from the measures of force and acceleration at the human-seat interface. Of these, the apparent mass has the advantage of indicating the subject mass at low frequencies. Furthermore, the apparent mass tends to simplify the inertial correction task [32, 52]. Although the magnitude of vibration could affect the shape of the apparent mass response, its sensitivity to the magnitude of excitation is known to be relatively low. Moreover, the apparent mass response does not consider the duration of vibration exposure [11, 14, 15, 25, 128]. Considering that the safety risk and discomfort caused by WBV is strongly related to both, the magnitude and duration of exposure, the biodynamic response in terms of absorbed vertical vibration energy has been reported as a better measure [11, 14, 15, 25, 128]. The apparent mass responses, on the other hand, are useful in deriving mechanical equivalent models and frequency-weighting functions [14, 31, 36, 37, 50, 51, 73, 75, 79, 113, 138]. The measured force response and acceleration excitations in this study are thus analyzed to derive both the APMS and absorbed power characteristics of the seated human body exposed to WBV along the x- and y-axes.

The whole-body vehicular vibration simulator was operated to produce the motion signals corresponding to a selected stimulus. The resulting forces and acceleration signals were acquired using the BRÜEL & KJÆR data collector, type 3109 (61 samples for white noise and 253 for sine sweep). These signals were subsequently used to compute the apparent mass response function, as the ratio of cross-spectral density of force and acceleration to the auto spectral density of the acceleration. The absorbed power due to the stimulus was computed as the real component of the cross-spectrum between the force and velocity ($S_{F\dot{x}}$). The analyses were performed in the 0.25-100 Hz frequency band with resolution of 0.125 Hz.

3.4.1 APPARENT MASS RESPONSE ANALYSIS

The force responses measured at the seat pan under x- and y-axis motion are used to compute the apparent mass responses in the following manner:

$$M_{ib}^{*} = \frac{S_{F_{ib}a_{ib}}}{S_{a_{ib}}}; \quad (i=x,\ y) \tag{3.3}$$

$$M_{ir}^{*} = \frac{S_{F_{ir}a_{br}}}{S_{a_{ir}}}; \quad (i=x,\ y) \tag{3.4}$$

where M_{ib}^{*} and M_{ir}^{*} are the apparent mass responses measured at the seat base and the backrest, respectively, under motion along axis i ($i=x, y$).

The measured apparent mass responses reflect the force-motion relationship or the coupled body-seat system. The apparent mass responses of the subject alone are obtained by subtracting the inertia force due to the seat and the supporting structure from the measured force responses [32]. The apparent mass response of the seated subject measured at the seat base is obtained by adjusting for the apparent mass of the entire seat structure supported on the force dynamometer at the seat base. This correction is performed at each frequency within the range of interest. The modulus and phase for the subject alone are then obtained, using the real and imaginary components of the resulting response function. The apparent mass of the subject measured at the seat base is thus given by:

$$M_{ib}(j\omega) = M_{ib}^{*}(j\omega) - M_{ib}^{s}(j\omega); \quad i = x, y \tag{3.5}$$

where $M_{ib}^{*}(j\omega)$ is the complex apparent mass responses of the coupled seated body-seat system measured at the seat base, and $M_{ib}^{S}(j\omega)$ is that of the seat structure alone measured under motion along an axis i.

The APMS response of the seated body at the backrest is computed in a similar manner:

$$M_{ir}(j\omega) = M_{ir}^{*}(j\omega) - M_{ir}^{s}(j\omega); \quad i = x, y \tag{3.6}$$

where $M_{ir}^{*}(j\omega)$ and $M_{ir}^{S}(j\omega)$ are the apparent mass responses of the seated body-seat system measured at the backrest and the backrest alone, respectively, corresponding to an excitation frequency of ω.

The resulting complex APMS responses are then expressed in terms of the respective moduli and phase response functions in the frequency range of interest. The APMS responses at the back support were not performed under the back not supported (BNS) postures. A few subjects, however, experienced difficulties in maintaining this posture under high magnitude excitation. The large fore-and-aft motion of the upper body caused occasional contacts with the backrest in few cases. The spectrum of the backrest force was constantly monitored during the experiment to ensure minimal backrest contact. The peak magnitude of the APMS response at the backrest was measured to be below 2 kg for majority of the trials with no back support posture. Under large magnitude excitations (2.0 m/s^2 sinusoidal and 1.0 m/s^2 rms random) along the x-axis, the peak apparent mass modulus approached as high as 6 kg in a few cases.

3.4.1.1 NORMALIZED APMS RESPONSE ANALYSIS

The APMS response characteristics of seated human body exposed to WBV are known to be influenced by many anthropometric, excitation and seat related factors [9, 10, 20, 22, 26, 51, 126]. Among these, the body mass affects the magnitude response most significantly. The APMS magnitudes at lower excitation frequencies and in the vicinity of the resonance tend to be considerably higher for a higher body mass. The measured APMS is thus normalized with respect to the static body mass supported by the seat. It has been suggested that the resulting normalized APMS response could eliminate the effect of body mass to an extent and thus permit the analyses of the effects of other factors, such as nature of WBV, sitting posture and seat geometry [32].

The reported studies on vertical whole body biodynamic have applied different methods to normalize the measured apparent mass responses. A few studies have performed the normalization by dividing the apparent mass modulus by the magnitude at 0.5 Hz or other low frequencies, believed to be the static mass supported on the seat [20, 32]. Other studies have applied the sitting mass [13, 15, 17, 18] and the standing mass [26, 127] to normalize the measured responses. While the APMS responses attained under vertical WBV have been widely normalized, the normalization tasks are not recommended under horizontal vibration [22]. The principal reason for this is attributed to the relatively lower resonant frequencies of the seated human subjects under horizontal vibration. While the vertically excited human body response compares well with that of a rigid mass at frequencies below 1 Hz [32, 53], the identification of static sitting mass is quite difficult from the response under horizontal vibration. Moreover, the response to horizontal vibration tends to be influenced by decoupled movements of different body limbs, principally the legs [26, 32]. In addition, Boileau [10], found divergences in the static weight supported by the seat under different postures. Rakheja et al. [125] measured the static body masses supported by the seat pan and the backrest for a total of 24 male and female subjects seated on the automotive seat used in this study. The mentioned study established that 75.6% of the body mass is supported on the seat pan, while the backrest supports 25.5% of the body mass. Under no back support posture, 73 % of the body mass is supported by the seat pan. In this study, these data are used to obtain normalized APMS responses of the seated subjects exposed to horizontal vibration.

3.4.1.2 MEAN APMS RESPONSE ANALYSIS

The APMS and absorbed power response characteristics of individual subjects are initially evaluated as the means of the two trials conducted under random excitations. The means attained for different subjects are further analyzed to derive the mean responses of the subject sample to study the important trends, and the effect of postural and excitation conditions. The mean responses, evaluated using different techniques, could differ considerably. Three different methods were attempted to derive the mean normalized responses. In the first method, the mean normalized APMS magnitude response ($\overline{M}_1$) is attained from the mean real and imaginary components of the normalized APMS responses of individual subjects, such that:

$$\overline{M}_1(j\omega) = \left| \sum_{i=1}^{n} \frac{\mathrm{Re}\,al[M_i(j\omega)]}{m_i} + \sum_{i=1}^{n} \frac{\mathrm{Im}\,ag[M_i(j\omega)]}{m_i} \right| \qquad (3.7)$$

where $M_I(j\omega)$ represents the measured APMS response of the subject i, m_i is the sitting mass of the same subject used for normalization, and n is the number of subjects.

In the second method, the normalized response $\overline{M}_2(j\omega)$ is computed from the mean real and imaginary components but normalized with respect to the mean seated mass:

$$\overline{M}_2(j\omega) = \frac{\left| \sum_{i=1}^{n} \mathrm{Re}\,al[M_i(j\omega)] + \sum_{i=1}^{n} \mathrm{Im}\,ag[M_i(j\omega)] \right|}{\sum_{i=1}^{n} m_i} \qquad (3.8)$$

In the final method the mean normalized modulus $\overline{M}_3(j\omega)$ is derived from the moduli obtained for individual subjects and normalized with respect to the mean sitting mass:

$$\overline{M}_3(j\omega)=\frac{\sum_{i=1}^{n}\left|\mathrm{Re}\,al\left[M_i(j\omega)\right]+\mathrm{Im}\,ag\left[M_i(j\omega)\right]\right|}{\sum_{i=1}^{n}m_i} \tag{3.9}$$

The above three methods yield significantly different results as is shown in Figure 3.10. The response based upon the mean of the moduli yields most significant deviation in the primary response frequency, while the other two methods yield comparable magnitudes and frequency of the peak response. Since the first method considers normalization of each individual data sets, this method is used for analysis of results presented in the subsequent chapters.

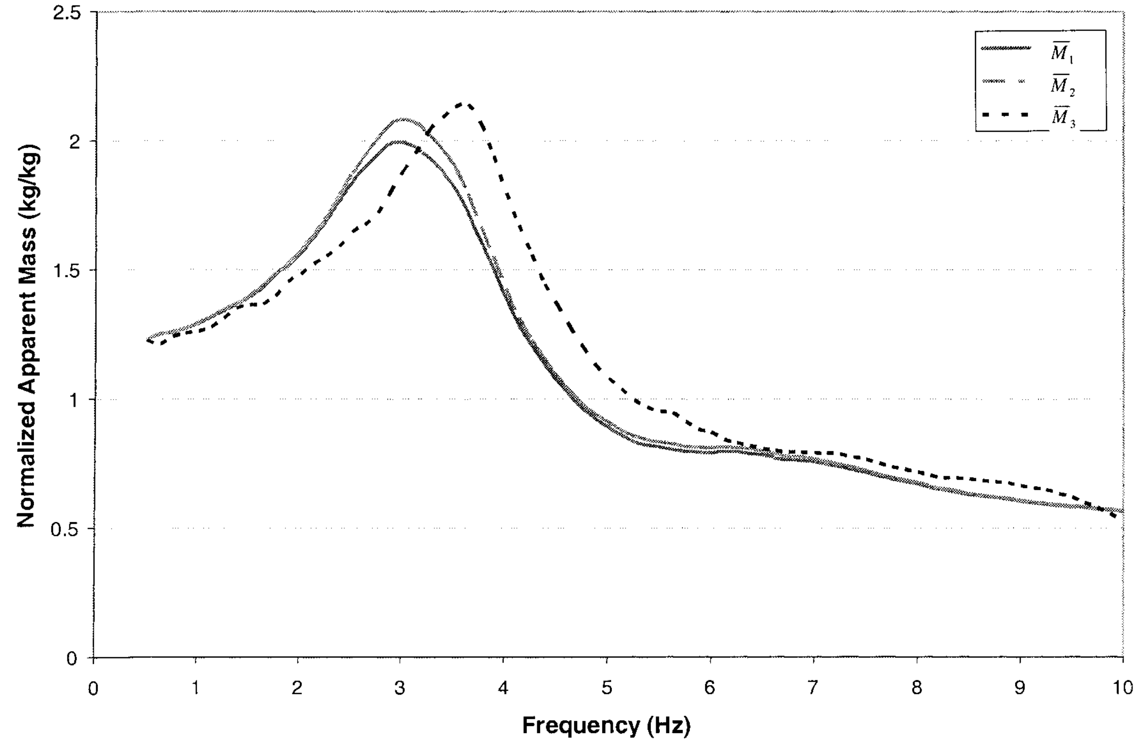


Figure 3.10: Comparison of mean APMS responses attained from different methods.

3.4.2 ABSORBED POWER

The amount of vibration energy, absorbed and/or exchanged between the source and the body, has been suggested as a better measure of the physical stress caused by exposure to the vertical WBV [11, 21, 25]. The use of absorbed power as an indicator of human response to WBV was first proposed by Lee and Pradko [104] in the 60's. The concept, however, has gained some attention for the WBV exposure only in the recent years [15, 15, 21, 25, 79]. By definition, the instantaneous power transmitted to the body may be represented by [106]:

$$P_{tr}(t) = F(t) \bullet v(t) = P_{abs}(t) + P_{el}(t) \tag{3.10}$$

where: $F(t)$ and $v(t)$ are the instantaneous force acting on the body and the input velocity at the driving point, respectively, $P_{abs}(t)$ is the absorbed part of the power; and $P_{el}(t)$ is the elastic power, which is continuously delivered to and removed from the body. The average energy transferred to the per unit of time during the time-period T can be expressed as [105]:

$$P_{(avg)} = \int_0^T F(t) \bullet v(t) dt \tag{3.11}$$

The above equation could be presented in the frequency domain as the cross-spectrum between force and velocity, which is normally complex, expressed as [105]:

$$G_{Fv}(\omega) = 2 \bullet \int_{-\infty}^{\infty} R_{Fv}(\tau) \bullet e^{-j\omega\tau} d\tau = C_{Fv}(w) - jQ_{Fv}(w) \tag{3.12}$$

where C_{Fv} is the coincident spectral density function and Q_{Fv} is the quadrature spectral density function. The real component of the spectrum reflects the energy absorption part, whereas the imaginary component reflects the energy stored part of the system. The average absorbed power has thus been expressed as::

$$P_{Abs}(\omega) = |G_{FV}(\omega)|\cos\phi(\omega) \tag{3.13}$$

where $|G_{FV}(\omega)|$ is the modulus and $\phi(\omega)$ is the phase of the cross-spectrum between the force and the velocity.

The above equation yields the absorbed power density, with units of $\mathrm{Nms^{-1}/Hz}$. The velocity excitation at the driving point was obtained through time integration of acceleration signal in the PULSE analyzer. The cross-spectral density of the measured forces and velocity at the driving-points (pan and backrest) were then attained through the FFT analyzer. An inertial correction was performed using the cross spectra of the seat and backrest alone, which were found to be of negligible magnitudes.

3.5 SUMMARY

Measurement and data analyses methods employed to characterize the biodynamic responses of seated human body exposed to horizontal whole body vibration are established. The methods are applied to compute the APMS and Absorbed power responses of individual subjects and the mean responses. The data are studied to quantify the influences of the nature of excitation and posture support on the responses in the following chapters.

CHAPTER 4

APPARENT MASS RESPONSE CHARACTERISTICS

4.1 INTRODUCTION

The principal interest in studying the biodynamic responses of seated human body exposed to whole-body vibration lies with the belief that some of the adverse effects of vibration can be understood from measurements of vibration transmitted to/through the body or limbs. Particularly, the relative importance of frequency components of either the force entering the body or the acceleration occurring at a point on the body, could be investigated. Many effects of vibration have been described by asserting that certain types of vibration are associated with resonance of parts of the biological system. As it is known, the human body exhibits complex dynamic response to WBV, which may include many resonances. The high damping associated with many components of the biological system and their resonance frequencies makes the definition of a single resonance frequency somewhat ambiguous. The reported studies on vertical biodynamics suggest that individual variability in mass and stiffness would be expected to result in differences in the resonant frequencies between the subjects [11, 12, 16, 17, 59, 61, 126, 134]. Moreover, the non-linear visco-elastic properties of the biological system may yield different resonant frequencies under different types of WBV excitations [11,32,106].

A great number of experimental studies on the driving-point frequency responses of the human body exposed to vertical WBV have been published in the recent years [8-10, 12, 17, 19, 23, 56, 58, 59, 61, 71, 128, 130]. On the basis of the synthesis of reported data, the ranges of the biodynamic responses of subjects seated with no back support and hands in lap, and exposed to vertical WBV, have been standardized (ISO 5982: 2001 [130]). However, there appears to be few published reports on experiments investigating the driving-point frequency response of the human body under horizontal WBV along the lateral and fore-and-aft directions [22, 24-26, 71]. The responses to horizontal WBV are investigated independently along the fore-and-aft and lateral directions, in order to neglect the coupling effects. Using the methods suggested in the studies, the measured data are analysed in this chapter to derive the frequency response characteristics of the driving-point measures as a function of the direction and nature of vibration, and sitting posture. As it is stated in chapter 2, measures of the biodynamic response of human body are characterized by transfer functions, relating the force and motion at the driving point. This chapter focuses on the relationship between the driving force at the seat-occupant interface and its related movement (acceleration), expressed in terms of apparent mass (APMS). The APMS under WBV tends to exhibit large inter-subjects variability due mainly to particular body responses (mechanical, physiological and psychological) as well as the exposure-dependence of these body responses [8, 13, 15, 17, 18, 20, 22, 26]. From all the aspects related to the above factors, the anthropometric constitution of the seated human, as well as the adopted posture, have been found as the most important features affecting the APMS responses. However, other aspects such as direction, nature and magnitude of excitation also tend to alter the APMS behaviour. The measured results are examined to highlight the inter-subjects variability, while the mean APMS responses are discussed to enhance the understanding of the effects of sitting posture and nature of vibration.

4.2 INTER-SUBJECTS VARIABILITY AT THE SEAT PAN AND THE BACKREST INTERFACES

Owing to considerable contributions due to anthropometric variations of the human body, the generation of reliable data forms one of the important goals of the study to explain, predict, and understand the responses to WBV. The data collection in such studies forms only one element of the study, while the appropriate interpretations and characterization require the identifications of known or expected sources of variability [135, 136]. The complex variations in the APMS responses depend on several factors, some of which directly relate to the individuals, and others relate to the sensitivity, accuracy and input characteristics of the experiments. It is thus expected that differences in subjects, such as body size or mass could affect the body response, which is clearly evident from many reported studies under vertical WBV. Variations in the body posture (such as back support and hands position), general physical health and muscle tension, however, have not yet been clearly defined to attain the generally applicable response characteristics [17, 36, 63]. Notwithstanding the above facts, attempts are made to derive important trends and quantify the contributions due to various factors. The objective of such experiments is to obtain a set of outcomes under defined conditions, which are repeatable under the same circumstances. Moreover, the causes of variability need to be identified when the data are not repeatable, which may help to either eliminate or reduce the degree of variability.

There are various methods to test this repeatability in the measured responses, which mostly use statistical analysis and procedures to find evidence of relationships between variables, and quantify the nature and strength of those relationships. From the published studies, it is evident that even with controlled parameters, the experiments often yield considerable variation in the outcome of the every single trial involving measurement of force-motion relationship [11, 13, 22, 25-27, 35, 50, 56, 73, 100, 137]. The set of outcomes, however, tend to lie within limits of a "reasonable" range under vertical excitations that permits for establishing important trends. The international standard ISO 5982: 2001 [130], defines the ranges of idealized driving point impedance responses of seated subjects exposed to vertical WBV, which reveal a wide variations in the responses, although the data is considered applicable for a narrow range of experimental conditions.

The data attained from the current experiments revealed some very clear tendencies with respect to the static and peaks magnitudes, and dominant frequencies, as evident in Figure 4.1 as an example. The results show that the response of subject number 5 is distinctly different from the others. The observed difference, however, may not be sufficient to determine whether or not the measured data is valid within the total set of data considered. In order to "quantify" if these differences could affect the total outcome of the present experiment, three different methods of statistical analysis were performed: the creation of an "envelope", thorough the assumption that for normal distributed data, 68% of the values lie within one standard deviation (SD) of the mean; the comparison between the coefficients of variation with the data containing the information for all the subjects and removing one or more data set considered as outliners; and a statistical Fisher Test, comparing the entire data and with the data attained after removal of the outliners.

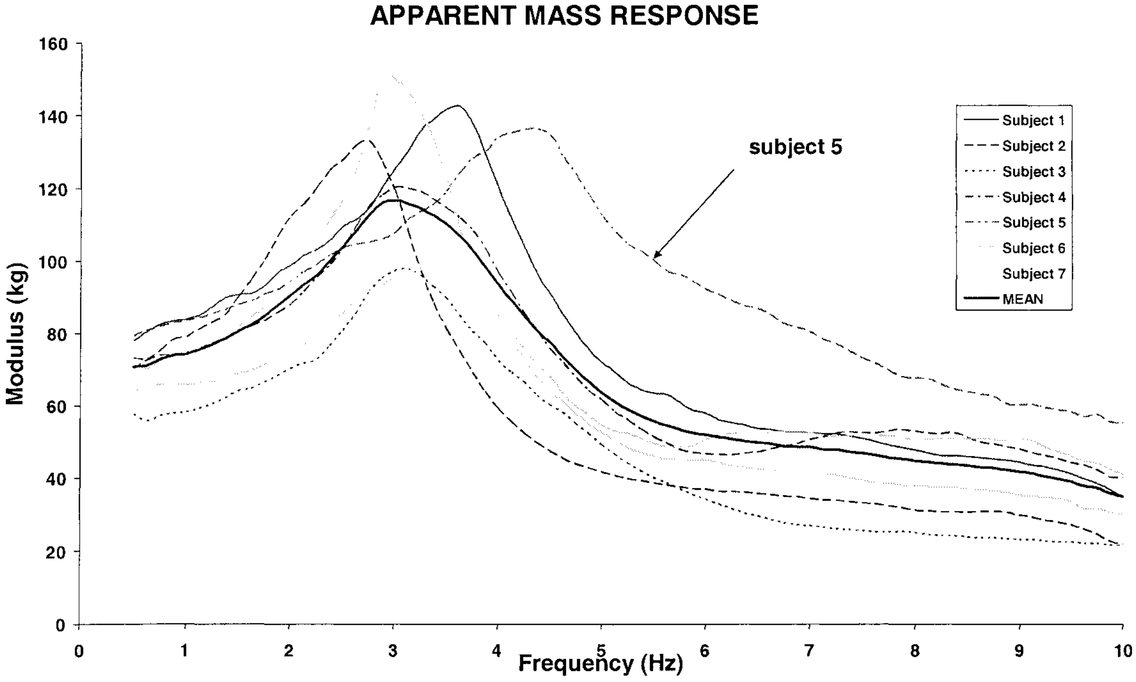


Figure 4.1 Apparent mass response for seven subjects under sinusoidal fore-and-aft acceleration of 1 m/s^2 and back support condition.

The characterization of the response for seated human body to horizontal vibration involves accumulation of several data sets obtained from different trials under similar conditions. From the possible methods, when no random events are involved, the set of data may characterize as a central measure with certain degree of dispersion. This central tendency or the mean is particularly informative measure of the variable, when reported along with its confidence intervals. The larger the sample size, the more reliable its mean. In the present study, the mean apparent mass biodynamic response is computed from the mean real and imaginary components of the responses such that:

$$\overline{M} = \sqrt{\left(\frac{\sum_{i=1}^{n} M_{i(real)}}{n}\right)^2 + \left(\frac{\sum_{i=1}^{n} M_{i(imag)}}{n}\right)^2} \qquad (4.1)$$

where $\overline{M}$ is the mean apparent mass at each frequency, $M_{i(real)}$ and $M_{i(imag)}$ are the real and imaginary components of the apparent mass of for subject i, respectively, and n is the sample size.

The most common numerical measure of spread in the data is the 'standard deviation', computed from:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}{n-1}} \qquad (4.2)$$

where M_i is the APMS magnitude of the subject i correspond to a particular frequency, and σ is the standard deviation.

Both quantities, mean and standard deviation, are used to described the general behaviour of the data through two analytical processes, as described below.

In order to distinguish variations in the central tendency that could not reflect the causal relations between variables and thus move away from the real behaviour of the investigated phenomena, analytical methods must be used. From Figure 4.1, a large variation in the subject number 5 response in relation to others is evident. In order to verify the validity of this data, the data is assumed to be an outliner and removed from the original set. The resulting mean response is compared with the mean and upper limit of the total data set (Figure 4.2). The upper bound is established on the basis of one σ. Although the data for subject number 5 lies outside the upper limit above 3.75 Hz, only little variation is observed in the mean value in terms of both the magnitude and the frequency of predominant response. The analyses thus suggest that this particular data set may not be considered as an outliner.

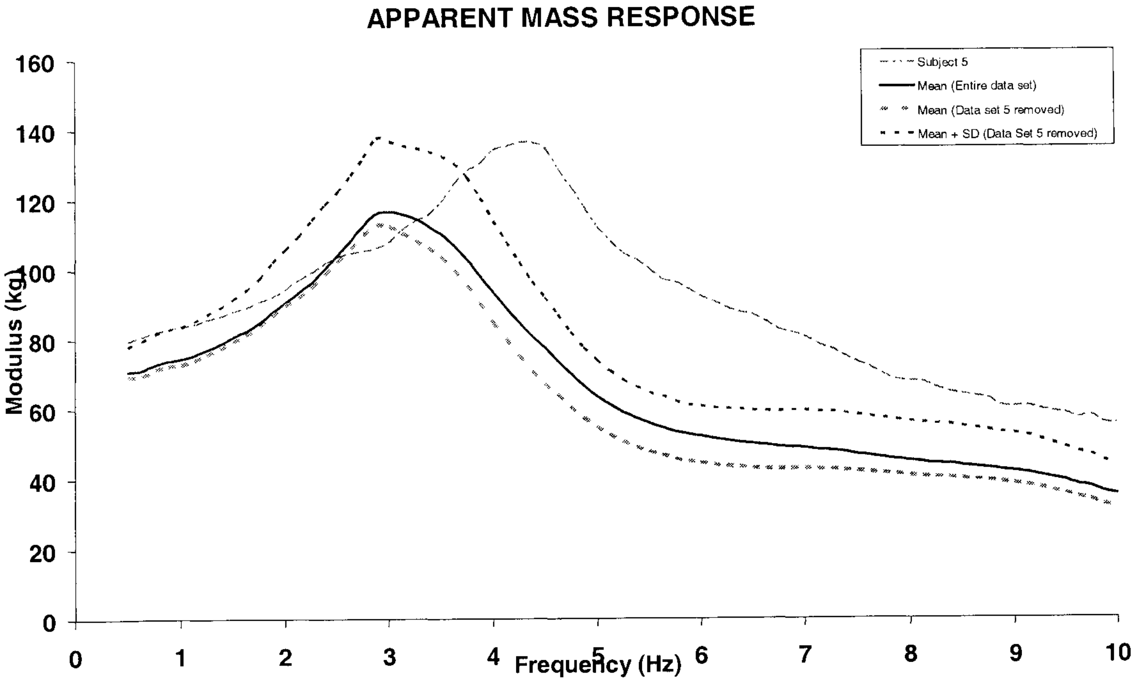


Figure 4.2 Comparison of mean apparent mass responses of the original data set and revised data set (outline, subject #5, removed)

The data acquired for all subjects are further analyzed to derive the coefficient of variation at each frequency and test condition, as a measure of relative dispersion of the data (expressed as a percentage). Table 4.1 summarizes the standard deviation and CV derived from the data sets attained for 7 subjects (6 for lateral excitation) corresponding to each axis and type of vibration. The results are present for the data attained for the seat pan and backrest driving points, and different back support conditions. Table 4.2 summarizes the same results for the data when the set for subject number 5 is removed. The peak standard deviation denotes the maximum value in the 0.25-10.0 Hz frequency range, while the CV value corresponds to the same frequency. From the tables, it is clear that the scatter of the data for trials with supported back is higher than the spread for those performed without contact at the back support interface, for fore-and-aft excitation, irrespective of the type and magnitude of the input. Removal of the perceived outliner data set (subject number 5) revealed lower degree of data dispersion only for trials involving back support, although the CV values improved only slightly. Moreover, the removal of the data set resulted in shift of the maximum deviation to alternate frequencies.

Table 4.1: Standard deviation and coefficient of variation for 7 subjects

Axis	Type of vibration	Vibration level (m/s^2)	Peak standard deviation			Coefficient of variation (%)		
			Seat pan		Back support	At seat pan		Back support
			No backrest	With backrest		No backrest	With backrest	
x	White Noise	0.25	15.5403	54.3603	12.8407	19.74	63.40	24.27
		0.50	13.7753	51.8103	15.6237	18.06	71.32	31.52
		1.00	16.3078	40.4894	15.0633	21.49	57.63	26.12
	Sine Sweep	1.00	16.4356	39.8595	12.3548	24.03	69.86	24.32
		1.50	15.1514	43.8231	18.1591	21.96	61.04	31.47
		2.00	17.4029	39.2401	16.7737	26.06	56.35	27.93
y	White Noise	0.25	21.4870	31.6708	----	26.61	37.17	----
		0.50	18.8476	30.7194		24.75	41.05	
		0.75	18.8299	24.9815		37.05	34.34	
	Sine Sweep	1.00	20.6753	21.7648		30.46	31.58	
		1.50	21.4552	16.1103		33.50	25.02	
		2.00	17.5637	16.4561		34.42	20.22	

Table 4.2: Standard deviation and coefficient of variation for 6 subjects

Axis	Type of vibration	Vibration level (m/s^2)	Peak standard deviation			Coefficient of variation (%)		
			Seat pan		Back support	At seat pan		Back support
			No backrest	With backrest		No backrest	With backrest	
x	White Noise	0.25	14.1037	38.4777	11.7274	17.96	54.34	
		0.50	12.2152	40.8986	15.5315	24.42	64.98	
		1.00	17.4492	33.4687	15.9801	23.10	49.74	
	Sine Sweep	1.00	17.5890	27.7559	13.1242	26.02	40.27	22.29
		1.50	13.7502	30.9118	17.8414	19.60	44.28	32.71
		2.00	16.6965	23.0800	14.4320	24.78	30.44	25.84
y	White Noise	0.25	22.7544	27.7983	----	29.21	36.13	----
		0.50	20.3181	27.4724		27.59	38.69	
		0.75	19.4079	25.7622		45.31	35.66	
	Sine Sweep	1.00	20.9073	21.9773		39.81	33.79	
		1.50	21.4772	17.1918		35.19	19.98	
		2.00	16.4206	18.3082		30.06	22.69	

The results presented in Tables 4.1 and 4.2 suggest considerable intra-subject variability of the measured data. The peak value of the CV at the seat pan with no back support is in the order of 26% under fore-and aft (x) vibration and up to 37% under side-to-side (y) vibration. The order of these values is comparable to those reported in another study on the biodynamic responses under horizontal WBV [26]. The peak value of CV increase most significantly when a posture with back support is considered, which is most likely attributed to inconsistency in pressure imparted by the subjects on the backrest, and increased angular motion of the upper body. The peak values of CV approach 71% and 41%, respectively, under x and y-axis vibration. It should be noted that such data are not available in the published studies. The CV of the data acquired at the back support are also high, in the order of 32 % under x-axis motion.

Owing to minimal effect of the data due to subject number 5 on the overall CV, an analysis of variance is undertaken to further qualify this observation. The equality of variances assumption can be verified with the F (Fisher) test, which employs the F-statistic to analyze various statistical hypotheses about the mean (or means) of the distributions from which a sample or a set of samples have been drawn [135, 136]. The two-tailed F-test was performed at every discrete frequency in the 0.25-10.0 Hz frequency range, using α=0.025. The analysis revealed that the variation in the subject number 5 is statically significant in only two tests (from a total of 36 performed). Besides, only one was observed to be relevant in more than 5% of the total frequency range. In order to determine the total contribution of all subjects, the F-test was also performed for every single subject, eliminating only one subject data per test. The outcomes did not reveal any differences that could be significant during the process. The results of the study thus suggest that all data sets represent the process reasonably well, and should be included in further trend and objective analyses on the basis of the overall means.

4.3 MEAN APPARENT MASS RESPONSE

Once the differences associated with subjects and their possible repercussions on the important trends have been understood, different data sets need to be synthesized in a manner so as to identify important behaviours of the seated body under horizontal WBV. This data synthesis is accomplished by simple averaging of the data for all subjects exposed to the same experimental conditions. Owing to the considerable variability of the data concerning the vibration characteristics of the human body, the analyses are performed upon certain considerations and restrictions, summarized below:

1) The current data describing the random stimuli trials was calculated by averaging all recordings under the same conditions for each subject. This process revealed little differences, lower than the previously reported horizontal apparent mass responses [26]. However, this average could cover trials outside from the real conditions of this experiment. In fact, the first resonance had been modified in frequency and magnitude, the second resonance had been mainly affected in magnitude, and the third resonance had been principally altered in frequency. These resonances observed from the peak responses are discuses in section 4.4.

2) Averaging process for all data sets, which had been selected to characterize the human body response, could cause some peaks being less clear. Such a trend can be observed in many published studies on vertical WB biodynamics [10, 11, 15, 17, 29, 57, 64, 89, 90, 100, 129]. Indeed, the process of averaging the individual data to obtain a mean apparent mass, magnitude and phase, for one condition loses the individual response and masks the large range of inter-subject variability. To some extent, these losses could leave the final average transmissibility with few useful applications, as it is suggested by Paddan [64]. Other studies lost the precise location of specific peaks [34]. In fact, third resonance for most of the data synthesis diminished or even disappeared. This loss is also found in other

biodynamic analyses, in the same range [29]. On the other hand, if each special condition for single subject is taken into account, some over-estimation of the individual characteristics could be followed. To avoid this situation, analysis of data, principally using statistical analysis, had been used throughout this chapter. The results attained are compared with the few published data available under exposure to horizontal WBV, and the differences and similarity between them are discussed.

3) The characterization is effective only in the frequency range considered, namely 0.5-10.0 Hz.

4) In order to offset for the strong contribution due to anthropometric characteristics, the measured data at the seat pan are normalized with respect to the sitting weight, while the data acquired at the backrest are normalized with respect to the static body mass supported by the back support.

4.3.1 MEAN APPARENT MASS RESPONSE AND STANDARD DEVIATION

The synthesized representation of seated human body under horizontal vibration is computed from the central tendency of all data sets corresponding to a particular test condition, such as magnitude and axis of vibration, and seated posture. The mean magnitude and phase apparent mass responses, are computed by averaging the real and imaginary components at each frequency, as described in Eq (4.1). The resulting mean responses are considered to describe the general trends in the biodynamic responses of seated subjects exposed to horizontal vibration, and the role of magnitude and direction of vibration, and back support. However, there are some differences that need to be highlighted. Comparisons of the mean response with the individuals response for the back support posture and exposed to fore-and-aft random vibration showed peak responses at low frequency (1.5 Hz -2 Hz) for 5 subjects under at least 2 lower magnitudes of stimuli, whereas the mean for these stimuli revealed peak response only for the lowest excitation level. Under no back support posture, low magnitude sweep sine excitation induced an additional peak response between the first and second peaks, while a change in the slope of the response was observed around the same frequency under random excitations. The response to lateral motion in the presence of the backrest support appeared to be quite different. The mean for trials with back support showed only one peak below 2.5 Hz, whereas the individual tendency for most of the subjects showed two peaks in the same range. The trends suggest that the first peak correspond to the principal resonance under low-level excitation, while the second peak is more predominant under high magnitude excitation. Both frequencies, however, occur in the close proximity of one another, which causes the mean response to emphasize the first resonance peak response only. The data attained for only two subjects revealed higher peak response at the second frequency. The results, in general, suggest non-linear behaviour of the biological system. Under random excitation, the frequency of predominant responses decreases with increasing magnitude of excitation. This trend suggests softening effect of the body under higher motion, and has been reported in many studies on vertical biodynamics [13, 15, 16, 71, 21, 114]. The swept harmonic excitations tend to emphasize additional peaks in the response, which may suggest the presence of other modes.

