ROLE OF SEAT DESIGN FACTORS AND BIODYNAMIC CHARACTERIZATION OF SEATED OCCUPANTS UNDER HORIZONTAL VIBRATION

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ABSTRACT

ROLE OF SEAT DESIGN FACTORS AND BIODYNAMIC CHARACTERIZATION OF SEATED OCCUPANTS UNDER HORIZONTAL VIBRATION

Santosh Chary Mandapuram

Occupational vehicle drivers are exposed to vibration environment which is known to cause discomfort, annoyance, and health and safety risks. The seated occupant responses to whole-body vibration have been widely investigated along the vertical axis alone. Owing to the comparable magnitudes of vibrations observed in heavy road and off-road vehicles along horizontal axes, there exists a need to investigate the occupant responses to horizontal vibration. Only a few studies have reported seated occupant responses to horizontal vibration, which consider either back unsupported posture or vertical back support. The applicability of the reported data for sitting postures adopted in typical vehicles is thus questionable. Moreover, the influence of the seat height has not yet been addressed. This dissertation research concerns with biodynamic response characterization of the seated human subjects exposed to horizontal vibration through measurements of dynamic interactions between the seated body and the seat pan, and the upper body and the seat backrest in terms of apparent mass and absorbed power. The experiments involved: (i) three different back support conditions (no back support, and upper body supported against a vertical and an inclined backrest); (ii) three different seat pan heights (425, 390 and 350 mm); and three different magnitudes (0.25, 0.5 and 1.0 m/s^2 rms acceleration) of band limited random excitations in the 0.5-10 Hz frequency range, applied independently along the fore-aft and lateral directions in an uncoupled manner. The body force responses, measured at the seat pan and the backrest along the direction of motion, are applied to characterize the total body response reflected on the seat pan, and those of the upper body reflected on the backrest. Unlike the reported responses to vertical vibration, the responses to horizontal vibration show strong effect of excitation magnitude.

The mean responses measured at the seat pan and the backrest suggest strong contributions due to the back support condition, and the direction and magnitude of horizontal vibration, while the role of seat height is important only in the vicinity of the resonant frequencies. In the absence of a back support, the seat pan responses predominate at a lower frequency under both directions of motion and the addition of back support causes the seat pan response to converge mostly to a single primary peak, resulting in a single-degree-of-freedom like behaviour. The backrest, however, serves as another source of vibration to the seated occupant, which tends to cause considerably higher magnitude responses. A relaxed posture with an inclined backrest, however, causes a softening effect, when compared to an erect posture with a vertical backrest. Absorbed power data revealed better correlation with the anthropometric factors and magnitude stimulus. The seated occupant responses to harmonic horizontal vibration were also investigated under comparable experimental conditions considered under random excitations. The results show significant differences in the responses to two types of excitations. The data reported in this study is expected to serve as an important basis for developing mechanical equivalent models of the seated occupant expose to horizontal vibration.

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NOMENCLATURE

a_{rms}	Frequency-weighted root-mean-square (rms) acceleration
$a_w(t)$	Frequency-weighted acceleration obtained by applying W_d- weighting filter defined in ISO-2631 (m/s^2)
$(a_w)_{peak}$	Peak frequency-weighted acceleration (m/s^2)
$a_w(t_0)$	Weighted rms acceleration corresponding to an observation time t_0 (m/s^2)
APMS	Apparent mass (kg)
ANOVA	Statistical analysis of variance
CoV	Statistical coefficient of variation
$C(\omega)$	Coincident spectral density function
DPMI	Driving point mechanical impedance
F_{bx}	Force response measured at backrest
F_{px}	Force response measured at seat pan
$F(t)$	Instantaneous force
FFT	Fast-Fourier transform
H_1	Height of seat (H_{1-3})
ISO	International Standard Organisation
j	Complex phasor $(=\sqrt{-1})$
$Q(\omega)$	Quadrature spectral density function
M_{bx0}	Apparent mass of the backrest
$\overline{M}_b$	Mean normalised APMS magnitude responses at backrest
M_{px0}	Apparent mass of the total seat
$\overline{M}_p$	Mean normalised APMS magnitude responses at seat pan

$M(j\omega)$	Complex APMS
NB	No back support
$P_{backrest}$	Power absorbed at backrest
$P_{seatpan}$	Power absorbed at seat pan
P_{γ}	Absorbed power ratio
P(t)	Instantaneous power
$P_{Abs}(t)$	Absorbed power
$P_{El}(t)$	Elastic power
r^2	Coefficient of determination
SD	Standard deviation
STHT	Seat-to-head transmissibility
$S_{\ddot{x}}$	Acceleration auto spectral density
$S_{F_{px}\ddot{x}}$	Cross-spectral density (CSD) of the total force measured at the seat base
$S_{F_{bx}\ddot{x}}$	Cross-spectral density (CSD) of the total force measured at the backrest
T	Exposure duration (s)
VDV	Vibration dose value
$v(t)$	Velocity
WB0	With backrest angle zero
WBA	With backrest at angle 12.5° with vertical
WBV	Whole-body vibration
$\ddot{x}$	Acceleration due to excitation
x_b	Along *x*-axis at the backrest

x_f	Along *x*-axis at the footrest
x_s	Along *x*-axis at the seat pan
y_b	Along *y*-axis at the backrest
y_f	Along *y*-axis at the footrest
y_s	Along *y*-axis at the seat pan
z_b	Along *z*-axis at the backrest
z_s	Along *z*-axis at the seat pan
z_f	Along *z*-axis at the footrest
$Z(j\omega)$	Complex DPMI
φ_{ki}	Phase difference

Chapter 1

INTRODUCTION AND SCOPE OF RESEARCH

1.1 Introduction

Occupational heavy vehicle drivers are exposed to considerably large magnitudes of vibration in the relative low frequency range (< 20 Hz), which is known to cause discomfort, annoyance, and several health and safety risks in extreme cases. The driver in such an environment is exposed to vibrations that occur simultaneously along the three translational and rotational axes. The low frequency and high magnitude whole-body vibration (WBV) has been related with reduced comfort and health. Chronic health effects of WBV include disorders of the musculoskeletal structure, such as spine and supporting structure. Many epidemiologic studies have suggested a strong association between the exposure to WBV and the low back pain [1, 2]. Therefore, considerable efforts are being made to design effective suspension seats and consecutively investigate the transmission of vibration to and through the human body to enhance the understanding of human response to vibration.

This dissertation attempts to study the biodynamic response characteristics of seated occupants exposed to horizontal vibration with low frequency components. Many studies have investigated biodynamic response characteristics of seated occupants exposed to vibration [3-13], while the vast majority have focussed on the vibration along the vertical axis. The biodynamic responses are often characterised in two ways: (i) 'to-the-body response' functions, which relate vibration motion entering the body and the human-seat interface force developed at the driving point; and (ii) 'through-the-body response' functions, which describe the transmission of vibration to various segments of the body and thus reflect the resonance frequencies of different body segments [14]. The resulting data in both the biodynamic functions have been used to identify critical frequency ranges of vibration to which the seated human is most sensitive. The data have also been applied to develop mechanical-equivalent models of the seated occupants, which could be used for design of seats and analyses of coupled seat-occupant system [15].

The majority of the vehicles transmit more significant magnitudes of vertical vibration than those along the other axes. The vast majority of the studies have thus focused on the seated occupants' responses to vertical vibration. The reported studies on the biodynamic responses of human occupants exposed to vertical vibration have provided considerable insights into the resonant behaviour of the biological system, and the role of posture and seat design factors in view of potentially injurious effects of the exposure [3, 4]. While the nature of vibration transmitted along the horizontal-axes is also known to be quite severe, particularly for many off-road vehicles, only a few studies have investigated the force-motion relationships under vibration along the longitudinal (x-axis) and lateral (y-axis) directions [5-8, 10, 11]. The relatively low flexibility of tires of off-road vehicles coupled with high location of the operator, and presence of localized slopes and cross-slopes in the terrain, contribute to considerable motions at the operators' location along the x- and y-axes. Moreover, the majority of the studies reported along horizontal axes, focus on motion sickness alone under extremely low frequency vibration.

The force-motion relationships at the driving-point(s) of a seated body are known to be complex functions of many factors related to the occupant anthropometry, seat design, assumed posture and nature of the vibration exposure (type, magnitude, frequency and direction). The reported studies have mostly considered unsupported back posture, which do not represent the posture assumed vehicle driving. Only a few studies have considered biodynamic responses of subjects seated against a vertical backrest [5, 6]. The responses of occupants seated with different back support conditions and seat height have not yet been explored.

This dissertation research presents the characterisation of biodynamic response of seated occupants exposed to harmonic and random vibration along the fore-and-aft and lateral axes in 0.5-10 Hz frequency range. The force-motion relationships of seated occupants under different intensities of random and harmonic vibrations are investigated to determine the influences of various back support conditions and seat heights. The measured force and motion data are analysed to characterise the biodynamic response in terms of apparent mass and absorbed power.

1.2 Literature review

Study of biodynamic responses of seated occupants exposed to vibration necessitates knowledge and considerations of human response to vibration, nature of vehicular vibration transmitted to the occupant, synthesis of significant vibration components in laboratory, human response measurement techniques, data analyses, seat geometry and design features, etc. the reported studies in these topics are systematically reviewed to develop a thorough understanding of the issues, and test and analyses methodologies, and to formulate the scope of dissertation research. The relevant reported studies are discussed in the following sections.

1.2.1 Human vibration

Studies on human responses to vibration involve certain ethical concerns related to vibration exposure of participants. The determination of safe but representative level of exposure, including intensity and duration of vibration, thus forms vital task in laboratory studies. The guidelines for evaluation of human exposure to WBV and safety procedures that need to be followed while performing tests with human are given in international standards ISO 2631-1 [16] and ISO 13090-1 [17], respectively. The reported studies are thus expected to follow these guidelines. Moreover, the reported studies tend to utilise similar methods of measurements and analyses to facilitate data interpretations under similar conditions of experiments.

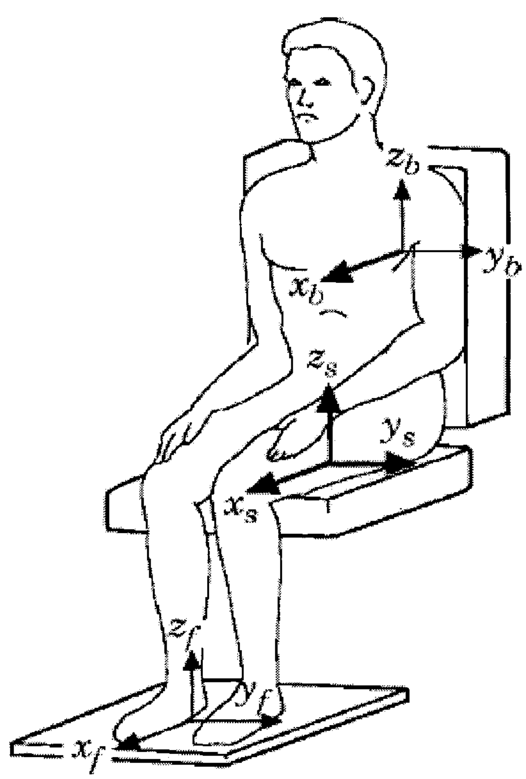


Figure 1.1: The seated body measurement axes at seat and backrest-from ISO 2631-1 1997 [17].

Human perception of vibration has been reported to depend on magnitude, frequency, duration and direction of the vibration exposure [14]. The study of human responses to vibration is performed using a common biodynamic coordinate system, where the point of contact is taken as the origin [16, 17]. Figure 1.1 illustrates the biodynamic axis system, for sitting position, where *x*, *y* and *z*-axes refer to the fore-aft, lateral and vertical axes, respectively.

The magnitude of continuous vibration exposure is usually characterised by frequency-weighted rms acceleration, as follows:

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

where $a_w(t)$ is the frequency-weighted acceleration obtained by applying W_d- weighting filter defined in ISO-2631 [35] for horizontal vibration, T is the exposure duration, and a_{rms} is the frequency-weighted root-mean-square (rms) acceleration due to transmitted vibration.

The shock events in the vehicles are characterised by relatively high acceleration peaks. The occurrence of such high peaks is often determined by the crest factor of vibration [2]:

$$\text{Crest factor} = \frac{(a_w)_{peak}}{a_{rms}} \tag{1.2}$$

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

The vibration exposure is said to confirm shock contents when the crest factor exceeds 12. It has been suggested that the exposure under such vibration may be characterised using the running rms method [16]:

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

where $a_w(t_0)$ represents the weighted rms acceleration corresponding to an observation time t_0 and τ is the integration time, usually takes as 1 second.

The Vibration with high crest factors are also characterised by the fourth power vibration dose method to obtain a vibration dose value (VDV), which is more sensitive to high magnitude events [14].

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

The major effects in work-places due to WBV have been reported to occur below 80 Hz [14]. The human body exhibits several resonances in this frequency range as illustrated in the Table 1.1.

Table 1.1: Resonance frequency ranges of seated human body, identified from vibration transmitted to body limbs [18].

Dominant mode (Limb)	Frequency range (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
Pelvis	10-14
Pelvis Rocking	4.5-6

Many studies have reported principal resonances of the human body and suggest that more than one vibration mode contributes to the principal resonance in the measured biodynamic responses [19]. However, amplification in the response and absorbed power within human body is generally believed to cause detrimental physiological effects on human, which is marked by increase in the pulse rate or respiratory rate, or more seriously as complaints of spinal muscles [2]. Changes in muscle tension are also believed to affect the fundamental frequencies, suggesting non-linear biodynamic behaviour, which is reflected in the relatively high inter-subject variability of the measured data [20].

1.2.2 Effects of vibration

Prolonged WBV exposure is expected to cause various effects on the exposed human body. Based on the range of subjective sensations, the threshold of perception is believed to interfere with the physical activities; unpleasant sensations could interfere with the comfort; and under extreme cases the vibration perception is identified to interfere with health by mechanical damage of the tissues and musculo-skeletal structure. On the basis of measured responses in laboratory, a few studies have established relationships between the vibration frequency and reported symptoms [21]. Table 1.2 summarises the vibration frequencies and associated symptoms.

Table 1.2: Symptoms of multidirectional vibration exposure in 1-20 Hz frequency range [21].

SYMPTOM	Frequency range (Hz)
Discomfort	4-9
Head	13-20
Lower jaw	6-8
Speech	13-20
Chest	5-7
Abdominal	4-10
Muscle contractions	4-9
Breathing	4-8

Back disorders and stresses on spinal column, digestive system diseases and cardiovascular system effects are invariably reported health effects of exposure to WBV, by various epidemiological, subjective and biodynamic studies [10, 22]. Exposure to low frequency vibration was suggested to affect the operator's control ability, reaction time, visual acuity and path tracking performance [23, 24]. The human perception of vibration and resulting fatigue is believed to depend on the sitting posture, which is also vibration frequency related [25, 26]. It has been reported that seated occupants exposed to vertical WBV in the 1-30 Hz frequency range experience an increase in postural swing and difficulties in maintaining adequate posture [17]. Moreover, slight motions below the threshold for motion perception are also believed to provoke postural readjustments [27].

Considerable efforts have been made to quantify the vibration-comfort sensations of occupants of automobiles, passenger vehicles and buildings [17, 23, 28, 29]. Occupant discomfort is suggested to be proportional to the magnitude of vibration, often expressed by either frequency-weighted or unweighted rms acceleration [16, 17]. International standard ISO 2631-1 provides ranges of overall total vibration magnitude and corresponding subjective sensation of comfort [16]. Under vertical vibration, the human body was reported to exhibit mass-like behaviour, under vibration frequencies up to 2 Hz. The low frequency vertical vibration is thus directly transmitted through the body. However, motions of different body segments experience amplification of vibration at slightly higher frequencies, which contribute to over all discomfort [21]. On the basis of the measured responses, the human body is believed to be quite sensitive to vibration at frequencies below 2 Hz and in the 4-8 Hz frequency range to fore-and-aft and vertical vibration, respectively. Human sensitivity to multi-axis vibration is considered to be about 18-25% higher, compared to uni-directional vibration [14, 29].

Owing to relatively higher perception of vertical vibration and its relatively higher intensity, the majority of the studies on biodynamics and human responses to vibration have considered vertical vibration alone. Relatively fewer such studies have been conducted under horizontal vibration [5-8]. Majority of the works related to horizontal vibration however, have investigated the motion sickness effects [31-33]. These studies have invariably concluded that WBV at frequencies near or below 1 Hz can cause motion sickness, which usually occur in the transport systems. The principal symptoms of motion sickness include dizziness, vomiting, disorientation, high blood pressure, drowsiness and so on [17, 30]. Moreover, tests performed have concluded that seated occupants exposed to horizontal vibration feel twice nauseogenic than under vertical vibration [31-33]. A part from the motion sickness, only a few studies have attempted to characterise the biodynamic responses of seated human body to horizontal vibration [5-8].

1.2.3 Evaluation of human exposure to WBV.

The seated occupant's perception and sensation of vibration is directly associated with the ride vibration environment of the vehicle. Many studies have been performed on human subjects to quantify vibration comfort boundaries and assessment guidelines [34]. Although, there is no general method of assessment due to highly complex nature of human response to vibration, somewhat similar methods have been used to evaluate the human tolerance and acceptance of vibrations [34, 35]. These methods can be classified in different groups depending on their measurement techniques: (i) subjective ride measurements involving selected subjects; (ii) repetitive shake table tests using synthesised harmonic vibration comparable to road input at discrete frequencies; (iii) shake table tests using stimulus representing the realistic road measured vibration environment; and (iv) measurement of ride environment and vibration exposure in vehicles under normal operating conditions [17, 34].

A number of guidelines for assessment of human perception of whole-body vibration exposure have been proposed and standardised [34-36]. These include: Janeway's comfort criterion [36] that is limited to vertical vibration, ISO 2631 [16] British Standard, BS-6841 [39]. Both the standards are most commonly accepted for evaluating human exposure to WBV. Vibration energy absorbed by the human body is also related to injury risk, and thus a few studies have also characterised the biodynamic responses of the seated occupants exposed to WBV in terms of the absorbed power [10-13, 40], although most of those are limited to vertical vibration. Moreover, these studies have not considered seating postures that are realised in the vehicle environments, and the sinusoidal excitations considered in most of the studies may not fully describe the human response to random vehicle vibration.

1.2.4 Vehicle vibration environment

The human occupants response and perception to vibration is directly associated with the nature of the ride vibration of the vehicle with more emphasis placed on the magnitude of vibration. The characterisation of the vibration environment thus forms the foremost task. Majority of the off-road vehicles are designed without wheel suspension. The ride behavior of such vehicles is thus characterised by the response of lightly damped system, where the damping arises from the tires alone. While most of the industrial vehicles employed in construction and service sectors are designed with primary suspension in order to obtain higher speeds, which tends to contribute to higher magnitudes of vibration along all translational and rotational axes [41]. A large number of analytical and experimental studies have been performed to define ride vibration levels as functions of various design and operating factors of on-road and off-road vehicles [2, 29, 42-44].

The ranges of vibration of urban buses, forklift trucks and side-walk snow-ploughs along the vertical, lateral, longitudinal, roll and pitch axes, under wide range of operating conditions, have been reported [18]. For off-road tractors with implements or when ploughing, harrowing or drilling, the magnitudes of frequency-weighted longitudinal and lateral vibration could be either comparable to or exceed those of the vertical vibration [1, 46, 47]. The relatively low flexibility of tires of off-road vehicles coupled with high location of the operator, and presence of localized slopes and cross-slopes in the terrain, contribute to considerable motions at the operators' location along the x- and y-axes. The relative magnitudes of horizontal vibration, however, would depend upon the type of vehicle and the task performed. Studies have reported high incidence of disorders among off-road vehicle drivers, being nearly 2-4 times higher than that among the crane operators (on-road) [1].

The agricultural and forestry vehicles have been most widely studied with respect to their ride vibration and safety [1, 2, 43, 44]. Occupational diseases due to WBV exposure are found to be the highest in such vehicle drivers [1]. The suspensions and tires properties, apart from the vehicles weights and dimensions of vehicles, strong affect the nature of transmitted vibration. However, the primary focus of these studies has been limited to vertical vibration, which is further applied in development of effective seat-suspension design [42, 46, 48]. Such vehicles cause appreciable frequency-weighted magnitudes of vibration transmitted to the driver seat along the longitudinal and lateral axes, which are summarised in Table 1.3. [2, 47, 49]. The vector sum of accelerations a_v is also presented in the table. The reported data suggest that the magnitudes of horizontal vibrations are considerable when compared to those in the vertical direction, particularly for the harrowing and ploughing tasks.

Table 1.3: Magnitudes of frequency-weighted rms accelerations due to vibration measured along the longitudinal and lateral and vertical axis, on the seats of agricultural/forestry tractors [2, 47, 49].