4.4 FACTOR INFLUENCING MEAN MAGNITUDE OF APPARENT MASS BIODYNAMIC RESPONSE

Apart from the differences in subject's characteristics, the postural changes and nature of vibration (magnitude and type) are expected to be the major factors influencing the measured biodynamic responses [22-29, 65, 79]. Considering that the present study follows the procedures outlined in the reported studies, the results are expected to show reasonable agreements with the reported data to an extent. The experimental conditions, however, differ in view of the posture and nature of excitations considered. Moreover, differences may also exist due to variations in the anthropometric characteristics of the subjects. The results presented in the following sections are discussed in view of their agreements with the reported results under similar conditions and the effects of various experimental conditions.

It is also essential to describe a few observations made during the experiments, which may not be interpretable from the objective measurements. At frequencies below 1 Hz, relatively high displacement of the base motion tends to cause the body to sway, which is resisted by the muscular action, and support from the seat to maintain a fairly stable position. The subjects also tend to pose higher pressure on the feet support to maintain a stable sitting posture. In the 1-3 Hz frequency range, it is difficult to stabilize the upper body and discomfort sensation of vibration tends to be the greatest. With increasing frequency, the transmission of horizontal vibration to the upper body tends to decrease resulting in more stable upper body posture. A backrest interface in general serves to support and stiffen the upper body [27]. At low frequencies, a backrest can help stabilize and even provide some restraint to the upper body motion and reduce the effects of motion. At higher frequencies, more likely in the 3-6 Hz frequency range, a backrest serves as the prime source of vibration transmitted to the upper body and it may greatly increase the effects of vibration, becoming a significant source of discomfort [26, 37, 41]. In contrast, lateral excitation with backrest has little influence in view of discomfort sensation.

Figures 4.3 and 4.4 illustrate mean APMS response (normalized magnitude and phase) derived from the data acquired at the seat pan under fore-and-aft stimuli (x-axis).

The data is normalized using the method described in section 3.4. The results show the mean responses corresponding to unsupported and supported back postures, and exposed to different types and levels of vibration. The APMS responses derived from the back support force corresponding to supported posture are illustrated in Figure 4.5 under different levels of x-axis excitations. The APMS responses derived under lateral stimuli are presented in Figures 4.6 and 4.7, respectively, for the back unsupported and supported postures. The mean results are discussed to highlight the trends observed under different postures and excitation conditions. It should be noted that the measurement of the force response of the seated human body imposed on the backrest along the y-direction of motion is not attempted.

The mean responses reveal peaks corresponding to different frequencies under varying postural support condition, and type and magnitude of vibration, as evident from Figures 4.3 to 4.7. It is evident that the effect of body mass can be more or less eliminated through normalization of the magnitude, specifically in the low frequency range. The results attained from the measured data at the seat pan under x-axis excitation and not back support posture reveal peak magnitude response near 0.7 Hz and 1.0 Hz under swept sine and random excitations, respectively. The magnitude response tends to be higher under random excitations. The magnitude responses also show peaks in the 2.375-2.75 Hz range and near 5.25 Hz. The magnitudes of those peaks, however, are considerably small, compared to the first peak magnitude, in the order of 40-60% for swept sine and of 50-70% for random. Both the magnitude and phase responses show definite effects of excitation type and magnitude, although the effect on phase is relatively small.

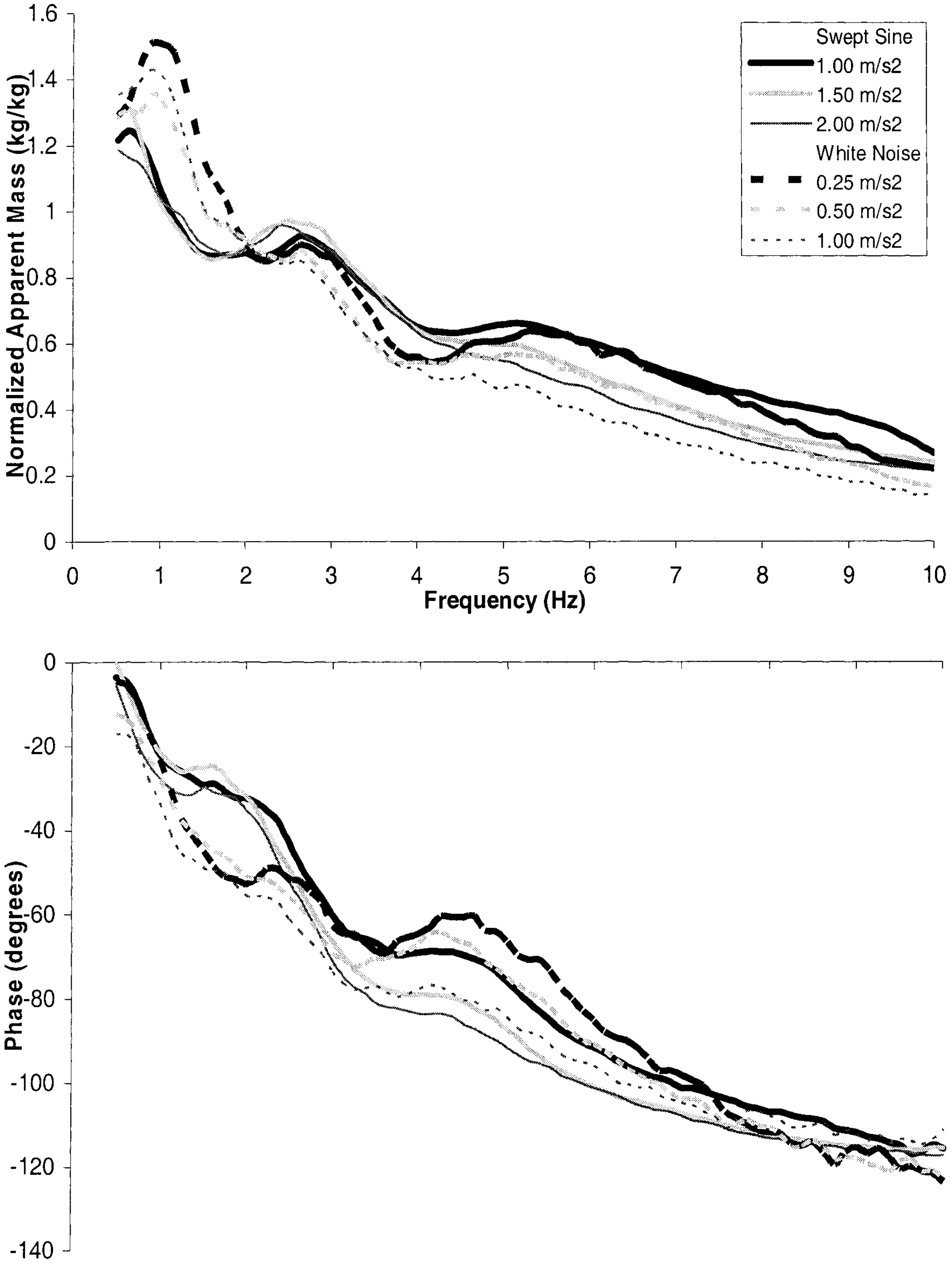


Figure 4.3: APMS response to fore-and-aft stimuli with unsupported back measured at the seat pan.

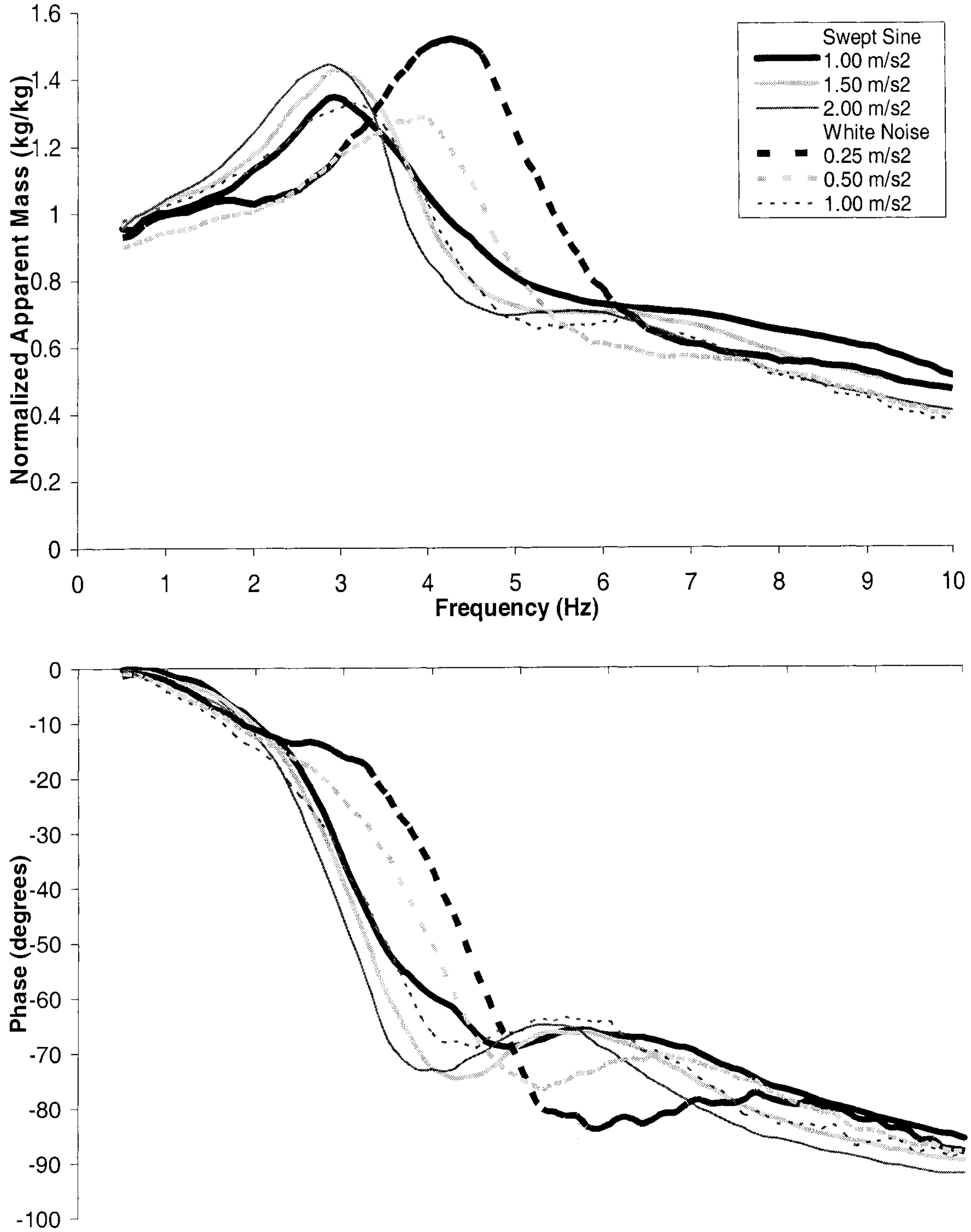


Figure 4.4: APMS response to fore-and-aft stimuli with supported back measured at the seat pan

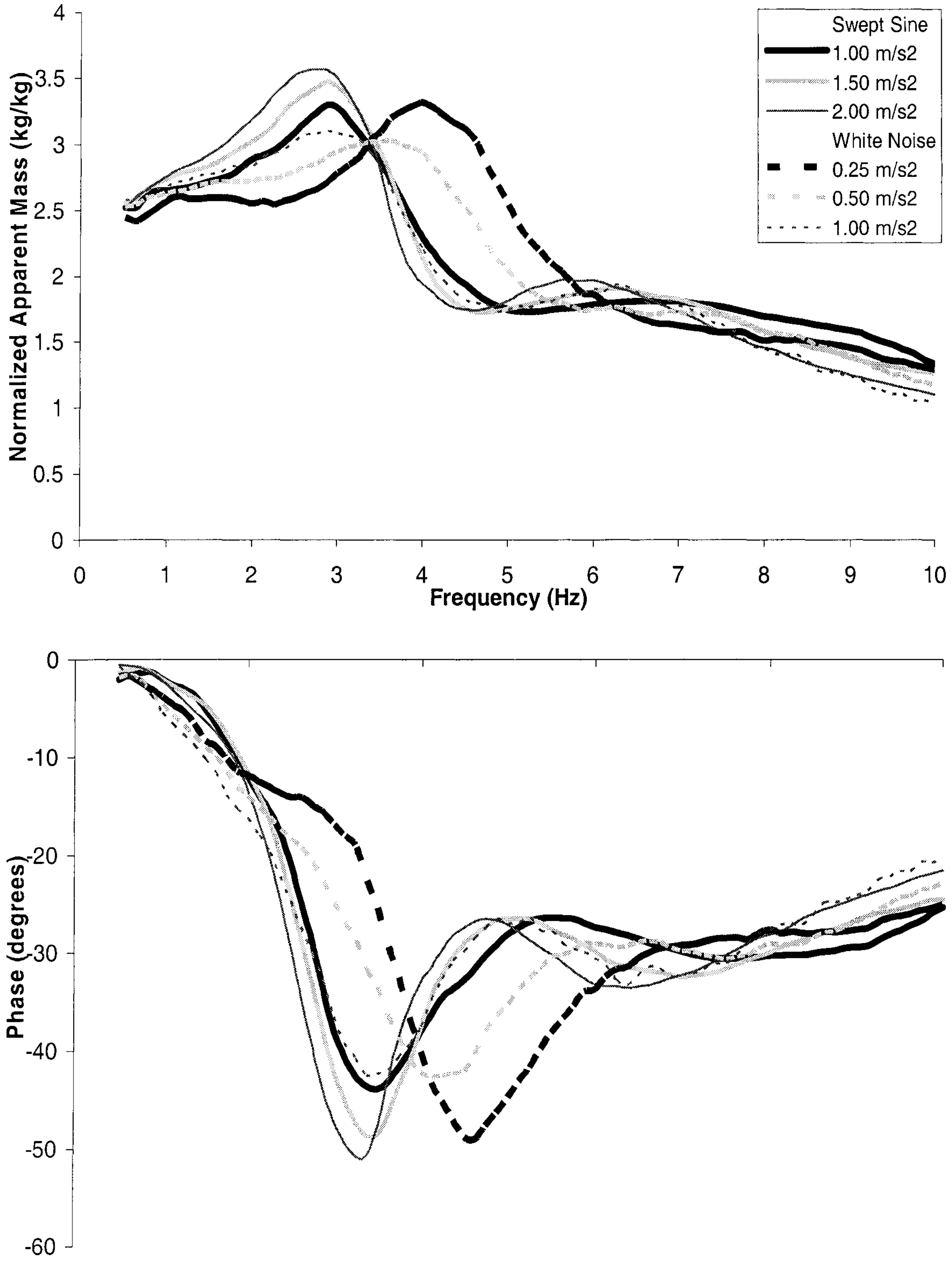


Figure 4.5: APMS response to fore-and-aft stimuli measured at the back support.

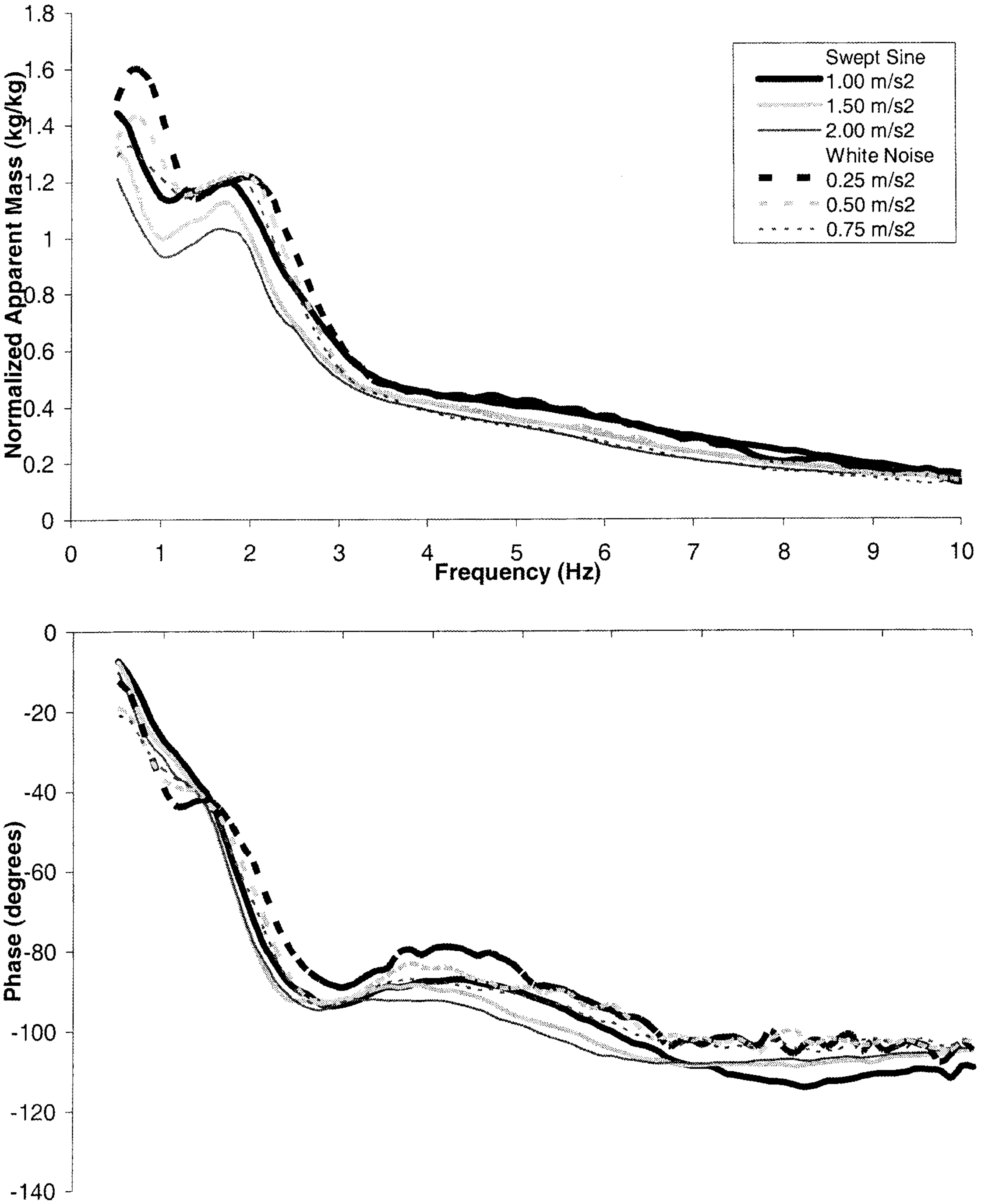


Figure 4.6: APMS response to lateral stimuli with unsupported back measured at the seat pan.

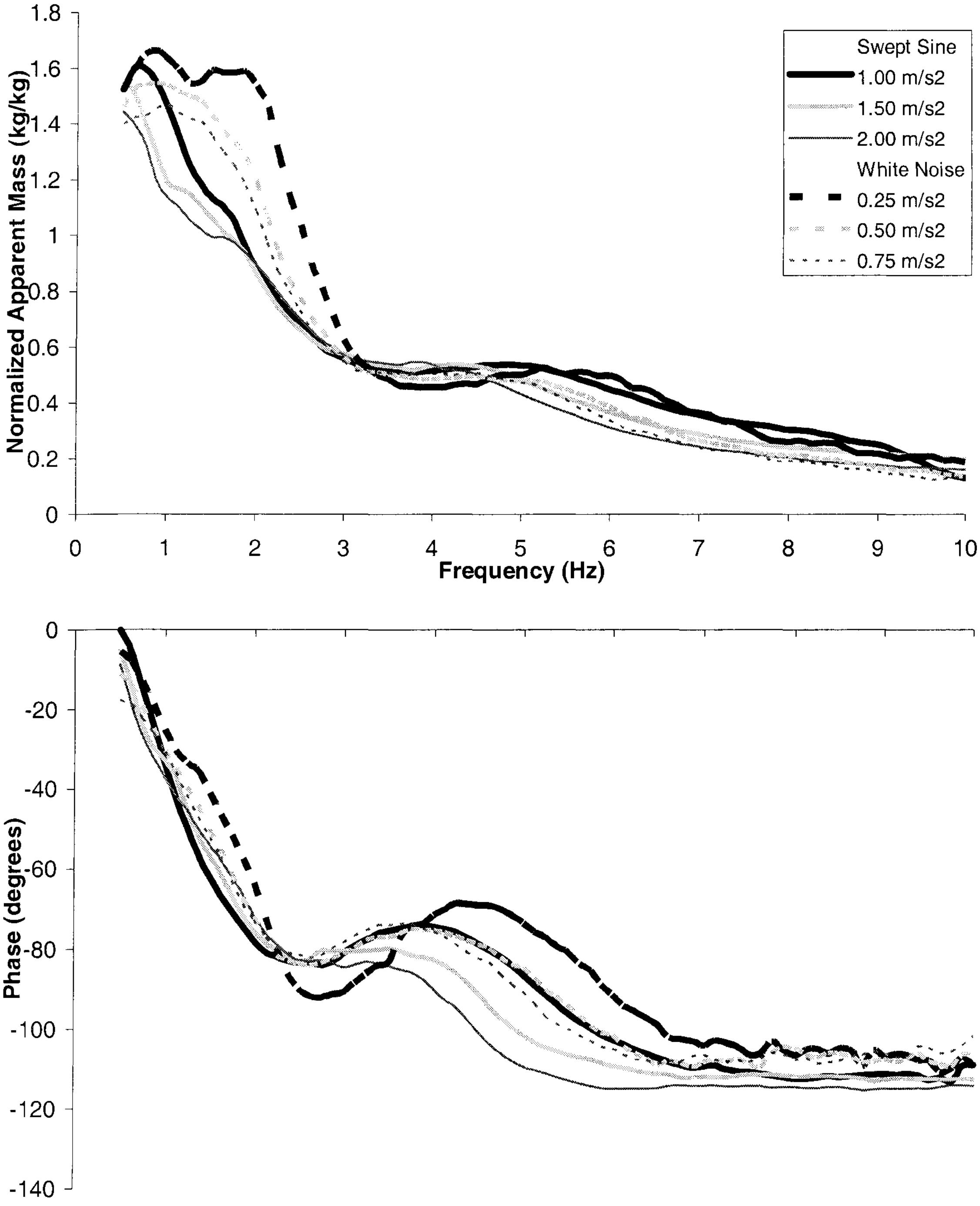


Figure 4.7: APMS response to lateral stimuli with supported back measured at the seat pan.

The magnitude response attained with back supported posture (Figure 4.4) is significantly different, when compared with no-back support condition (Figure 4.3). The results show predominant responses near 3 Hz and in the 3.125-4.25 Hz range for the swept sine and random excitations, respectively. The frequency of predominant response with back support is also comparable to that reported in a single available study by Fairley et al. [22]. The effects of the type and magnitude of vibration on the APMS magnitude and phase are far more significant for this posture. A secondary peak is also observed near 6.25 Hz under low magnitude excitations. The APMS responses derived from the force measured at the back support also reveal similar trends (Figure 4.5) while the primary peak responses occur at slightly lower frequencies, near 2.875 and 2.75-4.0 Hz range under swept sine and random excitation. A secondary peak of much lower magnitude is also evident in the 5.75 to 7.25 Hz range under both types of excitations. It should be noted that the data acquired at the back support have not been reported elsewhere.

The results presented in figures 4.3-4.5 under x-axis vibration clearly suggest strong influence of the back support conditions. This effect, however, is not as significant under side-to-side motion (Figures 4.6 and 4.7). The mean APMS magnitude response under no back support and y-axis excitations reveals peak magnitudes at frequencies near or below 0.75 Hz and in the 1.625-2.125 Hz range. The magnitude responses diminish rapidly at frequencies above 2 Hz. The corresponding mean phase responses show only little effect of type and magnitude of excitation. The mean magnitude responses attained with back support posture reveal primary peak response at frequencies below 1.0 Hz, while a secondary important peak is also evident near 2 Hz only under low magnitude random excitation (0.25 m/s^2 rms). A lower peak in the magnitude response can also be observed in the 4-6 Hz range, as observer for the x-axis excitation. The effect of type and magnitude of vibration on the phase response is negligible under not back support condition, while some effect is notable in the 3.5 to 6.5 Hz under back support.

4.4.1 INFLUENCE OF MAGNITUDE AND TYPE OF VIBRATION EXCITATION

The reported studies on horizontal biodynamic responses have invariably suggested strong effect of the excitation amplitude [22, 24, 26, 29]. Other studies on the vertical biodynamic responses, however, suggest relatively small influence of the vertical excitation magnitudes [1, 10, 11, 13, 17, 18, 136], and thereby nearly linear behaviour of the biological system. The variations in the apparent mass responses caused by variations in the intensity of fore-and-aft and side-to-side motions suggest non-linear behaviour of the biological system. More pronounced effect of excitation magnitude on the horizontal biodynamic response is partly attributable to relatively larger movements of the upper body, and involuntary movements of the subjects in stabilizing the sitting posture under horizontal motions, which was clearly observed during the experiments. The variations in the vibration magnitude tend to affect both the peak magnitudes and the corresponding frequencies that are associated with resonance modes of the biological system.

Under exposure to x-axis motion, while seated without a back support, the results show only little effect of the excitation magnitude and type on the phase response. The magnitudes at frequencies above 4 Hz, however, tend to be lower under higher magnitudes of sinusoidal excitation (Figure 4.3), while seated with no back support. The same trend is also evident under random excitation. A clear trend with respect to the excitation magnitude on the primary peak response below 1 Hz, however, is not evident. This is most likely attributed to involuntary actions of the subjects to stabilize their posture under high magnitudes of upper body motion, specifically at low frequencies of sinusoidal motion. Sitting with back support causes slightly higher peak magnitude under a higher magnitude of sinusoidal excitation, while only minimal change in the corresponding frequency is observed. The magnitude responses attained under random excitations, however, show strong influence of the excitation magnitude. The peak magnitude tends to decrease considerably as the magnitude of excitation increases from 0.25 m/s^2 to 0.5 m/s^2. Lower magnitude of random excitation (0.25 m/s^2) yields significantly higher magnitude response at 4.5 Hz. The frequency corresponding to the peak magnitude decreases significantly to 4 Hz and 3.25 Hz under 0.5 and 1.0 m/s^2 excitation, respectively. The results suggest strong softening effect of the body, which has also been reported in published studies under vertical and horizontal vibration [13, 15-17, 21, 114]. This trend, however, is not clearly evident under swept sinusoidal excitations. This is most likely attributed to relatively higher magnitudes of sinusoidal excitation used in the study. The overall rms acceleration due to swept sine excitations of 1.0, 1.5 and 2.0 m/s^2 peak acceleration were computed as 0.57, 0.95 and 1.35 m/s^2, respectively. The magnitude responses under sinusoidal excitation are thus closer to that attained under 1.0 m/s^2 random excitation. This trend is also evident in the phase response.

Apart from the differences in the magnitudes of sinusoidal and random excitations, the responses reflect different perception of subjects to deterministic and random excitation. Under sinusoidal excitation, high displacement amplitudes associated with low frequencies persist for a period of time and are well perceived by the subject.

The subjects thus react to stabilize the sitting posture by varying the feet and abdominal forces, stiffening the upper body in the low frequency range. The random excitations, however, do not provide such a perception for the seated subjects, and could thus yield different biodynamic responses. Similar trends are also evident from the APMS magnitude derived from the force measure at the backrest (Figure 4.5).

The mean APMS response of subjects seated with no back support and exposed to lateral sinusoidal excitations reveals somewhat opposite trends. A higher magnitude of excitation generally yields lower APMS in the entire frequency range for both postures, while the effect is more evident at lower frequencies. The effect of excitation magnitude on the APMS response with back support, however, is relatively small. The mean APMS responses of seated subjects exposed to horizontal vibration show significant effect of type of vibration. From Figures 4.3 to 4.7, it is apparent that responses under broad-band random excitation differ from those attained under swept harmonic excitations. This behaviour together with the trends observed under different excitation magnitudes suggest that the biological systems behaviour is non-linear.

It is known that the whole-body vibration environment of relevant work places is random in nature. The reported studies on the horizontal biodynamics have been applied discrete sinusoidal, swept sine and random excitation [22, 24, 26-28, 32]. Differences in response characteristics could be under different types of excitations, even with the same level of stimuli. This behaviour is partly attributed to higher perception of subjects of a repeated sinusoidal motion, which encourages variations in the body support. Mansfield [26] stated that the magnitude of sinusoidal motion cannot be directly compared to a similar magnitude of random motion, even though both types yield similar values of rms acceleration. For sinusoidal vibration, all energy occurs at a discrete frequency whereas for random vibration energy is spread over a wide band of frequencies. The magnitudes of the sinusoidal vibration, used in their earlier studies were effectively greater than those of the random vibration employed in [26].

In order to understand the effect of different type of vibration, the data attained under sinusoidal and random vibration with differences in the rms acceleration lower than 15% are compared. For fore-and-aft excitation, the responses to sine sweep signal of 1.5m/s^2 peak (rms value = 0.95 m/s^2) and the 1 m/s^2 rms white noise were considered. For lateral excitation, the response to only the sine sweep signal of 1.0m/s^2 peak (rms value = 0.575 m/s^2) is compared to that under 0.5 m/s^2 rms white noise excitation. Figures 4.8 and 4.9 show the comparisons of mean magnitude responses attained under selected sine and random excitation, and both postures. The results show very similar patterns under both excitations, irrespective of the posture and axis of vibration, while some differences in magnitude and correspondent are evident. The differences for the back supported posture, however, are relatively small under both axis of excitation, which further supports the observations made with regard to stabilizing tendencies of the subjects. As discussed earlier, the enhanced perception of repeated sinusoidal motions encourages the subjects to adjust their sitting posture, which is perhaps not needed when the back is supported. The magnitude of the resonant response near 3 Hz under x-axis sinusoidal motion is larger than that under random excitation. This behaviour is also observed for the backrest APMS responses.

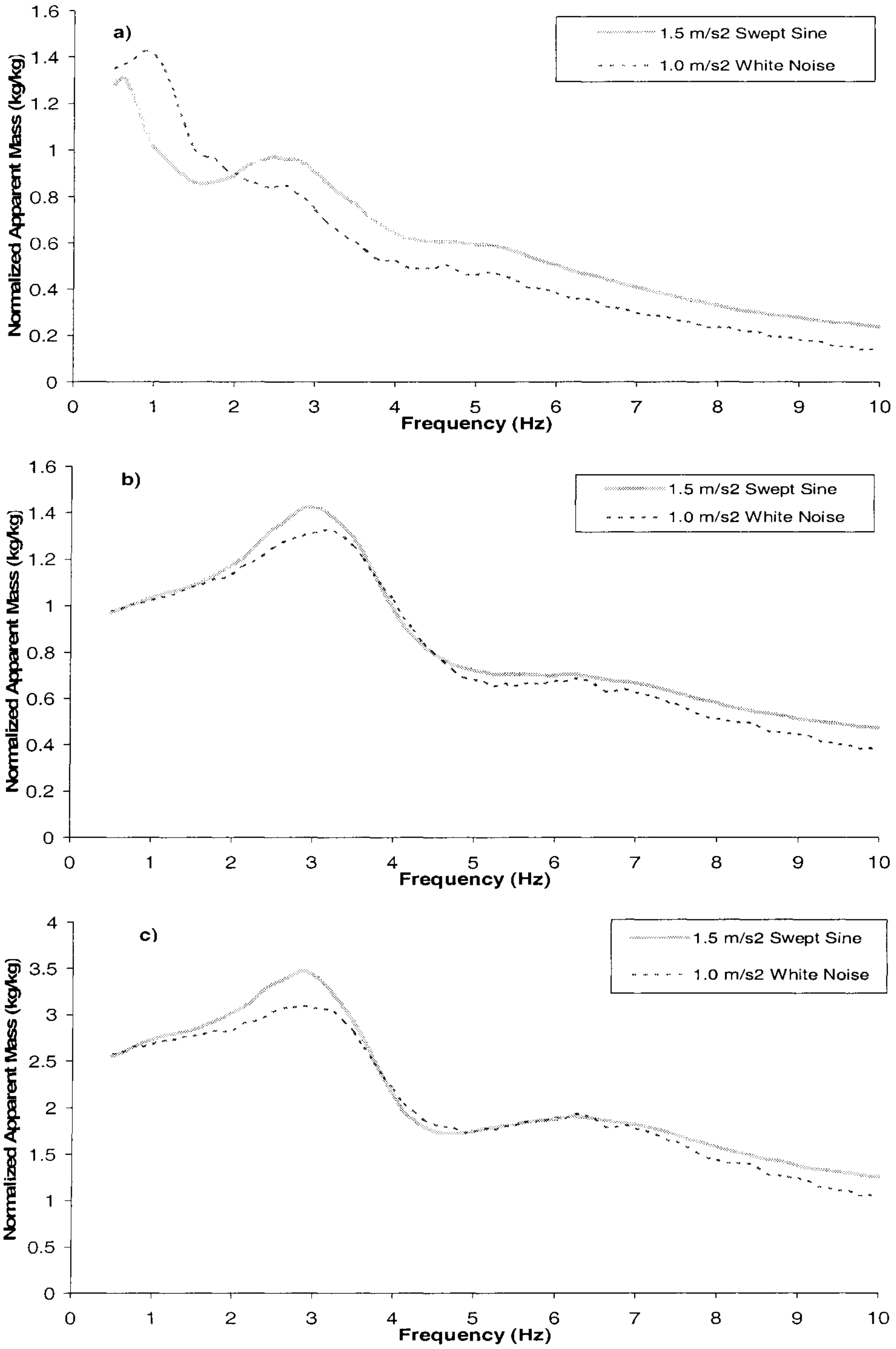


Figure 4.8: Comparison of mean APMS magnitude responses attained under comparable x-axis swept sine and random excitation: a) No back supported posture; b) Back supported posture; and c) Measured at the backrest interface.