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 ploughing	0.3-1.3	0.2-0.6	0.3-0.59	0.87-1.26
Tractor Harrowing	0.2-0.69	0.2-0.8	0.38-0.96	0.85-1.67
Band excavator harrowing	0.2-2.6	0.2-1.0	0.3-1.4	-
Band excavator ploughing	0.5-1.3	0.3-1.3	0.4-1.0	-
Fork-lift truck (off-road)	0.10-0.90	0.10-2.5	0.5-1.6	-

Various industrial and heavy road vehicles which include tracked forestry vehicles, cargo trucks and all terrain vehicles are reported to reveal considerable vibrations transmitted along the longitudinal, lateral and vertical axes [47, 50]. Owing to the high magnitudes of transmitted vibration to the operator and the anticipated health and safety risks, vast number of studies have been performed to moderate the levels of hazardous vibration and to enhance understanding of the human response to vibration. However most of these studies were limited to vertical vibration alone. Considering the comparable magnitudes of vibrations along horizontal vibrations to those in vertical particularly, in case of off-road vehicles as illustrated in the Table 1.3, it may thus be emphasized to characterize the human response to horizontal vibration.

On the basis of reported magnitudes of vibration in tractors, Kumar et al.[2] concluded that the ratio of lateral and longitudinal vibration to the vertical vibration in case of tractors lie in the 0.48 to 0.6 range. Marsili et al [47] concluded that the magnitude of lateral vibration could be higher than the vertical vibration during transport operation. In performing specific tasks like ploughing and harrowing, lateral vibrations were also reported to dominate [21]. Reported studies invariably suggest the occurrence of lower frequency (0.5-5 Hz) vibration in wheeled off-road vehicles as illustrated in the Table 1.4 [18].

Table 1.4: Frequency ranges of dominant vibration of off-road vehicles [18].

Mode of Vibration	Predominant Frequency range (Hz)
Roll	0.5-4.5
Pitch	2.0-4.5
Bounce	2.0-3.5
Lateral	≈ 1.0
Longitudinal	2.0-4.5

1.3 Biodynamic response of seated human body

The word seating is usually taken with respect to the vibration environment in vehicles. With the increase in the population and operating speeds of road and off-road vehicles, and growing risk of occupational diseases, a large number of studies have emphasised for additional efforts in understanding of the seated human system responses. It has been suggested that the seated human occupant exposed to WBV may lead to predictable behaviour, and thus be considered as a mechanical as well as a biological system [14]. Studies suggest fundamental resonant frequencies as a function of sitting posture, magnitude and direction of vibration, back support condition, and so on. Irrespective of the sitting posture and vibration condition, studies report first two resonances within ranges of frequency of vehicular vibrations. The ranges of frequencies reported by different studies are illustrated in Table 1.5.

Table 1.5: Principal resonant frequency ranges of seated human body [14].

Mode of Vibration	Resonant Frequency (Hz)	
	First Mode	Second Mode
Roll	1.5-2.5	4.5-7.7
Pitch	5-7/ 3-11	-
Yaw	1.7-7	-
Bounce	4-6/1.5-15	3-20
Lateral	1-1.25/ 2-4	6-11/5-7/4-5.5
Longitudinal	1-3/2-4/0.6-8.5	5.0-12

The studies illustrate that the first two resonances of seated human body occur in the frequency range below 20 Hz. Majority of the studies under horizontal vibration have reported the occurrence of motion sickness in roughly half the time that would be experienced under vertical vibration [31-33]. Griffin [14] summarized the effects of vibration under comfort, health, interference with activities, and motion sickness in terms of range of frequencies.

The studies on vertical vibration have culminated into the design of suspension seats in an attempt to reduce the magnitudes of vertical vibration experienced by the operator. However, the higher center of gravity, high magnitudes of angular motions of the vehicle chassis, and horizontal flexibility of the seat suspension and seat cushion, could lead to higher magnitudes of horizontal vibration [49]. Furthermore, lower natural frequency suspension seats tend to amplify both the horizontal and vertical vibration, when suspension travel exceeds the permissible stroke [43, 47, 48].

The methods for measuring the biodynamic responses of seated occupants exposed to vibration have been well established in the studies conducted in vertical and horizontal biodynamic [3-8]. Two different types of transfer functions that are used to characterise biodynamic response of the body include, the measurements obtained at the same point and those obtained at different points, typified as transmissibility [14]. 'To-the-body' force-motion relation at the human-seat interface, expressed as apparent mass (APMS) or the driving point mechanical impedance (DPMI); and 'through-the-body' response function, generally termed as seat-to-head transmissibility (STHT) in case of seated occupant. Additionally, 'to the body' response obtained, reveal the characteristics of energy dissipated/ stored by the biological system usually termed as absorbed power [40].

The APMS, computed as the ratio of the driving-point force to the acceleration, is directly proportional to the static mass of the human body supported by the seat at low frequencies. The measure provides the primary resonant frequencies of the biological system. While the DPMI, the ratio of driving force to velocity tends to emphasise the higher frequency response [51], the APMS is preferred in biodynamic studies as it tends to simplify the inertial correction of the measured force [3]. Moreover, the APMS emphasises low frequency response, and exhibits more similarity with the STHT compared to the DPMI [52]. The vibration transmissibility of the biological system yields considerable information on the nature of the vibration transmission particularly, the resonances of the body segments.

In addition to the above mentioned biodynamic functions, the absorbed power has been suggested as a better measure of the exposure and the biodynamic response. The absorbed power also relates to the same quantities: the dynamic force response and vibration acceleration or velocity. The amount of vibration energy, absorbed and / or exchanged between the source and the body, could be considered as a measure of the physical stress on the body, as it considers the interchange between the vibrating surface and the human body [40].

These biodynamic response functions have been employed to characterise the human body response to WBV. These biodynamic measures obtained along vertical axis reflect the strong effects of subject's body mass, sitting posture, nature of vibration etc. [3, 4, 9, 22]. The data acquired in different studies under comparable experimental conditions thus exhibit considerable deviation among them. The measured responses show considerable differences due to the variations in the test conditions and contributions due to various individual factors related to occupant mass and build. Boileau et al. [15, 53] have reviewed the test conditions employed in studies reported prior to 1997. The results from such tests performed on seated occupants with no back support under vertical WBV have been adapted in the ISO-5942 [53] documents, which outlines the ranges of biodynamic responses of seated occupants exposed to vertical vibration. Recent studies have also been performed to present the effect of sitting postures considering inclined back supports, seat heights and hands position (in lap and on steering wheel) on the vertical biodynamic response [9]. No such attempts, however, have been made under exposure to horizontal vibration.

Majority of the studies on vertical biodynamic responses have employed high magnitude harmonic and broad-band random vibration excitations, with magnitudes ranging from 0.125 to 2.5 m/s^2 rms acceleration. Only few works employed back supported posture against a vertical backrest [3, 22, 54], while majority considered seating postures without back support. However, a vertical back support does not represent automotive seating posture. The biodynamic responses considering automotive sitting postures involving inclined back support and hands on steering wheel have been investigated by Rakheja et al. [22, 54] under vertical vibration. The study reported that the biodynamic response is highly dependent on the posture. It has been widely reported that increasing the magnitude of vibration leads to softening of the body and thus affects the biodynamic response at higher magnitudes [13]. Irrespective of the contributing factors considered, the data under vertical vibration reveal primary resonance near 5 Hz, which could vary slightly depending on the contributing factors.

1.3.1 Seated occupants biodynamic response to horizontal vibration

Owing to the significant different behaviour and support characteristics of seated human system along the vertical and horizontal axes, the human response to horizontal WBV is found to be considerably different from that under the vertical vibration. Comparatively, more pronounced effects of postural conditions and excitation levels would be expected under vibration along the horizontal direction [14]. The majority of the studies have been performed under vertical vibrations even though similar magnitudes of horizontal vibration are imposed by a large number of the vehicles. This is attributed to scores of epidemiological works suggesting direct relationship between spinal injury and exposure to vertical vibration [25, 26, 55]. Considering that the ride vibration environment of vehicles comprises vibration along all the translational and rotational axes, such conclusions from the epidemiological studies are most likely based upon the belief that the vertical vibration predominate. Horizontal vibration along the longitudinal axis tends to cause a pitching motion of the upper body. The exposed subjects thus encounter difficulties in maintaining stable sitting posture, and increased muscular loading to sustain upright posture [14]. The exposure to low frequency and high magnitudes of horizontal vibration thus causes increased discomfort and musculo-skeletal loading. Majority of the studies on human response have focused on motion sickness effect, believed to be the primary symptom [31-33]. These studies suggest that exposure to vibration at frequencies below 1 Hz could trigger motion sickness and discomfort. The reported studies on biodynamic responses of seated occupants under vertical vibration have established proven tests and data analyses methods, which could be directly applied to study the biodynamic responses under horizontal vibration. The horizontal biodynamic responses are expressed in terms of measures used in vertical biodynamics, namely APMS, DPMI and absorbed power. Such biodynamic response measures have been explored to derive frequency-weighting functions to asses the severity and risk imposed by the vibration exposure, mechanical-equivalent models of the seated occupant for applications in analyses of coupled seat-occupant system, and to enhance an understanding of the vibration responses of the biological system. The data from the objective biodynamic measures is expected to provide more scientific basis for defining the frequency-weighting functions or to yield more effective means for assessing the human exposure to vibration. The reported studies on vertical biodynamics have been thoroughly reviewed in a few studies in view of the measured and test conditions used, and the role of anthropometric, postural and excitation conditions [3, 9, 22]. The similar reported studies on horizontal biodynamic responses are reviewed in this section to identify the major contributory factors and test conditions.

Holmlund and Lundstrom [7] investigated the driving-point mechanical impedance of male and female subjects seated without a back support and exposed to sinusoidal vibration along the orthogonal *x*- and *y*-axes in the 1.13-80 Hz frequency range the measurements involved the force and velocity at the base of the rigid seat. The measurements were performed under six different magnitudes of harmonic vibration, ranging from 0.25 to 1.4 m/s^2 rms acceleration, while the subjects assumed erect and relaxed postures. The data revealed significant effects of sitting posture and vibration intensity on the DPMI magnitude along the *x*- and *y*- axes. A change in the upper body posture from erect to relaxed revealed considerable effect on the magnitude of secondary peak in the DPMI response. The study showed higher mean impedance magnitude for the male subjects, when compared to that of the female subjects. Mansfield and Lundström [8] reported the APMS responses of the same number of male and female subjects seated without a back support under non-orthogonal horizontal random vibration in the 1.5-20 Hz frequency range of different magnitudes (0.25, 0.5 and 1.0 m/s^2 rms acceleration). The results revealed two distinct peaks in the DPMI magnitudes under *x*- and *y*- axes vibration. The responses to non-orthogonal horizontal vibration were measured along different axis with respect to the mid-sagittal plane, while the frequency of the identified primary peak reduced as the direction of vibration changed from *x*- to *y*-axis. An increase in the vibration magnitude resulted in slightly lower frequency of the primary peak, which was attributed to the softening of the body that has also been widely reported in many studies on vertical biodynamics.

The data acquired in both studies suggest the presence of the primary peak in DPMI and APMS at frequencies near or below 1.0 Hz. Since these studies have employed harmonic and random vibration at frequencies above 1 Hz, the response in the vicinity of the primary resonant frequency could not be qualified accurately. A few other studies have shown the presence of primary peak APMS response near 1 Hz. Fairley and

Griffin [6] performed measurements of APMS responses of eight seated occupants exposed to fore-aft and lateral vibration independently. The study considered three magnitudes of vibration (0.5, 1.0 and 2.0 m/s^2). The study showed the presence of a primary resonant peak at frequency below 1 Hz for the subjects seated without a back support. This peak was attributed to the pitch motion of the upper body. The secondary peak in both the x and y- axes, however, could not be observed in this study due to the higher magnitudes of acceleration considered, which is most likely attributed to the motion of the hands and the legs [8]. Under exposure to horizontal vibration, specifically along the longitudinal axis, a seat backrest serves as an important constraint for the upper body movement, and would thereby affect the biodynamic response, considerably.

Fairley and Griffin [6] reported the APMS responses of occupants seated with and without a back support and exposed to horizontal vibration. The data attained for the back-supported posture revealed a single primary peak in the APMS magnitude in the x- and y-axis responses. Nawayseh and Griffin [5] studied the occupants' interactions with the backrest under fore-aft motion through measurements of contact forces. The study revealed considerably higher magnitudes of the force along x-axis, while those along the y-and z-axes were very small. The study further showed significant effect of the feet support on the measured APMS response. The test conditions and measures employed in relevant studies under horizontal vibrations are summarised in Table 1.6.

The vehicle seats are designed to provide enhanced support for the occupant back through an inclined backrest, which may yield different magnitudes of dynamic forces at the body-backrest interface and thus need to be examined. The support against a backrest may cause increased transmission of vibration to the seated body. The total

Table 1.5: Summary of the relevant reported data on horizontal biodynamic responses of seated occupants.

Authors	*subjects*	*Posture*			*Excitation*				*Axis of vibration*	*Reported functions*
		Body Position	Back position	Feet vibrated	Type	Level (m/s^2 rms)	Frequency (Hz)	Exposure time		
Nawayseh and Griffin [5]	12 males	Upright, hands on lap	Vertical backrest	Yes	Random	0.125-1.25	0.25-10	60s	*x*	APMS
Fairley and Griffin [6]	8 males	Upright, hands on lap	No-back, vertical back support	Yes	Random	0.5, 1, 2	0.25-20	128 s	*x* and *y*	APMS
Holmlund and Lundström [7]	15 male / 15 female	Seated erect/ relaxed	No-back support	No	Sine	0.25,0.35,0.5,0.7,1,1.4	1.13-2.5, 31.5-80	20 cycles at each frequency	*x* and *y*	DPMI
Mansfield and Lundström [8]	15 male / 15 female	Up right posture, arms folded	No-back support	No/ 90°knee angle	Random	0.5,1,1.5	1.5-20	60s	0,22.5,45 and 90° (to mid sagital plane)	APMS
Coronel [10]	7 males	Upright, hands on lap	No-back support, inclined back support	yes	Sine and random	Random: 0.25,0.5,1.0 Sine: 1, 1.5, 2	0.25-10	128/ 512	*x* and *y*	APMS and absorbed power
Lundström and Holmlund [11]	15 male / 15 female	Seated erect/ relaxed	No-back support	No	Sine	0.5 1.0 1.5	1.13-80	180s	*x* and *y*	absorbed power

characterisation of the seated body biodynamic response to horizontal vibration may thus require consideration of two driving-points, the seat pan and the backrest. A recent study by Coronel [10], reported the biodynamic response of occupants seated in typical automotive seats with an inclined back support in terms of both the APMS and absorbed power. The study considered random horizontal vibration of three different magnitudes in the 0.25-10 Hz frequency range and total of 7 subjects. The test conditions considered were representative of automotive environment. The effect of type of vibration was analysed with respect to various contributing factors. The data revealed significant effects of the back support condition. The results suggested that the magnitudes of dynamic interactions between the upper body and the seat backrest would depend upon the degree of support and the inclination of the backrest.

1.4 Scope of research

Owing to the significant health and safety effects of WBV transmitted to the seated occupants, considerable efforts have been made to study human responses to vibration and contributing factors. However, majority of the studies have been conducted under vertical vibration. A large number of road and off-road vehicles are reported to impose significant levels of horizontal vibration. Only limited efforts, however, have been made to characterise the human response to horizontal vibration. Among these, a large number considered the motion sickness effects of horizontal vibration. The effects of seat design factors and sitting postures on the biodynamic responses have not been addressed.

The vast majority of the biodynamic studies reported in vertical WBV have provided considerable data on human sensitivity to vibration, resonances of seated occupant system and energy absorbed. These studies have further evolved into knowledge base on the seat design contributory aspects such as seat height, inclinations of pan and back support and footrest. Similar biodynamic response characterisations under horizontal vibration are essential to enhance the knowledge of human response to horizontal vibration. These are likely to yield considerable knowledge on the role of seat design, sitting posture on the biodynamic response and energy absorption. Moreover, the body interactions with both the seat pan and the backrest need to be examined, while the reported studies have mostly ignored the upper body interactions with a back support. The measurement of this interaction could yield additional knowledge on the angular motions of the upper body under exposure to horizontal vibration. A need thus exists study to study the biodynamic responses of seated occupants to horizontal vibration under varying test conditions to build the data sets on two driving-points formed by the pan and the backrest. The absorption of vibration energy by the exposed body has been suggested to serve as a better measure for investigating the potential injury mechanism, while only single study has attempted to measure absorbed power under horizontal vibration.

1.5 Thesis objective

The primary object of this dissertation research is to contribute to the knowledge base on the seated occupant responses to horizontal vibration and the role of postural and excitation conditions. The specific tasks include:

- Conduct a comprehensive review of the reported studies on biodynamic responses of seated occupants exposed to WBV to identify methodologies and representative test conditions, and major contributory factors.

- Design and develop a off-road vehicle seat with adjustable seat height and backrest to study the role of design factors on the measured biodynamic response.
- Synthesise an experimental set up to measure the dynamic forces at both the driving-points under horizontal as well as lateral vibration.
- Design the experiment to characterize the biodynamic response in terms of APMS and absorbed power considering different magnitudes and frequencies of random and harmonic vibration, and back support condition and seat height.
- Obtain the force-motion data under fore-aft and side-to-side, random and harmonic vibration, with various support conditions and magnitudes of vibration, and evaluate the biodynamic responses.
- Determine the inter-subject variability and analyse the contribution of magnitude and type of vibration, back support condition and seat height in terms of APMS and absorbed power.

1.6 Thesis organisation

This dissertation thesis is organised into six chapters, in the order of the development of preceding objectives. Chapter 1 presents the comprehensive review of the reported studies related to the vibration environment experienced by the occupational drivers, health and safety effects, and justification of the analysis under horizontal vibration components, measurements, and test methodologies considered.

Chapter 2 presents the experimental design involving the synthesis of selected vibration excitations, instrumentation, data acquisition and analysis. The measurement and analysis methodologies are furthered described.

The measured data are analysed to derive the inter-subject variability and mean values and ranges of the measured APMS responses in Chapter 3. The results are discussed to highlight the contribution of magnitude and direction of vibration, back support condition and seat height on the overall APMS responses measured at the seat-base under x- and y- axis vibration in an uncoupled manner. The upper body interactions with the backrest are also evaluated in terms of the backrest APMS responses. The backrest APMS responses are compared with the overall APMS responses and discussed to highlight the upper body motion.

In Chapter 4, the measured data are analysed to express the biodynamic responses in terms of absorbed energy. The results are discussed to demonstrate the contributions of magnitude and direction of vibration, back support condition and seat height to the absorbed power measured at the seat-base and the backrest.

The seated human responses to both random and harmonic vibration of different magnitudes and back supported condition are evaluated in Chapter 5 for fore-aft as well as side-to-side vibration. The results attained under two different types of vibration are compared and discussed to interpret the observed differences.

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

Chapter 2

EXPERIMENTAL AND DATA ANALYSES METHODS

2.1 Introduction

The methods for measuring the biodynamic responses of seated occupants exposed to vibration have been well established in the studies conducted in vertical and horizontal biodynamic [3-8]. The approach invariably considers a rigid seat, free from resonances in the frequency range of interest, idealised band limited vibration, either deterministic (harmonic) or random in nature, and single driving-point at the seat base. Similar methodology can be directly implemented for the present study, which involves measurement of force and acceleration at the driving point. The support against a backrest may cause increased transmission of vibration to the seated body, thus total characterization of the seated body biodynamic response to horizontal vibration may require consideration of two driving-points, the seat pan and the backrest. The majority of the studies have considered seating without back support, only single study [5] has considered the measurement at the backrest to explore and quantify human body interactions with the backrest, while the biodynamic response under back supported posture against a vertical back has been investigated in another single study [6]. The posture with inclined back support closely represents the off-road vehicle seating environment, which has not yet been considered.

This chapter describes the design of a test seat representative of the off-road vehicle seating and the design of experiments for measurements at both the seat-pan and the seat-backrest under whole body vibration along the fore-and-aft and side-to-side axes.

The whole body vibration simulator used in the experiments is briefly described together with the measurement and data analysis methods. The data acquisition and signal analyses method is further described for deriving both the absorbed power and the driving point apparent mass responses of the seated vibration-exposed human occupants.

2.2 Seat and measurement system

Considerable attempts have been made to describe ideal seat geometry for the off-road vehicles to provide the comfortable and controlled posture. Considering the need to study the effect of posture on the biodynamic responses of the seated occupants to the whole-body vibration which is in turn influenced by the seat geometry, it was deemed essential to design a representative off-road vehicle seat for experiments. A rigid seat consisting of a 500 X 400 mm flat seat pan and 470mm high backrest was thus designed to achieve adjustable seated height and backrest inclination. The pan and back support were installed on a truss structure constructed based on the design guidelines suggested for the off-road vehicle seat in the SAE handbook [56]. The backrest of the seat comprises a 1.25 cm thick aluminium plate installed on the truss structure through a three-axis dynamometer, which provide the measurement of forces, although the force developed along one direction alone is considered for the study. Two three-axis force-plates were also installed at the seat base between the vibration table and the seat to measure total forces at the seat pan. Figure 2.1 shows a pictorial view of the seat described and the force plates installed under the seat to measure the dynamic forces at the seat pan. The truss members holding the backrest were attached to the seat pan through hinges to permit variable backrest inclination. The seat was installed on a slip table that was coupled to a servo-hydraulic actuator capable of generating motions up to 24 cm in amplitude.