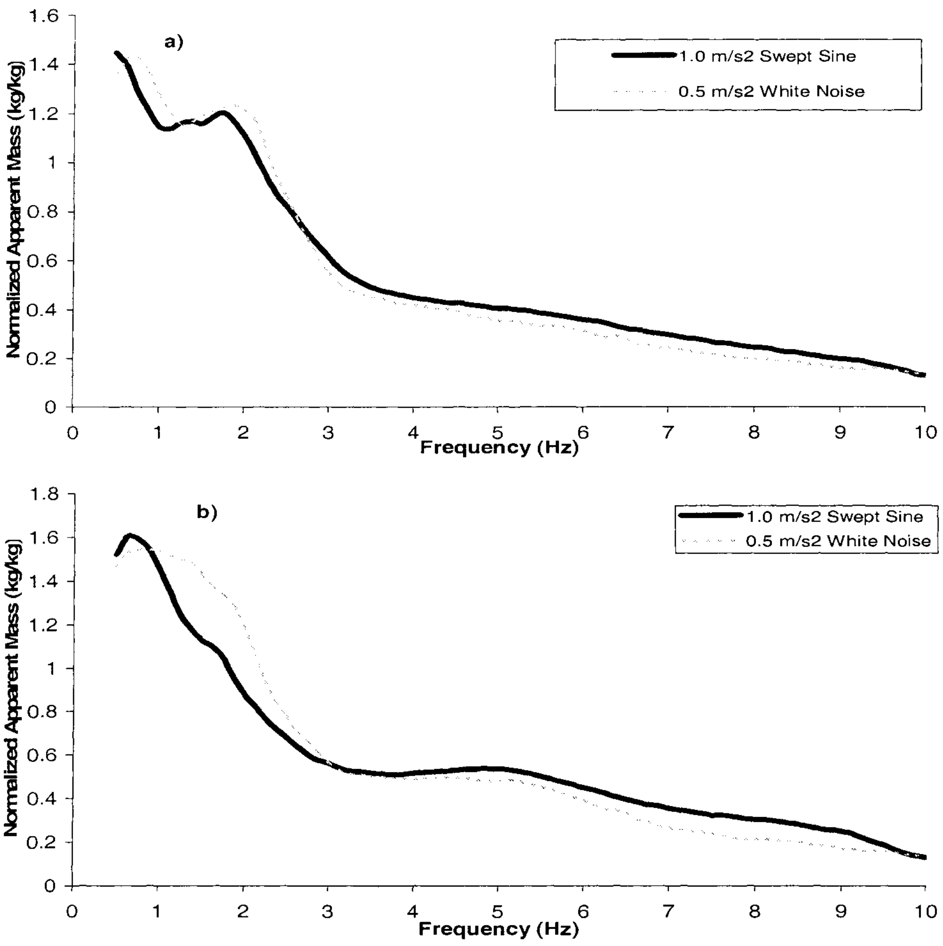


Figure 4.9: Comparison of mean APMS magnitude responses attained under comparable *y*-axis swept sine and random excitation: a) No back supported posture; and b) Back supported posture.

The mean responses with unsupported back exhibit relatively higher peak magnitude and corresponding frequency under *x*-axis random excitation at frequencies below 1 Hz. The responses under *y*-axis also show higher frequency of peak magnitude for random excitation, but slightly lower magnitude, while the differences are relatively small and occur at frequencies up to 2.5 Hz.

4.4.2 INFLUENCE OF SEATED POSTURE ON APMS RESPONSE

A number of studies performed on the vertical biodynamic response characterization have demonstrated strong effect of postural variations related to back support conditions [10, 17, 129]. Only a single study, however, has considered the back support posture from measurement the APMS response to horizontal vibration [22]. Other studies on the transmission of seat-to-head motion have also shown strong influences of back support condition under both horizontal and vertical vibration [27, 29, 35, 100, 129]. The postural effects may be attributed to three factors: i) the human body is subject of multidirectional vibration when an inclined backrest is used, in conjunction with multiple driving point; ii) a backrest offers a restraint for the upper body; and iii) the effective seated mass may vary with the back support posture when compared to that observed under unsupported sitting.

Figures 4.10 and 4.11 present comparisons of mean magnitude and phase responses attained for the two postures and x-axis sinusoidal and random excitations, respectively. The results show significant effect of the posture on the magnitude and phase responses. The mean magnitude response under back supported postures is considerably higher than that for the unsupported back in the vast majority of the frequency range (above 1 Hz for swept sine and above 1.625 for random). The phase responses for the supported back are considerably lower for both excitations. The unsupported back posture yields higher response at frequencies below 1.25 Hz and 1.5 Hz, respectively, for the swept sine and random excitations. The results exhibit distinctly different resonant behaviours of the seated body under two postures. The unsupported back yields primary resonance in the 0.625-0.875 Hz range, which is mostly attributed to

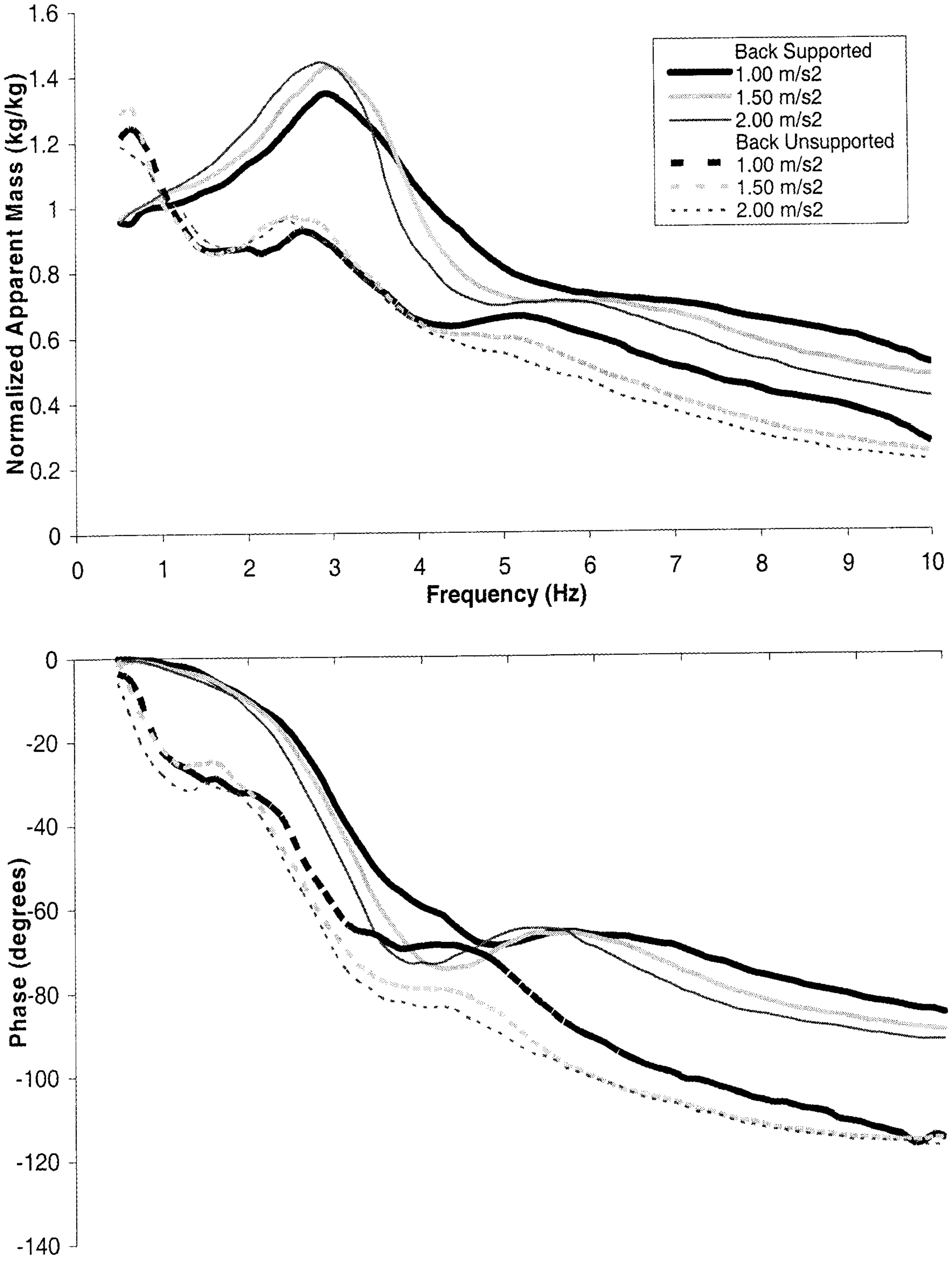


Figure 4.10: Comparison of mean APMS responses under back supported and unsupported postures and exposed to fore-and-aft swept sine stimuli.

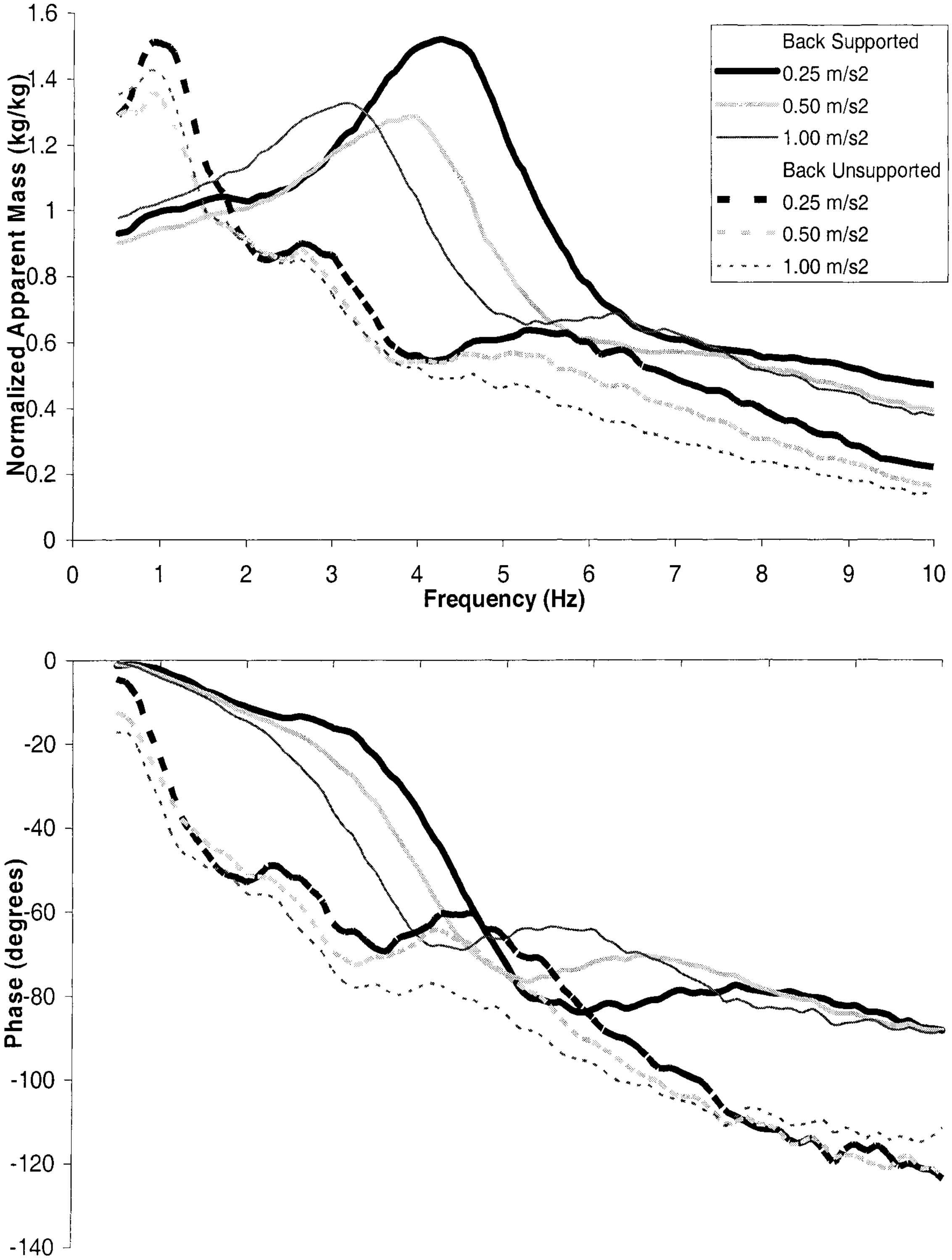


Figure 4.11: Comparison of mean APMS responses under back supported and unsupported postures and exposed to fore-and-aft white noise stimuli.

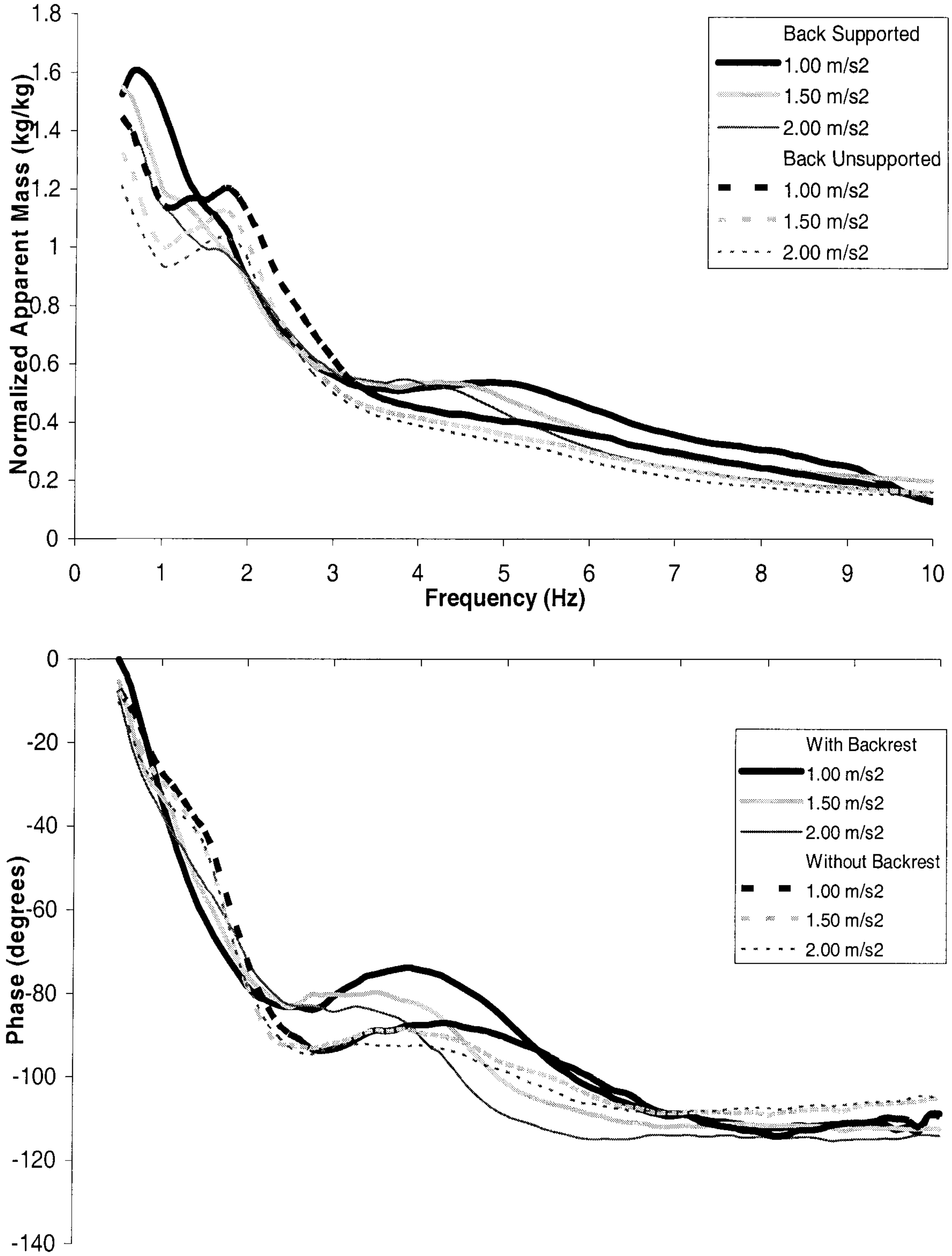


Figure 4.12: Comparison of mean APMS responses under back supported and unsupported postures and exposed to side-to-side swept sine stimuli.

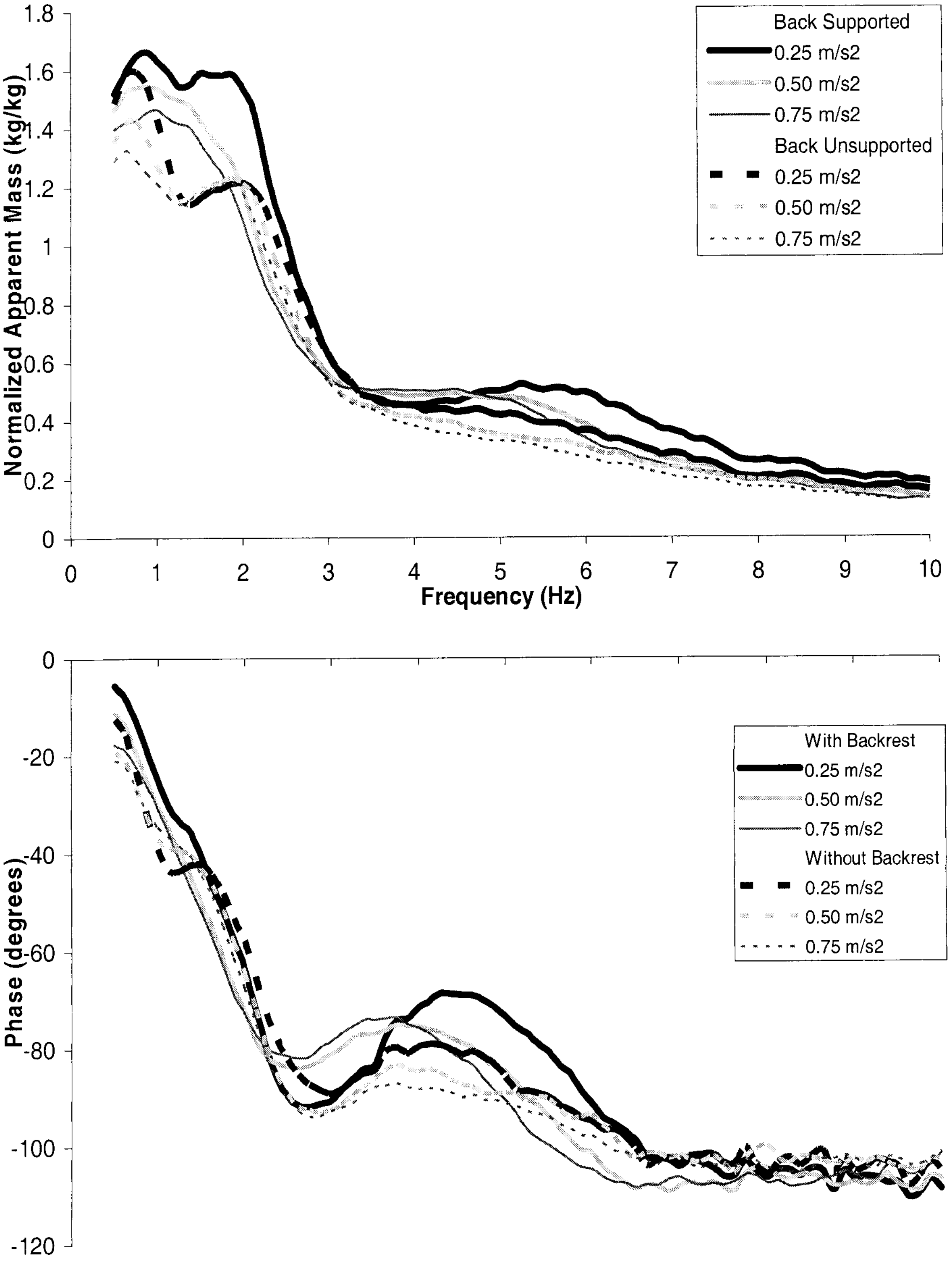


Figure 4.13: Comparison of mean APMS responses under back supported and unsupported postures and exposed to side-to-side white noise stimuli.

rotational motion of the unsupported upper body about the hip-joint. The posture with supported back yields primary resonance near 2.875 Hz and in the 3.125-4.25 Hz range, under swept sine and random excitations. Negligible phase response at frequencies below 2 Hz is also observed for this posture.

The results further show relatively small effects of the excitation magnitudes on the magnitude and phase responses under both postures. The effect of magnitude of excitation, however, are far more significant for the back supported posture, specifically under random excitations. This is again believed to be attributed to subjects' tendency to adapt for the well-perceived sinusoidal vibration. Higher fundamental frequency and involuntary softening behaviour under random vibration may also be attributed to this phenomenon. The subjects tend to utilize the back support more effectively under perceived sinusoidal motions and high magnitude random vibration, which is further evident from the responses measured at the backrest (Figure 4.5).

Unlike the x-axis response, the mean responses attained under lateral motions do not show significant influence of the back support posture, as illustrated in Figures 4.12 and 4.13. The responses of the back supported posture yield slightly higher magnitudes at frequencies below 1.5 to 2 Hz, while the responses of not supported subjects generally show slightly higher magnitudes in the 2-3 Hz range.

The reported studies have invariably concluded that the effect of back support is more distinct under horizontal direction than that observed under vertical motion [35, 126]. This study found that the greatest differences occur under fore-and-aft vibration. Considering that the interaction of the upper body with the backrest primarily occur along a direction orthogonal to the y-axis of vibration, the contributing due to the support tend to be relatively small under lateral motion. Such contribution may arise from sliding of the upper body along the y-axis. Furthermore, a backrest offers an effective restraint for the upper body under fore-and-aft motion. Excitation frequencies also play a central role in the backrest effect [27]. At low frequencies, a backrest can help stabilize and even provide some restrain to the upper body and reduce the effects of motion, which is evident from lower magnitude responses at lower frequencies. At higher frequencies, more likely in the 3-6 Hz frequency range, a backrest serves as a source of vibration transmitted to the upper body and it may greatly increase the effects of vibration, becoming a significant source of discomfort [26,29,37,41].

In vehicular application, the WBV is transmitted to the body from the seat pan, the backrest, the foot support and the hands in contact with the steering wheel. It has been reported that the effects of sitting contact with a back support could be annoying, or even influence the posture and the balance, which is related principally to the human response to low-frequency whole-body vibration [41, 43]. This motion in vehicles has been classified as an adverse health effect on the musculoskeletal system [46], aggravated by working conditions requiring the adoption of an uncomfortable posture [41]. The high seating position coupled with a short wheelbase tends to amplify the pitch motion of the vehicle and thus large magnitude fore-and aft motion at the seat. The resulting back slap type of motion at the backrest encourages the operator to detach from the backrest. In some cases, operators of specific vehicles have experienced a particular type of vibration and shock in which fore-and-aft motion of the backrest predominated [36]. Under an inclined posture, however, the subjects tend to make better use of the back support. Sitting posture with an inclined backrest affects the biodynamic response more singificantly, as evident from the reported data under vertical vibration [17, 29]. A backrest however can reduce loads on the lumbar spine by transmitting part of the gravity forces due to the head, arms and upper trunk to the backrest [43]. Moreover, the back support tends to reduce the electrical activities of the lower back and abdominal muscles [63, 88]. The backrest also serves to support and stiffen the response to the upper body in response to perceived vibration [27], which is evident from the results attained in this study.

The data reported in few studies suggest that the geometry of the seat may affect the resonant magnitudes and frequencies, when seated with the back support [17]. An inclined backrest tends to limit the backward motion of the upper body, while the forward motion could be reduced by the weight of the subject leaning against the back support. Consequently, adequate contact of the upper body with the backrest could be expected.

In the current experiment, larger variations in per cent body mass supported by the backrest were observed, as evident from high values of standard deviations reported in Tables 4.1 and 4.2. These variations were clearly evident for all subjects. The subjects revealed a tendency to shift their torso to maintain adequate contact with the seat pan and the backrest. High magnitudes of variation are also attributable to differences in sitting styles of individuals. While some subjects revealed sitting with erect upper body, the others showed slouched and relaxed upper body. The static body mass supported by the seat pan and the back support, however, were not measured in the current experiments in order to corroborate the observations.

The biological system exhibits a number of resonant modes when exposed to horizontal vibration [22, 26, 27], which are strongly influenced by the back support condition. The mean APMS responses attained under different types and magnitudes of horizontal vibration, and sitting posture, are examined to identify the predominant frequencies, which are believed to be associated with resonances of the seated body. The responses measured at the seat pan and the backrest are examined, and the frequencies are compared in an attempt to enhance an understanding of modes associated with upper body and the whole body. Figure 4.14 illustrates the range of frequencies corresponding to the peak magnitude responses observed in the seat pan and backrest APMS observed in the seat and backrest APMS under x-axis vibration. The magnitude response of the unsupported back posture reveals three peaks in the 0.625-0.875 Hz, 2.375-2.625 and near 5.5 Hz.

The first peak in the magnitude response body measured at the seat pan could be related to the fundamental natural frequency of the upper body [26], which is observed to occur in the 0.625-0.875 Hz frequency range for the unsupported back posture. The peak response within this frequency range tends to diminish, when a back support is introduced (Figure 4.4). Meanwhile, the measured response at the backrest shows a first peak of relative insignificant magnitude near 1 Hz. The frequencies corresponding to the second most significant peak, as observed from responses at the seat pan and the backrest, are comparable, and the results suggest that the peak magnitudes occur around 3 Hz for sinusoidal and in the 3-4.5 Hz range for random excitation, suggesting that these frequencies are most likely associated with the resonance of the upper body, as this peak is relatively small for no-back support posture. First and relatively low magnitude tends to lie within a broader range. The presence of this peak in the responses measured at the seat pan and the backrest.

4.4.3 INFLUENCE OF SUBJECTS CHARACTERISTICS

From all inherent subjects' characteristics influencing the apparent mass response of seated occupants, the body mass is recognized as the most significant factor for vertical biodynamics [17]. In a similar manner, the responses to horizontal vibration are also expected to be body mass-dependent. The reported studies on APMS responses to horizontal vibration have observed the strong influence of the body mass, while no attempts have been made to quantify its effect on the APMS magnitude and resultant frequencies. Owing to the upper body rotation about the pelvis under fore-and-aft motion, the upper body or the overall subject height may also affect the APMS response. The data attained for individual subjects are analyzed to derive the peak magnitudes and the corresponding frequencies, which are then evaluated in view of the individual body masses and standing heights. While the analyses are performed for both axis of vibration and postural variations, the detailed results are presented only for the back support posture and exposure to random excitations.

The analyses revealed that the APMS of seated body under fore-and-aft vibration is strongly influenced by the body weight, as is illustrated in Figure 4.14, which presents the variations in the peak magnitude and the corresponding frequency with the total body mass, when seated with supported back. The trends observed in the magnitude data suggest that the principal peak magnitude increases with increasing body mass. Even though considerable dispersion in the data is evident, the trend-lines suggest that peak apparent mass magnitude corresponding to the primary resonance generally between 2.875-4.25 Hz could be positively correlated with the body mass. This trend has also been observed in vertical APMS responses [17]. The values for the coefficient of

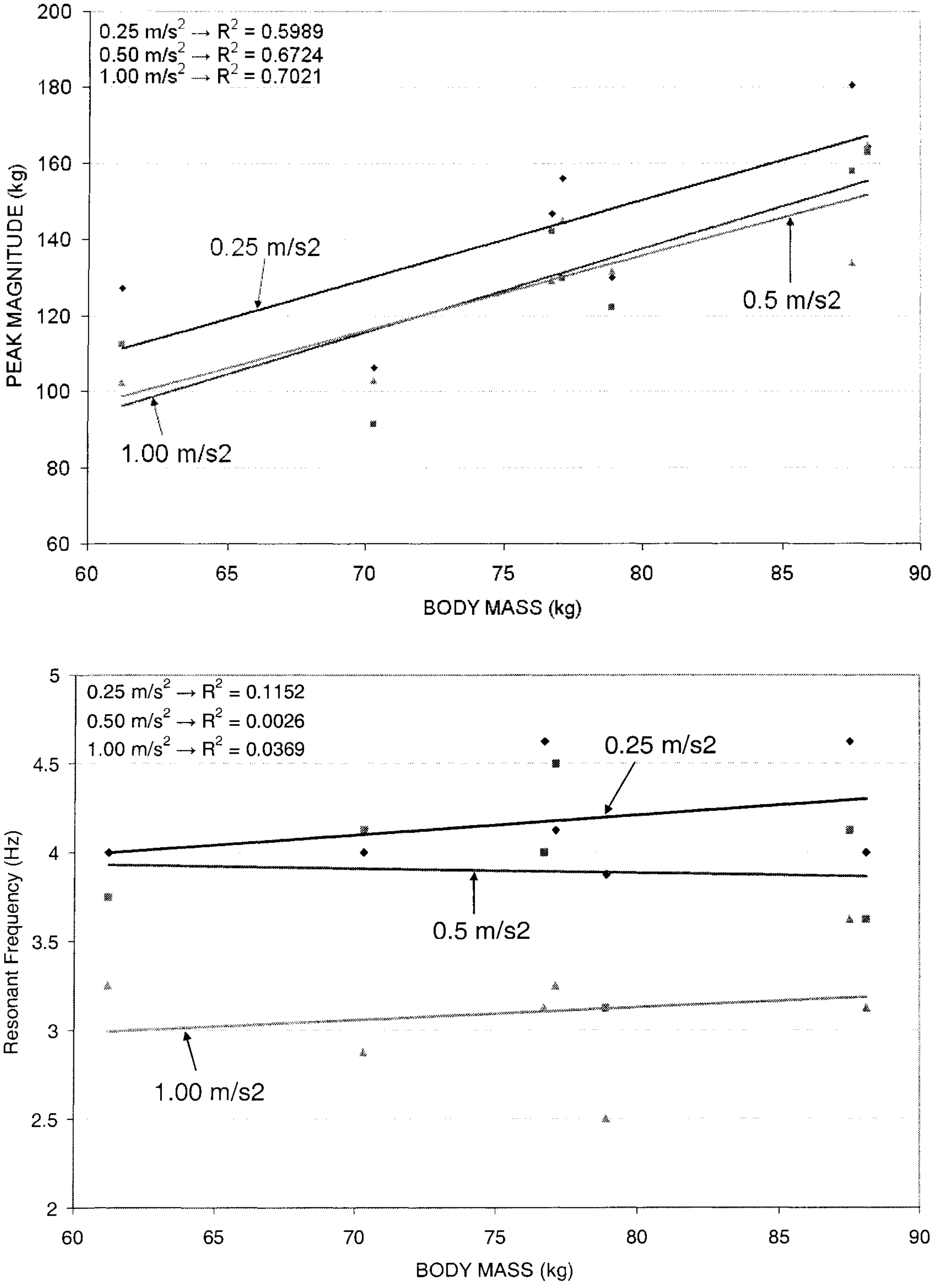


Figure 4.14: Dependence of peak APMS magnitude and corresponding frequency on the body mass when exposed to fore-and-aft random vibration with back support.

determination (r^2) range from 0.6 to 0.7 for different magnitudes of excitations (the minimum suggested under conventional criteria in order to be significant is 0.57). Higher r^2 values are attained under higher magnitudes of vibration. Considerably higher correlation, however, was obtained between the peak magnitude and the body mass, when exposed to sinusoidal vibration and seated with back support, as evident in Table 4.3. The r^2 values in excess of 0.9 are obtained for medium (1.5 m/s^2 peak or 0.95 m/s^2 rms) and high (2.0 m/s^2 peak or 1.35 m/s^2) magnitude sinusoidal excitations.

Table 4.3: Coefficients of determination (r^2) obtained for peak APMS magnitude with respect to the body mass under two different postures and axes of vibration.

Excitation Level	x-axis				y-axis			
	Backrest		No backrest		Backrest		No backrest	
	White Noise	Sine sweep	White Noise	Sine sweep	White Noise	Sine sweep	White Noise	Sine sweep
Low level	0.59894	0.63093	0.87822	<0.36	0.86450	0.83734	0.54522	0.62670
Medium level	0.67236	0.93541	0.80252		0.92624	0.15702	0.61807	0.77972
High level	0.70213	0.90300	0.64312		0.86979	0.48194	0.92789	0.56236

The absence of the back support promotes far more complex behaviour, specifically under sine excitations, which yields very poor correlation between the peak APMS magnitude and the body mass ($r^2 < 0.36$). It should be that the peak magnitudes for unsupported back corresponding to the principle resonance (0.625-0.875 Hz) alone are considered in the analysis. Reasonably good correlation, however, is observed for the unsupported back posture under random excitations (r^2 ranging from 0.64 to 0.88). Although the frequencies corresponding to the peak magnitudes tend to be different for different subjects, no particular trend was observed with the body mass, as illustrated in figure 4.14 for the back supported posture. Similar pattern was also observed for the unsupported back posture, irrespective of type and magnitude of excitation.

The analysis of the peak magnitudes and corresponding frequencies measured under *y*-axis also revealed comparable tendencies with the body mass (Figure 4.15). Reasonably good correlation between the peak magnitude and the body mass was obtained under random excitations for the both postures (r^2 values ranging from 0.55 to 0.93), as summarized in Table 4.3. Lower r^2 values were obtained under swept sine excitations and back supported posture, specifically under medium-high and high magnitudes of excitation. This poor correlation may be attributed to excessive sliding of the upper body with respect to the backrest at lower frequencies of excitation.

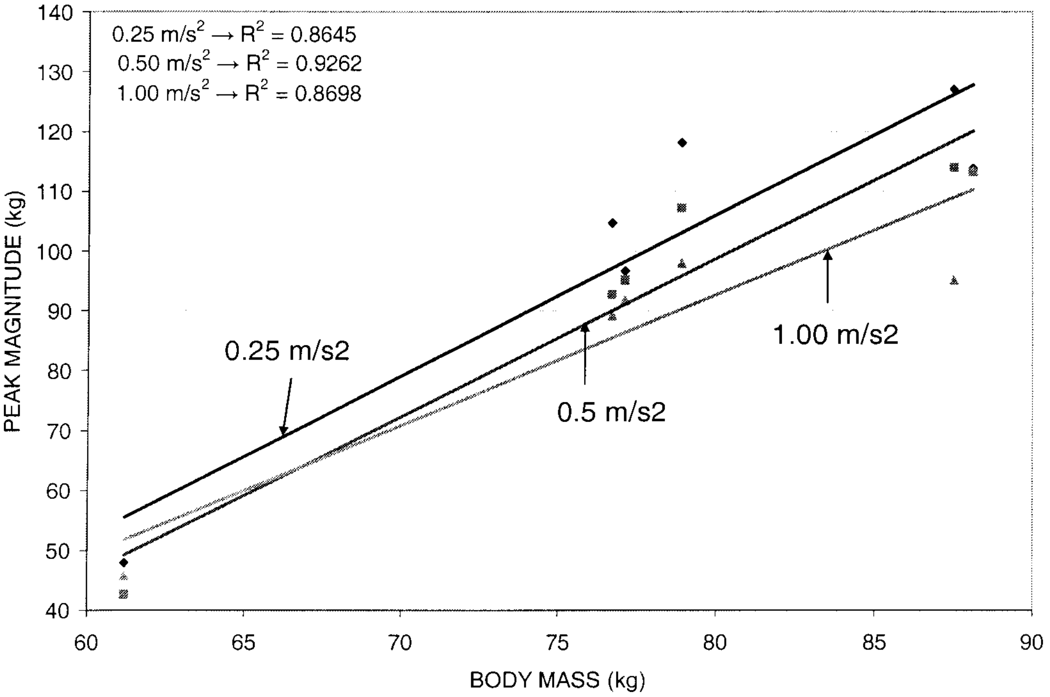


Figure 4.15: Dependence of peak APMS magnitude on the body mass when exposed to side-to-side random vibration with back support.

Figure 4.16 illustrates the variations in the peak magnitude and the corresponding frequency with the subjects' height, when seated with back support and exposed to random excitations. The results show poor correlation between the peak magnitude and the subjects' height, and between the principal resonant frequency and the height. Similar degree of correlation was also observed under the unsupported back posture, and *y*-axis of vibration. Significantly higher correlation, however, were observed between the peak magnitude and the body mass to height ratio, under both postures and axes of excitation. Figure 4.17 illustrates, as an example, the variations in the peak magnitudes with respect to the body mass to height ratio, when seated with back supported and exposed to three different levels of random excitation along the *y*-axis. The results generally suggest that the APMS magnitude response is more correlated with the total and the upper body mass rather than the body height.

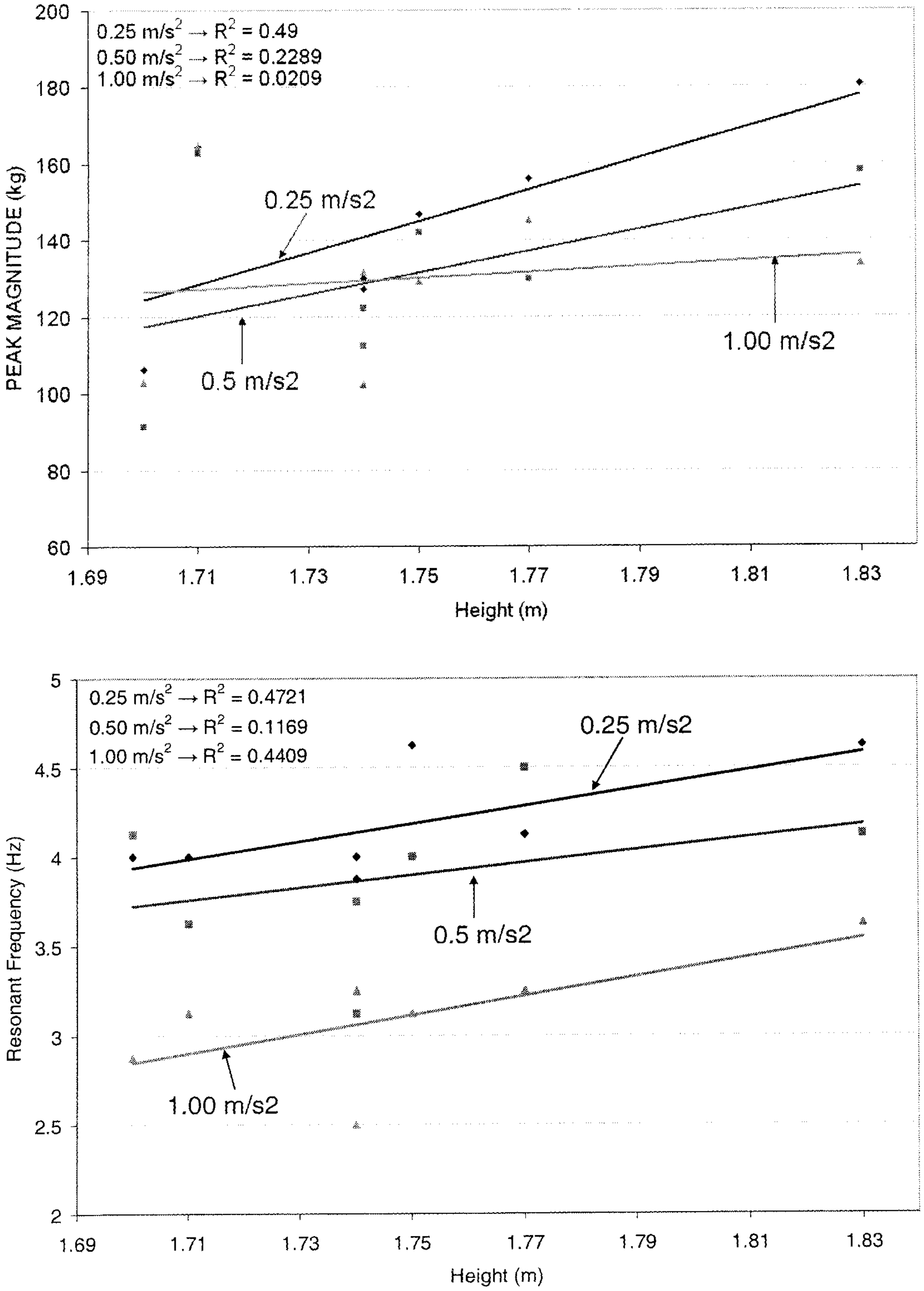


Figure 4.16: Dependence of peak APMS magnitude on the subject's height when exposed to fore-and-aft random vibration with back support

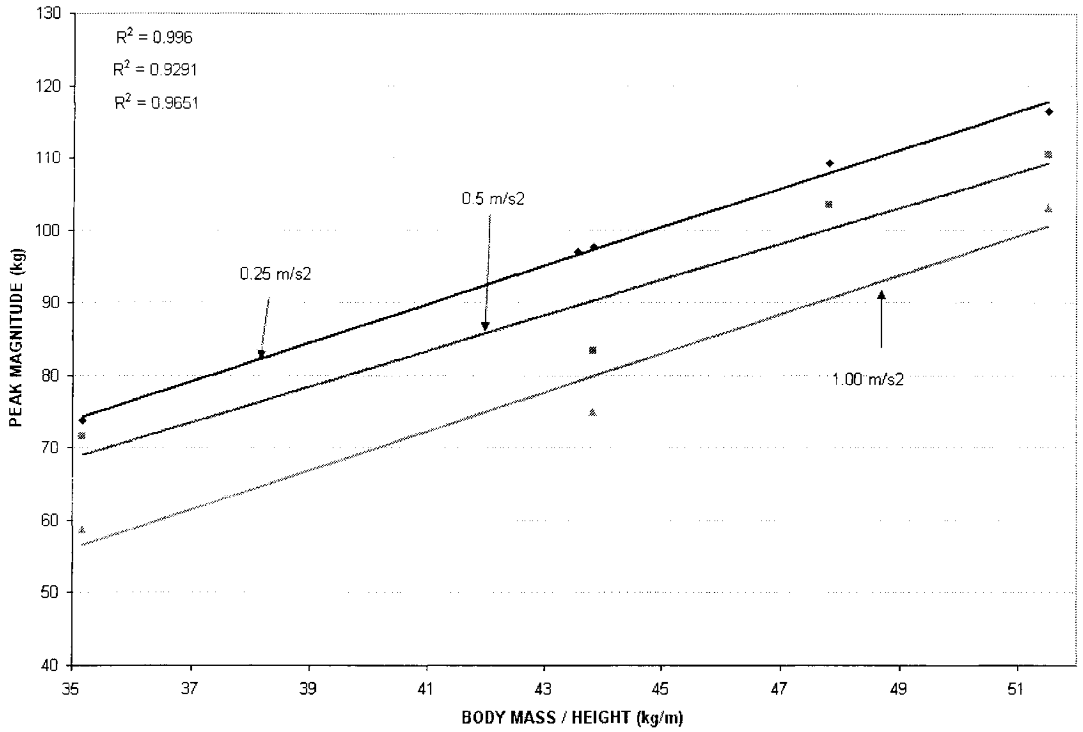


Figure 4.17: Dependence of peak APMS magnitude on the body mass to subjects' height ratio, when exposed to lateral random vibration and seated with back support.

4.5 COMPARISONS WITH REPORTED APMS DATA UNDER HORIZONTAL VIBRATION

As stated earlier, only a few studies have been reported the biodynamic responses of seated subjects exposed to horizontal vibration. These include two studies on the APMS, by Mansfield and Lundström [26], and Fairley and Griffin [22], a single study reports the DPMI [24], and a single study on the absorbed power by Holmlund and Lundström [25]. The experimental conditions employed in the reported studies [22, 24, 26] are thoroughly reviewed and compared with those considered in the present study. The comparisons are summarized in Table 4.4. All the three studies performed measurements under either random or sinusoidal motions at discrete frequencies along the x- and y-axes. Only one study, however, consider the back supported posture under a single level of vibration, while the backrest was oriented vertically [22]. The present study considers sitting postures with and without a backrest, while the backrest is inclined on an angle of 24^o with respect to a vertical axis, as it would apply to automotive seats. The seat pan in the present study is also inclined (13^o with respect to horizontal) as opposed to flat pans used in the reported studies. The mean mass and height of the test subjects in the studies were comparable. Moreover, the magnitudes of excitation used in all the studies fall within common ranges. Owing to the differences in the experimental conditions, the results attained in different reported studies tend to differ considerably, as reported in [26]. The results obtained in the present study are compared with the reported results, and differences and similarities among them are discussed below.

Table 4.4: Comparison of experimental Conditions with those employed in reported studies [22, 24, 26].

Authors	Fairley and Griffin [22]	Holmlund and Lundström [24]	Mansfield and Lundström [26]	Present Study
Year	1990	1998	1999	2003-2004
Measurement Objective	APMS under x- and y- axis motion	DPMI under x- and y- axis motion	APMS under x- and y- axis motion + 3 non-orthogonal	APMS under x- and y- axis motion
Sample size	8 Male	15 Males /15 Females	15 Males /15 Females	7 Males
Age (years) M,SD (min, max)	27.875, 4.612, (24, 38)	37, 11 (22, 59)	37, 14 / 39, 13	34.86, 9.62 (25, 50)
Height (m) M,SD (min, max)	1.79875, 0.085 (1.66, 1.93)	1.72, 0.07, (1.60, 1.88)	1.79, 0.07 / 1.65, 0.07	1.75, 0.04 (1.70, 1.83)
Weight (kg) M,SD (min, max)	71.875, 10.371(57, 85)	69, 10 (54, 93)	75.8, 9.3 / 62.0, 7.2	77.11, 9.41(61.2, 88.1)
Vibration Magnitude (posture)	0.5, 1.0, 2.0 m/s^{2*} (NB) 1.0 m/s^{2*} (WB)	0.25, 0.35, 0.5, 0.7, 1.0, 1.4 m/s^{2*} (NB)	0.25, 0.5 1.0 m/s^{2*} (NB) 0.38 m/s^{2*} (cte. either at x- or y- direction, NB)	Swept sine 1.0, 1.5, 2.0 $m/s^{2\dagger}$ (WB and NB) White noise 0.25, 0.5 m/s^{2*} (WB and NB) 1.0 m/s^{2*} (fore-and-aft) 0.75 m/s^{2*} (lateral)
Type of excitation	Random	Discrete sine	Random	Swept sine / random
Frequency range	0.25-20 Hz	1.13-80 Hz	1.25-20 Hz	0.25-10 Hz
Exposure time	128 s	20 sinusoidal cycles	60 s	512 s (sine); 125 s (random)
Trials per subject	4 / axis	12 /axis	4/axis; 12 non-orthogonal	12 /axis
Seat pan	Flat	Flat	Flat	Inclined (13°)
Backrest	Flat	Not used	Not used	Inclined (24°)
Sitting posture	upright	Upright (erect and relaxed)	upright	Upright and inclined
Feet	On the vibrator table	On the floor	----	On the vibrator table
Hands and arms	Rested in the lap	Rested on lap	Arms folded	Rested in the lap

* rms acceleration † peak acceleration NB unsupported Back WB supported back

It is common to conclude that human response to WBV is a very complex phenomenon, where the effects of different test conditions occur simultaneously in a coupled manner. One effect may thus promote the onset of another effect. During exposure to WBV, there are many different physiological, psychophysical and physical factors that may contribute to unique behaviour, such as individual susceptibility, body constitution and posture together with the frequency, direction, magnitude and duration of the vibration. Biodynamic responses measured using different measurement and excitation systems, and seat could also contribute to differences in the results. Even the response characteristics of human body must be measured under carefully controlled conditions, considerable differences are known to exist among the data reported by various investigators. Considering the availability of a relatively small datasets under horizontal vibration, no significant efforts have been made to identify the differences and/or similarities between the reported datasets. Such efforts, however, have been made for the vertical biodynamic responses to develop standardized values [129, 130]. Considerable differences among the reported data have been shown, although the datasets were selected corresponding to well-defined test conditions [129]. Despite these evident differences, the synthesis of the reported data has been considered to provide the range of values of the biodynamic response under defined test conditions.

In the present study, the resonant frequencies identified in the published studies are compared with the range of the frequencies observed from the measured data. The comparisons are performed for both postures and axis of vibration. The reported studies have identified three principal resonance responses under excitations along the horizontal direction (x- and y-), when there is not contact at back level between the upper body and the backrest [22, 26]. All of the three modes, however, are not identified by both studies. The study by Mansfield and Griffin [26] attempted the measurements in the 1.25-20 Hz frequency and not back support. The first mode observed in the 0.625-0.875 Hz was thus not identified in their study. The other study by Fairley and Griffin [22] did not reveal peak responses corresponding to the third mode (4.5-6 Hz range), which was attributed to relatively high magnitudes of excitation used in their study [26]. Since the majority of the available data apply only under for the unsupported back, the reported principal frequencies for this posture are compared with those observed in this study in Figures 4.18 and 4.19 for x- and y- axis, respectively. The figures show the mean frequencies reported in [22], and the range of frequencies reported in [26] and observed in the present study. It should be noted that the range are identified from the datasets obtained for individual subjects. The results generally show comparable frequencies corresponds to APMS response peaks. It is apparent that the present study could identify all of the three resonant modes that have been collectively identified [22, 26]. The comparisons show broader range of frequencies corresponding to the third peak in relation to those reported in [26] under both axis of vibration. This may be attributed to differences in subjects used in this study, and most of all the geometry of the seat used in the present study. The inclined pan of the seat made it difficult for the subjects to maintain a stable back-unsupported posture.

Figures 4.20 and 4.21 illustrate the comparison of the ranges of resonant frequencies observed for the back support posture in the present study with the mean values reported by Fairley and Griffin [22], under both axis of vibration. It should be noted that the reported study consider support with a vertical backrest and only one

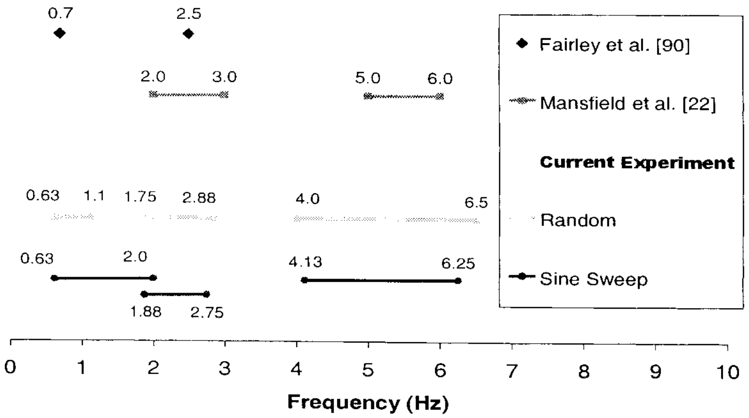


Figure 4.18: Comparison of observed principal frequencies with the reported frequencies (fore-and-aft axis, no back support)

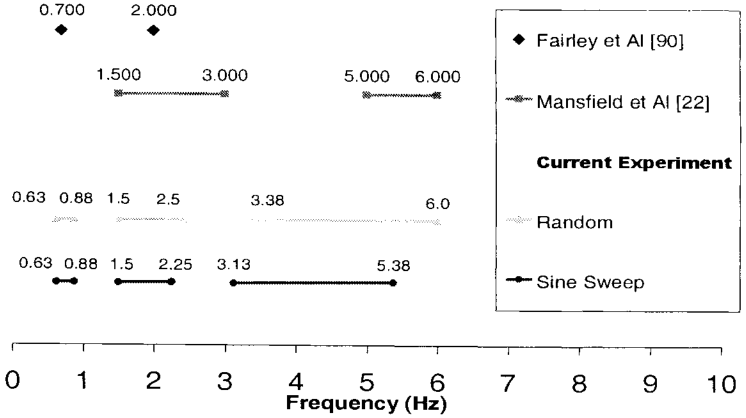


Figure 4.19: Comparison of observed principal frequencies with the reported frequencies (lateral axis, no back support)

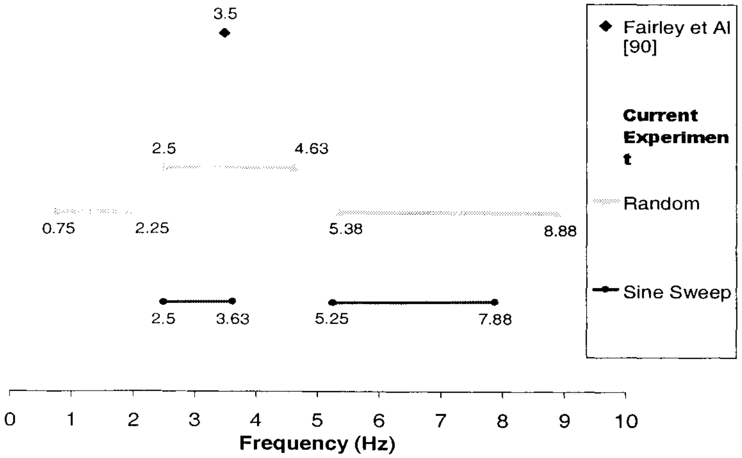


Figure 4.20: Comparison of observed principal frequencies with the reported frequencies (fore-and-aft axis, back supported)

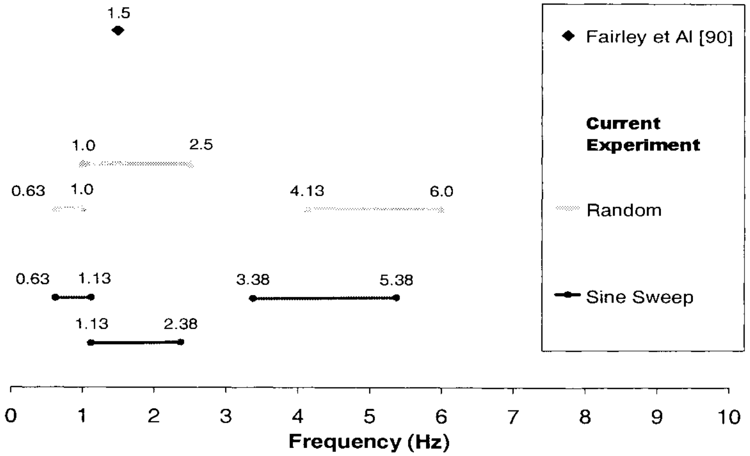


Figure 4.21: Comparison of observed principal frequencies with the reported frequencies (lateral axis, back supported)

magnitude of random vibration (1.0 m/s^2 rms acceleration). The reported study identified a single resonant frequency, while the current study could identify three modes as in the case of unsupported back posture. The magnitudes of the APMS response in the vicinity of the first resonant frequency (0.625-2.25), and the third resonant frequency (5.25-8.875), however, were observed to be very small under x-axis vibration. The predominant peak response occurred in the range of 2.5-4.625 Hz for the subjects considered. It is thus suspected that the reported study limited its identification on the basis of the predominant response at mean frequencies 3.5 Hz and 1.5 Hz under x- and y-axis of vibration, respectively. These mean frequencies fall within the ranges of frequencies corresponding to the predominant magnitude responses attained to this study.

The result shown in Figure 4.18 to 4.21 show reasonably good agreements with respect to the observed principal frequencies. Considerable differences, however, exist between the reported and measured APMS magnitudes, for all the test conditions considered. Figures 4.22 and 4.23 illustrate comparisons of the APMS magnitude resonances under 0.5 m/s^2 rms stimulus along x- and y-axis respectively, among four studies while seated with unsupported back. All four studies show a peak in the apparent mass at about 2.5 Hz in the x-direction and at about 2 Hz in the y-direction, with similar magnitude. The current study coincides with that developed by Fairley and Griffin [22] denoting a peak at lower frequencies (below 1 Hz). Whereas the corresponding frequency for this peak coincides for lateral direction, the current findings found the peak a slightly higher frequency for responses when exposed to fore-and-aft vibration. Besides, the magnitudes for this peak are slightly higher, irrespective of the input direction. From the reported studies, only Mansfield et al. [26] includes an additional peak in the apparent

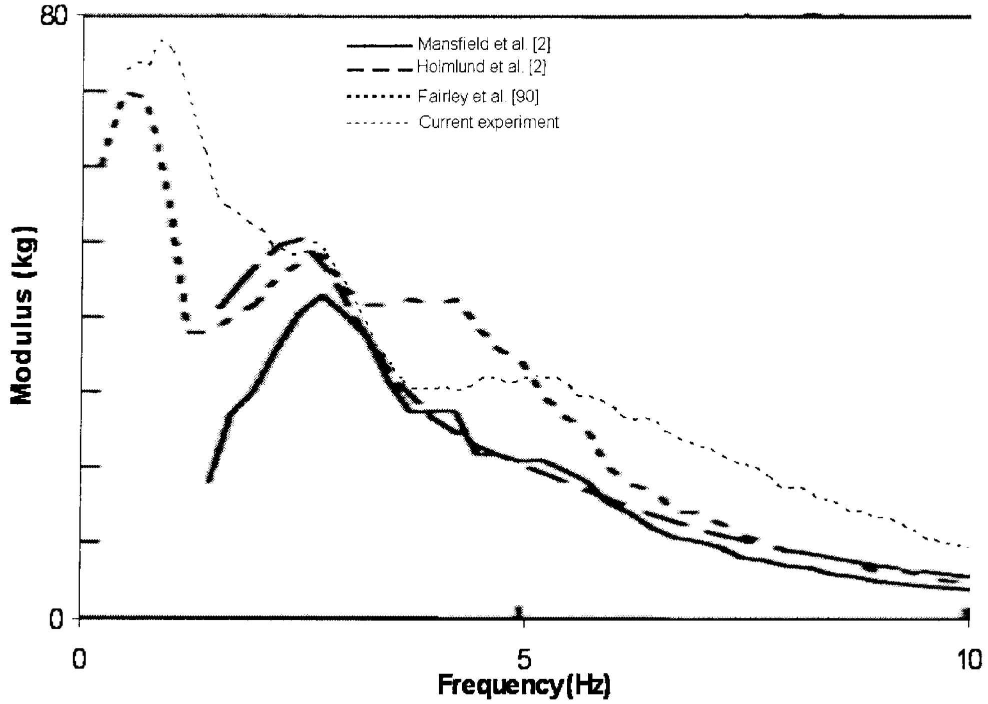


Figure 4.22: Comparison between studies of the measured APMS with unsupported back under fore-and-aft vibration

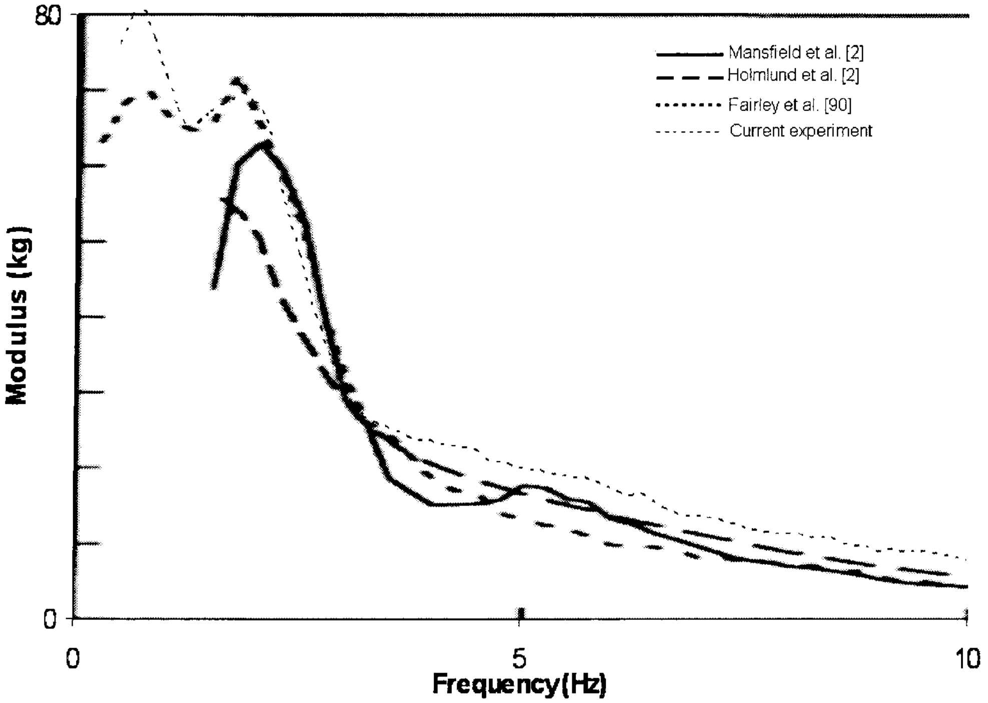


Figure 4.23: Comparison between studies of the measured APMS with unsupported back under lateral vibration

mass at about 5 Hz for both directions, which also has been reported by this study. The magnitudes and corresponding frequencies, as well as the slope around this resonance, however, differs in great manner. While the findings of Mansfield for fore-and-aft excitation showed a no-well defined resonant peak below 5 Hz, the current experiment showed a well-fitted curve and slightly higher magnitude and frequency for this peak. In the other hand, the lateral vibration induced a clearly mean response for the third peak under the Mansfield's experimental conditions, whereas the generally very well defined responses for individuals almost disappear under mean responses for the current experiment. The seat geometry is believed to play an important role in the scatter around this peak.

Figures 4.24 presents a comparison of the measured APMS response with supported back with that reported by Fairley and Griffin [22], under 1.0 m/s^2 rms random fore-and-aft acceleration. The principal peak is comparable in the corresponding frequency. The peak magnitude, however, seemed to be excessively higher in the Fairley's findings, with a flat peak around the stated frequency. The third peak did not reveal a clear trend for that study, under the logarithmic scale, contrasting to the curve described in the current experiment. The differences in the responses could be arise from the difference in the seat configuration, specifically to the inclined back-support, which provides better contact and at the same time reduces the possibility of slapping contact. In contrast, the lateral motion describes an acceptable fitted-curve, varying only due to the different levels of stimuli. Figure 4.25 illustrate the comparison between the current experiment and that developed by Fairley, under 0.75 (the highest level used in the current experiment) and 1.0 m/s^2, respectively. Only in the region around the third peak there is a noteworthy difference, which could be also related to the seat geometry.

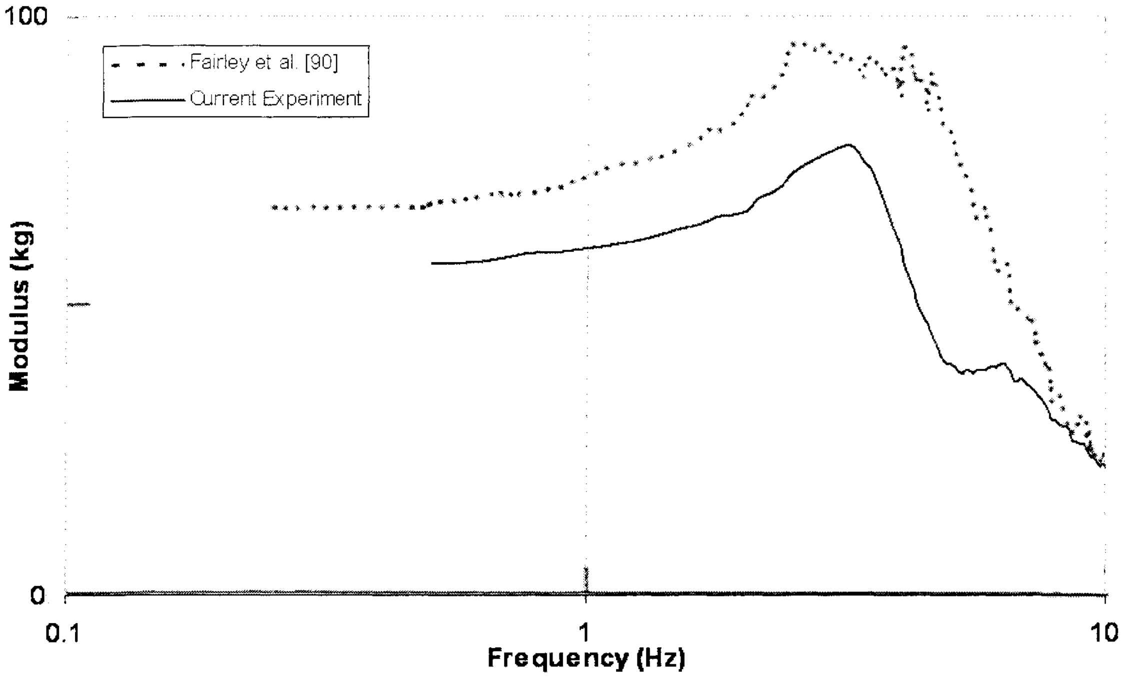


Figure 4.24: Comparison between studies of the measured APMS with supported back under fore-and-aft vibration

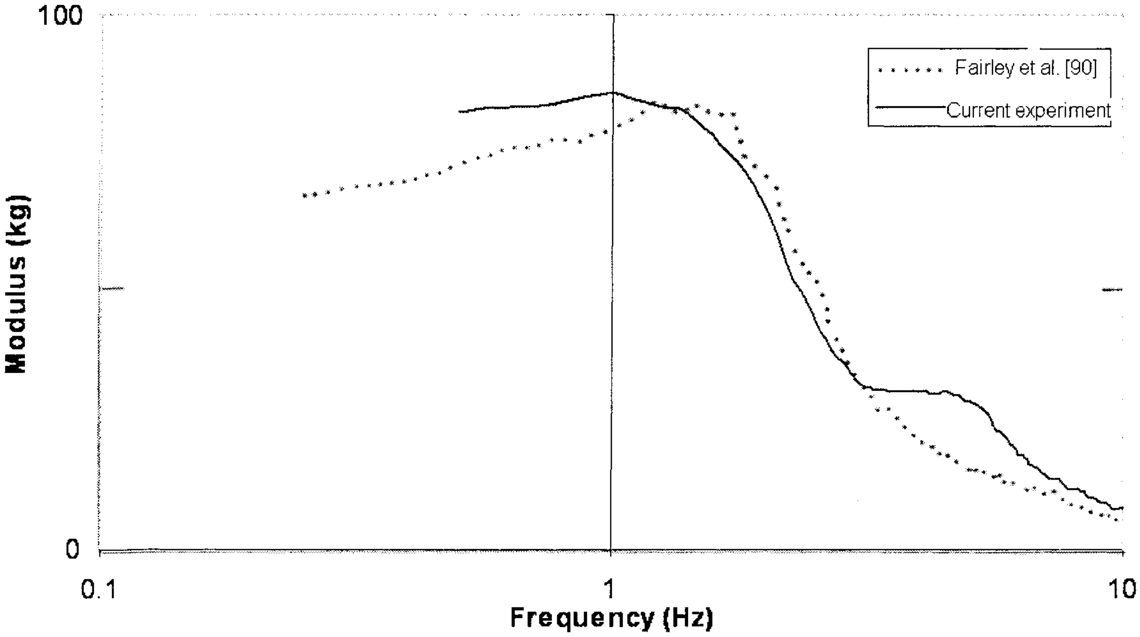


Figure 4.25: Comparison between studies of the measured APMS with supported back under lateral vibration

4.6 SUMMARY

The biodynamic responses of the seated human subjects exposed to horizontal vibration, in an automotive posture, are derived from the measured data. The data revealed relatively high inter-subject variability, which was attributed to individual factors and involuntary movements of the subjects. The mean responses are presented and the trends are discussed to highlight the effects of sitting posture, as well as axis and magnitude of vibration. The role of the type of vibration is further discussed to emphasize the increased human perception of repetitive sinusoidal motion. The measured data are compared to those reported in the published studies in view of the peak magnitudes and the corresponding frequencies. It is concluded that the present study has identified all the three important modes, which are collectively identified in the reported studies. The magnitudes of the responses differed considerably from those reported, which are believed to be attributed to the significantly different seat geometry used in the study. The peak APMS magnitude revealed reasonably good correlation with the body mass and body mass to height ratio. The principle frequencies, however, showed poor correlation with the body mass. The measured data are further analyzed to derive the power absorbed by the seated subject, and the results are discussed in the follow chapter.

CHAPTER 5

ABSORPTION OF ENERGY DURING EXPOSURE TO HORIZONTAL WHOLE-BODY VIBRATION

5.1 INTRODUCTION

Considerable efforts based on subjective and objective measurements have been made to enhance an understanding of the effects of whole-body vibration from a health, comfort or performance perspective. International Standard ISO 2631-1 [31] describes guidelines for evaluating vibration exposure in relation to human health, interference with activities, discomfort and the possibility of motion sickness. These methods consider the acceleration, frequency, direction and duration of transmitted vibrations as well as location and duration of measurements. The Standard does not give vibration exposure limits but provides guidance which can be used as the basis for setting limits, using acceleration as the primary quantity of vibration magnitude. It has been established that the human sensitivity to vibration is highly frequency-dependant. Different frequency weighting functions have thus been defined to assess the exposure to different axes of vibration. The differences in the sensitivity of the body to vibration along different axes are accounted for by the multiplying factors.

It is generally agreed that the severity of vibration exposure is related to the exposure duration, apart from the magnitude and frequency contents of the vibration [11, 51]. A number of studies have proposed different weightings to account for variations in the vibration frequency and exposure duration [30, 103]. However, most of them have been obtained from subjective studies [2, 23, 32, 35]. The vibration exposure guidelines specified in ISO Standard 2631 [31] are not exempted of pitfalls and errors due to the subjective nature of the underlying data. Besides, this standard only considers the mechanisms of the stimulus, describing the acceleration magnitude on the vibrating surface, while the dynamic force response of the human body is accounted for by the frequency weighting functions. The proposed weighting functions, however, have been subject to various criticism [21, 25, 29, 37, 41, 43, 50, 51, 58, 68, 73, 74, 78]. Moreover, the biodynamic responses measured under horizontal vibration do not seem to agree with the W_d-weighting function proposed in ISO 2631 [31], specifically for sitting with a back support. Although the biodynamic responses of the body when exposed to WBV, whether expressed in terms of the driving point mechanical impedance or apparent mass, relate to the dynamic force response and the acceleration due to vibration, these measures cannot account for exposure duration. Furthermore, the dependency of the biodynamic response on the magnitude of vibration is either not well-defined or not apparent, specifically for vertical vibration. These biodynamic responses thus do not effectively characterize the exposure effects in view of severity of the vibration and exposure duration.