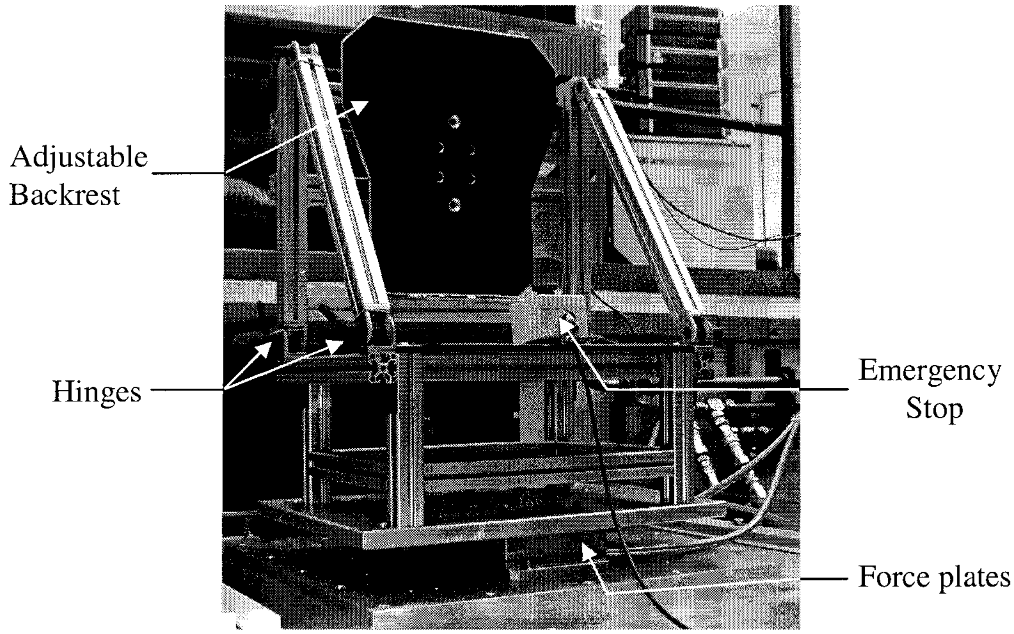


Figure 2.1: Rigid test seat used to measure the biodynamic response of the seated occupants.

Owing to the strong perceived effects of back supported conditions, which have been well established under vertical vibration, the seat was configured to realize three back support postures: (a) back unsupported, NB; (b) back supported against a vertical backrest, Wb0; and (c) back supported against an inclined backrest, WbA. Figure 2.2 schematically illustrates the seat configuration corresponding to the three postures. The backrest inclination is realised by adjusting the backrest hinges.

The vibration simulator designed in this study comprised of a magnesium slip table sliding on an oil film over a granite slab. The slip table was driven by a 48 cm stroke servo-controlled hydraulic actuator. A MTS-407 servo-controller was used to operate the actuator of the horizontal vibration simulator using the displacement feedback control.

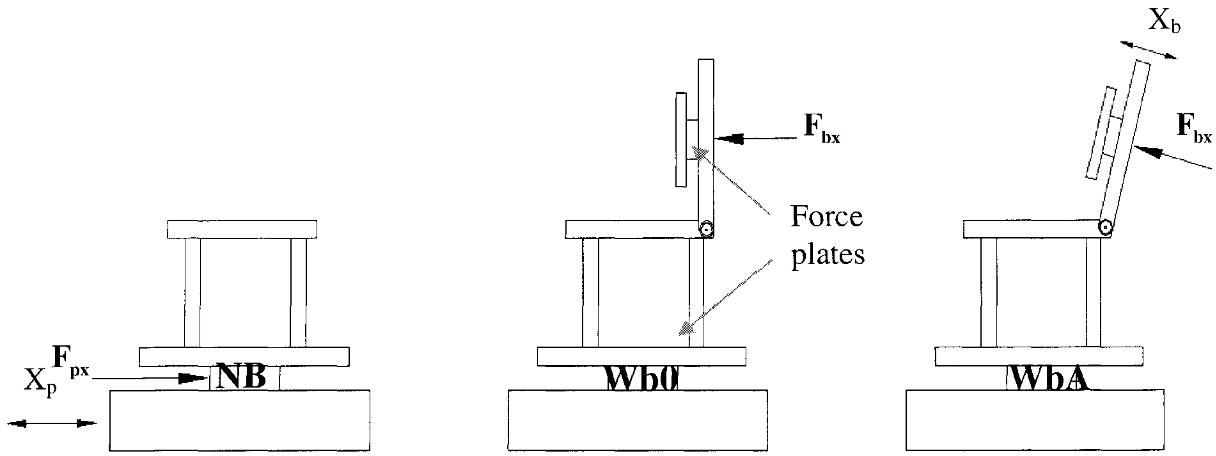


Figure 2.2: Schematic illustrations of back support conditions used in the study.

The test seat was instrumented to acquire the force responses and vibration excitations at the seat pan and the backrest as shown in the schematic diagram in the Figure 2.3. A micro-accelerometer was installed on the platform of the vibration simulator to measure acceleration due to vibration along *x*- and *y*-axes. Another single-axis accelerometer was installed on the truss member of the seat backrest to measure the acceleration along an axis normal to the backrest. A summing junction was used to sum the forces measured by two seat pan force plates along either *x*- or *y*-axis. The total force signal was conditioned using charge amplifier. Under *x*-axis motion, the force acting along an axis normal to the backrest alone, however, was acquired, since the forces along the lateral and vertical directions of the backrest were expected to be small in magnitude [5]. Under lateral excitations, the measurement of backrest force was limited to *y*-axis alone.

2.2.1 Safety procedures

It needs to be emphasized that measurement of biodynamic responses to whole body vibration in the laboratory involves complex challenges and many ethical concerns associated with human exposure to vibration. Consequently, a number of measures are

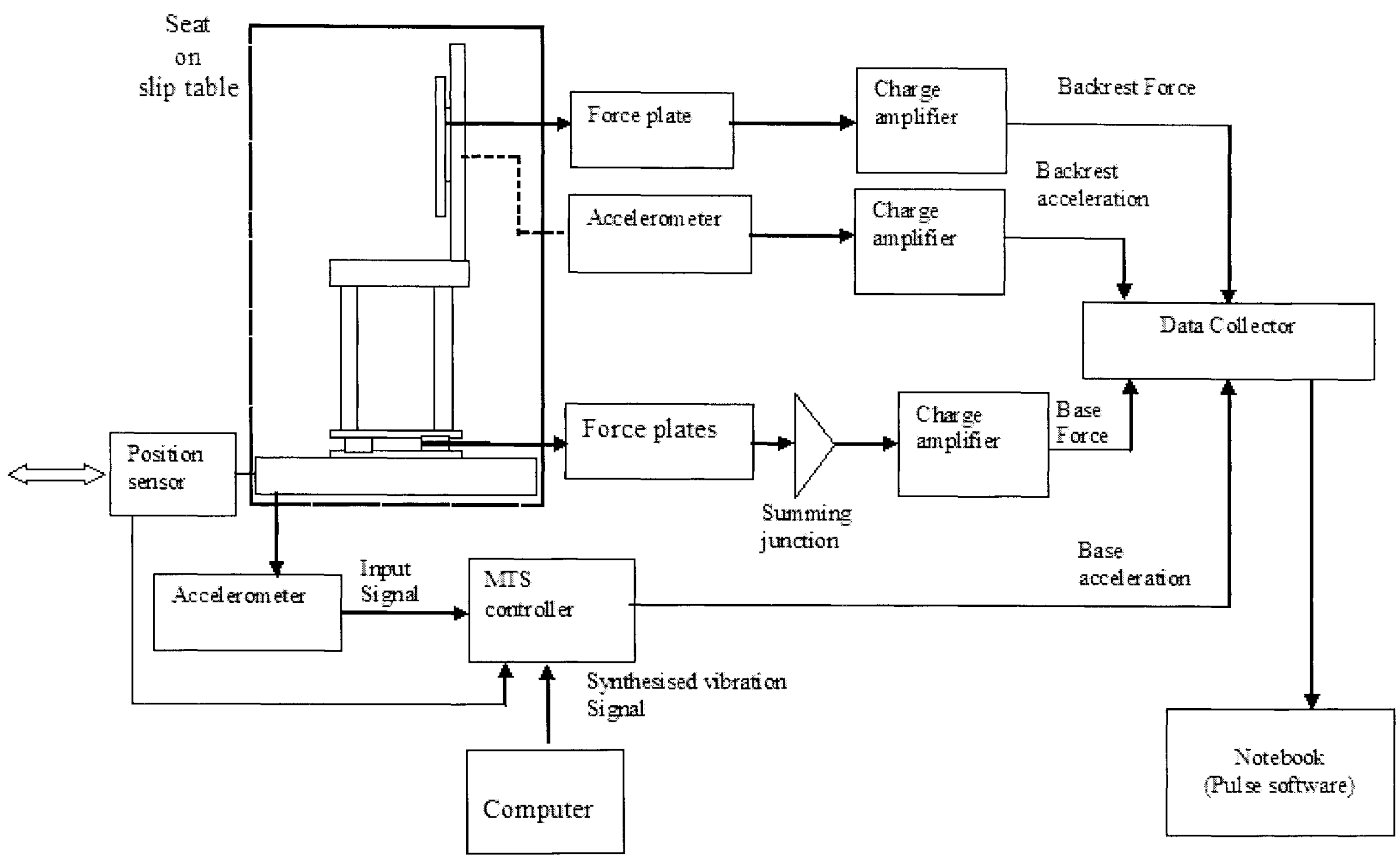


Figure 2.3: Measurement and data acquisition system.

undertaken to ensure safe limits on the level of exposure. Apart from the peak displacement limit imposed by the displacement feedback control, the controller was programmed to limit the peak acceleration to ±5.88 m/s^2. Each participant was asked to hold a hand held emergency stop and was advised to use it whenever a test condition caused discomfort or risk. The stops permit the stoppage of the actuator in a gradual manner using the ramp-down control. The operator/ experimenter was also provided with another emergency stop switch. The safety procedures were followed to as an attempt to eliminate potential safety risks for the subjects and those monitoring or conducting the experiments, arising from excess exposure or malfunction of the servo-hydraulic system. The level of exposure and the duration of exposure in the experiment design were chosen in accordance with the guidelines provided in ISO 13090-1:1998 [17]. The servo controller was configured with the various interlocks that limited the peak acceleration of the platform to ± 0.6g. The experimenter was required to undertake various safety checks prior to start of the experiment. To interrupt the experiment at any time both the subject and the operators were provided with emergency stop controllers, an emergency stop was also provided on the master pump control panel that could be used to interrupt the hydraulic flow under an emergency situation. Additionally, the characteristic motion of the vibrating platform and the use of emergency stop were demonstrated to the participants prior to the start of experiments.

2.3 Excitations and Biodynamic Measures

In present study, harmonic as well as random excitations were synthesized. Identical random excitations were used along *x*- and *y*-axes, while different magnitudes of harmonic excitations were used along x- and y- directions, as shown in the figure 2.4. The biodynamic response characteristics of the participants were measured under different levels of constant acceleration spectral density random excitations in the 0.5-10 Hz frequency range, since the horizontal vehicular vibration are known to predominate in the low frequency range [5-8]. Three different magnitudes of excitations were chosen to study the effect of exposure level on the biodynamic response.

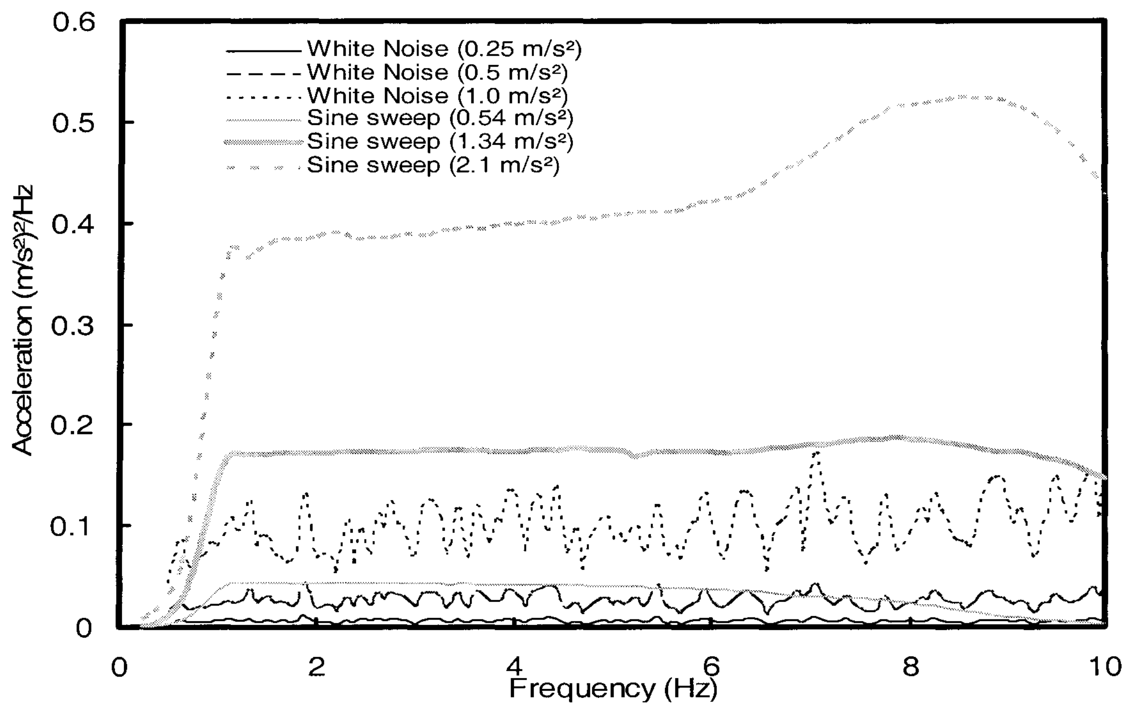


Figure 2.4: Acceleration PSD of synthesized Random and sine excitations used in the present study.

A white noise random signal was synthesized to yield flat acceleration spectrum in the 0.5-10 Hz frequency range. Three different magnitudes denoted by the overall rms accelerations were obtained by selected three different controller gains. The magnitude of random excitations were chosen to achieve overall rms accelerations of 0.25 m/s^2, 0.5 m/s^2 and 1.0 m/s^2, as illustrated in the Figure 2.4. Different forms of harmonic excitations swept in the 0.25-10 Hz frequency range were considered for the experiments. For this purpose, a trial and error method was used by varying the controller gain until the measured acceleration revealed a desired value of rms acceleration, which was evaluated using the PULSE software.

A constant displacement amplitude waveform resulted in significantly higher acceleration at higher frequencies and was thus considered inadequate. A constant acceleration amplitude waveform, on the other hand, would cause very high displacement at amplitudes at lower frequencies and very low displacements at higher frequencies. Thus an alternative waveform was synthesized to produce a constant displacement harmonic motion in the 0.5-1.0 Hz range and constant acceleration in the 1-10 Hz range. Three different magnitudes of excitations were synthesized to yield peak accelerations of 1.0, 2.0 and 3.0 m/s^2 at the transition frequency of 1Hz. Figure 2.4 illustrates the PSD of acceleration of the platform under three different magnitudes of harmonic excitations. The results show higher psd magnitudes at frequencies above 7 Hz under 2.1 m/s^2 harmonic excitation, which was attributed to the resonance of the platform and hydraulic starvation of the sliding platform. The experiments were conducted for one complete cycle involving forward sweep from 0.25 to 10Hz and 10 to 0.25 Hz frequency. A linear sweep rate of 0.038 Hz/s was chosen for the excitation. The total exposure time for the complete cycle was 512s, while the test duration for random excitation was chosen as 125s.

2.4 Experimental procedure

The measured data were acquired in a 4-channel signal acquisition and analysis system. The analyses of the measured signals were performed using bandwidth of 50 Hz and frequency resolution of 0.0625 Hz, for random excitations. The band width and resolutions were limited to 100Hz and 0.125 Hz for harmonic excitations to acquire sufficient samples of data. The experiments were initially performed to measure the resonant behaviour of the seat under synthesized harmonic and random excitations in the frequency range of 0.5-50 Hz. The seat revealed a number of resonances at frequencies above 15 Hz and nearly flat response in the concerned frequency range up to 10 Hz.

The experiments under selected excitation were then performed to measure the responses of the seat alone along the two-axes in an independent manner. The measured data were analysed using Fast Fourier Transform techniques to derive the apparent mass, absorbed power and frequency spectra of the forces and accelerations. A total of 30 averages were performed to derive the response measures. The apparent masses of the total seat and the backrest were derived from the acceleration due to excitation, and the total force measured at the seat base and the backrest, respectively. Under longitudinal excitations, these were computed from:

$$M_{px0}(j\omega) = S_{F_{px}\ddot{x}} / S_{\ddot{x}}$$
$$M_{bx0}(j\omega) = S_{F_{bx}\ddot{x}_b} / S_{\ddot{x}_b} \qquad (2.1)$$

Where M_{px0} is the complex apparent mass of the total seat corresponding to excitation frequency ω, referred to as 'seat pan APMS'. $S_{F_{px}\ddot{x}}$ is the cross-spectral density of the total force measured at the seat base along the x-axis (F_{px}) and the acceleration due to excitation $\ddot{x}$, and $S_{\ddot{x}}$ is acceleration auto spectral density. M_{bx0} is the complex apparent mass measured of the backrest, referred to as 'backrest APMS', $S_{F_{bx}\ddot{x}}$ is the cross-spectral density of the force measured at the seat backrest along an axis normal to the backrest (F_{bx}), as illustrated in Figure. 2.2, and the acceleration due to excitation along the same direction $\ddot{x}_b$, and $S_{\ddot{x}_b}$ is acceleration auto spectral density.

The absorbed power due to the seat and the seat occupant system was derived from the real part of the co-spectrum of the force and velocity, such that [15]:

$$P_{px0}(\omega) = \mathrm{Re}[S_{F_{px}\dot{x}}]$$

$$P_{bx0}(\omega) = \mathrm{Re}[S_{F_{bx}\dot{x}}] \qquad (2.2)$$

Where $\dot{x}$ and $\dot{x}_b$ are the velocities measured at the seat pan and the backrest, respectively, which were computed through time integration of the measured acceleration signals. P_{px0} and P_{bx0} are the power absorbed by the seat as derived from the forces developed at the pan and backrest. $S_{F_{px}\dot{x}}$ and $S_{F_{px}\dot{x}_b}$ are the cross-spectra of the forces and velocities measured at the pan and the backrest respectively.

The coherence response between the forces and accelerations and force and velocities were constantly monitored during experiments performed with subjects to ensure adequate signals. A measurement was rejected when coherence value was observed to be below 0.9 within the entire frequency range. The analysis software was also programmed to continually display the rms acceleration due to excitation in the third-octave frequency bands, which was monitored to ensure consistent excitation.

The measurements were performed with vertical and inclined backrest. Both the measurements revealed identical constant magnitude of the backrest APMS in the frequency range of interest with nearly zero phase response. It should be noted that $\ddot{x}_b = \ddot{x}$ for a vertical backrest, and $\ddot{x}_b = \ddot{x}\cos(\alpha)$, where α is the backrest inclination. Since the force measured at an inclined backrest is related to that measured on a vertical backrest by $cos(\alpha)$, both the measurements yield identical magnitude of the backrest APMS.

The experiments were performed under excitations along the longitudinal (x) and lateral (y) axes, applied independently in an uncoupled manner, thus the measurements under fore-aft (x) and lateral (y) directions were conducted in separate sessions. As the magnesium slip table can vibrate only in one direction, the seat is rotated by 90° to achieve vibration in both the directions independently. The arrangement of rigid seat to measure the response under y- axis excitation is illustrated in the Figure 2.5.