Alternatively, a measure based upon absorption of vibration energy by the exposed body has been proposed to assess the severity of the exposure [14, 25, 79, 108, 128]. The absorbed power measure can account for both the exposure duration and the magnitude of vibration. It has been shown that the energy-based absorbed power method can be effectively applied to assess the time-dependency of the exposure, and it correlates well with the magnitude of acceleration [17, 79, 128]. The absorbed power has thus been suggested to provide a better estimation of not only the exposure but also the biodynamic response, as it relates to the same quantities: vibration acceleration and the force response. The amount of absorbed vibration energy could thus be considered as a better measure of the physical stress, since it takes into consideration the interplay between the vibrating surface and the body, rather than the appraisal of acceleration alone. In fact, absorbed power had been suggested as an alternative to the frequency weightings defined in ISO 2631 [14, 25, 79, 108, 128]. Moreover, the absorbed power can also account for the effects of variations in the seat geometry and the sitting posture [11], which are not addressed by the defined frequency weighting functions. The effects of vibration direction and the coupled motions of the exposed body could also be directly evaluated using the absorbed power concept.

The concept of absorbed power due to vibration has been widely applied for assessing the exposure to hand-transmitted vibration [11, 15, 25, 105, 106, 140], only minimal efforts have been made in deriving the absorbed power due to whole-body vibration of the seated occupants. Pradko and Lee [104] proposed the use of absorbed power to asses the vibration exposure in military vehicles. Since the Pradko and Lee's study of mid 60's, very few studies could be found on the subject of the whole-body vibration power [11, 15, 25, 128]. Of these, only a single study has investigated the absorbed power under exposure to horizontal vibration. This study measured the absorbed power characteristics of subjects exposed to sinusoidal vibration along x- and y-axis at discrete frequencies in the 1.13-80 Hz range, while seated with no back support [25].

In this study, the measured force-responses of seated human subjects are analyzed to compute the absorbed power characteristics under both fore-and-aft and lateral vibration. The results are evaluated under different sitting postures, and types and magnitudes of vibration.

5.2 ABSORBED POWER RESPONSE TO HORIZONTAL VIBRATION

While the detrimental effects of vibrating environment on humans have been known for a long time, the mechanism and the vibration exposure required to cause the disorders is not yet known with respect to the vibration intensity and frequency, and the daily and lifetime exposure. The transmission of vibration causes relative motions of various tissues, muscles and various organs of the body, which could be translated into dissipation of vibration energy by the body due to its inherent energy dissipating properties. A higher quantity of absorbed energy per unit time (power) would represent an increased effort by the biological system and thus the risk of vibration injuries or reduction in comfort [32]. This, however, does not include the risk of injuries due to the elastic component of power, which for most practical cases has been considered to be insignificant. The elastic energy could be far most significant, when the elastic limits of soft tissues, organs, vessels and muscles, as well as bones and joints, are exceeded.

The absorption of vibration energy by the exposed body has been suggested as an alternative to the exposure assessment method ISO 2631 [31]. The merits of the absorbed power method could be attributed to four major factors: i) its good correlation with the acceleration magnitude, which is the principal measure used in the standard; ii) the convenient relation between the stimulus and the response, in comparison with the assessment method based solely on the vibration magnitude; iii) the inclusion of exposure duration and vibration magnitude, which cannot be addressed by other biodynamic measures; and iv) the absorbed power could be expressed by a single scalar quantity, which allows for assessing the variations due to individual characteristics and sitting conditions (seat geometry and posture), in a simple manner.

The absorbed power can be directly computed from the velocity and the force response, as described in Eq. (3.11). The absorbed power can also be estimated from the vibration excitation alone, when impedance characteristics of the seated subjects are well defined [32]:

$$P_{Abs}(\omega) = \mathrm{Re}[Z(j\omega)]v^2(\omega) \tag{5.1}$$

where Re designates the real component of the complex driving point mechanical impedance $Z(j\omega)$, and $v(\omega)$ is the velocity.

The above formulation, however, requires accurate characterization of the impedance response under varying excitation magnitudes and postures. Alternatively, the absorbed power characteristics of seated human body exposed to horizontal vibration can be directly computed in the frequency domain, as [105]:

$$P_{Abs}(\omega) = \mathrm{Re}[G_{FV}(j\omega)] \tag{5.2}$$

where G_{FV} is the cross-spectrum between the force and the driving-point velocity.

The measured force and acceleration excitations due to horizontal vibrations are analyzed to derive the cross-spectral density (CSD) of the force response and driving-point velocity. The real part of the CSD is used to define the absorbed power characteristics of the vibration-exposed seated subjects. The results attained are studied to highlight the significance of the magnitude of vibration and the back support condition in view of the absorbed power properties. The results are initially examined to derive the intra- and inter subjects' variabilities.

5.3 INTRA AND INTER-SUBJECTS VARIABILITY

From the factors influencing the measured absorbed power, it has been suggested that inter- and intra-subjects differences are among of the most important [11, 14, 15, 21, 25, 128]. It is thus essential to understand the sources of variations in the responses derived from the designed experiments. A clear understanding of the various experimental factors and the way they are organized in the experimental process is also vital for proper interpretations. For experiments concerning the vibration characteristics of the human body, there are indeed great variabilities and little repeatability, which are evident from many reported data [11, 15, 26, 27, 29, 35, 37, 50, 56, 58, 61, 73, 107]. The factors influencing the variations include the aspects of the experiment, which are more or less controlled, and features that are not related directly with the test conditions but dependent more on the physical, physiological or psychological characteristics of each individual. Dismissing the psychological factors, the mechanical and physiological responses of the human body could be predicted to derive reasonable interpretations of the responses and deviations in the expected responses to WBV.

The repeatability of the measured data acquired under different trials of the same conditions is initially investigated to estimate the intra-subject variations. In this study, the data attained during different trials for each individual and test condition were evaluated to compute the coefficients of variation (CV) as a function of frequency, and the total absorbed power. The total absorbed power corresponding to a given trial is computed from:

$$P_{Abs} = \int_{f_l}^{f_u} \mathrm{Re}[S_{FV}(jf)]df \qquad (5.3)$$

where S_{FV} is the cross-spectral density of the measured force and the driving-point velocity, and f_l and f_u define the lower and upper limits, respectively, of the frequency range. The analyses in this study were performed in the 0.5-10 Hz frequency range.

The computed values of the coefficient of variation (CV) of different trials under same conditions were observed to be quite high, where the peak variations invariably occurred at frequencies above 7 Hz, irrespective of the subject and the test condition considered. Considering that the magnitude of absorbed power in this frequency range is very low, the high values of CV yield only small magnitude variations between the trials. The intra-individual variation with respect to magnitude and frequency at which maximum absorption of energy occurs, on the other hand, could better reflect the variability. The frequency corresponding to peak power attained under two trials of fore-and-aft excitations were generally found to be consistent, except for one subject, where the deviation in frequency was in the order of 0.5 Hz. The trials under lateral excitation also revealed similar degree of deviations in the frequencies corresponding to maximum power absorption.

The variations in the peak magnitudes of absorption of energy observed over different trials were found to be higher. The results in general revealed CV values below 10% in the vicinity of the peak power under fore-and-aft excitations, while values up to 20% were observed for only three data sets. The results generally revealed higher degree of variation under higher magnitudes of excitations, with back unsupported posture. As discussed in Chapter 4, the subjects under this particular posture revealed tendencies to shift their upper body during experiments to adapt to a more stable posture. Relatively larger values of coefficient of variation were observed under lateral excitations. While majority of the observations under lateral excitations revealed CV values up to 20%, the peak values in a few observations approached 50%. The CV values in the order of 30% or more, have been also observed in many reported studies under vertical vibration [10, 17, 19]. The present study, however, involved only two trials for each experimental condition. It is anticipated that the intra-subject variability would be lower if additional trials could be considered.

The total absorbed power corresponding to each test trial was computed using Eq. (5.3). The intra-subject variability in the total power was further assessed in terms of the coefficient of variation (CV). The peak values of CV of the two trials used for different experimental conditions under fore-and-aft excitations were observed to be within 15% for back not supported and within 9% for the back supported posture. Only one data set revealed CV value in the order of 23%, for no back support posture under the lowest level of acceleration. For lateral excitations, the peak values were below 7% for both postures, with only one data set approaching a value of in the 27%. Tables 5.1 and 5.2 summarize the coefficients of variation in the total power measured under different conditions for the fore-and-aft and lateral vibration, respectively.

Table 5.1: The coefficient of variation of the total power measured during different trials of the same subject and same experimental conditions (fore-and-aft)

Posture	Magnitude	Coefficient of variation (CV)							
		Subject							PEAK CV
		S1	S2	S3	S4	S5	S6	S7	
no back	0.25 m/s^2	4.39%	10.42%	1.57%	1.23%	11.02%	22.97%	11.40%	22.97%
	0.50 m/s^2	2.16%	8.22%	4.41%	1.54%	0.47%	0.05%	3.04%	8.22%
	1.00 m/s^2	0.33%	8.38%	3.39%	1.12%	4.81%	6.47%	4.18%	8.38%
with back	0.25 m/s^2	1.08%	1.11%	1.97%	0.51%	5.92%	2.91%	3.58%	5.92%
	0.50 m/s^2	1.46%	0.92%	1.02%	1.82%	0.64%	1.82%	5.09%	5.09%
	1.00 m/s^2	2.73%	2.79%	0.50%	0.08%	0.46%	1.75%	0.87%	2.79%

Table 5.2: The coefficient of variation of the total power measured during different trials of the same subject and same experimental conditions (lateral)

Posture	Magnitude	Coefficient of variation (CV)						
		Subject						PEAK CV
		S1	S2	S3	S4	S5	S7	
no back	0.25 m/s^2	6.25%	26.84%	6.86%	1.98%	2.91%	0.88%	26.84%
	0.50 m/s^2	0.18%	2.73%	1.77%	0.54%	1.09%	3.01%	3.01%
	0.75 m/s^2	1.36%	0.66%	2.94%	1.18%	0.58%	1.60%	2.94%
with back	0.25 m/s^2	0.83%	3.09%	1.31%	5.09%	0.99%	1.22%	5.09%
	0.50 m/s^2	1.38%	0.45%	3.12%	3.26%	0.60%	1.50%	3.26%
	0.75 m/s^2	1.11%	2.93%	1.35%	0.65%	3.12%	1.29%	3.12%

The intra-subject variability of the data is considered to be reasonable in relation to those reported in the published studies. The mean values of the two trials attained with each subject are thus examined to study the inter-subject variabilities. It is well known that the absorbed power characteristics are strongly dependent upon the individual's mass and build, which can be ascertained from the mean responses. Figure 5.1 illustrates the absorbed power responses of the seven subjects exposed to 1 m/s^2 rms fore-and-aft white noise vibration. The responses under 0.75 m/s^2 rms lateral random vibration are presented in Figure 5.2. Each figure presents the mean individual responses with back unsupported and supported sitting posture, together with the overall mean values.

While the results show comparable trends in terms of the frequencies corresponding to the peak power, considerable differences in the peak magnitudes are evident. The absorbed power characteristics of all subjects seated with no back support and fore-and-aft excitations, consistently reveal three peaks at frequencies below 2.75. The frequencies corresponding to the peak generally increased under lower magnitudes

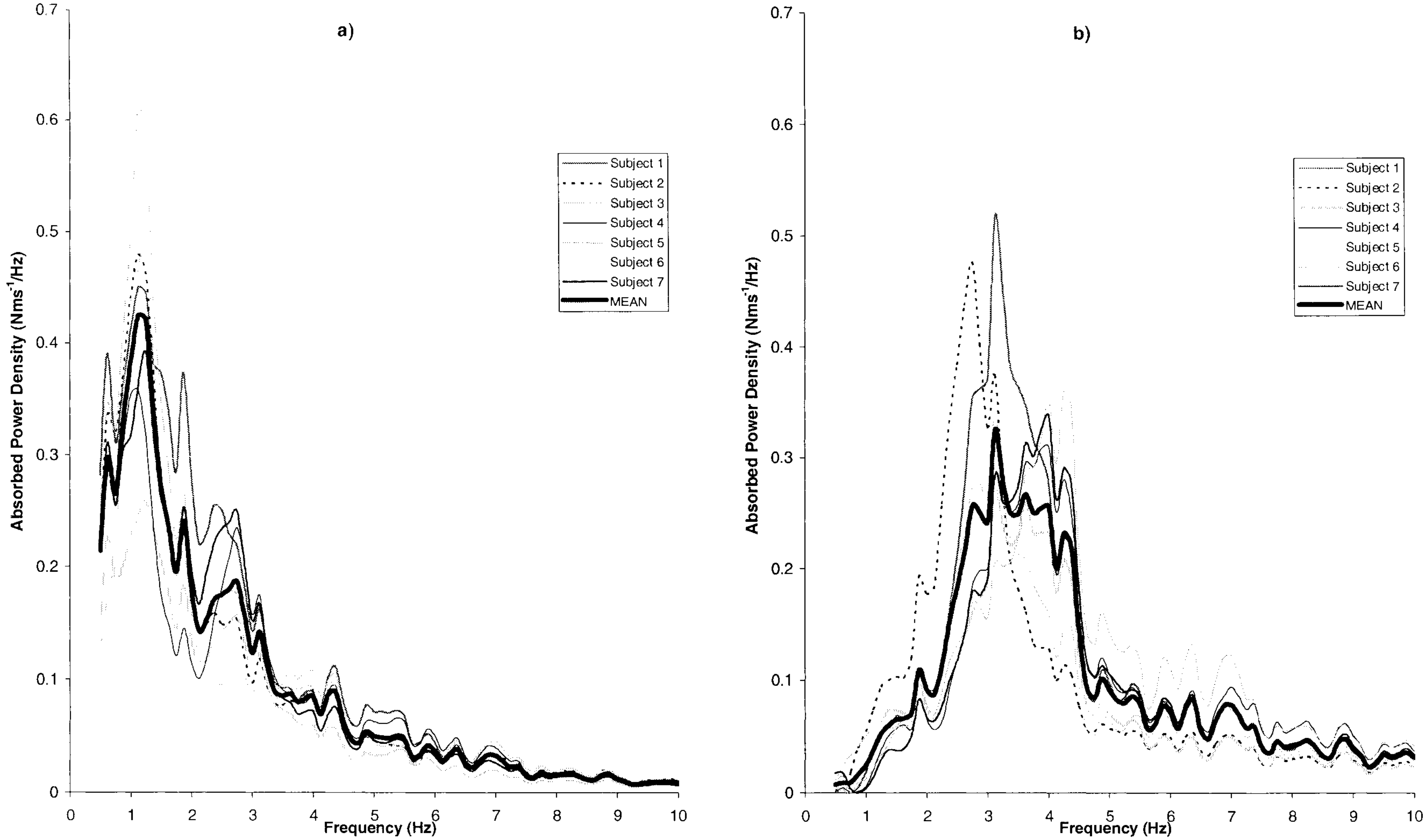


Figure 5.1: Comparisons of absorbed power characteristics of seven subjects exposed to 1 m/s^2 rms fore-and-aft acceleration stimulus: a) unsupported back; and b) supported back.

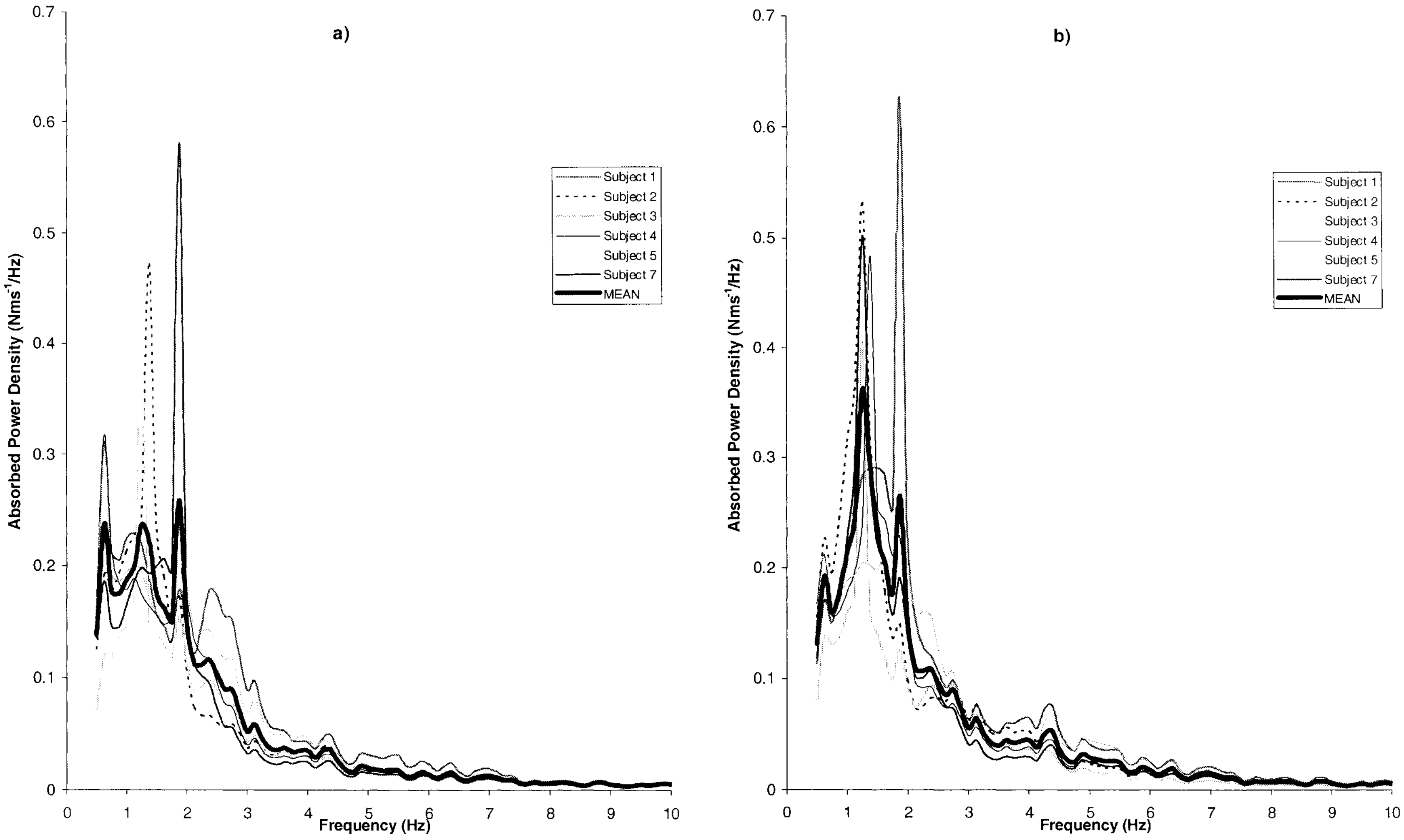


Figure 5.2: Comparisons of absorbed power characteristics of seven subjects exposed to 0.75 m/s^2 rms lateral acceleration stimulus: a) unsupported back; and b) supported back.

of excitations. The addition of back support under this condition tends to shift the peak at higher frequencies near 3.25 and 4.5 Hz, as observed earlier from the apparent mass responses. The responses under lateral acceleration excitations are observed to be generally similar for both postures as it was observed for the APMS responses. The absorbed power characteristics of different subjects reveal 2 to 3 peaks in the low frequencies up to 2 Hz. Table 5.3 summarizes the ranges of frequencies corresponding to peak absorbed power density derived from the data sets attained for 7 subjects (6 for lateral excitation) corresponding to each axis and type of vibration.

Table 5.3: Ranges of frequencies corresponding to peak absorbed power density.

CONDITION			PRINCIPAL PEAK (Hz)	SECONDARY PEAKS (Hz)
Fore-and- aft direction	No Backrest	White Noise	1.1250 – 1.250	1.875 2.375 – 2.75 4.25 – 4.375
		Sine Sweep	1.000 – 1.500 1.750 – 2750	3.250 – 4.125 4.375 – 5.250
	Backrest	White Noise	2.7500 – 4.375	6.375
		Sine Sweep	2.750 – 4.500	5.875 – 7.125
	At the back interface	White Noise	2.750-4.375	----
		Sine Sweep	2.625-4.125	----
Lateral direction	No Backrest	White Noise	0.875 – 1.375 1.875	3.875 – 4.250
		Sine Sweep	1.000 – 1.375 1.750 – 2.250	2.375 – 2.750 3.125 – 4.375
	Backrest	White Noise	1.125 – 1.500 1.875	2.375 – 2.75 3.125 4.25 – 4.375
		Sine Sweep	1.000 – 1.500 1.75 – 2.000	3.875 – 4.875

The results in-general show significantly higher inter-subject variabilities. The responses under fore-and-aft excitations revealed peak values of coefficients of variations up to 30% for the unsupported back posture and up to 67% for the back supported posture. The peak values of CV mostly occur in the vicinity of the peak absorbed power.

The higher degree of CV can be partly attributed to variations in the body mass and height. The peak CV values in the vicinity of the absorbed power peaks under swept harmonic excitations were observed to be significantly lower in the order of 15%. This would be attributable to subjects' tendencies to adopt more stable posture under well-perceived harmonic motions, as discussed earlier in Chapter 4. The responses under lateral excitations also revealed similar degrees of inter-subject variabilities.

From the results presented in chapter 4 and those in Figures 5.1 and 5.2, it is apparent that different postures lead to significantly dissimilar responses. The contact with the back support changes not only the peak magnitude and the corresponding frequency, but also the total energy absorbed by the human body. It could thus be expected that sporadic contact with the back support, when the posture is without back contact, could change the corresponding responses. In this situation, the measured response at the back support it is expected to have two defined behaviours: a "flat" response when the back is not supported, the measured response at the seat alone; and a "shaped" curve under contact with back surface. The force response at the back support under this posture was thus considered monitored to minimize the occurrences of sporadic contact. While exposure to white noise excitation revealed occasional contact at frequencies distant from frequencies of main peaks, the exposure to sine sweep excitations showed backrest contact within the frequency range, where the maximum energy occurs. Despite this contact, from 42 possible trials, only 8 reveal slight contact. Of those, only a single trial for one subject resulted in considerably different response attributed to contact with the back support.

The important variations in the principal tendencies observed from the data attained from the current experiments could be summarized below:

- Figure 5.3 (a and b) illustrates, as an example, a comparison between the absorbed power density under high and low magnitudes of horizontal excitations, computed for the subject number 4 under unsupported back posture. The results suggest diverse trends for the absorbed power density under exposure to different acceleration magnitudes. The absorbed power density under 0.25 m/s^2 rms excitation appears to be significantly different and smaller in magnitude, when compared to that attained under 1 m/s^2 rms excitation. The variations in the absorbed power density with frequency, however, are quite comparable under both magnitudes, when plotted on different scale, as seen in Figure 5.3 (c and d). The right-side scale refers to the power density under lower excitation magnitude (0.25 m/s^2 rms). The supported back posture and lateral excitations, irrespective of posture, show indeed less discrepancies. Only the lightest subject showed different behaviour under the highest level of vibration, suggesting different body-response, either mechanical or physiological factors associated with the low- body mass.

- Most of the subjects showed at least two significant peaks in the absorbed power, irrespective of the direction or type of stimuli. For some of them, the region where the absorption of energy is the highest changes from one frequency to another. This situation affects the principal 'mean'. This peculiar behaviour seemed to be related to the different mechanism associated with each peak: whereas low levels of acceleration shows little effect on specific peaks, higher stimuli levels reverberate them. Besides, a third peak within the same range and comparable magnitude was found for two subjects.

- Although the data attained for four subjects revealed occasional contact with the back support while seated without the back support, only eight trials of the possible 42 trials revealed different tendencies in the force response at the back support. Notable differences in the absorbed power response, however, were observed for only a single dataset, which suggest only occasional contact.

- The peak absorbed power density revealed certain proportionality with the excitation magnitude, which varied with the subjects' mass, specifically when seated without back support.

- Different types of stimuli also play an important role in the differences in the absorbed power density. As the absorbed power is a "time-dependent" function, the differences in exposure time (125 s for white noise and 512 s for swept sine) could account for differences in the attained responses. Increasing the time also increases the possibility of involuntary postural changes.

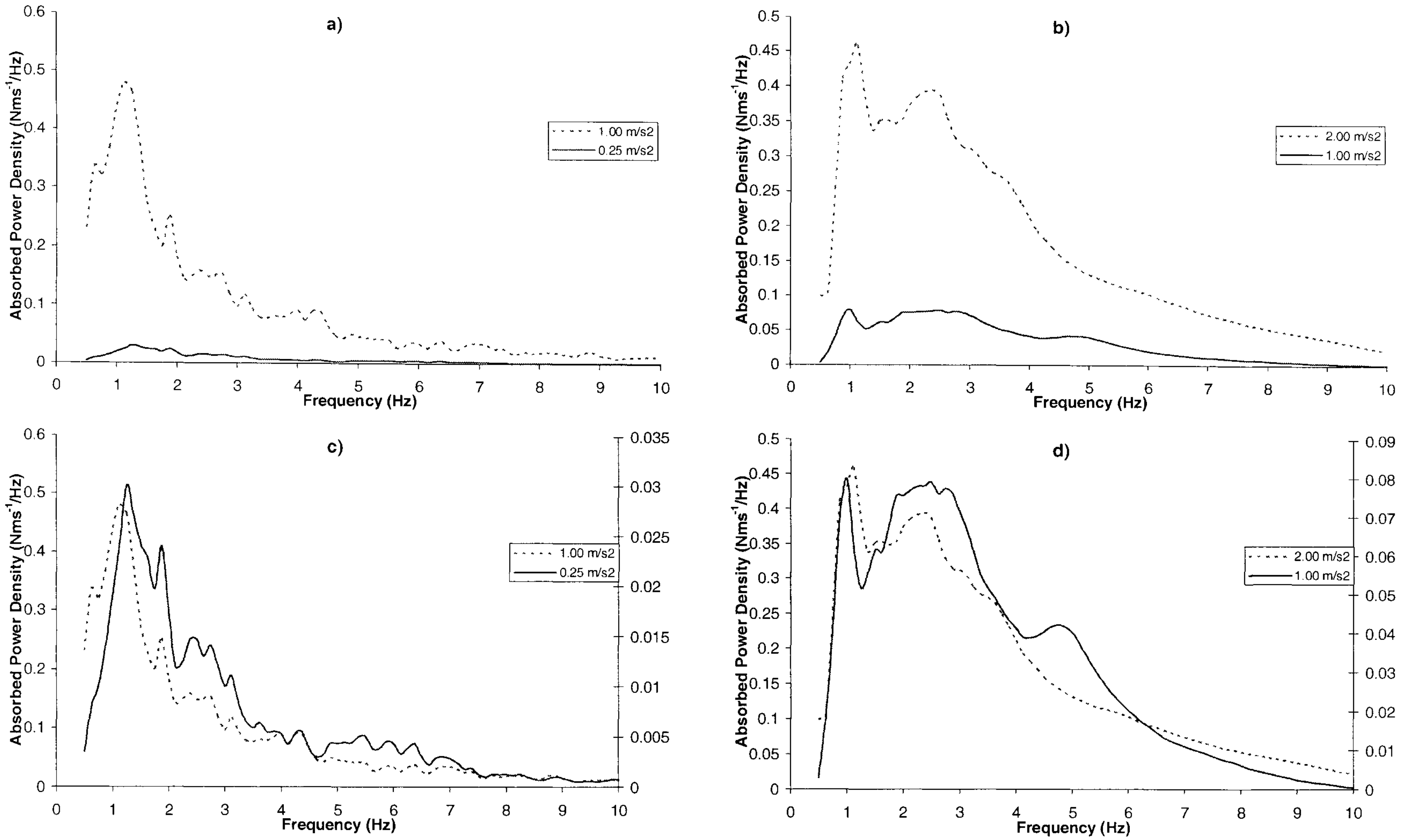


Figure 5.3: Comparisons of absorbed power density under different levels of fore-and-aft acceleration: a) and c) back not supported posture; b) and d) back supported posture.

5.4 MEAN ABSORBED POWER CHARACTERISTICS

The absorbed power characteristics of the seven subjects under conditions involving same magnitudes and type of vibration, and posture, are analyzed to derive the mean responses characteristics. Despite the large degree of inter-subject variability of the data, the mean responses can provide significant insight into the general trends and effects of sitting posture, magnitude and type of vibration. Figures 5.4 and 5.5 illustrate the mean absorbed power characteristics derived from the data acquired at the seat pan under fore-and-aft (x-axis) and lateral (y-axis) stimuli, respectively. The figures present comparisons of the absorbed power characteristics attained for the two postures under both swept harmonic and random excitations.

The mean responses under unsupported back posture and fore-and-aft harmonic and random excitations reveal primary peak near 1.125 Hz and a secondary peak in the 2.5-2.75 Hz range, irrespective of the magnitude of excitations. The peak absorbed power tends to occur in the 3.25-3.375 Hz and 3.125-4.375 Hz ranges under harmonic and random excitations, respectively, when the back is supported. Higher excitation magnitudes, in general, yield peak responses at slightly lower frequencies. The frequencies corresponding to the peak responses attained under unsupported back posture alone could be compared with the reported data in [25]. The reported data, however, is presented under excitations in the 1.13-80 Hz frequency range, and consequently it does not identify the peak near 1.125 Hz. The frequency of the secondary peak observed in this study (2.5-2.75 Hz) agrees reasonably well with that reported in [29]. The peak magnitudes of the mean power characteristics increase most significantly with increasing the magnitude of excitation and tend to be larger under harmonic excitations, as observed

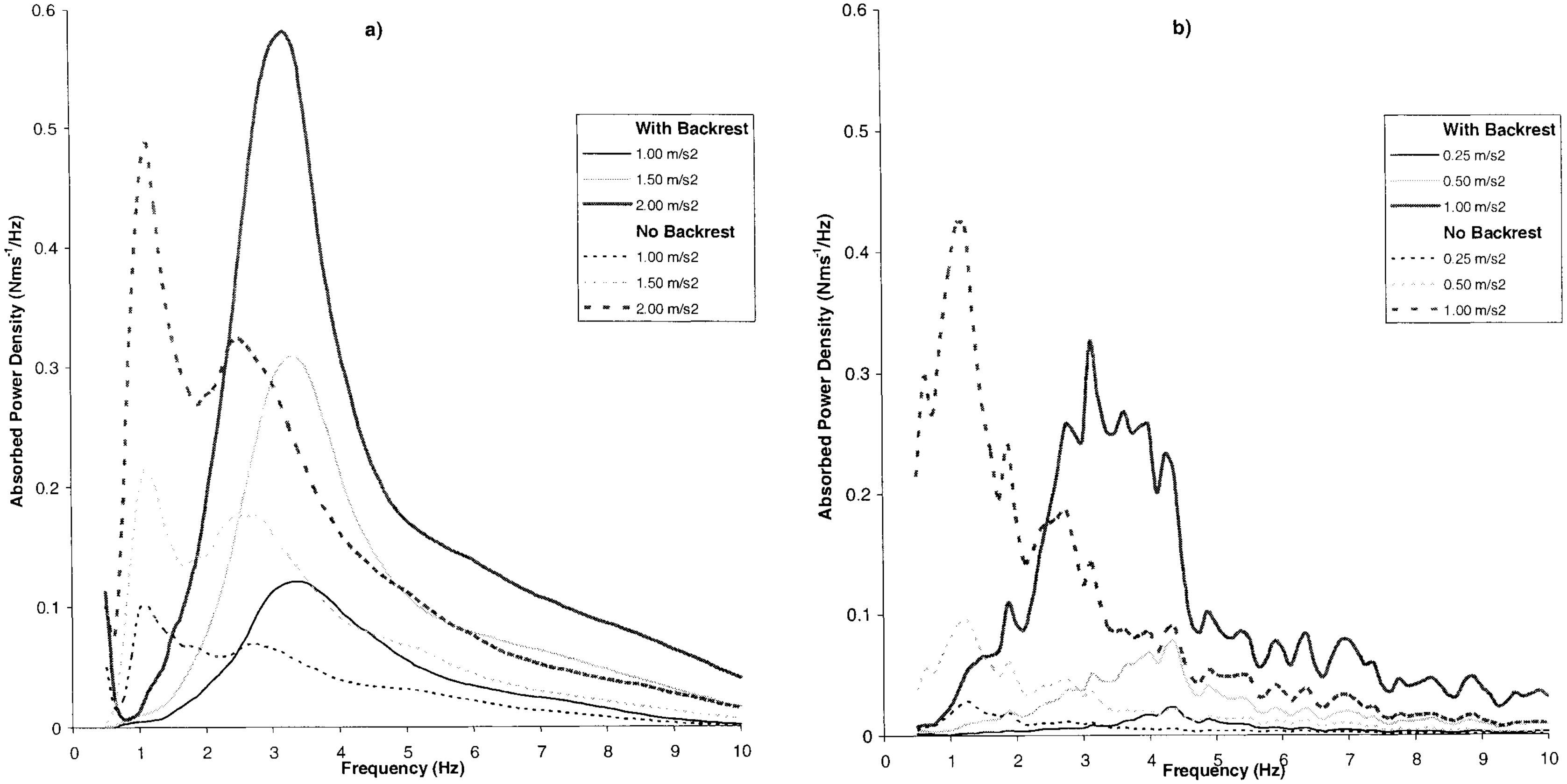


Figure 5.4: Comparisons of mean absorbed power characteristics attained under different magnitudes of fore-and-aft excitation and postures: a) swept sine excitations; and b) random excitations.