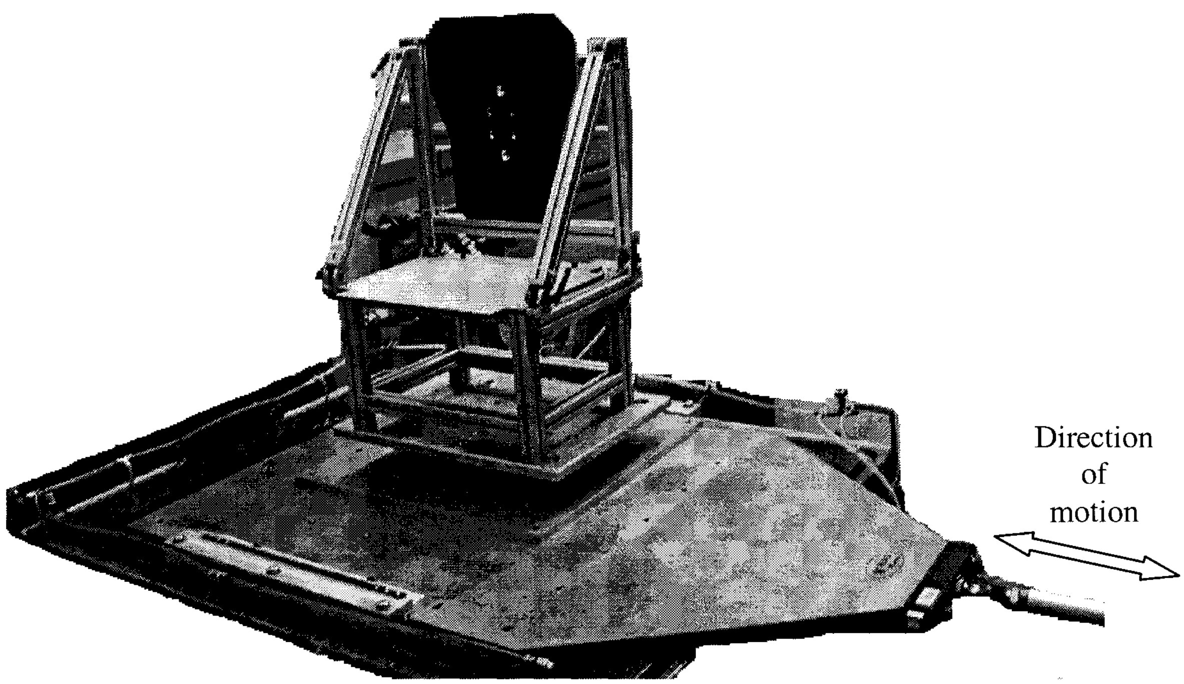


Figure 2.5: Test seat arrangement on the vibration platform for measurement of the responses under y-axis excitation.

The experiments involved a single trial for each level of sine sweep excitations and two trials under white noise excitations, for a total of 54 trials for each subject and axis, under random excitation involving three different back support conditions (no back support, and upper body supported against a vertical and an inclined backrest); three different seat pan heights (425, 390 and 350 mm); and three different magnitudes of band limited random excitations, and for a total of 4 trials for each subject and axis involving two (no back and back supported against inclined backrest) and two different magnitudes of sinusoidal excitations. The subjects were advised to relax between the successive trials for 3 to 5 minutes.

The APMS measured at the seat pan revealed constant magnitude in the 0.5-10 Hz frequency range with negligible phase under both white-noise and harmonic excitation, as shown in Figures 2.6 and 2.7. The results show nearly constant magnitude up to 20 Hz, and sharp resonant responses near 42 Hz and 30 Hz under *x*- and *y*- axis excitations respectively. The lower resonant frequency of the seat under excitation along y- direction can be attributed to relatively lower stiffness of the backrest structure supported on the hinges. Some differences were also observed in the resonant frequency of the seat with vertical and inclined backrest. The figures show the over all rms accelerations corresponding to the chosen harmonic excitations of peak acceleration of 1, 2 and 3 m/s^2. From the preliminary trials attained with a few subjects, the high excitation of 3m/s^2 under *x*- axis was judges to be too severe, as the subject had difficulty maintaining a consistent posture. The experiments under x-axis were thus limited to 1.0 and 2.0 m/s^2 peak accelerations (0.54 and 1.34 m/s^2 rms). The experiments under y-axis were performed under higher peak accelerations of 2.0 and 3.0 m/s^2 (1.34 and 2.1 m/s^2 rms).

The subject's name, address, age, weight, height, body build and physical fitness were also recorded. Each subject was asked to put on a cotton lab coat to ensure uniform friction between the back and the backrest, particularly under lateral excitation. Each participant was advised to assume a stable selected posture prior to start of the experiment while holding the emergency stop in his hand. The horizontal vibration platform was then driven using a selected excitation signal. The sensors signals were

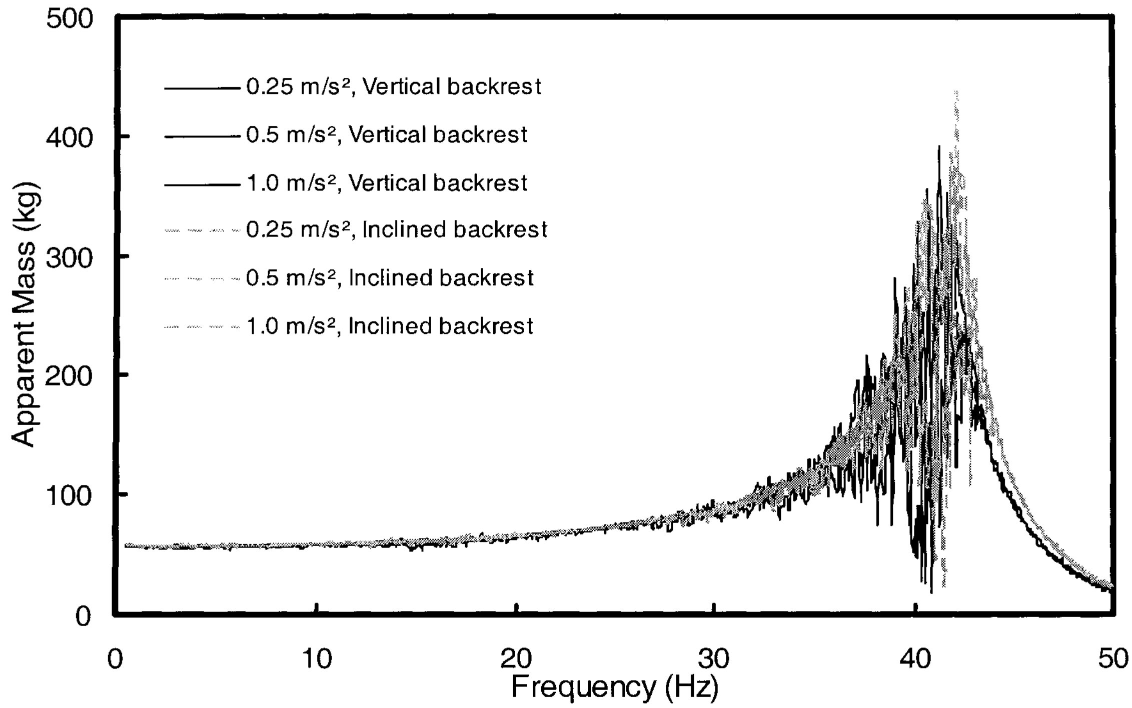


Figure 2.6: Apparent mass response of the seat pan with vertical and inclined backrests under different magnitudes of white noise excitations along *x*- axis.

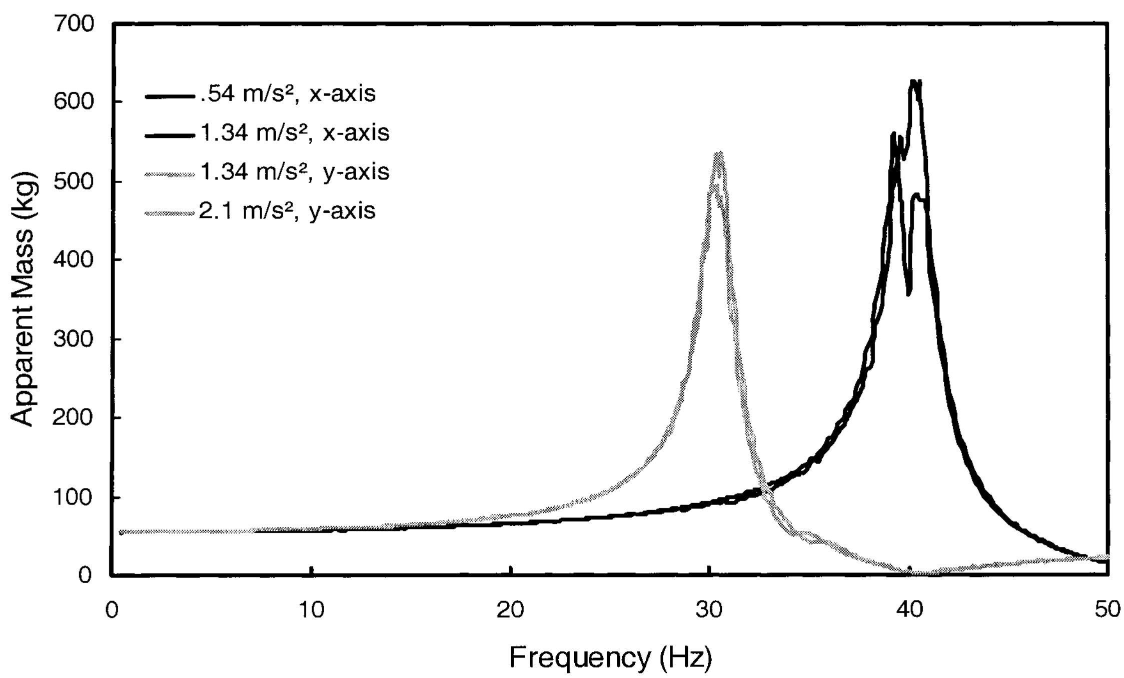


Figure 2.7: Apparent mass response of the seat pan under different magnitudes of harmonic excitations (0.54 m/s2 – 2.1 m/s^2) along the *x*- and *y*-axes.

acquired using the 4-channel pulse analyzer after a steady motion of the platform was realized. These included the force response measured at the seat base from the Kistler dynamometer, acceleration excitation at the seat base from the single axis micro-accelerometer, force response measured at the backrest from the Kistler dynamometer, and the acceleration of the backrest along the direction of excitation.

The acquired data were analyzed using the CPB (constant percentage band width) and FFT (Fast Fourier Transform) analyzers of the pulse system. The following responses were displayed on the screen using the pulse software to monitor the results:

- Magnitude and phase of the APMS response at the seat pan that was derived from the force and acceleration measured at the seat base.
- Magnitude of APMS response at the backrest that was derived from the force and acceleration measured at the backrest.
- Coherence function of the force and acceleration signals at the seat base.
- Coherence function of the force and acceleration signals at the backrest.
- Real part of cross-spectrum of force and velocity measured at the seat pan.
- Real part of cross spectrum of force and velocity measured at the backrest.
- Third-octave band spectra of the seat pan acceleration.

The measured APMS responses and cross-spectra were stored in terms of their real and imaginary components for further analyses. The APMS and the cross-spectra responses of the seat alone were 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 8 healthy adult male volunteers, with no history of prior musculo-skeletal system disorders, took part in the experiment. Each subject was asked to attend twelve different test sessions, three for each seat height, and two per axis of vibration involving sinusoidal and random excitation. A test session involving random vibration included minimum of a 18 trials including 3 postures, two repeats each and 3 levels of vibration. Unlike tests with random vibration, sinusoidal vibration session included a minimum of 4 trials including two postures and two levels of vibration. The experimenter rejected a particular trial, when it revealed either poor correlation or considerable different trends between the two trials or when the subject showed notable shifting of the upper body.

Table 2.1 summarizes the ranges of subjects' age, weight and height. The subjects aged between 21-51 years with standing body mass from 59.4 kg to 92 kg (mean mass =71.2 kg and standard deviation of the mean =10.6 kg). The standing height of the subjects varied from 1.7 m to 1.78 m (mean =1.73 m and standard deviation = 0.025 m).

Table 2.1: Age, mass and height of the subjects.

N=8	Mean	SD	Minimum	Maximum
Age (years)	28.5	9.38	23	50
Weight (kg)	71.2	10.6	59.4	92
Height (m)	1.73	2.5	1.70	1.78

The measurements were performed for each subject assuming three different sitting postures, three different seat heights (H_1:425 mm, H_2:390 and H_3:350mm), and three different levels of random vibration along the lateral and longitudinal directions, applied independently. The variations in sitting postures were realized by different back support conditions: (i) sitting erect with no back support, NB; (ii) sitting erect with upper body supported against a vertical backrest, Wb0; and (iii) seated relaxed with upper body supported against backrest inclined at an angle of 12.5° with respect to the vertical axis WbA, as shown in Figure 2.2, and summarized in Table 2.2.

Table 2.2: Summary of body postures adopted during the experiment.

Posture	Description
Back	NB: Sitting erect with no back support. Wb0: Sitting erect with upper body supported against a vertical backrest WbA: Seated relaxed with upper body supported against inclined backrest (angle of 12.5°).
Thighs	H1: Maximum thigh contact with the seat pan. H2: Medium thigh contact with the seat pan. H3: Minimum thigh contact with the seat pan.
Feet	Feet supported on the vibrating platform with full contact with surface.
Hands	Resting on lap.

The subjects were advised to sit upright with hands in the lap for the duration of each test with no-back posture and lean against the backrest for tests involving back-supported postures. Each test was performed two times and the data were examined for the repeatability. The duration of each measurement lasted 128s under random excitations and 512s under sinusoidal excitations, while the subject's posture during a trial was visually checked by the experimenter to ensure consistency. Table 2.3 summarises the total test matrix.

Table 2.3: Test matrix.

Test conditions	***Levels***	***Description of levels***	
Type of Excitation	2	Random	Sinusoidal
Magnitude of excitation	3(2!)	0.25, 0.5 and 1.0 m/s^2 rms	*x:* 0.54 and 1.34m/s^2 *y:* 1.34 and 2.31m/s^2
Back postures	3	NB, Wb0 and WbA:	NB and WbA
Seat height	3	H1, H2 and H3	H1
Direction of Excitation	2	*x* and *y*	*x* and *y*

! under harmonic excitations

2.5 Data analysis

Force and acceleration responses obtained in the experiment were used to derive both the APMS and absorbed power characteristics of seated occupant exposed to WBV along the *x*- and *y*-axes. A total of 30 samples for white-noise and 262 samples for sine sweep excitations were analysed within the FFT analysis software of the Pulse system. The signals were accordingly used to compute the APMS response functions, as the ratio of cross-spectral density of force and acceleration to the auto spectral density of the acceleration, as described in Equation (2.1). The absorbed power due to the stimulus was computed as the real component of the cross-spectrum between the force and velocity, Equation (2.2). The measurements at the seat base revealed high coherency of the force and acceleration signals under both axes of motion, greater than 0.97 in the 0.5-10 Hz frequency range, except for those acquired with the vertical back posture, which showed coherence magnitude greater than 0.95 at frequencies above 5Hz.

The measurements at the backrest along x and y-axes also revealed coherence values greater than 0.95 under lower magnitude (0.25 m/s^2) of vibration. The measurements at the backrest under higher magnitude of vibration (1 m/s^2) revealed coherence values greater than 0.9 in the frequency 0.5-4.5 Hz for both axes of motion. The coherency of the y-axis measurements increased with frequency, but decreased for the x-axis measurements with the vertical backrest (Wb0). This was attributed to the rocking motion at the subject's back and intermittent loss of contact with the vertical backrest. The measurements with the inclined backrest, however, revealed good coherency of the force and acceleration signals measured at the backrest under both axes of motion in the entire frequency range. The coherence values generally improved with the decrease in seat height showing increased stability of the posture.

2.5.1 APMS response analysis

Force responses measured at the seat pan under x- axis excitation are used to compute the APMS responses of the complete seat-occupant system, as shown in equation (2.1). The APMS response characteristics measured at the backrest are derived in a similar manner. The APMS responses of the seated occupant are obtained by subtracting the inertia force due to the seat and the supporting structure from the measured force response [14]. Both real and imaginary components of the measured response functions for the seat alone, and the seat-occupant system, are applied to compare the APMS response of the occupant in the frequency range of 0.5-10 Hz. Such that:

$$M_{pi}(j\omega) = M_{pic}(j\omega) - M_{pi0}(j\omega)$$

$$M_{bi}(j\omega) = M_{bic}(j\omega) - M_{bi0}(j\omega) \qquad (2.3)$$

Where $M_{pi}(j\omega)$ and $M_{bi}(j\omega)$ are complex APMS responses of the subject alone reflected at the seat pan and the backrest, respectively, when exposed to vibration along the direction i (i=x, y). $M_{pic}(j\omega)$ and $M_{bic}(j\omega)$ are measured apparent masses of the coupled seat-occupant system at the pan and the backrest.

The resulting real and imaginary components of the seated occupant's APMS response are expressed in terms of magnitude and phase in the frequency range of interest. The responses measured at the backrest for NB posture were further examined to verify that the involuntary interactions of the subject with the backrest were either absent or minimal.

2.5.2 Normalization of the measured APMS magnitude response

A number of studies on vertical biodynamic responses of seated individuals and a few on horizontal vibration biodynamics have mostly attributed the dispersion in the measured data to variations in the body mass. The reported data are thus frequently normalized with a measure of the body mass to reduce the variability in the data and to study the role of other contributing factors [3, 4, 9]. Owing to the negligible contribution of the legs, the vertical APMS responses are mostly normalized with respect to the static seated mass, ranging from 70-74% of the total body mass. This further compares well with the measured APMS magnitude response at 0.5 Hz [3]. Under horizontal vibration, the APMS magnitudes at such low frequencies have been observed to be higher than the static seated mass, suggesting contribution due to a relatively larger portion of the seated body. This may also be partly attributed to the presence of a low frequency resonance, particularly with NB posture, and possible influence of the legs. The normalization of the measured data thus requires identification of the representative portions of the body mass reflected at the seat pan and the backrest, while undergoing horizontal motions.

Holmlund and Lundström [7] normalized the measured impedance response under horizontal vibration on the basis of the body mass supported by the seat pan. In the present study, the subjects tended to continually shift weight to and from their legs in order to realize a more stable sitting posture. The knee joints rotations about the y-axis, and ankles rotations about the x axis were observed under x- and y-axis motions, respectively. Mansfield and Lundstrom [8] speculated that the role of seated occupants legs in the horizontal APMS response may vary with the direction of vibration, and thus normalized the measured APMS response using the total body mass. The effective mass reflected at the seat pan may be considered as the sum of those of the upper body and the thighs, while upper body mass alone would constitute the mass reflected at the backrest. The anthropometric data reported for the North American male population suggest that the upper body and the thighs account for nearly 67.8% and 20% of the total body mass, respectively [58]. In the present study, the normalization factors for the seat pan and the backrest APMS magnitudes are thus taken as 87.8% and 67.8%, respectively, of the total body mass.

2.5.3 Absorbed power

It has been widely recognised that the severity of vibration exposure of a seated body is directly influenced by the magnitude and duration of exposure. The APMS responses reported under vertical vibration, however, do not consider the exposure duration and show little effects of vibration magnitude, suggesting nearly linear behaviour with respect to excitation level. The validity of the APMS responses for assessing the exposure severity has thus been questioned. Alternatively, the vibration energy absorbed by the body has been suggested as a better measure of physical stress caused by the vertical WBV [1, 13]. The instantaneous power transmitted to the body or the energy flowing into the human body at the body-seat interface can be computed from the force (body exerts at the body-seat interface) and velocity of vibration.

$$P(t) = f(t)v(t) \tag{2.4}$$

Where P is the total power, $f(t)$ is the instantaneous force measured at the body-seat interface and $v(t)$ is the velocity due to vibration.

The total power comprises two components, such that $P(t) = P_{Abs}(t) + P_{El}(t)$. Where $P_{Abs}(t)$ is the absorbed part of the power that relates to energy necessary for keeping pace with the energy dissipated through structural (body) damping, and $P_{El}(t)$ is the elastic power that is continuously delivered to and removed from the body during each period of excitation and averages to zero for each sinusoidal cycle of motion [13].

The average energy transferred to the body during the time period T can be expressed as [12]:

$$P_{(avg)} = \int_0^T f(t).\mathrm{v}(t)dt \tag{2.5}$$

The instantaneous power in the frequency domain can be obtained from the cross-spectrum of the force and velocity as described in EQ (2.2). The complex cross-spectrum expressed as:

$$P(j\omega) = S_{F\dot{x}}(\omega) = c(\omega) - jq(\omega) \tag{2.6}$$

Where $c\ (\omega)$ is the coincident spectral density function (co-spectrum) and imaginary component, $q\ (\omega)$ is referred to as quadrature spectral density function (quad-spectrum) [57, 60]. In context of the vibration energy transferred to a seated human body, the real component reflects the energy dissipated in the biological structure per unit time and the imaginary component reflects the energy stored/ released by the system [11]. The biological system with finite damping consumes the vibratory energy by means of relative motions between the tissues, muscles and skeletal systems, which is transformed in the form of heat. The vibration power absorbed by the vibration-exposed seated body, $\mathrm{P}_{\mathrm{Abs}}(\omega)$ can thus be derived from the real part of the cross-spectrum between the force and velocity signals, such that [14]:

$$P_{Abs}(\omega) = \mathrm{Re}[S_{F\dot{x}}] \tag{2.7}$$

The total power absorbed by the human body subjected to vibration environment is computed through integration of the real component of the cross-spectrum:

$$\overline{\mathrm{P}}_{\mathrm{Abs}} = \int_{\mathrm{f}_1}^{\mathrm{f}_2} \mathrm{Real}[\mathrm{S}_{\mathrm{F}\dot{\mathrm{x}}}] = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{P}_{\mathrm{Abs}}(\overline{\omega}) \tag{2.8}$$

where $P_{Abs}(\omega)$ is the power absorbed in a third-octave frequency band centered around $\bar{\omega}$ and n is the number of bands, when a spectrum in the constant percent band is considered. f_1 and f_2 define the lower and upper frequency limit of interest, when cross spectrum in the constant band (resolution) is considered.