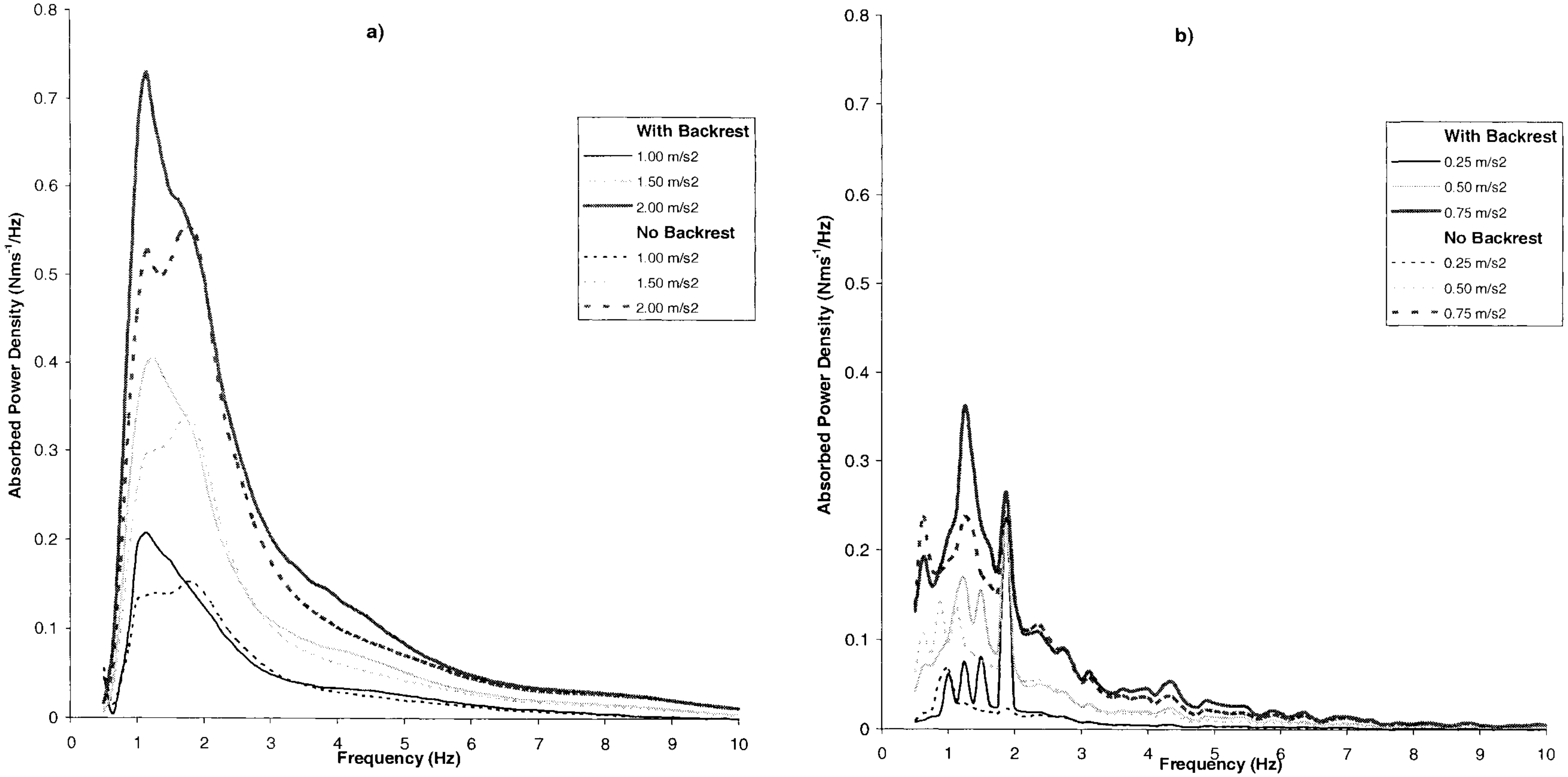


Figure 5.5: Comparisons of mean absorbed power characteristics attained under different magnitudes of lateral excitation and postures: a) swept sine excitations; and b) random excitations.

in Figure 5.4, which is mostly related to higher acceleration rms values associated with these stimuli.

The above ranges depict the frequencies were the maximum absorption of energy occurs, as is described earlier. The frequencies corresponding to peak responses however, do not coincide with those of the peak APMS responses described in the previous chapter, specifically for the back unsupported posture when exposed to fore-and-aft excitation, and for the supported back posture when exposed to lateral excitation. Further in this chapter, the trends corresponding to the peak APMS and absorbed power responses will be compared. The trends observed in the mean absorbed power responses are further analyzed in an attempt to enhance an understanding of the effects of various factors.

5.5 FACTORS INFLUENCING MEAN ABSORBED POWER

The data attained with previous experimental studies suggest that differences in the assessment of human exposure to vibration depend on a number of factors, such vibration exposure (direction, magnitude, frequency, type of signal or duration), human factors (anthropometric characteristics, habits, health, gender or psychological and physiological reactions), and intrinsic (posture, seat geometry, human-source of vibration interfaces) or extrinsic surrounding features (nocturnal-diurnal exposure, sensory experiences or environmental conditions) [22-29, 65, 79]. Apart from the differences in subject's characteristics, the postural changes and nature of vibration (magnitude and type) are expected to be the major factors influencing the measured biodynamic responses. Considering that the present study follows the procedures outlined in the reported studies, the results are expected to show reasonable agreements with the reported data to an extent. The experimental conditions, however, differ in view of the posture and nature of excitations considered. In the following sections, the effects of anthropometric characteristics of the subjects on the response, as well as the features related to changes in the stimuli, such as acceleration magnitude, waveform and direction, have been explored. Besides, the effect of seated posture is also examined.

Figures 5.4 and 5.5 illustrate mean magnitude of the absorbed power derived from the data acquired at the seat pan under fore-and-aft and lateral stimuli (*x*- and *y*-axis respectively). The results show the mean responses corresponding to unsupported and supported back postures, and exposed to different types and levels of vibration. The mean results are discussed to highlight the trends observed under different postures and excitation conditions. The mean responses reveal peaks corresponding to different frequencies under varying postural support condition, and type and magnitude of vibration, as evident from the Figures. The magnitude response attained with back supported posture is significantly different, when compared with no-back support condition, irrespective of the excitation magnitude and the direction. The results clearly suggest strong influence of the back support conditions.

5.5.1 INFLUENCE OF ANTHROPOMETRIC CHARACTERISTICS

From all inherent subjects' characteristics influencing the biodynamic response of the seated occupants, the body mass is recognized as the most significant factor for exposure to vertical vibration [17]. In a similar manner, the responses to horizontal vibration are also expected to be body mass-dependent. Owing to the upper body rotation about the pelvis under fore-and-aft motion, the upper body or the overall subject height may also affect the absorbed power response. The data attained for individual subjects are analyzed to derive the peak magnitudes of absorbed power density and the corresponding frequencies, which are then evaluated in view of the individual body masses, standing heights, and body mass to subjects' height ratio. In order to allow effective statistical analysis, the correlation coefficient (r) for a sample of 7 subject must be at least 0.755, which means a coefficient of determination (r^2) equal or higher to 0.569 (0.811 and 0.658, respectively, for a 6-subjects sample used in lateral direction) [135, 136].

The analyses revealed that the absorbed power density of seated body under horizontal vibration is influenced by the body weight for a few experimental conditions (4 of 12 possible), as is illustrated in Figure 5.6 (a and c). The figure presents the variations in the primary peak magnitude with the total body mass. The trends observed in the magnitude data suggest that the principal peak magnitude increases with increasing body mass. Even though considerable dispersion in the data is evident, the peak absorbed power magnitudes generally occurred in the 1.125-2.75 Hz and 2.75-4.5 frequency ranges, for the unsupported and the supported back postures, respectively. The peak magnitude could generally be positively correlated with the body mass. This trend has also been observed in the reported APMS responses in the current study, which showed relatively higher r^2 values. The analysis of the peak magnitudes and corresponding frequencies measured under y-axis vibration also revealed comparable tendencies with the body mass (Figure 5.7, a and c). The results show relatively consistent correlation under low magnitudes of random excitation and not supported back posture, irrespective of the excitation direction. The lower r^2 values were attained with higher magnitudes of harmonic excitation, irrespective of the direction of the stimulus. The results, however,

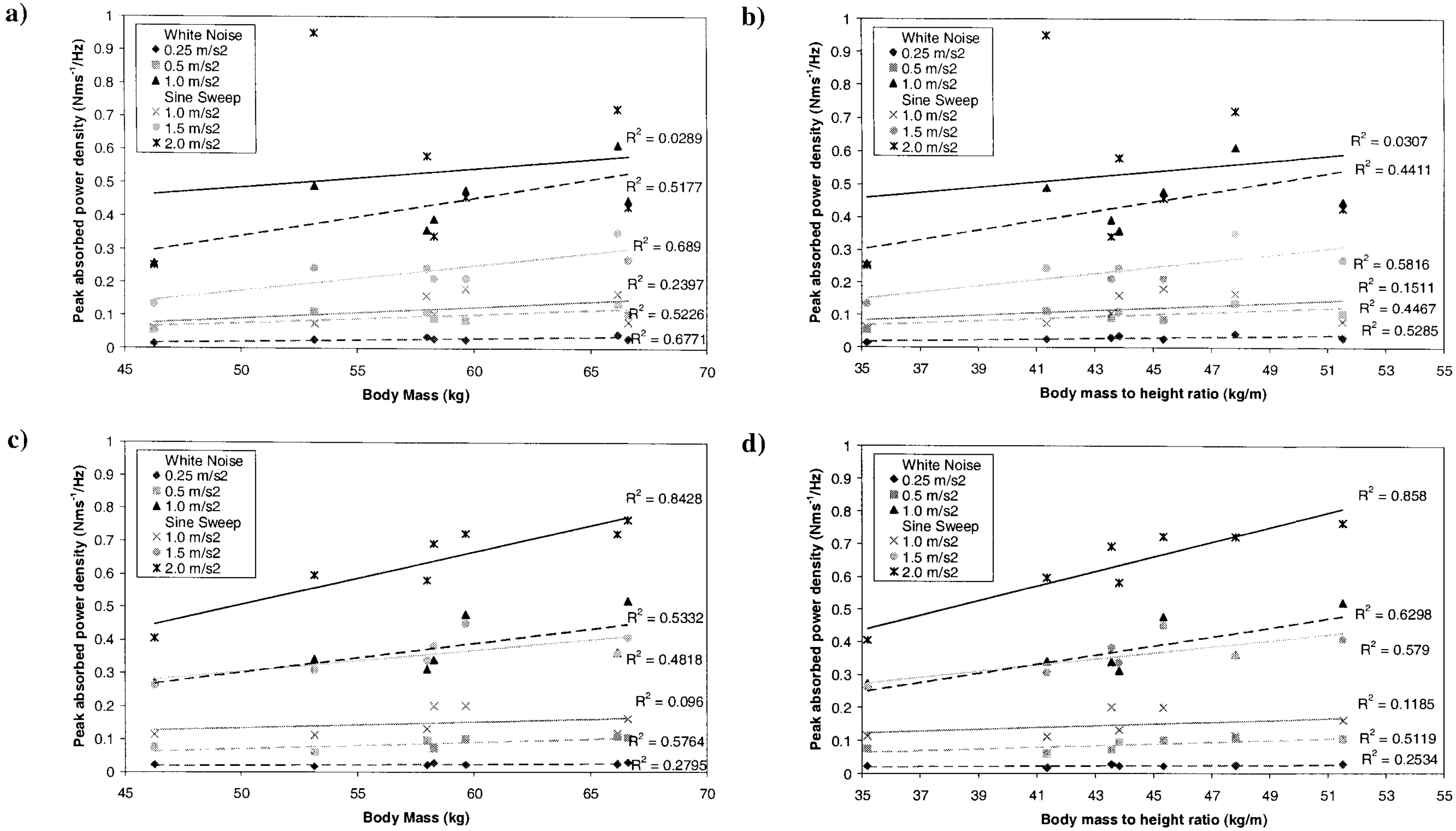


Figure 5.6: Dependence of peak absorbed power magnitude on the body mass and on the body mass to subjects' height ratio, under fore-and-aft vibration: a) and b) Back unsupported posture; c) and d) Back supported posture.

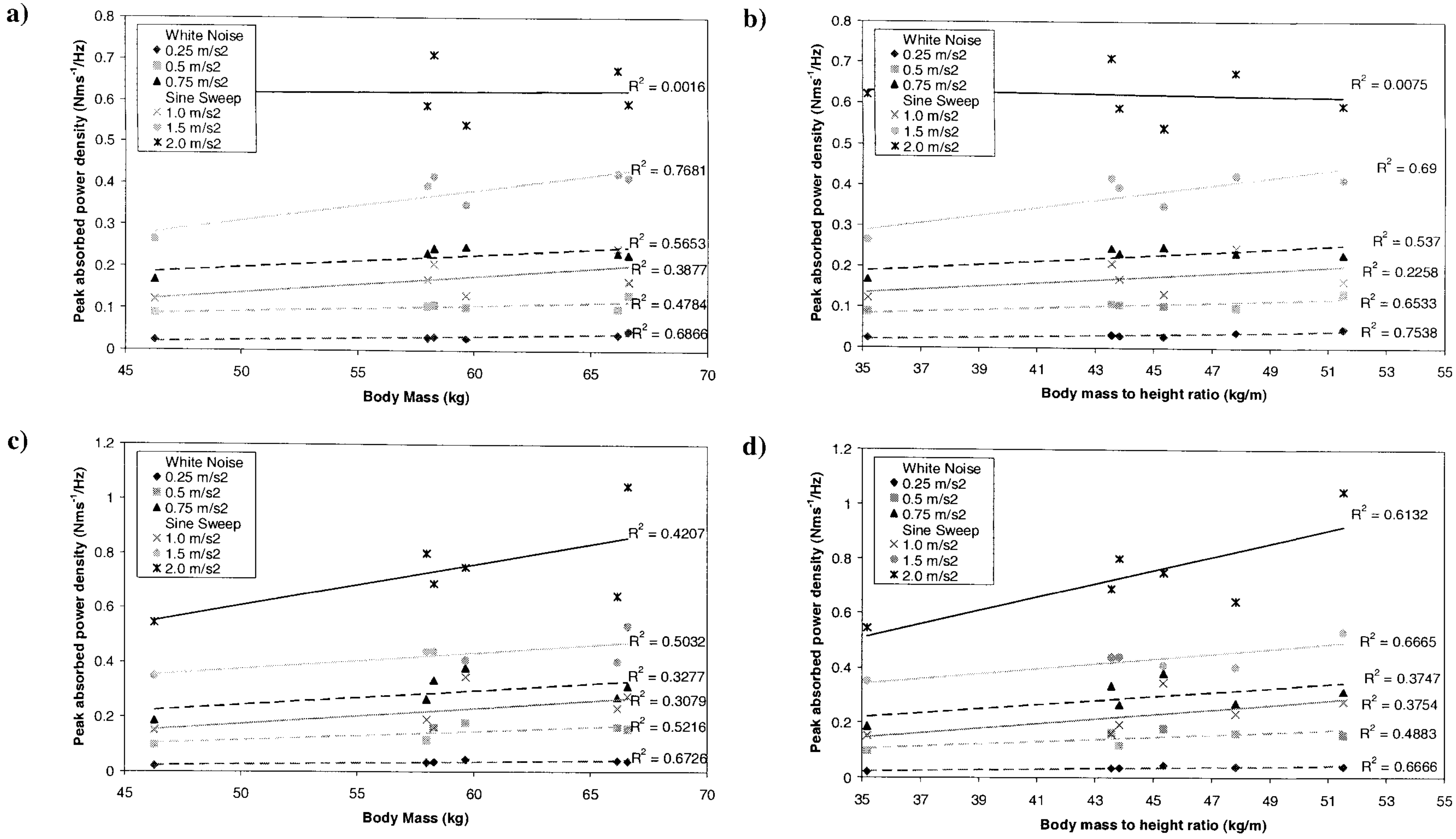


Figure 5.7: Dependence of peak absorbed power magnitude on the body mass and on the body mass to subjects' height ratio, under lateral vibration: a) and b) Back unsupported posture; c) and d) Back supported posture.

did not show reasonable correlation between the frequency of the principal magnitude and the body mass.

With regards to the other anthropometric characteristics, the subjects' height revealed poor correlation with the peak magnitude, as well as with the frequency corresponding to the principal peak. Significantly higher correlations, however, were observed between the peak magnitude and the body mass to height ratio, under both postures and axes of excitation. Figures 5.6 (b and d) and 5.7 (b and d) illustrate, the variations in the peak magnitudes with respect to the body mass to height ratio, when seated with and without back supported and exposed to three different levels of random excitation along the *x*- and the *y*-axis. The results generally suggest that the peak magnitude of the absorbed power response is more correlated with the body mass to height ratio than the body height alone. The correlations, however, are generally lower under lateral excitations.

In contrast, the total amount of power absorbed by the exposed seated human body generally reveals superior correlation with the subjects' characteristics. Figure 5.8 (a and b) illustrates the variations in the total absorbed power magnitude with the subjects' body mass, when exposed to fore-and aft vibration, and seated with back unsupported and supported postures. The r^2 values are mostly in the order of 0.9 under random vibration for both sitting postures. Reasonable correlation between the total power and the body mass is also observed under harmonic excitation when seated with no back supported, while poor correlation is attained with back supported posture, specifically under 1.5 and 2.0 m/s^2 excitations. The results also show considerable higher absorbed power under harmonic excitations. The corresponding r^2 values for the total power associated with the body interactions with the backrest are clearly lower to those attained for the data attained at the seat pan, as shown in Figure 5.10. The analysis of the total absorbed power measured under y-axis also revealed similar degree of correlation with the body mass as shown in Figures 5.9a and 5.9b. The r^2 values, however, are higher for the lateral excitation under back unsupported posture than under the fore-and-aft excitation. The total amount of absorbed energy under random excitation showed better correlation with the subjects' mass than the harmonic excitation, irrespective of the magnitude of stimuli or direction. The results suggest that the total power absorbed by the seated human body exposed to horizontal vibration increases nearly linearly with the body mass.

The total absorbed power revealed poor correlation with the subjects' height as observed in the case of peak power density and APMS, irrespective of the type and magnitude of excitation vibration, direction and seated posture. Significantly higher correlation, however, were observed between the total absorbed power and the body mass to height ratio, under both postures and axes of excitation. Figures 5.8 and 5.9 (c and d) illustrate the variations in the total absorbed power with respect to the body mass to height ratio, under two postures and exposed to three different levels of random excitation along the *x*- and *y*-axis, respectively. The results show reasonably good correlation between the total power and the mass height ratio under fore-and-aft harmonic excitation, and slightly lower under lateral harmonic excitation with back supported posture. The results present in Figures 5.8 to 5.9 show excellent correlation between the peak power density and the body mass under fore-and-aft movement only, while the total absorbed power is equally correlated for both directions of excitation. While the peak magnitude is observed to be more dependent on the subjects mass, the total absorbed power shows better correlation with the weight-height ratio index.

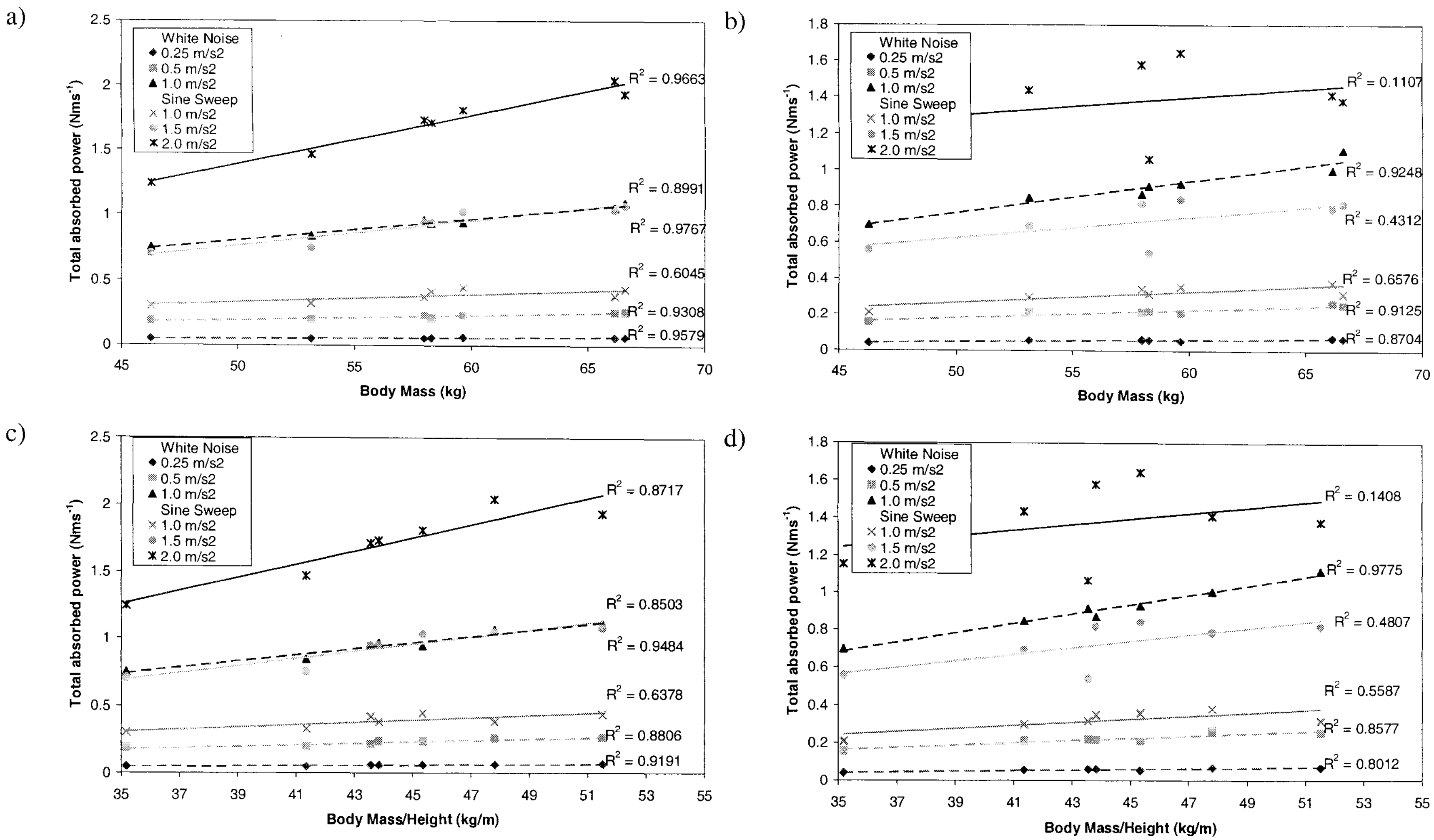


Figure 5.8: Dependence of total absorbed power on the body mass and body mass to subjects' height ratio under fore-and-aft vibration: a) and c) under back supported posture; and b) and d) under back unsupported posture.

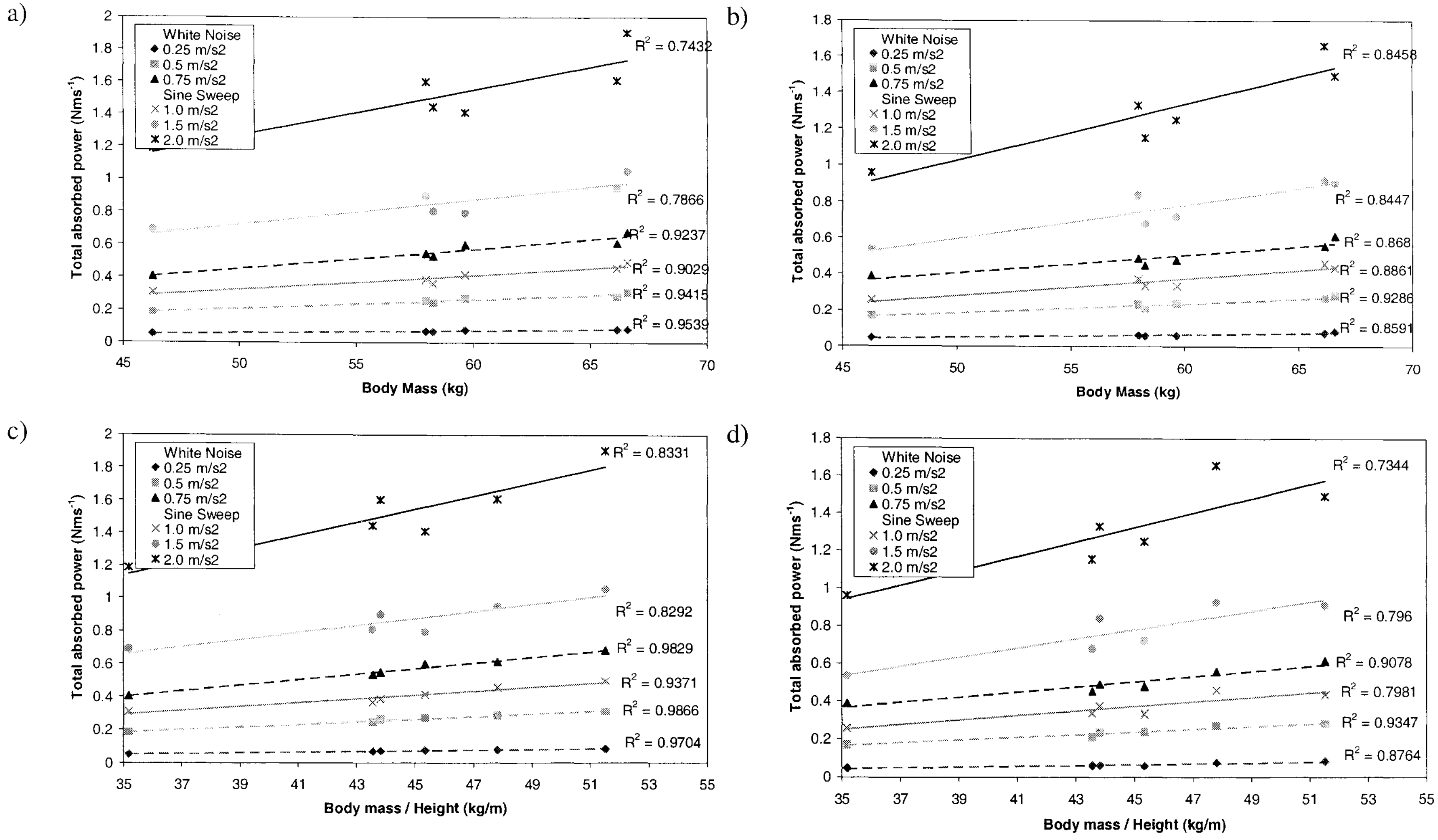


Figure 5.9: Dependence of total absorbed power on the body mass and body mass to subjects' height ratio under lateral vibration: a) and c) under back supported posture; and b) and d) under back unsupported posture.

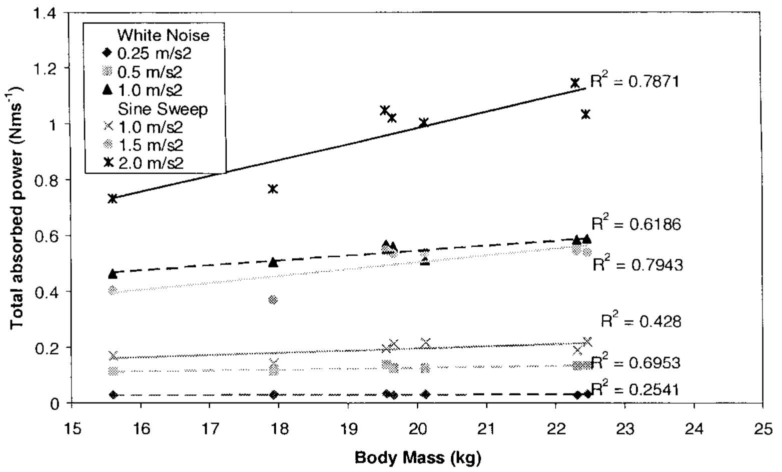


Figure 5.10: Dependence of total absorbed power derived from the force response at the backrest on the body mass under fore-and-aft vibration at the seat back support.

5.5.2 INFLUENCE OF EXCITATION MAGNITUDE

The reported studies on absorbed power under vertical vibration have invariably suggest strong effects of the excitation magnitude [11, 15, 21, 25, 79]. The variations in the total absorbed power caused by variations in the intensity of excitation, however, suggest non-linear behaviour of the biological system. Moreover, the variations in the vibration magnitude tend to affect mainly the peak magnitudes of absorbed power, whereas little or null effect is observed in the frequencies associated with the maximum absorption of energy by the biological system. While the reported studies have mostly focussed on the analysis of absorbed power under vertical vibration alone, a single study has investigated the power absorption under horizontal vibration [17]. This study has shown more pronounced effects of excitation magnitude on the horizontal response, which can be partly attributable to relatively larger movements of the upper body, and involuntary movements of the subjects in stabilizing the sitting posture under horizontal motions, which was clearly observed during the current experiments.

Under fore-and-aft excitation, as is shown in Figure 5.4, the absorbed power responses tend to retain similar characteristics in terms of frequency, irrespective of the magnitude of acceleration. The response to low magnitude random stimuli with supported back posture alone shows some changes in the frequency corresponding to the primary absorbed power peak. The peak power absorption under higher intensity vibration generally occurs at a lower frequency, which is most likely caused by softening of the body associated with excessive movement of the upper body. This phenomenon has also been reported in studies on vertical biodynamics [11, 128]. Under lateral excitations, illustrated in Figure 5.5, the trends in the absorbed power spectra remain comparable under different magnitudes of harmonic stimuli. The responses to random excitations, however, show two trends: the predominant response with back supported posture with the lowest level of acceleration occurs at higher frequency, which in-part could be attributed to the same effect found under fore-and-excitation; and comparable frequency characteristics of the absorbed power density, irrespective of the magnitude of excitation. The proclaimed shape and trends follows generally similar patterns: the amount of absorbed power increases with frequency up to a principal peak in the range of 3.125-4.375 Hz for back supported posture and around 3.125 Hz for unsupported back posture, when exposed to fore-and-aft stimuli. The exposure to lateral excitation leads to a principal peak in the 1.0-1.875 Hz frequency range, for both postures. The responses beyond these frequencies decrease gradually, irrespective of the type, direction, and magnitude of excitation.

It has been suggested that the increment in the amount of energy absorbed by the human body is proportional to the magnitude of the acceleration [128]. A number of studies on the power absorption by the human hand-arm exposed to hand-transmitted vibration, and those under whole-body vibration have suggested that the absorbed power is proportional to the square of the level of vibration exposure expressed in terms of acceleration magnitude [11, 25, 79, 105]. A few of these studies have also observed nonlinear dependence on the acceleration intensity. The data acquired in the current study are analyzed to study the effect of vibration magnitude on the peak and total absorbed power as functions of the seated posture and direction of vibration. Figure 5.11 illustrates the dependence of peak absorbed power magnitude on the unweighted acceleration level,

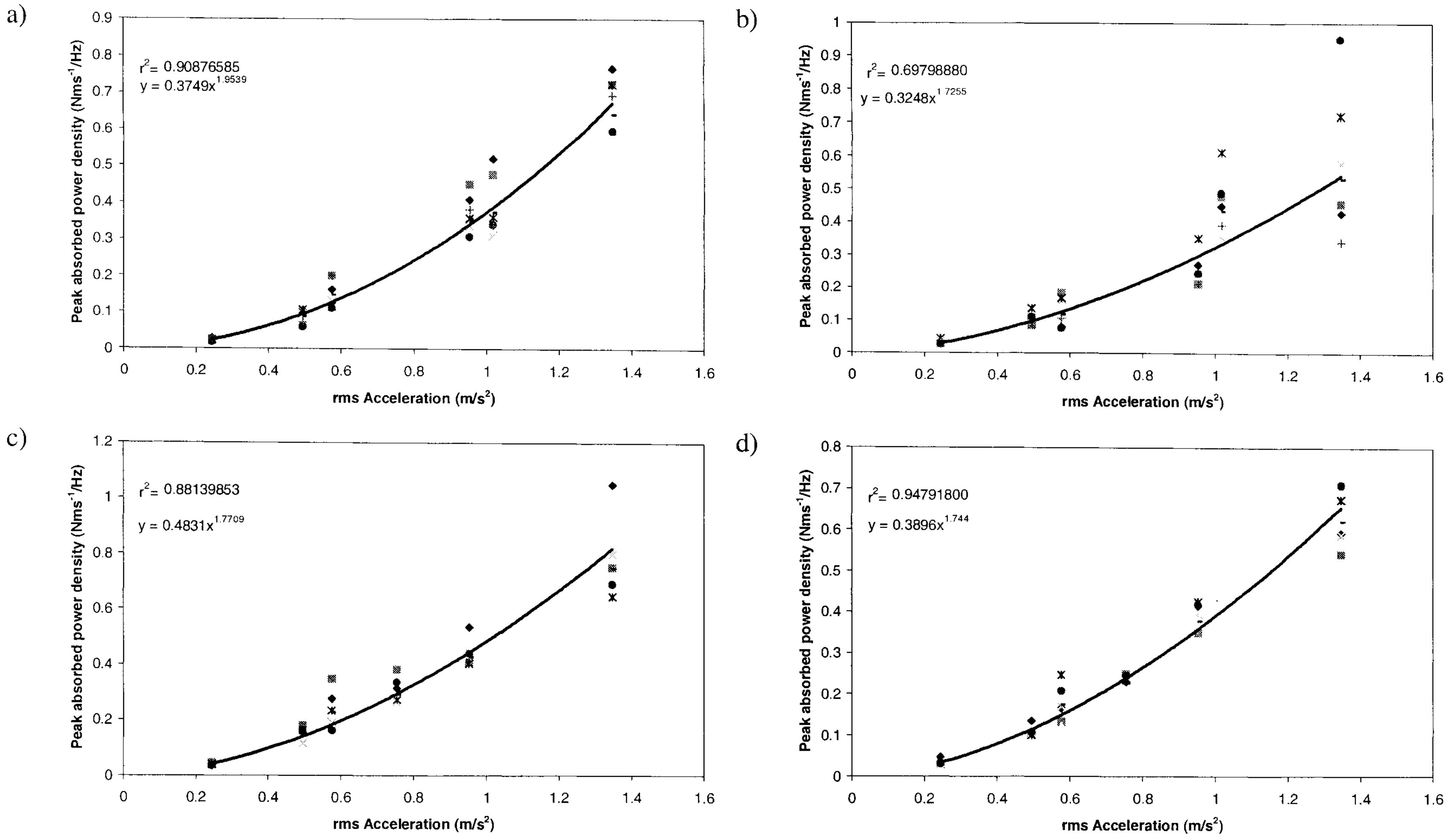


Figure 5.11: Dependence of peak absorbed power density on the acceleration magnitude : a) Back supported, fore-and-aft excitation; b) Back unsupported, fore-and-aft excitation; c) Back supported, lateral excitation; and d) Back unsupported, lateral excitation

under two directions of exposure and two sitting postures. The results are attained upon combining the data acquired under random as well as harmonic excitations. The results show the data acquired for the seven subjects, and the regression-based trend lines. The results in general show that the peak absorbed power density increases with the acceleration magnitudes in a nonlinear manner. The peak power density can be related to the rms acceleration by a power relationship, where the exponent could lie in the 1.72 to 1.95 range, depending upon excitation direction and posture. The results generally show reasonably good correlation between the peak magnitude of power density and rms acceleration for all cases, while the back not supported posture under x-axis excitation yields relatively lower r^2 value, in the order of 0.7.