2.5.4 Mean biodynamic responses

The APMS and absorbed power response characteristics of individual subjects are initially evaluated as the mean of two trials conducted under random excitations. The data acquired during the two trials revealed high degree of consistency for all the subjects and experimental conditions considered. The mean responses attained for the 8 subjects, however, showed considerable variability in the seat pan as well as the backrest magnitudes but similar trends for the entire test conditions considered. The mean normalized APMS magnitude and phase, and absorbed power are data are evaluated to study the important trends related to the effect of sitting posture, seat height and magnitude of vibration on the seat pan and backrest responses. It has been reported that the mean responses, evaluated using different techniques involving either magnitudes or complex data, may differ considerably [10]. In this study, the mean normalised APMS magnitude responses at the pan ($\overline{M}_p$) and at the backrest ($\overline{M}_b$) are attained from the mean real and imaginary components of the normalised APMS responses of individual subjects, such that:

$$\overline{M_{ki}}(j\omega) = \left| \frac{1}{n} \sum_{l=1}^{n} \frac{\mathrm{Re}\,al[M_{kil}(j\omega)]}{m_l} + \frac{1}{n} \sum_{l=1}^{n} \frac{\mathrm{Im}\,ag[M_{kil}(j\omega)]}{m_l} \right| \qquad (2.9)$$

$$\varphi_{ki} = \tan^{-1} \left[\frac{\sum_{1}^{n} \mathrm{Im}\,ag[M_{kil}(j\omega)]}{\sum_{1}^{n} \mathrm{Re}\,al[M_{kil}(j\omega)]} \right] \qquad (2.10)$$

Where $M_{ki}(j\omega)$ represents the normalised mean APMS response of n subjects measured at k^{th} (k=p, b) driving point under vibration along axis i (i= x, y). M_{kil} is the complex apparent mass of subject l measured under a particular condition at location k under direction i. m_l represents the portion of the body mass used for normalisation as described in section 2.3.2. φ_{ki} is the phase measured at k^{th} (k=p, b) driving point under vibration along axis i (i= x, y).

The mean absorbed power response of n subjects as derived from the pan and the backrest are computed from:

$$\overline{P}_{ki}(\omega) = \frac{1}{n}\sum_{l=1}^{n} \text{Real}\,[S_{F\dot{x}}]_l \qquad (2.11)$$

where $\overline{P}_{ki}(\omega)$ represents the mean absorbed power response of the n subjects measured at k^{th} (k=p, b) driving point under vibration along axis i (i= x, y). Re [CS] is the real component of the cross spectrum between force and velocity.

2.6 Statistical data analysis

The peak magnitude responses of the subjects occur within narrow frequency ranges, and were strongly dependent upon the sitting posture and the direction of excitation. The mean normalized magnitude and phase data in case of APMS responses and mean real component in case of absorbed power responses, were evaluated to study the important trends related to the effect of sitting posture, seat height and magnitude of vibration on the seat pan and backrest responses. Owing to the relatively high values of Coefficient of Variation, specifically in the vicinity of the resonant frequencies, the mean data were considered to provide trend information on the effects of various factors. Further, statistical analyses are performed to check the variation of the data under the influence of the contributing factors. With-in subjects t-test is performed to analyse the significance of the contributing factors, since each experimental condition was repeated for the all subjects. ANOVA, the analysis of the variance method is performed, to analyse the data of the different experimental conditions and identify the significance of the contributing factors. ANOVA performed in this study, considered the individual subject's responses at selected discrete frequencies over the concerned frequency range are performed. Thus, single ANOVA method is performed to identify the significant effect due to each contributing factor individually and two-factor ANOVA method is also performed to analyse the significance of interactive contribution of two factors to the responses measured at seat pan and backrest. The significance of the contributing factors is stated based on the p values less than 0.05.

Owing to the large data obtained in various experimental conditions considered and subjects individual response, SPSS software was used to perform repeated measure, within-subject ANOVA method. The effect of the magnitude of excitation, back supported postures and seat height was stated based on the significance factor ($p < 0.05$) computed using the SPSS software.

2.7 Summary

Experimental and data analysis methods employed to characterize the biodynamic responses of seated occupant exposed to horizontal whole-body vibration are established. A rigid seat was designed to realize off-road vehicle sitting postures and applied to perform the biodynamic measurements on 8 male subjects exposed to horizontal vibration levels considered to be representative of the off-road vehicle vibration environment. The apparent mass and absorbed power responses are applied to determine and quantify, the influences of the back supported posture, seat height and, nature and direction of excitation in the following chapters.

The data was analyzed to derive the seated occupant's biodynamic response and absorbed power response to whole-body horizontal vibration. The tests were performed with three different back postures (unsupported, vertical and inclined back supports), three different seat heights (H_1=425, H_2=390 and H_3=350 mm) and different levels of random and harmonic, broad band excitations. The measured data was analyzed to establish biodynamic response characteristics of seated occupants, upon performing the necessary corrections for the inertial forces of the seat assembly and the backrest structure. The analyses of the measured data provided the biodynamic response and absorbed power characteristics of seated subjects, as reflected on the seat pan and the backrest as function of the back posture, seat height, and excitation type and magnitude. The response characteristics are discussed in the following chapters.

Chapter 3

APPARENT MASS RESPONSE CHARACTERISTICS

3.1 Introduction

Seated occupant response to WBV is evaluated using two methodologies. These include the measurement of transmission of vibration to different body segments, and measurement of driving-point force-motion relationships. The latter methods involve the study of forces developed at the body-seat interface and can be expressed as the DPMI (driving point mechanical impedance) or the APMS (apparent mass) [3-7]. The apparent mass of the human body is more frequently used to characterise the human biodynamic response to vertical or horizontal vibrations, since it permits greater convenience for performing the necessary corrections to account for inertia force due to the seat structure [3].

The apparent mass, computed as the ratio of the driving-point force to the acceleration, is directly proportional to the static mass of the human body supported by the seat and it provides measures of resonant frequencies of the biological system. The studies reported on vertical as well as horizontal biodynamics invariably suggest that individual variability in mass and stiffness would be expected to result in differences in the resonant frequencies and the APMS magnitudes between the subjects [3-6, 9, 14]. A number of studies have shown the influences of magnitude of vibration and direction, and sitting posture on the APMS magnitude responses [3, 5, 6, 8, 9]. On the basis of reported data, the ranges of the biodynamic responses of subjects exposed to vertical WBV have been standardised [16]. A few studies have also reported that standardised values do not represent the responses under conditions representative of vehicle driving [22]. Standardised values are considered applicable for sitting without a back support, with hands in lap, magnitudes of vibration in the 1-3 m/s^2 range, and vibration frequencies up to 20 Hz. A few studies have also reported the characteristics of human response exposed to horizontal whole-body vibrations [5-8]. In these studies, the experiments were conducted independently along fore-aft and lateral directions, assuming negligible coupling effects. These studies also suggest strong effects of a number of contributory factors, such as anthropometry related factors, magnitude and frequency of vibration, and postural factors.

Based on the methods suggested in the reported studies, the measured data are analyzed in this chapter to derive the frequency response characteristics of driving-point measures as a function of the direction and magnitudes of vibration, back support condition and seat height. The biodynamic responses of the seated human body are characterized by the transfer functions relating force and motion at the driving point. The measured data are analysed to derive the inter-subject variability, while the mean normalized APMS responses are discussed to enhance the understanding of the effects of sitting posture and nature of vibration.

3.2 Inter-subject variability

Generation of reliable data on the biodynamic responses of seated occupants to WBV necessitates thorough understanding of the factors that contribute to variability. The anticipated sources of variation could permit for better interpretations of the results. The reported studies under vertical vibration have related the variations in the response to individual differences, such as body mass or size [3]. The large inter-subjects variability observed in APMS responses can be attributed mainly to the anthropometric constitution of the seated human body. The effects of variations in the body postures (such as back support and seat height), general health and muscle tension, however, have not yet been clearly defined to attain the generally applicable response characteristics [3, 8, 9]. This study attempts to derive important trends in APMS response under defined conditions, and quantify the contributions due to various factors, namely the postural condition, seat height, and magnitude and direction of horizontal vibration.

The measured data are statistically analysed to test the repeatability in the measured responses and to establish relationships between the variables, and quantify the nature and strength of those relationships. International standard [16], presents the variations in the driving-point responses of the trials performed under supposedly comparable experimental conditions of vertical excitations, which suggests that responses obtained in different studies lie within reasonable ranges so that the mean data could be applied for establishing important trends.

The apparent mass responses of 8 subjects exposed to horizontal vibration, in this study however, showed considerable variability in the seat pan as well as the backrest APMS magnitudes but similar trends for all the test conditions considered. The measured data revealed concentration of magnitude peaks in the vicinity of same frequencies for most of the subjects. Figure 3.1 illustrates, as an example the seat-pan APMS magnitude and phase responses obtained for the subjects seated with an inclined back support on a seat with height H_1 (425mm) and exposed to lower magnitude of broad band random vibration (rms acceleration = 0.25 m/s^2) along the fore-and-aft direction. Figure 3.2 illustrate the corresponding responses measured at the backrest. The results show considerable scatter in the magnitude responses, which are mostly attributed to variation in the individuals mass, but some what consistent trends with respect to the frequency of peak response, which could be considered as the resonant frequency of the occupant. Table 3.1 summarises the coefficient of variation (CoV) derived from the data sets attained for 8 subjects corresponding to different combinations of sitting posture, seat height, excitation level and axis of vibration. The coefficient of variation value denotes the ratio of peak to mean value corresponding to the frequency of peak standard deviation (SD) of the mean in the 0.5-10 Hz frequency range.

Table 3.1: Coefficient of variation for the APMS data measured at the seat base and the backrest.

Axis	*Seat Height*	*Vibration Level*	*Coefficient of Variation (%)*				
			Seat Pan			Backrest	
			NB	Wb0	WbA	Wb0	WbA
x	425mm	$0.25 m/s^2$	33.47	27.9	30.78	24.07	22.25
		$0.5 m/s^2$	38.35	24.56	30.14	27.19	18.03
		$1.0 m/s^2$	40.51	32.71	26.45	45.06	27.39
	390mm	$0.25 m/s^2$	33.93	27.03	26.72	25.12	23.04
		$0.5 m/s^2$	42.04	25.66	29.01	27.08	26.54
		$1.0 m/s^2$	40.07	33.69	29.84	53.73	35.82
	350mm	$0.25 m/s^2$	48.51	29.02	26.41	25.84	29.0
		$0.5 m/s^2$	42.86	26.62	25.64	27.37	24.07
		$1.0 m/s^2$	45.70	25.64	24.06	44.15	25.32
y	425mm	$0.25 m/s^2$	41.41	46.24	46.57	59.56	47.33
		$0.5 m/s^2$	43.93	39.45	47.83	67.09	50.68
		$1.0 m/s^2$	35.94	38.66	34.89	87.74	67.63
	390mm	$0.25 m/s^2$	42.61	50.05	54.24	64.66	51.67
		$0.5 m/s^2$	47.37	44.93	49.70	61.37	51.79
		$1.0 m/s^2$	38.42	30.97	33.27	59.63	42.79
	350mm	$0.25 m/s^2$	47.93	46.73	47.84	50.71	44.28
		$0.5 m/s^2$	43.61	41.47	46.80	39.77	41.30
		$1.0 m/s^2$	38.93	38.13	35.07	53.27	43.95

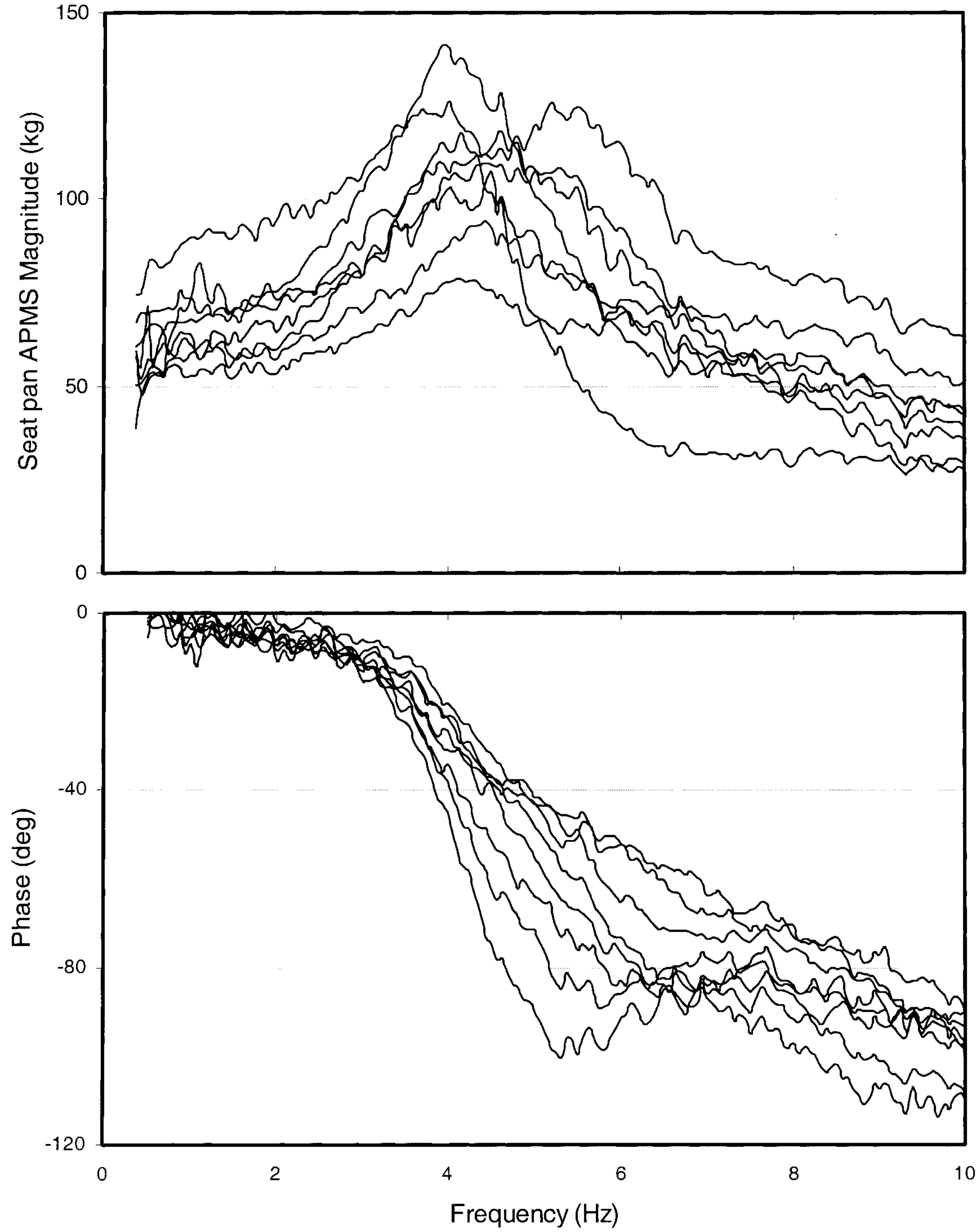


Figure 3.1: Comparisons of seat pan APMS magnitude and phase responses of eight subjects seated with WbA posture and exposed to white noise fore-and-aft excitation of 0.25 m/s^2 (Seat height: H1).

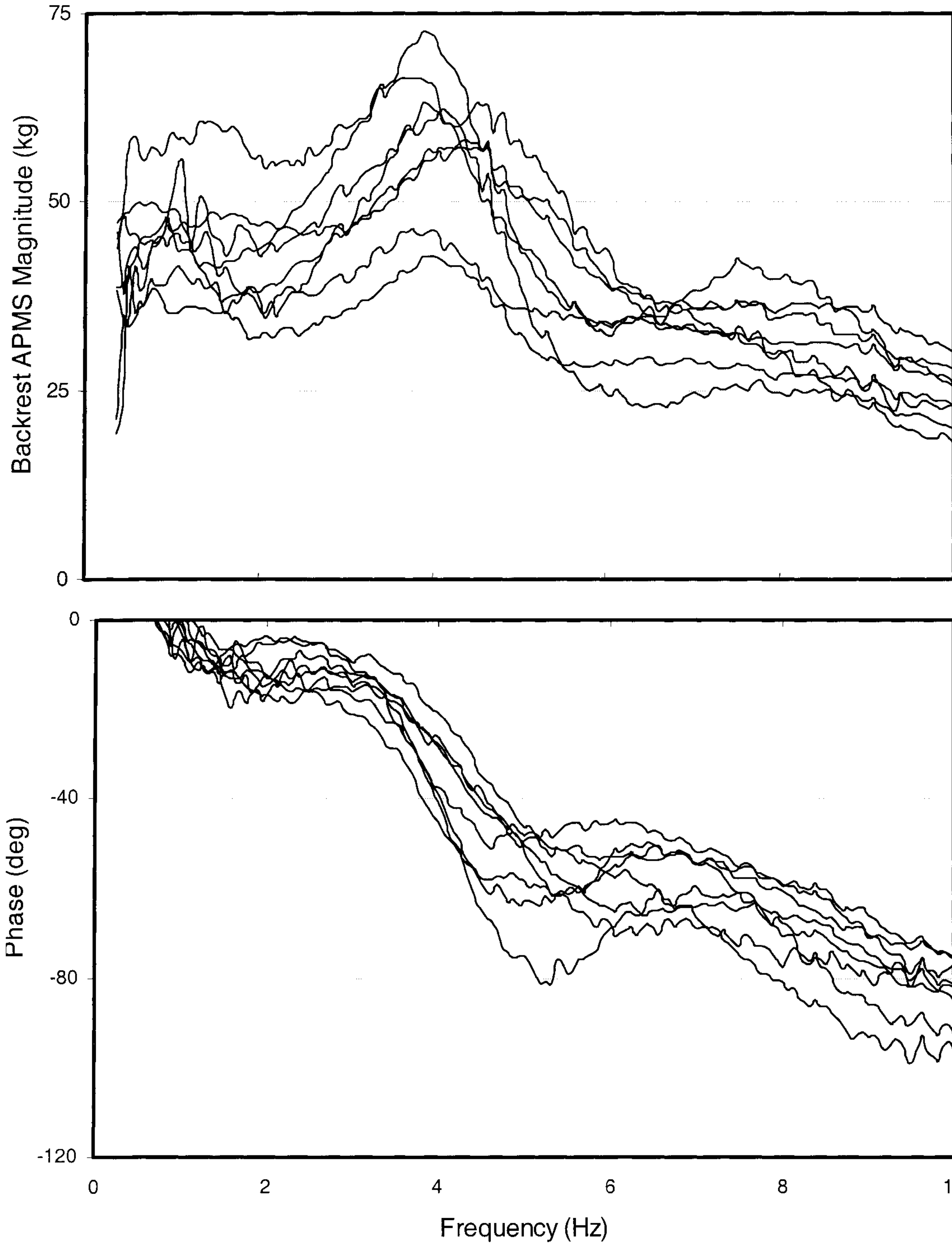


Figure 3.2: Comparisons of backrest APMS magnitude and phase responses of eight subjects seated with WbA posture and exposed to white noise fore-and-aft excitation of 0.25 m/s^2 (Seat height: H1).

Higher values of coefficients of variation (CoV) were observed in the vicinity of the frequencies corresponding to peak APMS magnitudes. The CoV of the seat-pan APMS data acquired under NB postures generally increased with the magnitude of excitation, except for the data measured along *y*- axis where it decreased with the magnitude of excitation, particularly with the lower seat height. This trend however, was not evident from the seat-pan APMS data acquired for the back supported postures along *x*- axis. However, seat-pan APMS data acquired for the back supported postures along *y*-axis revealed decrease in CoV values with the increase in magnitude of excitation. Peak values of the CoV of the data acquired at the seat pan ranged from 24% to 49% under *x*-axis of excitation, depending on the postural condition and magnitude excitation. These values were observed to be higher under y-axis excitation, and ranged from 31% to 54%. The effect of seat height on the CoV values is relatively small. The observed CoV values for the seat pan response are comparable to the reported variability under horizontal vibrations [8].

The measured data for the backrest also revealed similar trends in CoV values, but considerably higher variability in the magnitude responses, particularly under *y*-axis excitation. This could be attributed to extreme variations in the contact forces developed at the backrest-upper body interface, and sliding of upper body under *y*-axis motions. The peak values of CoV approach as high as 88% in the 1-2 Hz range for the data obtained along *y*-axis. Under fore-and-aft motions, the peak values approached as high as 54%. The excessive variability in the data can be partly attributed to intermittent loss of contact between the upper body and the backrest under fore-aft excitation, and subjects' tendency to continually shift more weight towards their feet.

3.3 APMS response

3.3.1 Influence of anthropometric factors

A number of studies on vertical biodynamics of seated individuals and a few studies in horizontal vibrations have attributed the dispersion in the measured biodynamic responses obtained under similar experimental conditions, to variations in the body mass [3-8]. The reported seat pan APMS responses to horizontal vibration have suggested strong effect of body mass [6, 8], while very few works have attempted to quantify its effect on APMS magnitude and the resonant frequency. Owing to the upper body rotation about the pelvis under fore-and-aft motion and out of phase rotation of the legs and upper body in side-to-side motion, it was suggested that subject's height could also influence the APMS response [10]. The peak magnitude and corresponding frequency of the individuals APMS data obtained at both seat pan and backrest are analysed with respect to individual body mass. This analysis was performed on the data obtained in all the postural conditions, seat height, and magnitude and direction of horizontal vibration.

The peak APMS magnitude generally increases with the body mass in most of the experimental conditions. Figures 3.3 and 3.4 illustrate the trend lines of the peak APMS magnitudes and the corresponding resonant frequencies of the individual subjects seated with inclined back support and maximum seat height, while exposed to different magnitudes of broad-band fore-and-aft excitations. Although the APMS magnitude responses revealed considerable dispersion, the trend lines suggest that the peak APMS magnitude corresponding to primary resonance is generally positively correlated with the body mass. Similar trends have also been reported in a few studies on vertical as well as horizontal APMS responses [9, 10]. The coefficients of determination (r^2) are also

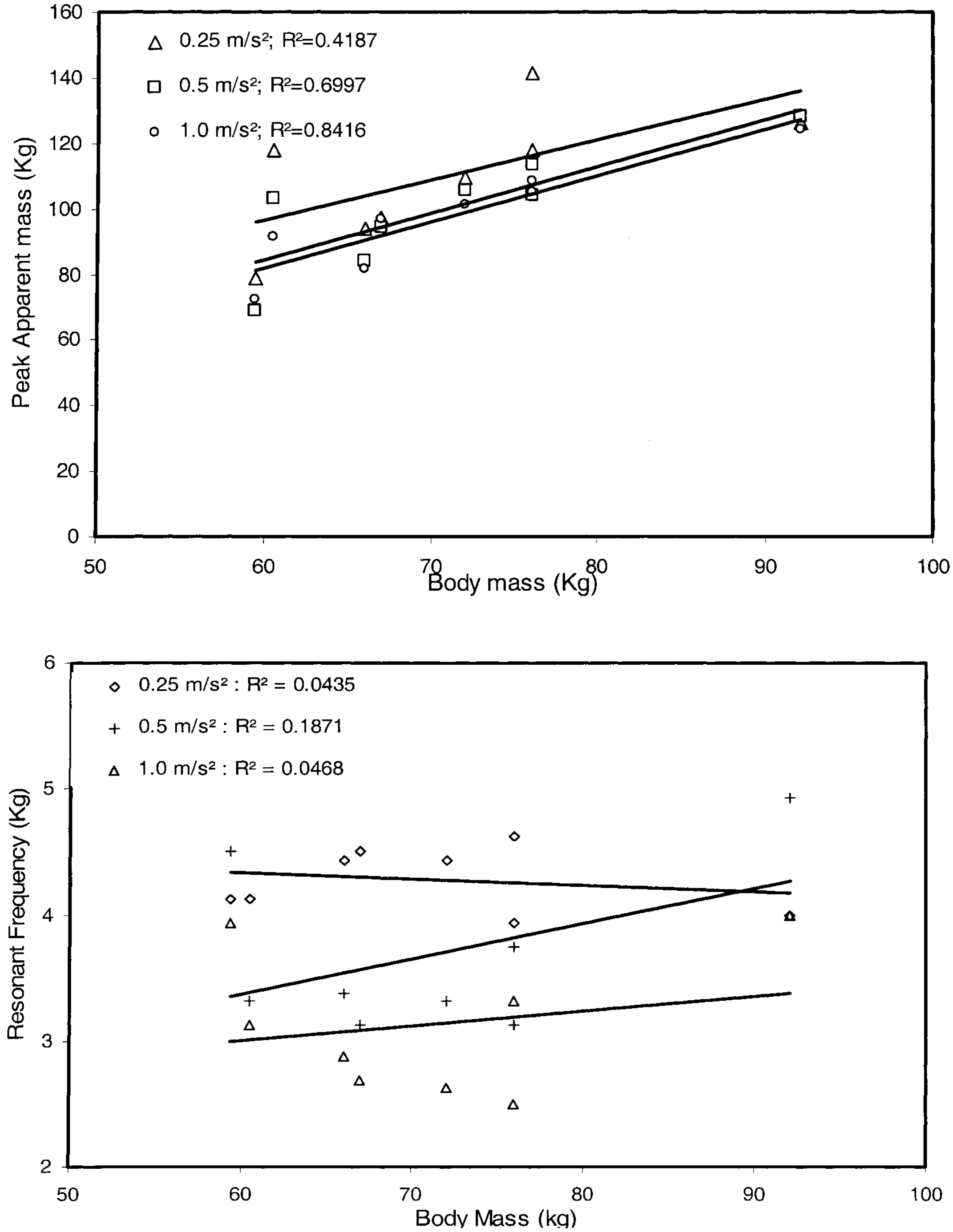


Figure 3.3: Dependency of peak seat-pan-APMS magnitude and corresponding resonant frequency on the body mass, when exposed to fore-and-aft random vibration with WbA posture (Seat height H1).

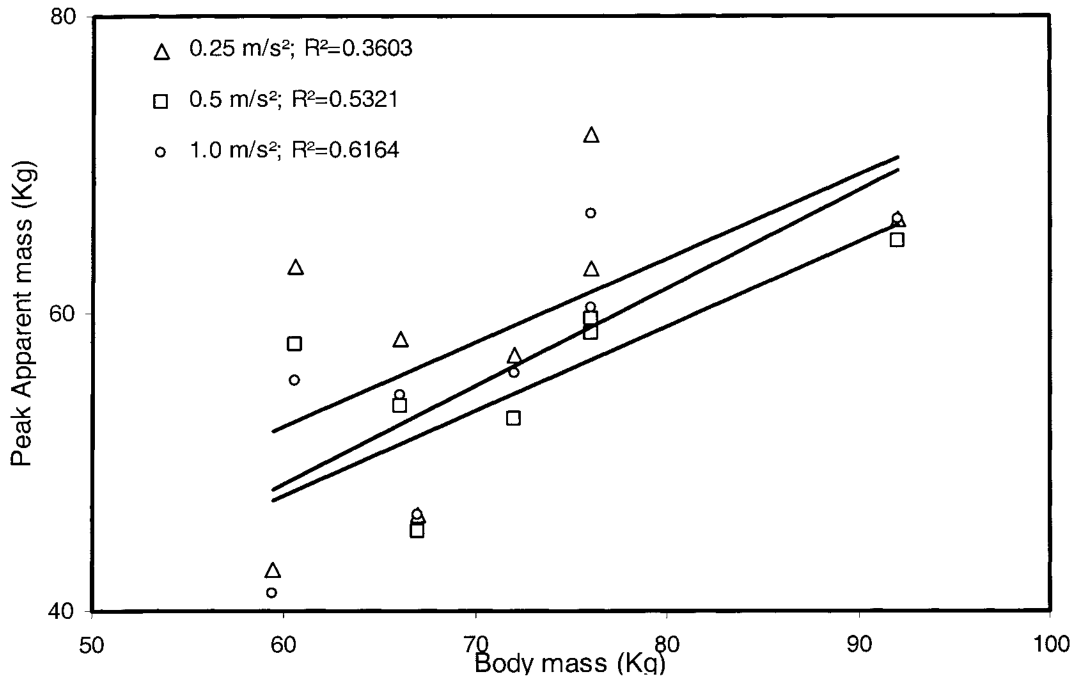


Figure 3.4: Dependency of peak backrest-APMS magnitude on the body mass when exposed to fore-and-aft random vibration with WbA posture (Seat height H1).

computed to study the linear relation between the peak APMS magnitudes and the body mass. The minimum r^2 value suggested under conventional criteria for the sample of 8 subjects, in order to be significant is 0.49. Both the seat pan and backrest APMS magnitudes reveal r^2 values in excess of 0.53 for the excitation magnitudes of 0.5 and 1.0 m/s^2. The r^2 values tend to be considerably lower under lower magnitudes of excitation. Higher r^2 values were generally obtained for the APMS magnitude and the body mass under varying experimental conditions, as shown in the Table 3.2. Reasonably good correlation was observed with data obtained at the seat pan, in most of the experimental conditions (r^2 values ranging from 0.45 to 0.95), while higher r^2 values were attained under side-to-side motion when compared to that in fore-and-aft motion suggesting strong correlation between the peak APMS magnitudes measured along side-to-side motion and the body mass when compared to that in the fore-and-aft motion.

Table 3.2: Coefficient of determination for the peak APMS magnitude measured at the seat base and the backrest with respect to the body mass.

Axis	*Seat Height*	*Vibration Level*	*Coefficient of determination (r^2)*				
			Seat Pan			Backrest	
			NB	Wb0	WbA	Wb0	WbA
x	425mm	0.25m/s^2	0.9133	0.4126	0.4187	0.1503	0.3603
		0.5m/s^2	0.5168	0.77438	0.6997	0.2922	0.5321
		1.0 m/s^2	0.4834	0.7077	0.8416	0.5287	0.6164
	390mm	0.25m/s^2	0.4591	0.5551	0.4093	0.296	0.5662
		0.5m/s^2	0.4984	0.7046	0.3407	0.6381	0.7649
		1.0 m/s^2	0.4023	0.8606	0.2719	0.7553	0.8128
	350mm	0.25m/s^2	0.3295	0.1989	0.0642	0.4421	0.6578
		0.5m/s^2	0.1287	0.6067	0.2128	0.3482	0.676
		1.0 m/s^2	0.2163	0.9563	0.507	0.8052	0.5316
y	425mm	0.25m/s^2	0.8864	0.8978	0.8594	0.3310	0.2550
		0.5m/s^2	0.9232	0.7996	0.8274	0.0444	0.1173
		1.0 m/s^2	0.8048	0.6443	0.7755	0.1092	0.0863
	390mm	0.25m/s^2	0.929	0.811	0.8856	0.2869	0.0805
		0.5m/s^2	0.8039	0.765	0.8247	0.0709	0.4037
		1.0 m/s^2	0.78.69	0.8323	0.6878	0.1571	0.3319
	350mm	0.25m/s^2	0.9503	0.8361	0.6983	0.6947	0.5812
		0.5m/s^2	0.9133	0.4126	0.4187	0.1503	0.3603
		1.0 m/s^2	0.5168	0.77438	0.6997	0.2922	0.5321

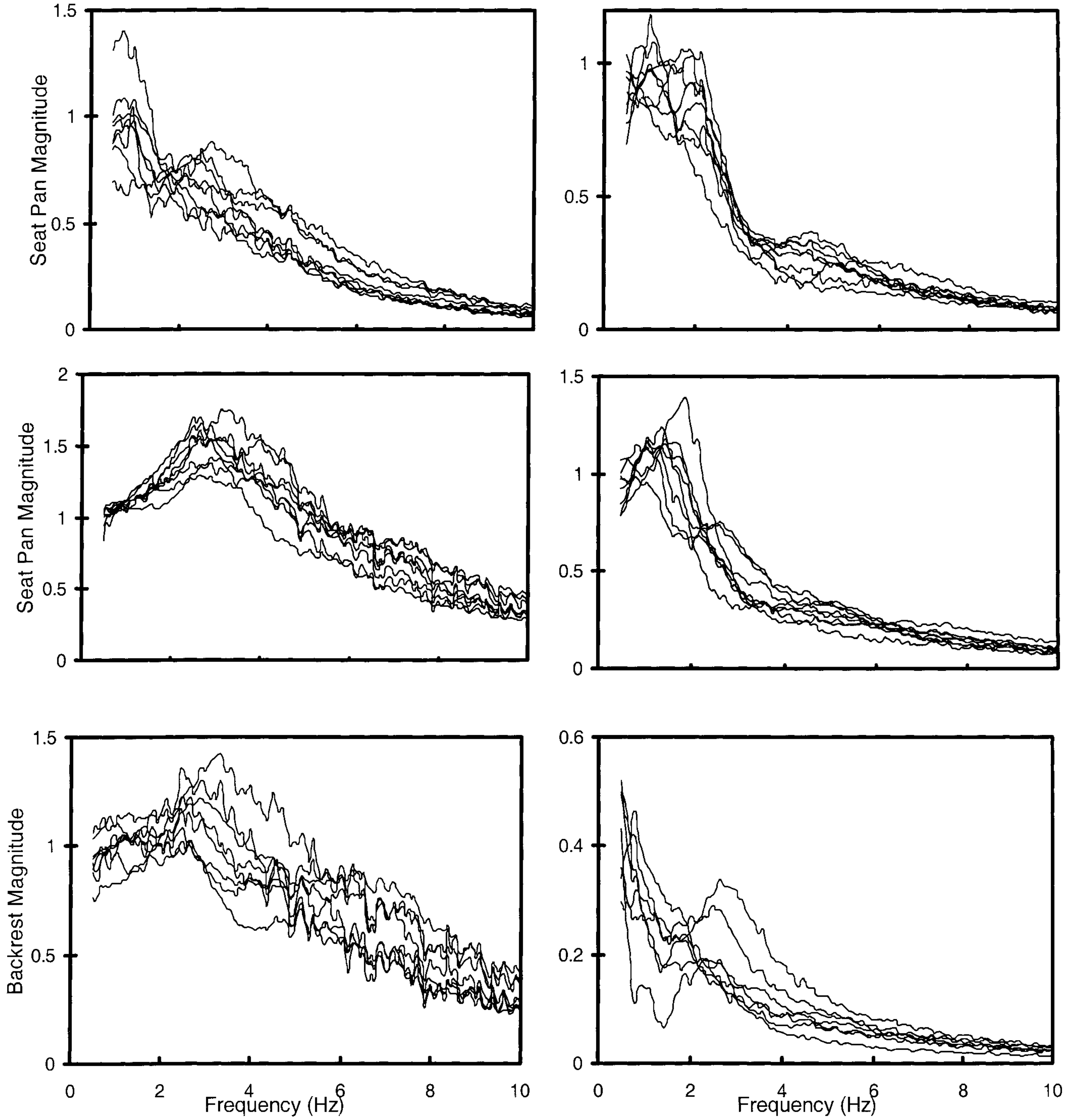
However, the r^2 values obtained with respect to the backrest-APMS magnitude and body mass, irrespective of the axis of excitation, revealed considerably lower values, ranging 0.15 to 0.80, this is believed to be caused due to the intermittent loss of contact between the upper body and the backrest under fore-and-aft excitation, sliding against the backrest under side-to-side motion, and subjects' tendency to continually shift more weight towards their feet. Figure 3.4 illustrates the reasonable correlation between peak backrest-APMS magnitude and the body mass with WbA posture support under fore-and-aft random vibration.

Although the frequencies corresponding to the peak magnitude of APMS tend to different for different subjects, no particular trend was observed with the body mass, as illustrated in Figure 3.3 for the inclined back supported posture. Similar trends were also observed for other sitting postures. The lack of correlation between the resonant frequency and the body mass has been reported for vertical APMS response [22]. Relatively poor co-relations of the peak APMS magnitude and corresponding frequency were also observed with the individual height. This was partly attributed to relatively small variation in the heights of the selected participants (1.73± 2.3m).

3.3.2 Normalised APMS response

Owing to the strong body mass effect on the APMS magnitude response presented in section 3.3.1, the measured data are frequently normalised with respect to a body mass measure in order to reduce the degree of dispersion in the data and to study the effects of other contributing factors [7, 8]. The normalised APMS magnitude responses and the mean values are computed as discussed in section 2.3.2. The mean responses thus obtained are expected to show some trends with regards to variations in other contributory factors, while reducing the degree of dispersion in the data.

The applications of normalizing factors described in section 2.3.2 resulted in near unity values of the normalized seat pan and backrest APMS magnitudes at low frequencies around 0.5 Hz, with the exception of the *y*-axis backrest APMS, which tends to be considerably lower. This exception is attributed to relatively low level interactions of the upper body with the backrest along the *y*-axis. Figure 3.5 illustrates, as an example, comparisons of the normalised magnitude data obtained for individual subjects exposed to 1 m/s^2 *x*- and *y*-axis vibration and seated with WbA (seat pan and backrest) and NB (seat pan) postures (seat height – H_1). The normalized magnitude responses for the NB postures clearly show the presence of resonance at frequencies below 1 Hz, and relatively smaller dispersion among the data when compared to the true measured data as illustrated



(a) *x*-axis (b) *y*-axis

Figure 3.5: Comparisons of normalized APMS magnitude responses measured at the seat pan and backrest of eight subjects seated with NB and WbA postures, and exposed to 1 m/s^2 rms acceleration (seat height H1).

in Figures 3.1 and 3.2. The peak values of CoV of the mean normalized magnitudes were generally 10% lower than those observed from the true magnitude data, shown in Table 3.3. The figure also shows comparisons of the data attained under 1 m/s^2 lateral excitation, where the dispersion among the data is generally higher. The results also show that the normalized magnitude response measured at the backrest is well below 1.0 under lateral excitations. Owing to considerably lower degree of dispersion of the normalised data, the mean data trends could be utilised to study the role of the contributory factors, namely magnitude and direction of vibration, posture and seat height.

Observations during the experiments revealed relatively high displacement of the base motion at lower frequencies (< 1Hz) that led to considerable sway of the upper body. The participants resisted this motion by their muscular actions, increased support from the seat to realise a stable sitting posture. The subjects also tended to pose higher pressure on the feet support to maintain stable sitting posture. In the lower frequency range the discomfort sensation tends to be high due to difficulties in stabilising the upper body, while in the higher frequency range a stable upper body posture is realised due to lower transmissibility of horizontal vibration to the upper body. The presence of backrest interface generally provides added support and stiffening effect for the upper body, and thus helps to stabilise the upper body against sway motion and reduce the discomfort sensation. Contrarily, in the higher frequency range, (about 3-6 Hz) the backrest serves as a primary source of vibration transmitted to the upper body and thus a significant source of discomfort. A relaxed posture with an inclined backrest, however, causes a softening effect, when compared to an erect posture with a vertical backrest. The APMS responses measured at the backrest also revealed similar trends, three peaks in the 1-1.2 Hz, 2.6-4

Hz and 7-8 Hz ranges were observed. These trends are further discussed in the following sections presenting the influence of various factors considered.

Table 3.3: Coefficients of variations of the normalised APMS data measured at the seat base and the backrest under different postures, and magnitudes of fore-and-aft and lateral excitations.

Axis	*Seat Height*	*Vibration Level*	*Coefficient of Variation (%)*				
			Seat Pan			Backrest	
			NB	Wb0	WbA	Wb0	WbA
x	425mm	$0.25 m/s^2$	23.85	19.79	25.11	28.58	19.98
		$0.5 m/s^2$	24.03	21.9	18.43	31.94	21.60
		$1.0 m/s^2$	28.92	35.1	24.35	51.55	33.06
	390mm	$0.25 m/s^2$	30.25	21.5	18.85	28.01	28.95
		$0.5 m/s^2$	41.72	27.46	17.39	32.82	26.96
		$1.0 m/s^2$	36.59	36.8	23.81	59.09	38.22
	350mm	$0.25 m/s^2$	39.0	25.04	24.91	34.79	30.9
		$0.5 m/s^2$	43.81	24.25	19.52	30.20	24.36
		$1.0 m/s^2$	34.64	31.82	19.68	50.47	28.46
y	425mm	$0.25 m/s^2$	35.8	39.62	40.44	58.11	50.3
		$0.5 m/s^2$	36.59	31.91	40.96	71.26	55.15
		$1.0 m/s^2$	27.27	26.12	26.61	93.25	72.96
	390mm	$0.25 m/s^2$	38.23	45.47	50.66	62.53	51.49
		$0.5 m/s^2$	41.60	39.1	44.68	65.75	50.79
		$1.0 m/s^2$	36.01	25.1	27.33	64.15	48.3
	350mm	$0.25 m/s^2$	23.85	19.79	25.11	28.58	19.98
		$0.5 m/s^2$	24.03	21.9	18.43	31.94	21.60
		$1.0 m/s^2$	28.92	35.1	24.35	51.55	33.06

3.4 Factors influencing APMS response

The peak magnitude of the APMS response of the subjects occur within narrow frequency ranges, and are strongly dependent upon the sitting posture (back supported condition and seat height) and the direction of excitation. Owing to the relatively high values of CoV, specifically in the vicinity of the resonant frequencies, the mean data are considered to provide trend information on the effects of various factors. The mean magnitude and phase data are thus evaluated to study the important trends related to the effect of sitting posture, seat height and magnitude of vibration on the seat pan and the backrest responses.

Statistical data analysis was also performed considering the subjects individual data to support the trends revealed by the mean data and further analyse the interactive effect of two contributing factors that is not revealed by the mean data. Single and two-factor, within-subject ANOVA are thus performed to identify the most significant factors affecting the seat pan and the backrest APMS responses. Tables 3.4 and 3.5 summarize the *p*-values obtained for the seat pan responses under *x*- and *y*-axis excitations, respectively. The results are presented for at different discrete frequencies, considering the three levels of each of the excitation magnitude and seat height, and their interactions, for each sitting posture. The significant differences between the seat pan APMS magnitudes obtained for the two back-supported postures (Wb0 *vs* WbA) and all three postures are also summarized in Table 3.6, for both axes of vibration. Table 3.7 summarise the *p*-values obtained for the backrest responses under *x*-axis excitations. The results show that all factors, namely, the excitation level, posture and seat height, are significant. Significances of the factors considered are discussed in the following sections.

Table 3.4: *p*-values attained from single and two-factor ANOVA performed on the seat pan APMS magnitude under fore-aft vibration.

Factor	Excitation (.25, .5, 1.0 m/s^2)			Height (H_1, H_2, H_3)			Excitation*Height		
Frequency(Hz)	NB	Wb0	WbA	NB	Wb0	WbA	NB	Wb0	WbA
0.75	0.000	0.049	0.970	0.041	0.009	0.088	0.63	0.729	0.11
1.0	0.000	0.013	0.506	0.000	0.118	0.018	0.489	0.055	0.299
1.5	0.002	0.000	0.000	0.000	0.763	0.115	0.012	0.536	0.008
2	0.949	0.000	0.000	0.220	0.304	0.005	0.15	0.435	0.031
2.75	0.000	0.001	0.000	0.005	0.043	0.004	0.063	0.141	0.209
4	0.000	0.383	0.000	0.004	0.001	0.478	0.03	0.013	0.015
4.5	0.000	0.021	0.000	0.002	0.003	0.725	0.02	0.001	0.403
5	0.000	0.000	0.000	0.083	0.051	0.958	0.063	0.001	0.913
6	0.000	0.000	0.000	0.337	0.378	0.623	0.325	0.008	0.194
8	0.000	0.000	0.000	0.110	0.007	0.454	0.129	0.233	0.921

Table 3.5: p-values attained from single and two-factor ANOVA performed on the seat pan APMS magnitude under lateral vibration.

Factor	Excitation (.25, .5, 1.0 m/s^2)			Height (H_1, H_2, H_3)			Excitation*Height		
Frequency(Hz)	NB	Wb0	WbA	NB	Wb0	WbA	NB	Wb0	WbA
0.75	0.000	0.000	0.000	0.268	0.067	0.019	0.377	0.282	0.031
1.0	0.000	0.000	0.000	0.196	0.803	0.153	0.168	0.672	0.451
1.5	0.005	0.000	0.000	0.131	0.743	0.028	0.246	0.097	0.463
2	0.001	0.000	0.000	0.001	0.811	0.153	0.755	0.535	0.428
2.75	0.000	0.000	0.000	0.363	0.220	0.238	0.453	0.357	0.582
4	0.000	0.000	0.000	0.003	0.000	0.279	0.004	0.52	0.001
4.5	0.008	0.000	0.000	0.050	0.002	0.136	0.63	0.01	0.04
5	0.000	0.000	0.000	0.065	0.000	0.030	0.841	0.157	0.617
6	0.000	0.000	0.000	0.207	0.004	0.000	0.559	0.26	0.261
8	0.001	0.000	0.000	0.357	0.141	0.717	0.135	0.688	0.042

Table 3.6: Effect of posture shown by the p-values derived from single-factor ANOVA performed on the seat pan APMS magnitude data under Fore-and-aft and lateral excitations.

Axis	Frequency (Hz)	0.75	1.0	1.5	2.0	2.75	4.0	4.5	5.0	6.0	8.0
x-	Wb0VsWbA	0.428	0.037	0.000	0.000	0.038	0.854	0.011	0.000	0.000	0.002
	3 Postures	0.563	0.820	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
y-	Wb0VsWbA	0.876	0.148	0.000	0.000	0.179	0.000	0.000	0.000	0.045	0.456
	3 Postures	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

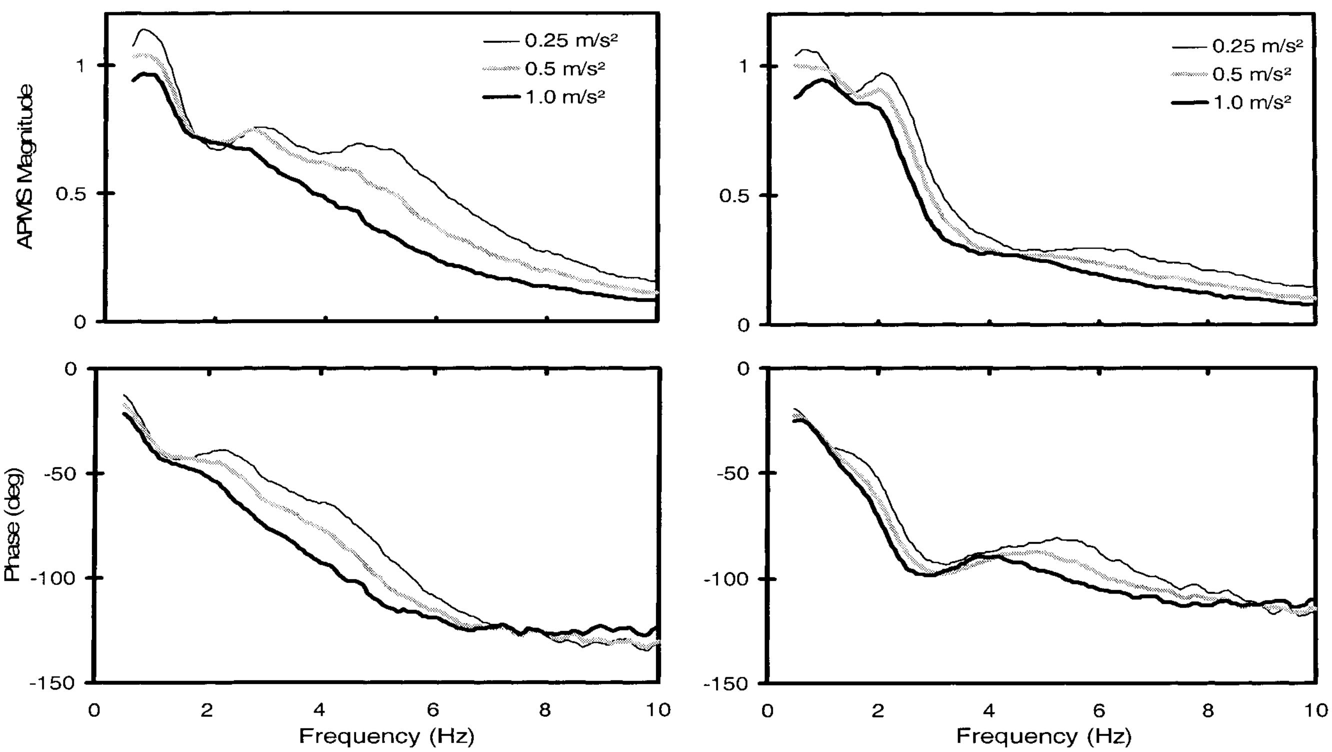
Table 3.7: *p*-values attained from single and two-factor ANOVA performed on the backrest APMS magnitude under fore-aft vibration.

Factor	Excitation (.25, .5, 1.0 m/s^2)		Height (H_1, H_2, H_3)		Excitation*Height		Posture (Wb0 *vs* WbA)
Frequency(Hz)	Wb0	WbA	Wb0	WbA	Wb0	WbA	---
0.75	0.045	0.821	0.010	0.731	0.585	0.255	0.200
1.0	0.001	0.217	0.352	0.249	0.506	0.010	0.990
1.5	0.000	0.000	0.311	0.245	0.218	0.014	0.000
2	0.000	0.000	0.452	0.100	0.156	0.121	0.000
2.75	0.001	0.000	0.278	0.446	0.577	0.089	0.090
4	0.090	0.000	0.075	0.097	0.107	0.150	0.925
4.5	0.341	0.000	0.046	0.016	0.33	0.255	0.032
5	0.232	0.002	0.137	0.002	0.917	0.407	0.000
6	0.000	0.817	0.925	0.063	0.908	0.413	0.000
8	0.000	0.000	0.155	0.037	0.054	0.124	0.009

3.4.1 Magnitude of vibration

The effect of vibration magnitude on the APMS responses of seated occupants exposed to vertical vibration is known to be relatively small [3, 4, 9]. The reported responses under horizontal vibration, measured at the seat pan, however, have shown strong effects of the vibration magnitude [5-8, 9], which are most likely attributed to many factors, such as, the nonlinear behaviour of the seated body, excessive upper body movements under higher excitations, involuntary shifting tendencies of the occupants to realize more stable posture, and contributions due to rotation of the pelvis and legs. The mean magnitude and phase responses attained under different excitation levels are studied to derive the effects of excitation magnitudes as the APMS responses measured at the seat pan and the backrest.

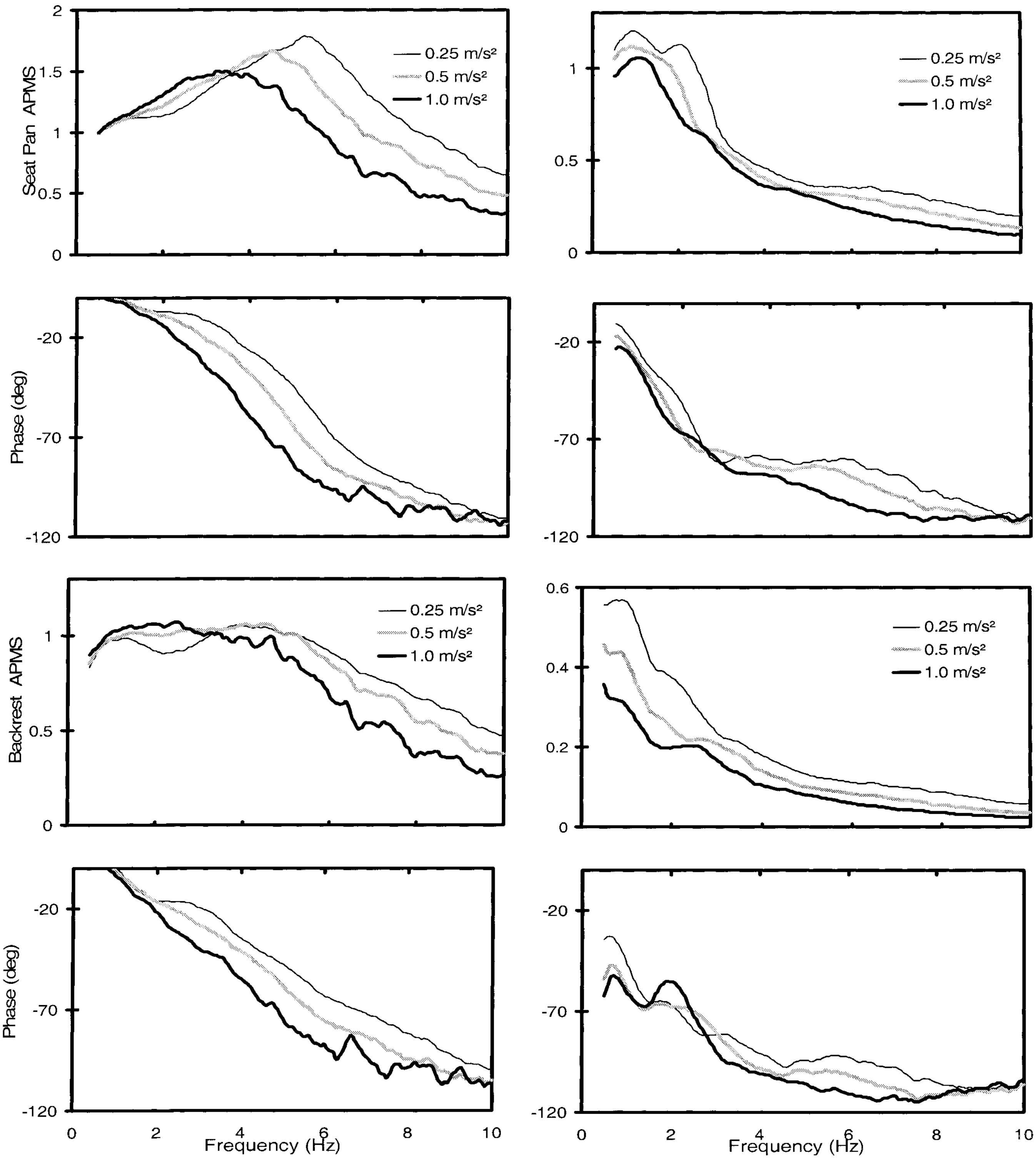
Figure 3.6 illustrates mean normalized magnitude and phase responses of the APMS measured at the seat pan attained under different magnitudes of *x*- and *y*-axes of excitations, and NB posture. Figures 3.7 and 3.8 illustrate the effects of excitation magnitude on the *x*- and *y*-axis seat pan and backrest APMS responses for the Wb0 and WbA postures, respectively. The results show that variations in the magnitude of vibration tend to affect both the peak magnitudes and the corresponding frequencies that are associated with the resonance modes of the seated occupant. The results clearly show strong and nonlinear effects of vibration magnitude on both the seat pan and backrest responses, irrespective of the direction of excitation. The strong influence of the vibration magnitude is also evident from the results attained from ANOVA, presented in Tables 3.4 and 3.5 for the *x*- and *y*-axes, respectively, where $p<0.005$ in majority of the frequency range, suggesting nonlinear behaviour of the seated occupant to horizontal vibration. The effect of vibration magnitude on the seat pan APMS magnitude is highly significant ($p<0.002$) in the entire frequency range under both axes of vibration and all three sitting postures, with the exception of the low frequency response ($\leq$1.0 Hz) under WbA posture and *x*-axis motion.



(a) x-axis (b) y-axis

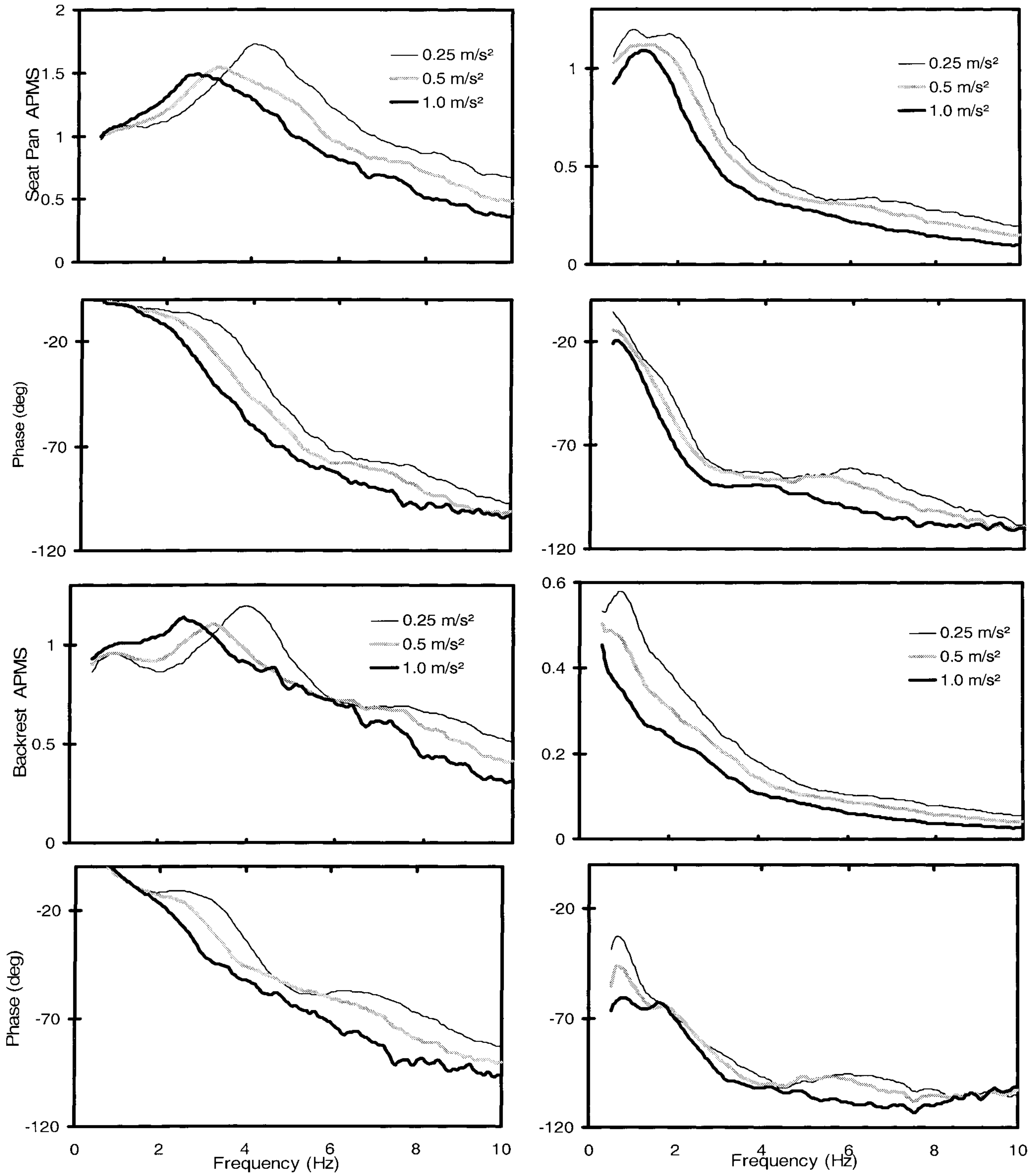
Figure 3.6: Influence of excitation magnitude on the mean normalized seat pan APMS magnitude and phase (seat height-H1 and posture-NB).

The variations in the vibration magnitude tend to affect the peak magnitudes and their corresponding frequencies, and the phase response, irrespective of the axis of motion and sitting posture. The magnitude responses for the NB (Figure 3.6) reveal peaks near 0.7, 2.8 and 4.75 Hz under x-axis, and in the 0.7-1.0 and 1.9-2.1 ranges, and around 6.4 Hz under the y-axis motion. The second and third resonant peaks are more evident under lower magnitude of vibration (0.25 m/s^2), which tend to damp out under higher excitations along both the x- and y-axes. The primary peak occurs near low frequency of 0.7 Hz, associated with rocking and swaying of the upper body under x- and y-axes excitations, irrespective of the excitation magnitude. The primary peak as well as the magnitude response in the entire frequency range tends to decrease with increasing excitation magnitude. The frequencies corresponding to the second and third peaks



(a) *x*-axis (b) *y*-axis

Figure 3.7: Influence of excitation magnitude on the mean normalized magnitude and phase responses measured at the seat pan and the backrest (Seat height – H1; Posture – Wb0).



(a) x-axis (b) y-axis

Figure 3.8: Influence of excitation magnitude on the mean normalized magnitude and phase responses measured at the seat pan and the backrest (Seat height – H1; Posture – WbA).

decrease under higher magnitude excitations, suggesting softening effect in these modes. An increase in excitation magnitude generally yields lower phase response for all postures and directions of excitation, particularly above 1 Hz. This may be caused by higher energy dissipation under higher excitations.

Both the magnitude and phase responses show significantly different trends when a vertical back support is used, as shown in Figure 3.7. Unlike the NB posture, the response characteristics attained under the two directions of motion also differ considerably. Under *x*-axis, the constraint imposed by the vertical backrest generally yields a single-degree-of-freedom like behaviour of the seat pan APMS magnitude, similar to the vertical biodynamics response, with peak magnitude occurring in the 3.3-5.4 Hz range. The inclined back support posture also yields similar seat pan magnitude response with peak occurring at relatively lower frequencies 2.7-4.1 Hz (Figure 3.8). A lower magnitude peak is also observed near 1 Hz under lower vibration magnitude (0.25 m/s^2) for both postures. The strong effect of the excitation magnitude on the seat pan normalized magnitude is clearly evident from Figures 3.6 and 3.7, which show lower magnitude and the corresponding frequency under higher excitation magnitudes.