Figure 5.12 illustrates the variations in the total power absorbed by the seated body with the magnitude of unweighted excitation along the two different directions and two postures, while combining the data attained under harmonic as well as random excitations. The results show variations in the total absorbed power with the rms acceleration, which are comparable to those present in Figure 5.11. The results also suggest better correlation for the total absorbed power than that observed for the peak magnitudes. The correlation coefficient (r^2) values exceeded 0.90 for both postures and axes of vibration, while the exponent value range from 1.74 to 2.01. These regression relationship suggest that the relationship between the unweighted rms acceleration and the total energy absorbed by the seated human body in the 0.5-10.0 frequency range is nearly quadratic. The non linear dependence on the excitation magnitude is also clearly evident. The peak power density as well as the total power absorbed under sine sweep conditions generally results in lower correlations with the input acceleration. This could

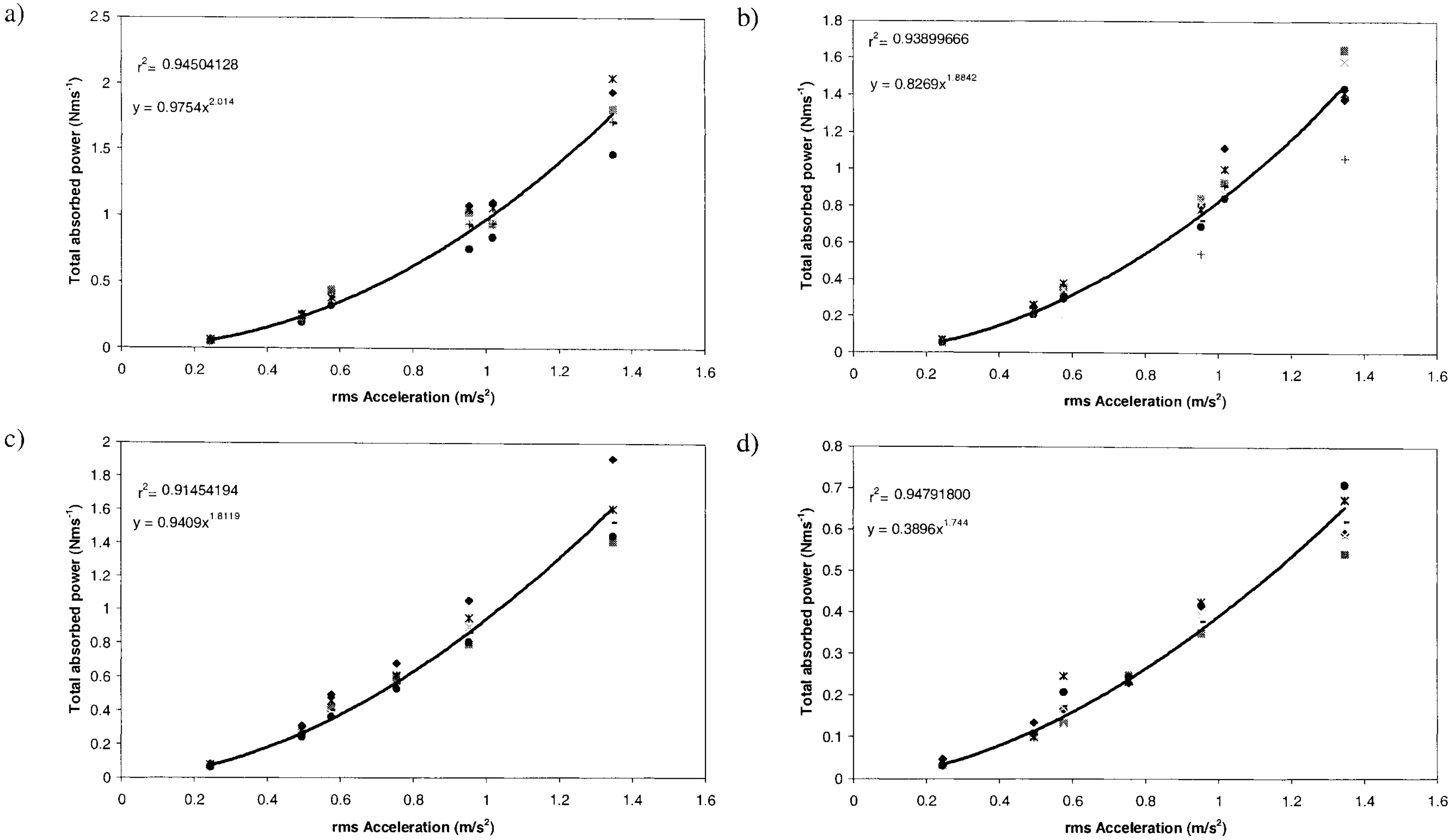


Figure 5.12: Dependence of total absorbed power on the magnitude of acceleration: a) Back supported, fore-and-aft excitation; b) Back unsupported, fore-and-aft excitation; c) Back supported, lateral excitation; and d) Back unsupported, lateral excitation

relate to the way the signal reverberates the different mechanism within the peak behaviour, the higher exposure time or even the suggested changes in muscle-response under different signals [14, 25]. Through combining the data for both stimuli, however, the correlation showed in general a better relationship than any excitation under the same type of stimulus. The peak power density magnitude was better correlated under lateral excitation.

5.5.3 INFLUENCE OF SEATED POSTURE

A single study performed thus far on the horizontal biodynamic response characterization has suggested strong effect of postural variations related to back support conditions [22]. Other studies on the transmission of seat-to-head motion have also shown strong influences of back support condition under both horizontal and vertical vibration [27, 29, 35, 100, 129]. The postural effects may be attributed to three factors: i) the human body is subject to multidirectional vibration when an inclined backrest is used, in conjunction with multiple driving points; ii) a backrest offers a restraint for the upper body; and iii) the effective seated mass may vary with the back support posture, when compared to that observed under unsupported sitting. The absorbed power characteristics of seated human body exposed to horizontal vibration, however, have not yet determined under different back support conditions.

The effect of sitting posture on the mean absorbed power density under both harmonic and random horizontal vibration is evident from Figures 5.4 and 5.5. The results show significant effect of the sitting posture on the magnitude responses under both directions of excitations. Under fore-and-aft excitation, the peak magnitude response under back supported postures is generally considerably higher than that for the unsupported at frequencies above 2.5 Hz for swept sine and at about 3.25 Hz for random excitation. The results exhibit distinctly different responses of the seated body under two postures in terms of frequencies corresponding to the peak magnitudes. The unsupported back posture yields primary peak at frequencies near 1.125 Hz, while the posture with supported back yields peaks for the maximum absorption of energy in the 3.125-4.375 Hz range. The results also show a secondary peak for the unsupported back posture at slightly lower frequencies that the principal peak observed under back supported posture. The results further show different magnitude responses under different types of stimuli. Whereas the principal peak for the harmonic fore-and-aft excitation reveals a higher magnitude under back supported posture, while the random fore-and-aft excitation yields higher peak magnitudes under back unsupported posture. The total absorbed power under exposure to white noise vibration, however, reveals comparable magnitudes, while the total absorption of energy when exposed to swept sine vibration shows magnitudes up to 22% higher under back supported posture. Under lateral stimuli (Figure 5.5) the plots reveal similar patterns under different postures. The presence of back rest, however, seems to add an "extra dose" of absorbed energy by the human body. The data attained with the supported back posture generally shows total absorbed power values around 12% higher than those attained under the unsupported posture.

The presence of back support tends to restrain the movement of the upper body, irrespective of the direction of vibration, while it increases the transmitted energy to the body at certain frequencies. The two principal peak responses observed under the back unsupported posture seem to merge into a single more comprehensive principal response when the backrest is added. This single peak tends to occurs in a higher frequency range under front-back excitations and in a lower frequency range under lateral excitations.

As it is explained in the previous chapter, the back in vehicular application, the WBV could be transmitted to the body from the seat pan, the backrest, the foot support and the hands in contact with the steering wheel. It has been reported that the effects of sitting contact with a back support could be annoying, or even influence the posture and the balance, which is related principally to the human response to low-frequency whole-body vibration [41, 43]. This contact and its related psychological and physiological effects “shape” the biodynamic responses in a particular manner. Sitting posture with an inclined backrest affects the biodynamic response more significantly, as evident from the reported data under vertical vibration [17,29]. A backrest however can reduce loads on the lumbar spine by transmitting part of the gravity forces due to the head, arms and upper trunk to the backrest [43]. Moreover, the back support tends to reduce the electrical activities of the lower back and abdominal muscles [63, 88]. The backrest also serves to support and stiffen the response to the upper body in response to perceived vibration [27], which is evident from the results attained in this study. The data reported in a few studies suggest that the geometry of the seat may affect the APMS resonant magnitudes and frequencies, when seated with the back support [17]. An inclined backrest tends to limit the backward motion of the upper body, while the forward motion could be reduced by the weight of the subject leaning against the back support. Consequently, adequate contact of the upper body with the backrest could be expected.

In Chapter 4 it was shown that large variations in per cent body mass supported by the backrest exist for all subjects. The subjects revealed a tendency to shift their torso to maintain adequate contact with the seat pan and the backrest. High magnitudes of variation are also attributable to differences in sitting styles of individuals. The responses measured at the seat pan and the backrest are examined, and the frequencies are compared in an attempt to enhance an understanding of modes associated with upper body and the whole body.

Figure 5.13 illustrates the mean absorbed power density response within the 0.5-10.0 Hz frequency range measured at the back support and at the seat pan under random and harmonic fore-and-aft excitations. The frequencies corresponding to the maximum absorption of energy observed from the seat pan coincides with the data attained for the backrest under the random excitation (3.123-4.135 Hz frequency range), whereas the data for the harmonic excitation reveal maxima absorption at slightly lower frequencies (3.0-3.25 Hz frequency range). The magnitudes of peak energy absorption attributed to the back support also reveal certain degree of correspondence with that observed at the pan, in the order of 40-50%. The corresponding results under swept sine are relatively higher than those attained under random excitation. In view of the similar trends in the absorbed power at both measurement points, it could be expected that the total absorbed power also are related. The total absorbed power measured at the seat pan is generally higher than that measured at the back support. The results clearly show that the backrest support contributes considerably to the total absorbed power by the seated body.

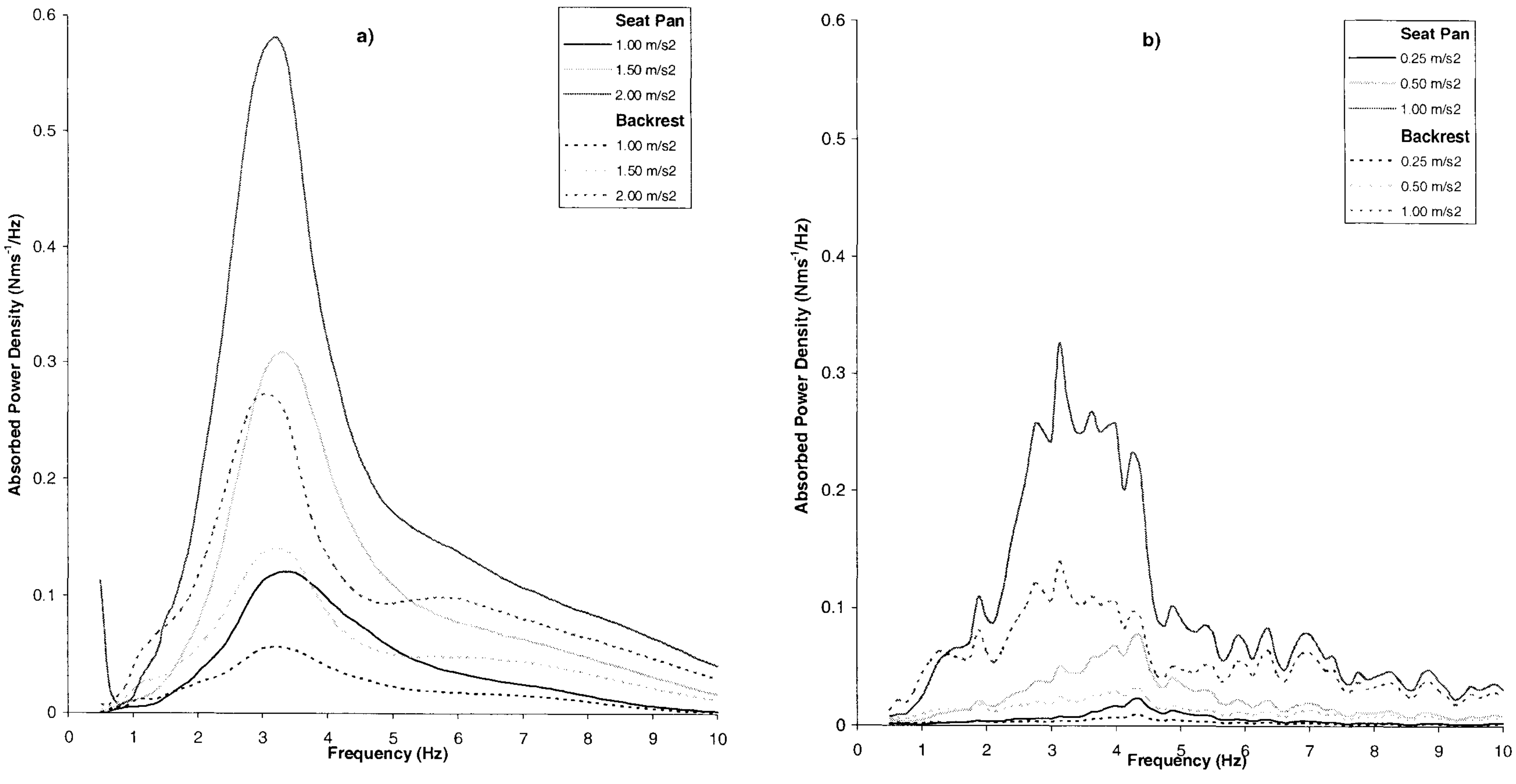


Figure 5.13: Mean absorbed power density measured at the seat pan and the back support interfaces under fore-and-aft excitation: a) sine sweep and b) white noise stimuli.

5.5.4 INFLUENCE OF TYPE OF VIBRATION EXCITATION

The published data on normalized absorbed power responses of the seated subjects exposed to vertical WBV suggest only little influence of different stimuli types [15]. Similar shapes of the absorbed power curves and little differences in the peak response were reported under exposure to vertical vibration. The data attained in the current experiments, however, suggest strong influence of the type of stimulus on the absorbed power response, when the seated subjects are exposed to horizontal WBV. The observed differences in the total absorbed energy suggest that the biodynamic behaviour of seated subjects under horizontal vibrational environment is determined by the type of stimulus. Lundström et al. [25] suggest that sinusoidal vibration could induce muscle-responses synchronized with the input, there by altering the vibration transmissibility and the absorbed power. It is thus desirable to compare the effects of different types of stimuli. Mansfield et al. [11] suggested the normalization of the data by dividing the measured absorbed power by the acceleration power spectral density. The proposed analysis performed for data attained during the current experiment, however, revealed noteworthy changes in the frequency response, specifically the frequency of the peak energy absorption. Figure 5.14 illustrates, as an example, a comparison of the measured absorbed power density with the normalized power for the subject number 1. The results clearly show that the proposed normalization alters the peak response and most of all the frequency corresponding to the peak absorbed power. This effect was also observed by Lundström et al. [25], notably at low frequencies.

In order to understand the effect of different types of vibration, the data attained under sinusoidal and random vibration with differences in the rms acceleration lower than 15% are compared. For fore-and-aft excitation, the data attained under swept sine excitation of 1.5 m/s^2 peak acceleration (0.95 m/s^2 rms) were compared with the data attained for 1.0 m/s^2 rms acceleration random excitation. For lateral excitation the responses under 1.0 m/s^2 (peak) swept sine stimulus was considered. In order to diminish the variations caused by the differences in the level of the excitations, the values were normalized using the square of the rms vibration magnitude, as suggested in [11].

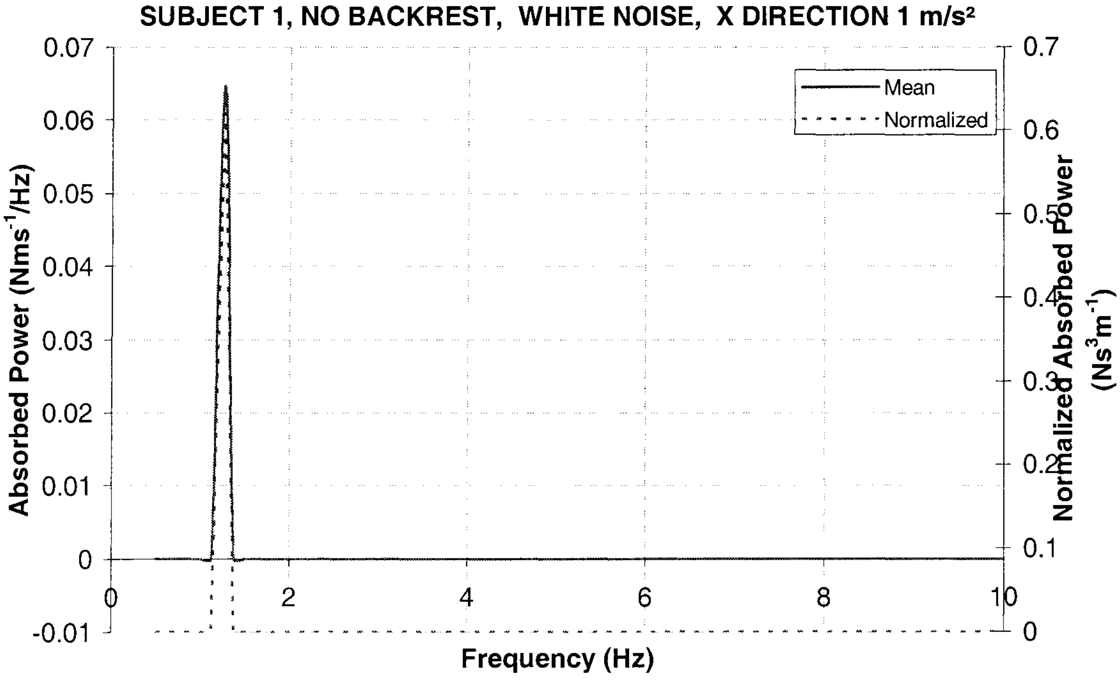


Figure 5.14: Comparison of mean absorbed power density and normalized power responses attained from the data acquired for subject #1 (unsupported back posture, fore-and-aft random excitation, 1m/s2 rms acceleration).

Figure 5.15 shows the comparisons between normalized mean magnitude responses attained under selected sine and random excitation, and both postures, for fore-and-aft and lateral stimuli, respectively. The results show very similar patterns for the principal peaks under both excitations, irrespective of the posture and axis of vibration, while some differences in magnitudes and the corresponding frequencies for the maximum absorption are evident. The differences for the back supported posture, however, are relatively small for the fore-and aft direction, which further supports the observations made with regard to stabilizing tendencies of the subjects. This behaviour, however, appears to be in contrast with the observations made from the APMS responses, which revealed no relevant differences for the supported back posture, irrespective of the excitation direction. The responses under the unsupported back posture and fore-and-aft excitation reveal a stronger influence of the excitation type on the peak magnitude of energy absorption. Random excitation causes significantly larger response under this posture, while the responses corresponding to the secondary peak showed similar magnitudes for both stimuli. Such differences, however, are very small when back supported posture is considered. For lateral stimuli, both postures show similar trends, while the back supported causes considerably higher peak responses under harmonic excitation.

The observed differences in the absorbed power density under random and harmonic excitations suggest that the biological systems behaviour is non-linear. Apart from the differences in the magnitudes of sinusoidal and random excitations, the responses reflect different perception of subjects to deterministic and random excitation. Under sinusoidal excitation, high displacement amplitudes associated with low

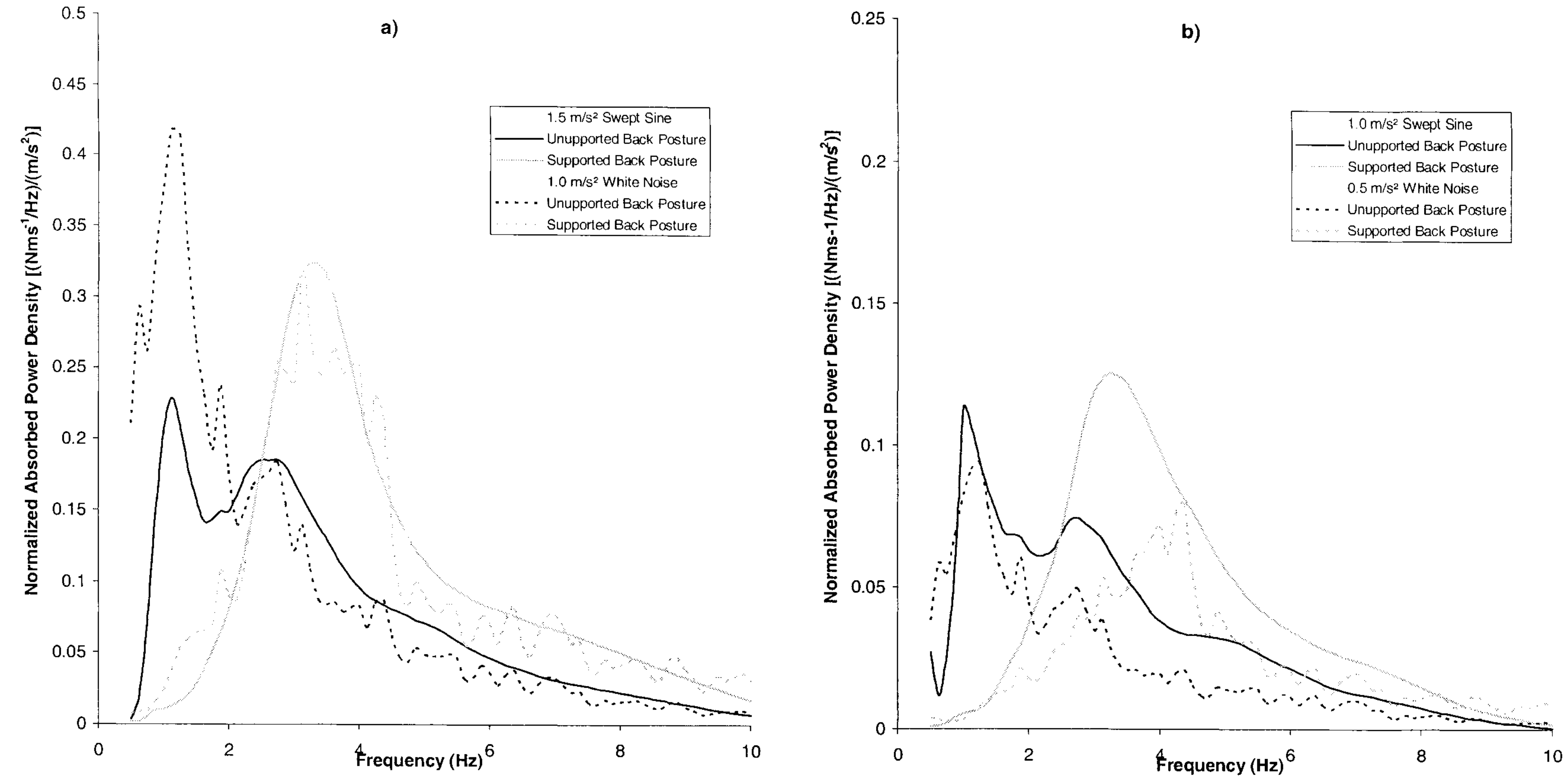


Figure 5.15: Comparisons of normalized absorbed power attained under swept sine and random stimuli: a) fore-and-aft excitation; and b) lateral excitation.

frequencies persist for a period of time and are well perceived by the subject. The subjects thus react to stabilize the sitting posture by varying the feet and abdominal forces, thereby stiffening the upper body in the low frequency range. The random excitations, however, do not provide such a perception for the seated subjects, and could thus yield different biodynamic responses. Similar trends were also found in the APMS responses described in the previous chapter. Mansfield et al. [26] stated that the magnitude of sinusoidal motion cannot be directly compared to a similar magnitude of random motion, even though both types yield similar values of rms acceleration. For sinusoidal vibration, all energy occurs at a discrete frequency, whereas for random vibration energy is spread over a wide band of frequencies. Despite the observed differences due to the type of vibration excitation, combining the results attained under both excitations seem to improve the correlations between the peak and the total absorbed power responses and the acceleration magnitude (Figures 5.6 and 5.7).

5.5.5 INFLUENCE OF EXCITATION DIRECTION

Previous studies on absorbed power under horizontal excitations suggest similar responses under excitations along the fore-and-aft and lateral directions [25]. Nonetheless, this reflected only the unsupported back posture. Figures 5.16 and 5.17 illustrate comparisons of mean absorbed power density responses obtained under fore-and-aft and lateral excitations, and back supported and unsupported postures, respectively. The results suggest reasonable similarity between the responses under two axis of vibration only for the back unsupported posture and random excitations. Significant differences in the *x*- and *y*- axes responses could be observed for the back supported posture,

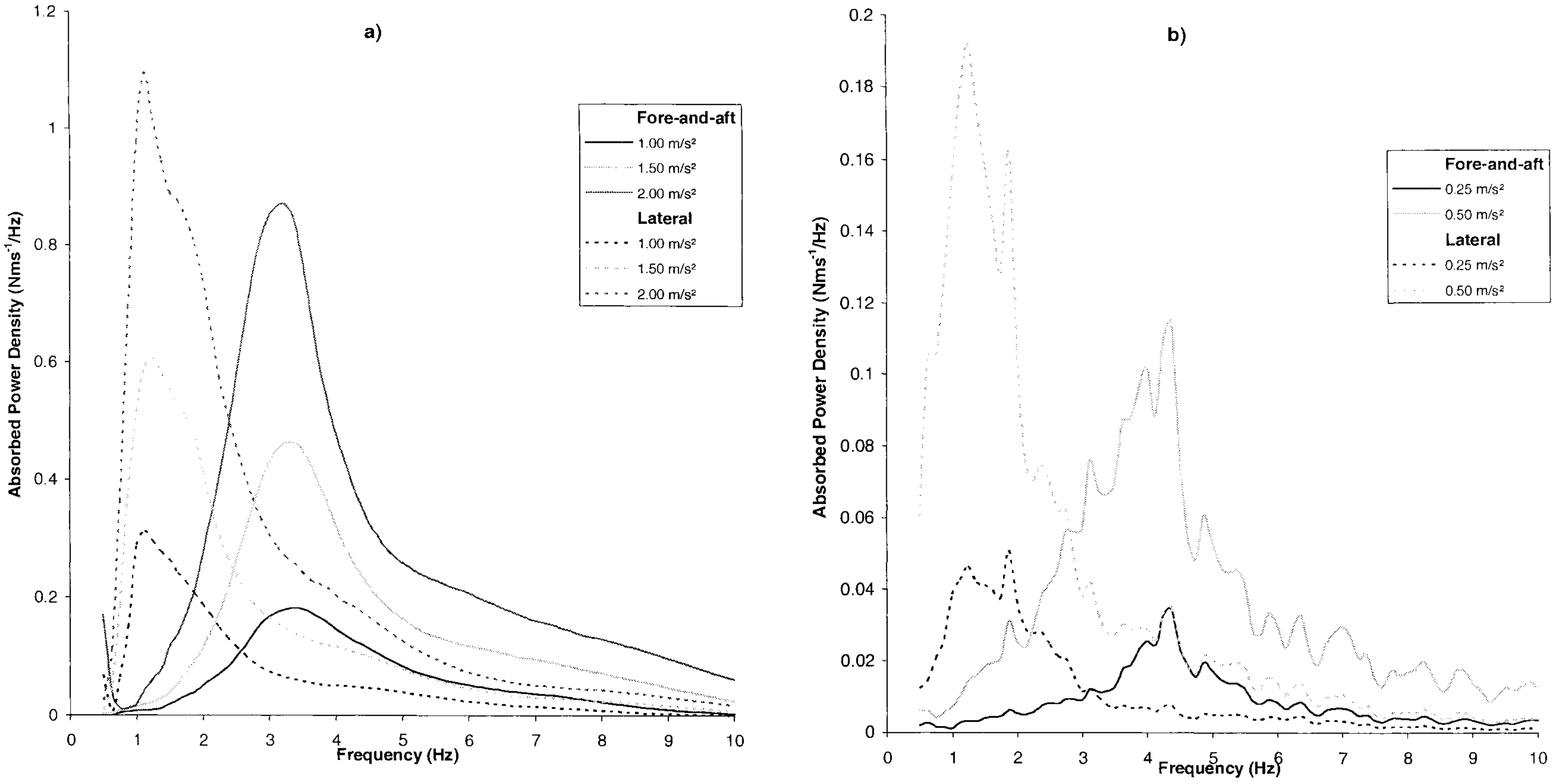


Figure 5.16: Comparisons of mean absorbed power density due to fore-and-aft and lateral excitations: a)sine sweep; and b)white noise stimuli (back supported posture).

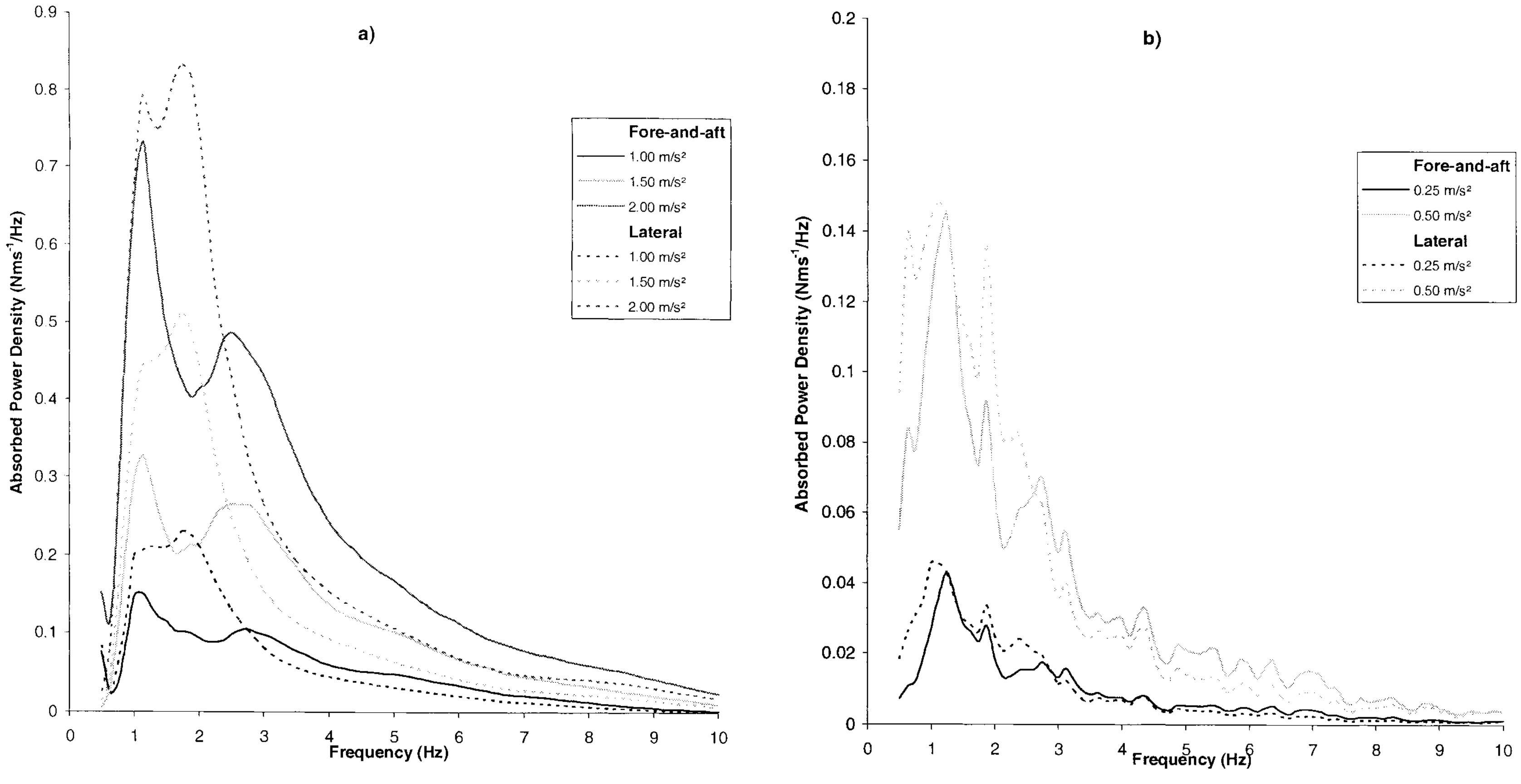


Figure 5.17: Comparisons of mean absorbed power density due to fore-and-aft and lateral excitations: a)sine sweep; and b)white noise stimuli (back unsupported posture).

irrespective of the type of vibration. Distinct differences are evident in both the peak magnitudes and the corresponding frequencies, which are more pronounced under fore-and-aft excitations.

5.6 COMPARISONS WITH PUBLISHED STUDIES ON ABSORPTION OF ENERGY DURING HORIZONTAL VIBRATION EXPOSURE

As it has been stated throughout this dissertation, only a few studies have been reported the biodynamic responses of seated subjects exposed to horizontal vibration. These include two studies on the APMS, by Mansfield and Lundström [26], and Fairley and Griffin [22], a single study reports the DPMI [24], and a single study on the absorbed power by Holmlund and Lundström [25]. The experimental conditions employed in the reported study describing the absorption of energy under x- and y- directions are thoroughly reviewed and compared with those considered in the present study. Besides, a single study comparing the absorbed power density under vertical excitation is also included [11]. The comparisons are summarized in Table 5.4. The study under vertical motion was performed using random excitations, while the study under horizontal motion was performed under sinusoidal excitations at discrete frequencies, while none of the studies considered the back support posture. In contrast, the present study considers sitting postures with and without a backrest, while the backrest is inclined at an angle of 24° with respect to a vertical axis, as it would apply to automotive seats. The seat pan in the present study is also inclined (13° with respect to horizontal) as opposed to the flat pans used in the reported studies. The mean mass and height of the test subjects employed in the reported studies were comparable. Moreover, the magnitudes of excitation used in all the studies fall within the common ranges. Owing to the differences

Table 5.4: Comparison of experimental conditions employed in reported studies.