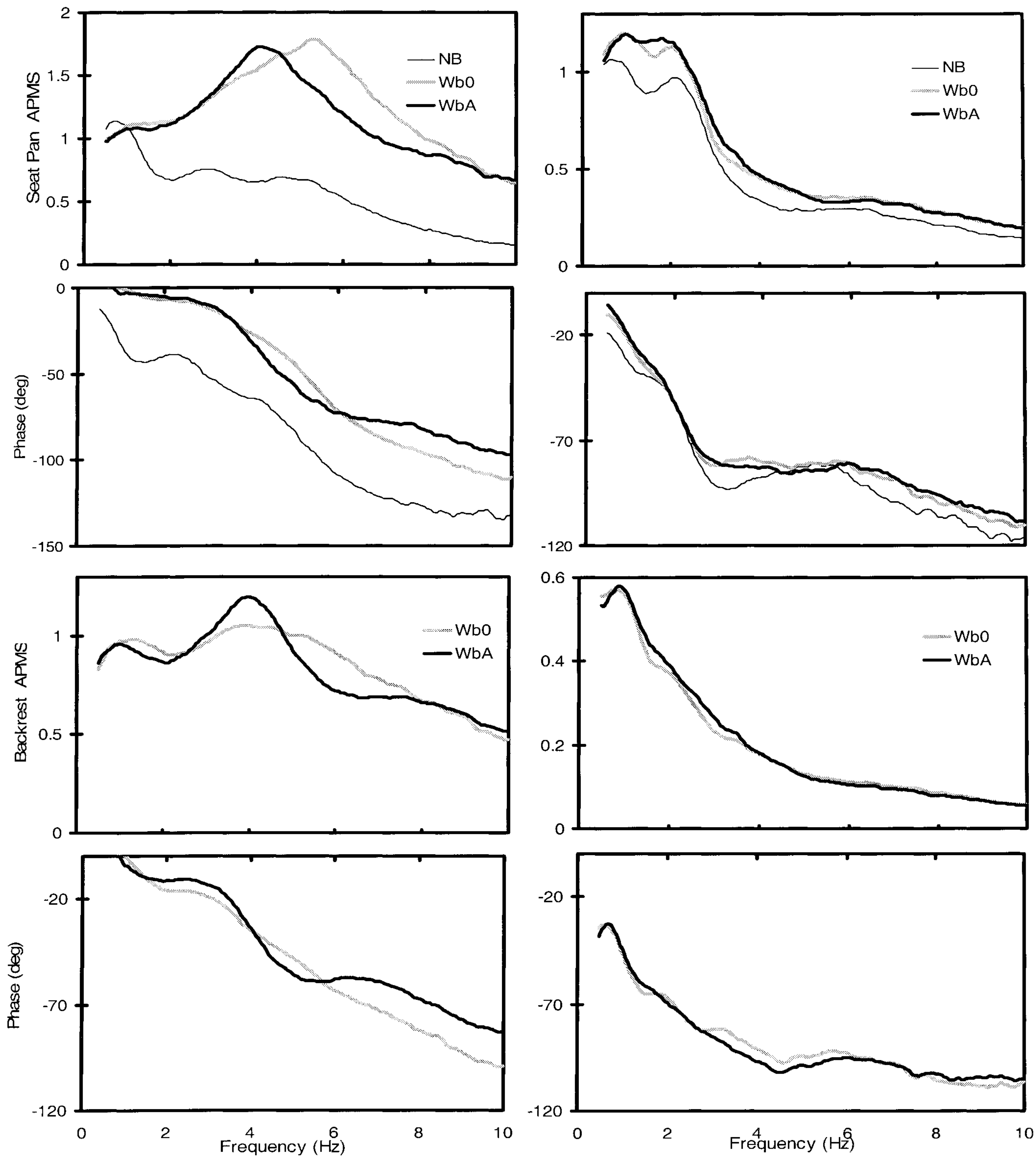
The *x*-axis backrest APMS responses show two peaks for the Wb0 postures in the 1.25-2 Hz and 4-4.5 Hz ranges, and three peaks for the WbA posture in the 1-1.2 Hz, 2.6-4 Hz and 7-8 Hz ranges. The normalized magnitudes of the backrest APMS, however, are considerably smaller than those of the seat pan. The two peaks observed for the Wb0 posture are clearly evident under the lower excitation magnitudes (0.25 and 0.5 m/s^2), which tend to converge to a single frequency near 2 Hz under higher excitation (1 m/s^2). Unlike the seat pan APMS, an increase in excitation level yields higher magnitude and the corresponding frequency of the backrest APMS in the lower frequency range for both postures. The second mode frequency and the peak magnitude, however, decrease with increasing excitation level, as observed in the seat pan APMS magnitude. The similar behaviour is also observed for the third magnitude peak for the WbA posture.

The mean APMS responses for the back-supported postures under *y*-axis show trends similar to those observed for the NB posture. Under *y*-axis motion, the upper body tends to slide against the backrest resulting in relatively lower interactions with the backrest, while the backrest offers little resistance against the upper body sway. The biodynamic response measured at the seat pan thus resembles that with the NB posture. While the magnitudes of the seat pan APMS are only slightly higher than those for the NB posture, the corresponding frequencies tend to be higher. Lower level excitation yields two magnitude peaks in the 0.9-2.1 Hz range for both postures. An increase in the excitation level yields a single peak occurring in the 1-1.25 Hz frequency range. The peak magnitude decreases with increase in the excitation level, while effect on the corresponding frequency is very small. A smaller magnitude peak is also observed in the vicinity of 6.6 Hz for both postures. The variations in the backrest APMS response with the frequency also show trends comparable to those observed for the seat pan APMS. The primary peak tends to occur around 1 Hz for both postures under lower level of excitation. Higher excitation causes this frequency to shift towards a lower frequency, suggesting that the peak may occur at a frequency below 0.5 Hz. Higher excitation level also yields lower magnitude response in the entire frequency range for both postures. The effects of excitation magnitude on the phase responses are relatively small, when compared to those observed under *x*-axis motion.

3.4.2 Back supported postures

Studies on vertical biodynamic response have reported strong effect of postural variations related to back supported conditions [3, 4, 9], only a few studies, however, have considered the back support posture for characterising the APMS response to horizontal vibration [5, 6]. The results presented in Figures. 3.6 to 3.8 clearly show the significant effect of the sitting posture on both the seat pan and the backrest APMS responses, which is further evident from Tables 3.6 and 3.7. The results show significant effects of posture on the seat pan APMS magnitude (p<0.001), when the variations are considered for all three postures, with the exception of the x-axis response at low frequencies (≤ 1.0 Hz). The variations in the back support (vertical *vs* inclined) also show significant effect on the seat pan APMS magnitude in most of the frequency (p< 0.04), except in the vicinity of the resonant peaks around 4Hz in the x-axis. The back support condition is also significant under the y-axis motion in the 1.5-2.0 Hz and 4-6 Hz frequency ranges. The mean normalized seat pan and backrest magnitude and phase responses attained for the three postures, higher seat (H_1=425 mm) and 0.25 m/s^2 rms acceleration excitation, are further compared in Figure 3.9 for both axes.

The results clearly show strong effects of the sitting postures, related to the back support condition, on the peak magnitudes, the corresponding resonant frequencies, and the phase. The NB posture yields considerably lower seat pan magnitudes under both axes of excitation, with three noticeable peaks as discussed above. The frequencies corresponding to the peak magnitudes are comparable with those reported in earlier studies [6-8]. The backrest offers an important resistance to the upper body motions, particularly under longitudinal and vertical excitations. The effect of the back support on



(a) x-axis (b) y-axis

Figure 3.9: Variations in the mean normalized magnitude and phase responses measured at the seat pan and the backrest with sitting posture, particularly the back support condition (Seat height: H1; excitation magnitude: 0.25 m/s^2).

the x-axis responses, however, is far more significant than those reported for the vertical biodynamics [3, 9]. This may be attributed to relatively large rocking motion of the upper body under longitudinal vibration, participation of comparatively larger portion of the body mass in the horizontal biodynamics and possible contributions due to legs. The effect of the back support on the y-axis response is also evident, even though the dynamic interactions of the body with the back support are small to moderate.

Under the NB postures, the primary peaks in the seat pan APMS magnitudes occur around 0.7 Hz, which are attributed to high magnitude rocking and sway motions of the upper body caused by the x- and y-axis excitations, respectively. These motions are stabilized by the muscular actions of the upper torso and by applying increased pressure on the lower legs (calf and feet).

The addition of a back support tends to limit the low frequency rocking motion of the upper body under x-axis motion, while considerable dynamic interactions with the backrest would occur. The backrest support causes the stiffening of the body under x-axis motion, as evident from considerably higher frequency corresponding to the primary peak response (near 5.4 and 4.1 Hz for the Wb0 and WbA postures, respectively). The biodynamic behaviour of the seated occupant seated with a back support and exposed to x-axis vibration tends to dominate around this mode, and thereby resembles that of a single-degree-of-freedom system. The backrest, however, serves as another source of vibration to the seated occupant, which tends to cause considerably higher APMS magnitude responses, as observed in Figure 3.9, for both Wb0 and WbA postures. A relaxed posture with an inclined backrest causes a softening effect when compared to an erect posture with a vertical backrest. An inclined back-supported posture thus yields peak seat pan APMS response at a lower frequency (near 4.1 Hz). The peak seat pan APMS magnitude also decreases slightly with the WbA posture; both the lower magnitude and lower frequency may be beneficial in reducing the strain on the lumbar spine. An inclined backrest, however, supports a larger portion of the upper body mass and thus causes higher backrest magnitude response near 4.1 Hz.

Under lateral vibration, the back support offers limited resistance against the body sway to help stabilize the sitting posture. The back-supported postures thus yield relatively higher frequency of the primary peak in the seat pan APMS response, when compared to that of the NB posture. The additional vibration energy transmitted to the upper back also yields relatively higher peak magnitude, as evident in Figure 3.9. The backrest APMS responses, however, are not influenced by the back support due to relatively lower interactions of the upper body with the backrest along the lateral axis. Moreover, the variations in the back support conditions considered in this study have only minimal effects on the seat pan as well as the backrest APMS phase responses under lateral excitations. The phase responses under longitudinal excitations, however, are strongly influenced by the back support. The NB posture yields considerably lower phase response between the seat pan force and the longitudinal acceleration, when compared to those attained with the back-supported postures. At excitation frequencies above 6 Hz, an inclined back support yields higher phase response than the vertical back support.

3.4.3 Seat height

Figure 3.10 illustrates comparisons of the mean seat pan magnitude responses of the seated occupant obtained for the three seat heights considered in the study. Figure shows the responses attained with three sitting postures, while exposed to 0.25 m/s^2

excitation along the x- axis. The effect of seat height was observed to be very small on the seat pan APMS phase and the backrest APMS magnitude and phase under x-axis, and all the responses under y-axis. The figure thus illustrates the effects on the x-axis seat pan normalized magnitude responses alone. The effect of the seat height is predominant on the magnitude response in the vicinity of the resonant frequencies, which is further evident from the ANOVA results ($p<0.04$; Table 3.4), irrespective of the posture. The results also show strong interactions between the seat height and the excitation magnitude around the same frequencies.

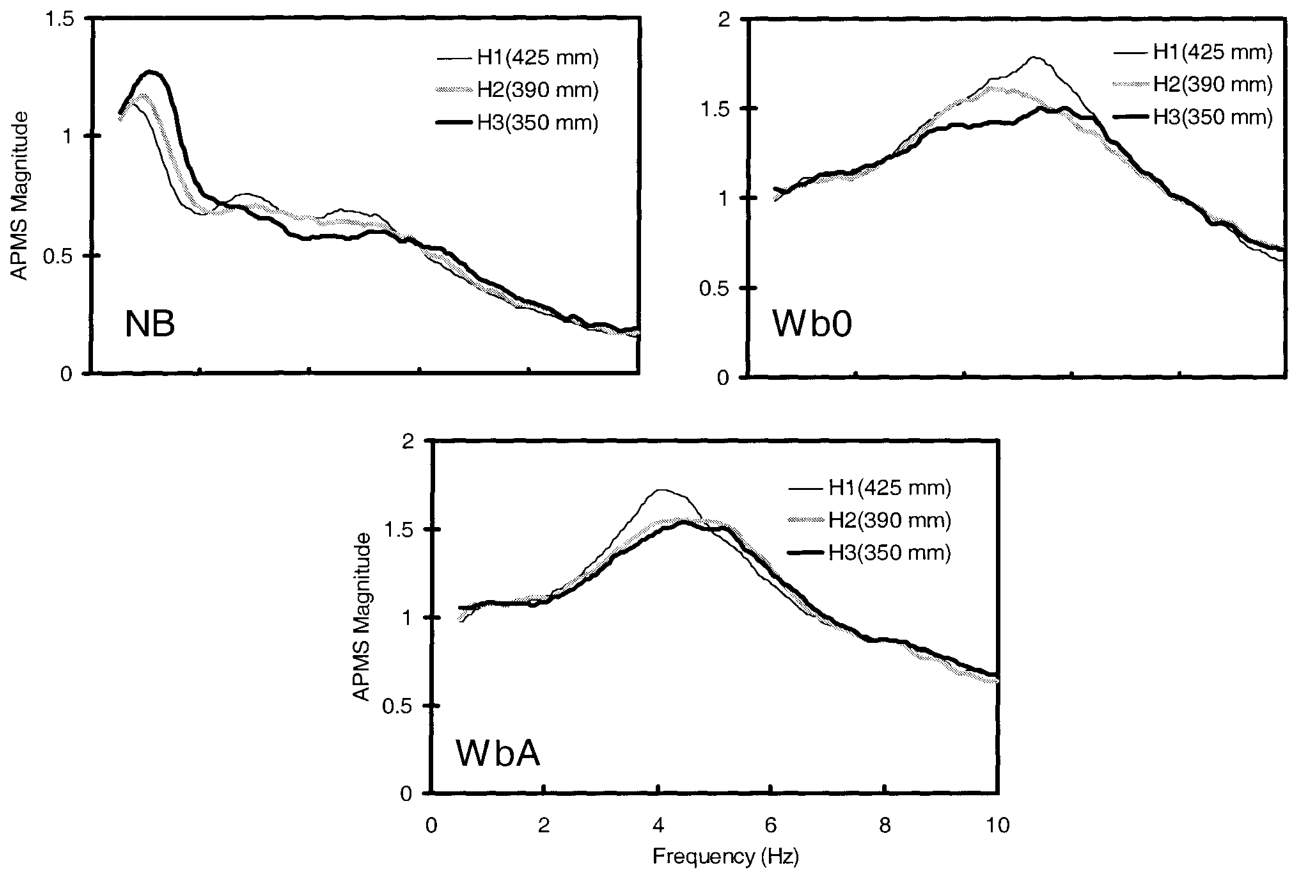


Figure 3.10: Influence of seat height on the mean normalized seat pan APMS magnitude and phase under x-axis excitation (excitation magnitude – 0.25 m/s^2).

The seat height effect was more evident for the NB posture. A higher seat with this posture generally encouraged the subjects to shift more weight towards the feet in an attempt to stabilize their posture. A lower seat height provided a more stable posture, and the resulting stiffening effect caused the fundamental frequency and the magnitude to increase slightly. The peak magnitude response with back supported postures, however, decrease with the decrease in the seat height. It is speculated that the subjects seated on a lower seat tend to make full use of the back support and thereby reduce the forces on the seat pan, which could cause lower peak APMS magnitude in the vicinity of the resonant frequencies. While the effect of seat height is more evident under lower vibration magnitude, the effect was observed to be smaller under higher magnitudes of excitations.

3.5 Comparisons of mean responses with the reported data

The biodynamic responses measured at the seat pan of seated occupants without a back support exposed to sinusoidal and random horizontal vibration along the *x*- and *y*-axes have been reported in a few studies. The reported studies on the responses of seated occupants exposed to horizontal vibration have mostly considered seating without a backrest. These include a study on APMS, by Mansfield and Lundström [8], and a study on DPMI [7], and a single study on absorbed power by Holmlund and Lundström [11]. Only two studies, however, have investigated the biodynamic responses of occupants exposed to horizontal vibration, while seated with a backrest support. Fairley and Griffin [6], reported the biodynamic responses of occupants seated with and without the backrest under both fore-and-aft and lateral vibration, applied independently. Nawayseh and Griffin [5], have reported the influence of vertical backrest on the biodynamic response under fore-and-aft vibration. The reported studies are thoroughly reviewed and the results are compared with the data obtained in the present study, under comparable experimental conditions. All the reported works have concluded that the seated occupant system response to horizontal vibration is a complex phenomenon, where the effects of different test conditions occur simultaneously in a coupled manner.

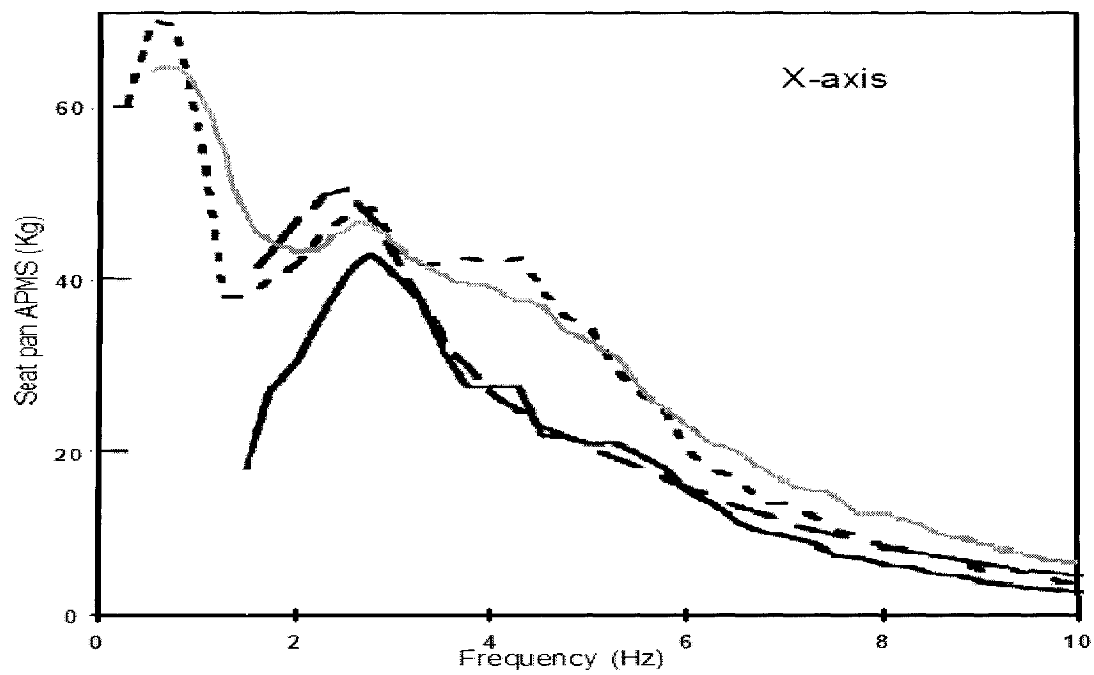
The experimental conditions employed in the reported studies [5-8] are reviewed and summarized in the Table 3.8. Owing to the differences in the experimental conditions employed in different reported studies, the results are expected to differ from those attained in the present study. These include the different measurement and excitation systems, sitting posture and the seat design, which could also contribute to the differences in the biodynamic responses. Despite these differences, the measured data are expected to yield some comparable trends with the reported data under similar or comparable experimental conditions. Owing to the availability of a relatively few data sets availability under horizontal vibration, no significant efforts are made to identify the sources of variables among the reported and measured data sets. It should be pointed out that in spite of the evident differences in experimental conditions, anthropometric features of the test subjects and expected differences in measurement system and seat design, synthesis of the reported data under vertical vibration has reasonable range of values of the biodynamic response under defined test conditions [52].

The mean seat pan APMS responses obtained in the present study are compared with those reported, in Figures 3.11 – 3.14. The comparisons reveal reasonably good agreements of the mean measured data with the reported results for the back-unsupported posture, in terms of the magnitudes as well as the corresponding frequencies, under x- and y-axis motions (Figure 3.11).The resonant frequencies identified in the published

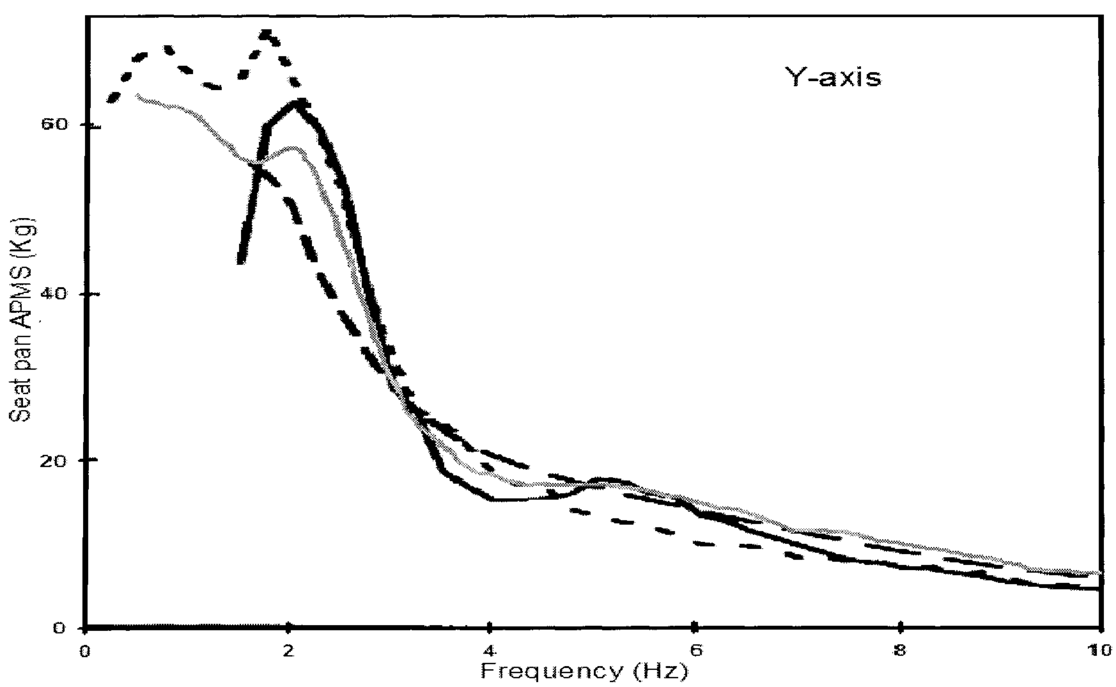
Table 3.8: Comparison of the conditions employed in