Authors	N. J. Mansfield M. J. Griffin	R. Lundström P. Holmlund	Current experiment
Year	1998	1998	2003-2004
Measurement Objective	Absorbed power density (vertical)	Time-averaged absorbed power (horizontal and vertical)	Absorbed power density
Sample size	12 Males	30 (15/15 Males/Females)	7 Males
Age (years) M, SD (min, max)	26.25, 5.19 (21, 37)	38, 12 / 35, 10 (24, 59) / (22, 51)	34.86, 9.62 (25, 50)
Height (m) M, SD (min, max)	1.79, 0.07 (1.89,,	1.77, 0.06 / 1.67, 0.04 (167, 188) / (160/173)	1.75, 0.04 (1.70, 1.83)
Weight (kg) M, SD (min, max)	68.3, 7.3 (60, 85)	75, 9 / 63, 7 (55, 93) / (54, 76)	77.11, 9.41 (61.2, 88.1)
Vibration Magnitude (posture)	0.25, 0.5, 1.0, 1.5, 2.0, 2.5 m/s^2 rms (NB)	0.25, 0.35, 0.5, 0.7, 1.0, 2.5 m/s^2 rms (NB)	Swept sine 1.0, 1.5, 2.0 $m/s^{2\,\dagger}$ (WB and NB) White noise 0.25, 0.5 $m/s^{2\,*}$ (WB and NB) 1.0 $m/s^{2\,*}$ (fore-and-aft) 0.75 $m/s^{2\,*}$ (lateral)
Type of excitation	Random	Sinusoidal, increased in steps of 1/6 octaves	Swept sine / random
Frequency range	0.2 – 20 Hz	1.13-80 Hz	0.25-10 Hz
Exposure time	60 s	180 s	512 s (sine); 125 s (random)
Trials per subject	Not reported	Not reported	12 /axis
Seat pan	Flat	Flat	Inclined (13°)
Backrest	Not used	Not used	Inclined (24°)
Sitting posture	upright	Upright (erect and relaxed)	Upright and inclined
Feet	On the vibrating table	On the floor	On the vibrating table
Hands and arms	Not reported	Not reported	Rested in the lap

* → rms acceleration † → peak acceleration   NB → unsupported Back   WB → supported back in the experimental conditions and the reported function (time-averaged absorbed power and absorbed power density, for the horizontal and vertical studies, respectively), the results attained in different reported studies tend to differ considerably. The results obtained in the present study are compared with the reported results, and differences and similarities among them are discussed below.

In the present study, the frequencies where the peak absorption of energy occurs are compared with those identified in the published studies, for both postures and at each axis of vibration. The reported study under unsupported back exposed to horizontal vibration identified one principal peak response, slightly below 3 Hz, which coincides with the observed frequencies in the current experiments. The results obtained in the current study, however, reveals at least three peaks in the absorbed power spectra under white noise excitation and two peaks for the corresponding data when the excitation was swept sine, within the proclaimed frequency range. The study by Lundström and Holmlund [25] attempted the measurements in the 2.5-80 Hz frequency range for the highest level of acceleration, and thus could not identify the peaks responses below 2.5 Hz. Other conditions, such as the seat geometry could also play an important role with respect to the frequencies corresponding to the peak magnitudes. The frequencies corresponding to the peaks related to absorbed power density (Nms^{-1}/Hz) peaks observed in the current experiments are generally comparable with the proposed ranges related to average absorbed power (W). The magnitudes of measured absorbed power density, however, are considerably different due to different conditions employed.

Until now, the majority of the studies on biodynamic characterization of vibration-exposed seated subjects have been performed under vertical WBV. The absorbed power analyses performed by Lundström et al. [25], however, revealed that the absorption of energy under horizontal exposure is greater than that observed under vertical vibration exposure. The median values of the total absorbed power attained under lateral vibration exposure and lower levels of fore-and-aft vibration in the present study, are higher than those the reported under vertical vibration in [11]. The observed magnitudes are nearly 40% higher than those reported for the vertical vibration, with the exception of the responses measured under highest level of lateral, which revealed relatively lower magnitude of absorbed power.

The reported studies have suggested that the absorbed power could yield better correlations with the subjective discomfort than the acceleration-based method standardized in ISO 2631-1 [14, 31]. It is thus believed that the absorbed power could reflect the physical strain of the body. The ISO 2631-1 [1], recommends the use of W_d-weighting function to account for human perception of horizontal vibration. Figure 5.18 exhibits a comparison of the W_d-weighting with the mean absorbed power density responses for the unsupported back posture under fore-and-aft excitation and both postures under lateral excitation. For the purpose of comparisons, the absorbed power density responses were normalized with the respect to the magnitude at 1.25 Hz. Moreover, the data attained under harmonic excitations alone are considered for the analyses. The results suggest that the W_d-weighting follows comparable trends with the non-dimensional power density at excitation frequencies below 4 Hz and 3 Hz, respective, under x- and y- axes of vibration. The results also suggest that the weighting factors could underestimate the peak absorbed power, in the 1-1.125 and in the 2.5-3.625 Hz frequency ranges, for the fore-and aft excitation. For the lateral responses, the

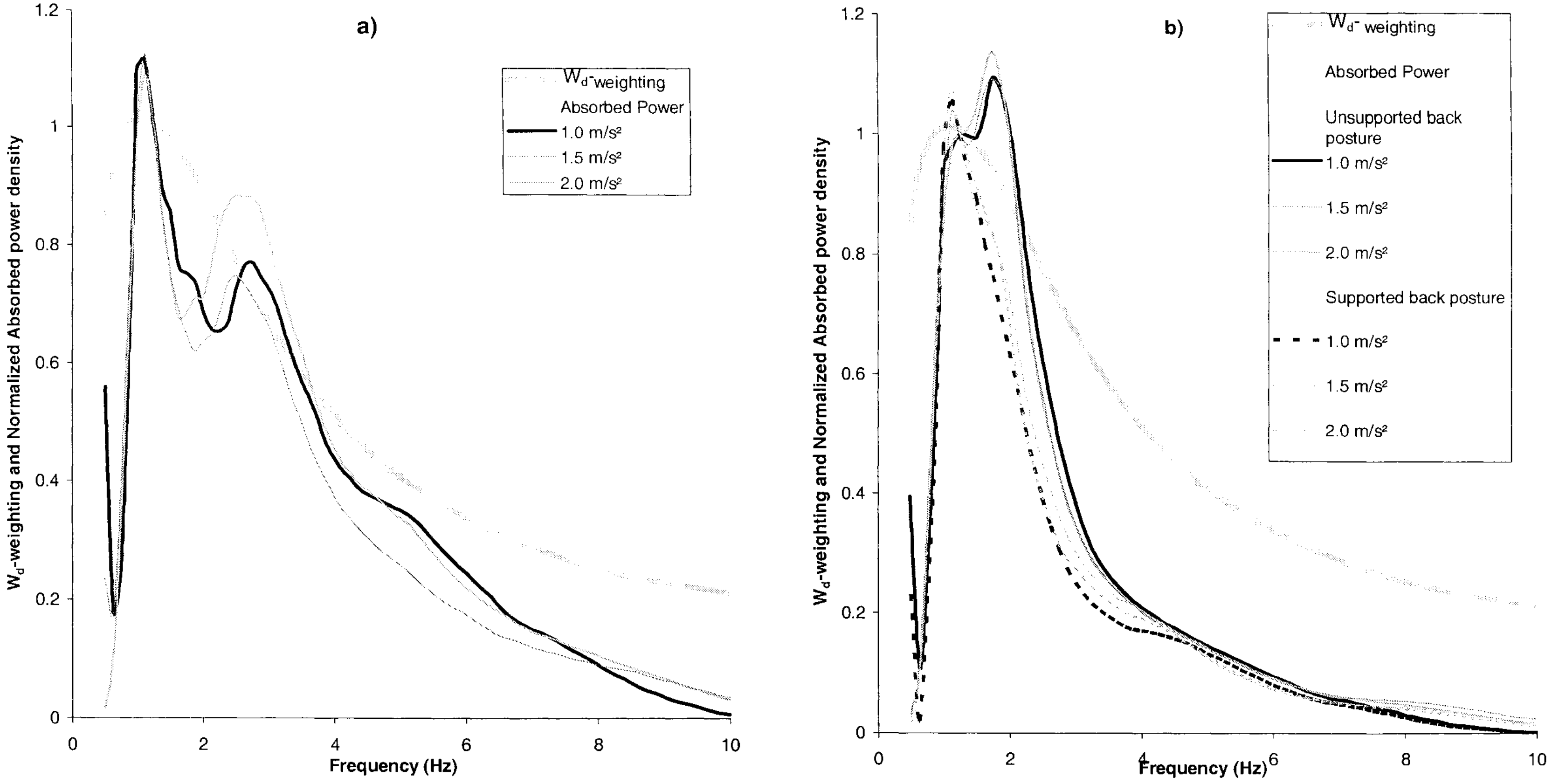


Figure 5.18: Comparisons between the W_d-weighting and the mean absorbed power density: a) fore-and-aft excitation; and b) lateral excitation.

weighting factors seem to underestimate the peak responses in the 1.0-1.25 and 1.25-2.25 Hz frequency range for the unsupported and the supported back postures, respectively. Lundström et al. [25] stated that the underestimate-region corresponds to 1.5-3.0 frequency range for the horizontal exposure to vibration.

5.7 SUMMARY

The energy-based absorbed power characteristics of the seated human subjects exposed to horizontal vibration, in an automotive posture, are derived from the measured data, in the 0.25-10.0 Hz frequency range. The data revealed relatively high inter-subject variability, which was attributed to individual factors and involuntary movements of the subjects. The observed degree of variability in the absorbed power, however, was lower that observed from the APMS biodynamic response. The mean absorbed power responses are presented and the trends are discussed to highlight the effects of sitting posture, as well as axis and magnitude of vibration. The role of the type of vibration is further discussed to emphasize the increased human perception of repetitive sinusoidal motion, which promotes a better contact at the backrest interface. Notwithstanding the existing differences in the responses under different types of input signals, the combined data increased the correlation between the anthropometric features and the responses. Along with discussion of the vibration effects, the computation of the total absorbed power, a single value that describe the absorbed energy within a frequency range, was developed.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

6.1 GENERAL

The exposure to whole-body vibration has been considered not only as a causal factor affecting the occupant health and safety but also as a source of significant discomfort. The injurious and discomfort effects of WBV among the seated human occupants, however, has been limited to the vertical component of the vibration, assuming that the vertical vibration predominate in vehicular environment and thus contribute mostly to the problems related to the exposure to vibration. The ride vibration characteristics of a large class of heavy road as well as off-road vehicles, however, show that the horizontal components of vibration could be as great as those encountered along the vertical component. Under these premises, the characterization of interaction of the seated human being with the biodynamic forces exerted by the vibrational environment under exposure to horizontal vibration could yield significant knowledge and insight into the assessment of exposure and means to diminish the injurious effects related to this exposure. The assessments, however, must take into consideration the contributions due seat design and the resulting postures, which have been revealed to be sources of extreme variation. Owing to the different and representative experimental conditions applicable to automotive seating considered in this study, the data set provided could serve as an important resource of information leading to characterization of biodynamic responses and energy absorbed by the seated occupant under horizontal vibration.

6.2 MAJOR CONTRIBUTIONS

The biodynamic characterization of seated occupant under horizontal vibration have been derived from the frequency-response functions, such as apparent mass (APMS) and absorbed power, under repetitive and well controllable experimental conditions. Owing to the lack of data available for typical automotive sitting postures, the study emphasizes the postural factors. The dissertation research thus involved: (i) design of the experiment, which involved the synthesis of selected vibration excitations, instrumentation, data acquisition and analyses, as well as the measurement methodology; (ii) designs of a horizontal vibration simulator and a test seat to simulate the desired postures; (iii) computation of the mean values and ranges of the measured biodynamic responses, along with the analysis of the effects of nature of vibration and back support on APMS response; and (iv) analysis of vibration energy absorption properties of the human occupant, and the effects of vibration magnitude and sitting posture. Considering that the biodynamic characteristic of seated occupants under horizontal vibration have been presented in only few studies, this dissertation research in its entirety is believed to represent a major contribution to the subject, the major contributions are summarized as follows:

- Establishment of Horizontal WBV as a potential Risk Factor: Published studies on vibration characteristics of various vehicles are thoroughly reviewed to establish the significance of horizontal vibration. It is shown that the magnitudes of horizontal vibration transmitted to the occupant are as significant as that of the vertical vibration, even though the studies on biodynamics focus mostly on vertical vibration.

- Review of Reported Biodynamic Studies: The reported studies are thoroughly reviewed to establish the lack of data on the biodynamic responses under horizontal vibration, specifically under typical automotive postures.

- Design of Seat and Vibration Simulator: An automotive seat coupled to a horizontal vibrator, operating under feasible and repeatable conditions, as well as capable of synthesizing representative vehicular vibration, including instrumentation and designed signals, has been developed and used to conduct the desired experiments.

- Analysis of Data to Characterize the APMS Response: The multifaceted biodynamic response of seated human body is characterized by several factors, which includes anthropometric features, adopted posture, and vibration attributes (magnitude, direction and excitation type). The analysis of the attained data sets revealed some degree of dependence on all these aspects. The analysis focus on one of the less reported variable, which implies no- or fully-supported human dorsum, which revealed the strongest influence on the human occupant response. The role of multiple point excitations at the seat pan and backrest on the biodynamic responses is investigated, which has not been addressed under exposure to horizontal vibration. The data are analyzed to systematically assess the effects of excitation magnitude, frequency and axis of vibration, sitting posture and anthropometric factors on the APMS response.

- Analysis of Data to Characterize the Absorbed Energy: The vibration energy dissipation properties of seated occupants exposure to horizontal vibration are investigated, and the effects of nature of excitation and sitting posture are described. The results attained are considered to form the major contribution since the power absorption of human subjects exposed to horizontal vibration has been reported in a single study with back unsupported posture.

6.3 MAJOR CONCLUSIONS

This dissertation research has provided the essential data on the human response to mechanical horizontal vibration in the 0.25 to 10 Hz frequency range, which is expected to contribute to the knowledge base under more realistic test conditions, such the role of seat design factors and sitting posture on the biodynamic response and energy absorption. The major conclusions and observations derived from the study are summarized below:

- It is established that a wide range of heavy road and off-road vehicles transmit comprehensive magnitudes of low frequency horizontal vibration. The magnitudes of such vibration could be either approach or exceed those of the vertical vibration.

- The reported data on the biodynamic characteristics of seated occupants exposed to horizontal vibration can be considered applicable for postures without back support or contact with a vertical backrest. This sitting condition does not represent automotive seating that involves inclined pan and contact with an inclined backrest.

- Both the APMS and absorbed power responses revealed considerable inter-subject variabilities, which could be attributed o anthropometric differences, involuntary movements of the subjects under high magnitudes of vibration, individual sitting habits involving the use of backrest contact, etc.

- The backrest provides a source of support, restraining the backwards movement but inciting, as the direction of motion changes, the upwards movement of the upper body, which adds complexity to the response. For lateral excitation, this body movement mostly depends on the friction rather than the support. However, measurements at the back support interface showed that the front to posterior displacement of the upper body could be limited by the backrest. In fact, it appeared to add supplementary energy to the structure. The absorbed energy characteristics under lateral vibration revealed emphasized resonant peaks caused by extra-doses of absorbed energy, which is reflected in the total amount of absorbed power in the range. The contribution due to this additional dosage is also found in the fore-and-aft responses to sine sweep stimulus.

- The biodynamic responses to horizontal vibration in the 0.25-10.0 Hz frequency range differ significantly from those under vertical vibration. This behaviour could explain the use of different frequency weightings to compensate for differences in human susceptibility to vibration direction.

- The back support condition affects the APMS and absorbed power responses in a most significant manner. Sitting with unsupported back causes peak APMS responses in the vicinity of 1 Hz, while the supported back shifts the peak responses in the vicinity of 3 Hz.

- The effect of vibration intensity has been generally observed to be negligible for vertical biodynamic responses. The horizontal biodynamic responses are strongly dependent upon the vibration intensity, suggesting that the biological system is strongly nonlinear when exposed to horizontal vibration.

- The absorbed power due to horizontal vibration increases in proportion to the magnitude of transmitted vibration. The regression analyses confirmed that the power increased approximately in proportion to the square of the exposure level. The APMS response showed lower correlation with the vibration magnitude.

- Variations in the input level showed no defined trends in view of the resonant frequency of the seated body under horizontal stimuli, contrasting the reported inverse correlation found under vertical excitations.

- The total energy absorbed during exposure to random stimulus appeared to be stimulated by the upper body, while during exposure to sinusoidal stimulus it is partially controlled by the muscles-actions. It had been proposed that deterministic signals could induce muscle-contractions due to enhanced perception of such motion by the seated subjects, which encourages muscle-reactions to limit upper body motions. But the variations appeared to be not only due to muscle-activity: constant supplementary peaks around the principal resonances suggest that random stimulus induced reverberation of limbs contributing to these resonances, while sinusoidal response seemed to be linked to the whole-body response.

- With regards to the subjects' anthropometric characteristics, the body mass displayed the highest influence on the biodynamic responses in the 0.25-10.0 range. The absorbed power revealed high correlation with the subjects' mass. The peak APMS magnitude and the corresponding frequency are also strongly influenced by the body mass. Heavier subjects tend to yield lower magnitude of the principle peaks under fore-and-aft motion, and exhibit a third resonance under lateral motion.

- The body stature also showed some influence on the biodynamic response. For the apparent mass, the third peak was better defined for shorter subjects under fore-and-aft excitations. In contrast, the absorbed power revealed poor correlation with the subjects' height. Both the APMS and the absorbed power magnitudes suggested better correlation with the body mass to height ratio.

- The back support emerged as the biggest distinction, exhibiting principal resonant responses with higher magnitudes and at higher frequencies. It had been proposed that this change obeys to a stiffening process in the upper body. The presence of secondary resonances with lower magnitudes but in similar ranges to those acquired under no-back conditions could suggest other related phenomena: the contact with the back support really stiffness the upper body, but the contribution of other mechanisms in the resonance at low frequencies is still there; the backrest-touch reverberates resonant mechanisms at the same time that constrains others.

- The APMS responses under fore-and-aft excitation and unsupported back posture revealed three distinct peaks in the frequency range reported in earlier studies. The first peak, occurring at frequencies below 1 Hz revealed no clear tendency with increasing excitation level, as previously reported. The second peak, occurring around 2.5 Hz, increased in magnitude, while the corresponding frequency decreased as the stimuli augmented. This particular peak for most of the subjects was judged as the principal resonance. The third peak, occurring in the vicinity of 5 Hz, reduced in magnitude and the corresponding frequency as the vibration intensity increased.

- The APMS response of occupants seated with back supported have been reported to predominate around a single frequency of 3.5 Hz. The current study suggests the presence of two additional peaks in addition to the one near 3.5 Hz. The APMS responses reveal first peak near 1.5 Hz, which was also evident from the measurements performed at the backrest. A third peak observed in the vicinity of 6 Hz, displayed a higher intra-subject's spread than the unsupported dorsum, which can be described as a muscle-induction at higher magnitudes of stimuli.

- The APMS responses under lateral excitation revealed central tendency for the resonant responses and the corresponding frequencies regardless of the posture. The responses under back not supported postures revealed principal peak near 1.125 Hz. The peak magnitudes tend to diminish with increasing excitation level. A secondary peak was also observed in the 1-2.5 Hz range. The frequency of this peak decreased with increasing excitation magnitude. The two peaks merged into a single one under higher magnitude of excitation.

- The APMS responses should be normalized to suppress the apparent effect of the body mass. The normalization method involving the quotient of the real and imaginary components of the responses divided by the individual seated mass yields the most accurate results.

- The absorbed power characteristics suggest that 50% or more of the total energy was found concentrated in a band of 2 Hz around the resonance zone. This range coincides with the region where wheeled off-road vehicles transmitted their maximum vibrational energy. Besides, this range is also close to the one that denotes the frequencies where the sensation of discomfort is higher.

6.4 RECOMMENDATIONS FOR FURTHER STUDIES

The present study constitutes a preliminary effort in quantifying the human response to horizontal vibration under typical automotive seating postures. Owing to the complexities associated with the biological system, far more efforts are needed to attain reliable data in terms of both the APMS and the energy dissipated by the exposed occupant. The current study has been limited to investigate the seated human biodynamic responses to horizontal excitations of harmonic and random nature, while seated with two different postures and exposed to vibration along the two directions. Furthermore, the study involved idealized white noise and sinusoidal excitations of different magnitudes and only 7 subjects. In order to enhance the characterization and thus, their application, it is recommended that the further studies consider the following guidelines:

- The present study suggests strong contributions due to back support with an inclined backrest. It is recommended that the role of back support under different inclinations of the backrest and pan be considered. Moreover, the effect of hands position on a steering wheel should be considered to represent a typical driving posture. Other factors, such as seat height, may also be considered important.
- Owing to the strong influence of the sitting posture, alternate methods are desirable to ensure consistent and controlled posture. This may be realized using visual as well as instrumented indicators of palpable variations. Besides, this control could help to avoid extra muscular strength due to psychological and physiological reactions to slapping contact.
- Considering that the APMS biodynamic response is independent of the exposure time further efforts in characterizing the biodynamic responses in terms of time-dependent energy absorption are desirable.
- The analysis of the acquired data for the current experiments definite relationship between the changes in acceleration stimuli and the biodynamic responses, with better correlation for the absorbed power method. The absorbed power may thus serve as a better assessment method. A refined method however needs to be developed on the basis of additional data acquired with a larger sample and representative test conditions.

- A seated human body in a working vibration environment is exposed to multi-directional stimuli. Further studies are thus desirable under multi-axes stimuli.

- The to-the-body functions, as a result of using only one driving point of measurement, are indeed limited to detect the resonances triggered by limbs close to the interface. As the complexity of the working vibration environment includes the use of back support, the characterization of the responses must be explained in terms of both contact points, backrest and seat pan. Besides, an analysis of vibration transmission to different body segments could help in the determination of the precise limbs involved in the resonance behaviour, as well as in the understanding of the differences due to shifting of the principal resonance mechanisms. Both, to-the-body and through-the-body biodynamic responses, could thus provide some understanding of the resonance behaviour under non-orthogonal directions.

- Further efforts should be made to acquire multi-axis force and motion at the back support, while limiting the friction. Besides, to avoid involuntary contact with this surface, the backrest must be designed as a removable feature.

- From the biological point of view, the human body exposed to vibration comprises diverse histological, psychological and physiological reactions. This study supposed psychological factors inducing expected or unexpected reactions, mainly at the muscular level. However, in order to confirm the veracity of these assumptions, the muscle-activity under vibrational environment must be measured. Besides, heart rate and other vital measures could be performed to understand other complex reactions.

- The current experiments have been limited to low vibration frequencies. It would be desirable to extend the frequency range to 20 Hz to study the effect of wheel hop modes of road vehicles occurring in the 12-15 Hz range.

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Appendix A

Consent Form

and

Test Protocol

PARTICIPANT CONSENT FORM
CONCAVE RESEARCH CENTRE
DEPARTMENT OF MECHANICAL ENGINEERING
CONCORDIA UNIVERSITY

PROJECT: Biodynamic characterization of seated human occupants under horizontal vibration.

A. PURPOSE OF THE EXPERIMENT:

The primary goal of the experiments is to characterize the human responses to horizontal vibration in terms of absorbed energy and apparent mass. The knowledge acquired under a wide range of experimental conditions will serve as a basis to define means of simulating the driver-seat interface while conducting laboratory seat performance testing intended for various categories of vehicles, and for developing nonlinear occupant models. The program of work will be carried out in the CONCAVE laboratory using the custom-designed whole-body horizontal vibration simulator. The simulator consists of 1.25 m x 0.75 m horizontal platform supported on a servo-controlled hydraulic actuator. The actuator and controller are programmed to synthesize the horizontal motions encountered in automobiles, city buses and industrial vehicles, such as a forklift truck. The controller is equipped with following unique safety control loops:

a. FORCE-CONTROL LOOP: To limit the maximum compression and extension force to the simulator. The force limits ensure maximum true acceleration of the simulator less than or equal to 2 m/s^2 rms (root mean square), during an experiment. An acceleration level exceeding the preset limit will cause the shut down of the motion simulator.

b. POSITION-CONTROL LOOP: A position feedback control loop is employed to limit the maximum displacement during a test, which further limits the acceleration to 2 m/s^2 . The motion corresponding to this acceleration level would be similar to the side-to-side motion encountered while riding a train. A displacement input exceeding the set limits will shut the motion simulator automatically.

c. SUBJECT AND OPERATOR CONTROL SWITCHES: The subject and operators both are provided with a hand-held safety switch, which when activated will cause the shut-down of the motion base.

B. PROCEDURES

A rigid seat and a steering column are installed on the motion simulator. The seat is instrumented using a miniature accelerometer (5 mm diameter and 5 mm high), which is installed underneath the seat pan. This accelerometer measures the vibration levels at the subject-seat interface. A total of two force sensors are installed between the seat base and the platform to measure the resultant force of the seat-occupant system. It should be noted that no sensors would be applied to the occupant.

Each subject will be asked to sit on the seat, mounted on the motion simulator, in a typical posture defined by the experimenter. The motion simulator will be driven to generate low frequency vibration, similar to those experienced in automobiles, city buses and industrial vehicles. Each subject will be asked to maintain four different postures representing a driving posture (sitting erect with hands on the steering wheel, and with and without back support) and a passenger posture (sitting relaxed with hands in the lap, and with and without back support) during an experiment. Each experiment will be repeated three times. The nature and levels of vibration and the corresponding duration of the tests are summarized below:

a. Sinusoidal motion of 5 cm peak displacement in the 0.5 Hz to 1 Hz frequency range, and 2 m/s^2 peak acceleration in the 1 Hz to 8.0 Hz frequency range. (Duration: 5 minutes). The sinusoidal motion is a cyclic motion that comprises forward and backward motions in a given cycle, where the frequency in Hz refers to cycles of forward and backward motion in one second.

b. Vibration spectra (pattern) of automobiles measured on the GM test track. (Duration: 1 minute)

c. White noise random vibration of magnitudes 0.1, 0.2 and 0.3 m/s^2 rms (Duration 1 minute each). This motion pattern causes similar level of acceleration (motion), irrespective of the rate of cyclic motion (cycles/s).

d. Horizontal vibration spectra of a city bus measured on the STM buses. (Duration: 1 minute)
e. Horizontal vibration spectra of a forklift truck, as acquired during earlier studies. (Duration: 1 minute).

A total of 84 tests will thus be performed with total exposure duration of approximately 132 minutes. The vibration data will be acquired during each test for later analyses. The objective of the study is to study the human response to vibration during this test duration only. The tests will be conducted over 4 different days to limit the vibration exposure to nearly 33 minutes on a single a day.

C. RISK:

None to the best of researcher's knowledge, since the levels of vibration are well below the safe levels recommended by the International Standard, ISO-2631. Furthermore, the cumulative daily exposure of 33 minutes per day is is well below the criterion defining safe exposure in the International Standards ISO 2631-1:1997 and ISO 13090-1:1998. The individuals with history of severe previous back injury(ies), however, are not permitted to participate in the study.

D. CONDITIONS OF PARTICIPATION

- I understand that I am free to withdraw my consent and discontinue my participation at anytime without negative consequences.
- I understand that the data from the study will be available to me, when published. A copy will be made available to me, if I am interested.
- I acknowledge that I do not have a history of previous back injury(ies).
- I understand the purpose of the study and know that there is no hidden motive of which I have not been informed.

I HAVE CAREFULLY STUDIED THE ABOVE AND UNDERSTAND THIS AGREEMENT. I FREELY CONSENT AND VOLUNTARILY AGREE TO PARTICIPATE IN THIS STUDY.

If you have questions regarding your rights as a research participant, please contact Michelle Hoffman, Compliance Officer, Concordia University, at (514) 848-7481 or at michelle.hoffman@concordia.ca.

NAME (please print): ______________________

SIGNATURE: ______________________

WITNESS SIGNATURE: ______________________

DATE: ______________________

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	Wenping Wang Concave Research Centre Department of Mechanical Engineering
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TEST PROTOCOL

The present protocol has the finality to conduce the experiments in the area of vibration and shock with the designation: ***BIODYNAMIC CHARACTERIZATION OF SEATED OCCUPANT UNDER HORIZONTAL VIBRATION, CONCAVE 2003***

to be conducted by: ***Dr. Subhash Rakheja / I.M.E. Marco Antonio Peña Coronel***

at: ***Concordia Center for Advanced Vehicle Engineering, Concave Research Center***
6277 St. Jacques West, N.D.G. section of Montréal, Québec H4B 1T8, Canada

during the period to: **May-Jun 2003**

The present test will be labelled as BCSO-HV

OBJECTIVE AND BACKGROUND:

The main purpose of the experiments is to characterize the human responses to horizontal vibration in terms of absorbed energy and apparent mass. The knowledge obtained under a wide range of experimental conditions will serve as a basis to define means of simulating the driver-seat interface while conducting laboratory seat performance testing intended for various categories of vehicles, and for developing nonlinear occupant models. The program of work will be carried out in the CONCAVE laboratory using the custom-designed whole-body horizontal vibration simulator. The simulator consists of 1.25 m x 0.75 m horizontal platform supported on a servo-controlled hydraulic actuator. The actuator and controller are programmed to synthesize the horizontal motions encountered in automobiles, city buses and industrial vehicles, such as a forklift truck.

SUBJECTS:

Seven subjects will be tested. Personal information (gender, age, weight, etc) will be registered in the format labelled "Biodynamic Response Measurement Documentation"; the criteria for their selection or exclusion due to medical/physical disorders will be based on the "Questionnaire of Viability" form.

Previous any test, after be approved as subject of experiment, subjects will be measured, weight and height, in standing position; if the subject is required for any other session in different day, the weight must be measured at the beginning of that session.

PROCEDURES:

Start-Up Sequence

In a start-up sequence is necessary to include verifications in all the monitoring equipment and delimitating systems, and in the integrity of the controls and input circuits. The procedure to star-up the backup equipment, such are the oil pumps, air compressor, water and oil supplies, etc., has previously been development by the technicians and personal of Concordia Center for Advanced Vehicle Engineering, Concave Research Center (Operation Procedure for Horizontal Tester System).

Initial Set-Up

- The expected magnitudes of the stimulus must be verified without subjects (seat alone).
- All emergency devices must be proven to verify that their operation is correct:
  - Safety System 1: While the mechanism is shaking without any subject, push the red button on the MTS 407 controller panel. Verify the system has stopped.
  - Safety Systems 2 and 3: Verify their set-point in the MTS 407 controller; if they are correct, scroll the knob until reach levels of displacement-acceleration over the set-point (no subject must be on the mechanism). Verify the system has stopped.
  - Safety system 4: The mechanism must be tested shaking in low level with the subject on it. While the system is running, the subject must push the red button placed on the seat. Verify the system has stopped.
  - Safety system 5: At the beginning of the session each session, the procedure when started principal oil pump includes to push the red button at the master pump control.
- In regular intervals, and at least before and after each series of tests, the calibration of transducers and circuits used for the control and supervision must be verified.

Normal Operating Sequence

The protocol for this experiment will be:

1. Start up auxiliary systems (pumps, water-oil supplies, etc); verify no presence of leaks, sounds or smells no related to the test.
2. Star up Control System (MTS 407 Controller); verify set points:
   a. Span = 0
   b. Wvform = ext input
   c. P. gain = according the required input.

3. Star up Analyzer
    a. Start up Notebook C6000; verify there are not error messages.
    b. Start up Pulse Labshop version 6.0 software; verify there are not error messages.
    c. Verify inputs (signal, transducers) and outputs (transducers), physical conditions and configuration in the software.
4. Prior to beginning the first trial, and before start any series of trials, the correct operation of the test mechanism, must be tested. This includes:
    a. Emergency stops.
    b. Alarm /warning signals in the MTS 407 controller and in the Pulse Labshop software.
    c. Presence of objects/people near to the slip table and/or shaker.
5. With the test seat mechanism empty and the gain in the MTS 407 controller at zero, start the signal from the Pulse labshop software.
6. Increase the gain in the the MTS 407 controller.
7. Test two complete cycles without subject.
8. Verify there are no alarms, warnings, sounds, smells or leaks no related to the experiment. n the case of any incidence, return this sequence to the element is wrong. If can be corrected, continue sequence, If not, abort the experiment until secure conditions are established.
9. Stop the excitation on the shaker. The subject never must be in standing position without the complete stop of the shaker.
10. The subject must raise to the slip table, using stairs provide. If any help is required, the experimenter could be help.
11. Sit down the subject, adopting the posture indicated in the "Biodynamic Response Measurement Documentation"; also this document provides the trial sequence.
12. Restart the excitation on the shaker, with slow increment in the gain.
13. The measurement must be through all the cycle, with the gain in the nominal level.
14. The excitation could be interrupted if the subject feels discomfort, annoyance or motion sickness, or if the experimenter/observer detects any of these effects on the subject.
15. The excitation must be interrupted if the crew detects any variance during the experiment that could affect the subject integrity.
16. Once the measures have been obtained, stop the excitation shaker, in order to allow the subject move down from the slip table. Follow the observation in point 10.
17. Repeat from point 11 to 17, changing only the subject posture (according to information).
18. Every 6 trials, verify the conditions of the test mechanism, regarding changes in the initial conditions.

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Emergency Procedure

The experiment, inputs and protective equipment has been development in order to prevent any risk in the integrity of the subject; however, the test must be aborted if there are any signals of discomfort, motion sickness or potential risk in health.

If the subject feels raise in the corporal temperature, raise in the cardiovascular rate, difficulty to breathe, or sudden twinge in any body part, the subject must stop the trial.

If the subject loses the conscience or has any difficulty to stop the current event, any person is allowed to stop the trail, using the regular equipment provides in this matter.

If It's necessary the use of first aids or the use of ambulance, the emergency procedure at Concave Research Center is applied.

- Phone (9)-911 if emergency, AND ALSO PHONE **3707**, giving the next information:
    - Your name,
    - The address & location (concave)
    - Phone number,
    - Type of incident,
    - Number of persons injured,
    - Type of injuries (let the operator hang up first before you, in order to make sure that he/she has all the information necessary,
    - Wait at or near the scene of the problem to assist when the Security Officer arrives.

STAFF AND CREW:

Experimenter A:	***Dr. Subhash Rakheja***	Experimenter B:	***Marco Antonio Peña Coronel***
Instrument controller	***Harry Politis***	Witness:	***Wenping Wang***
technical support	***Dainius Juras***	Technical Support	***José Esteves***

Experimenter (signature): Experimenter (signature):

Approved by the Ethical Committee:

Date:

Name and Signatures: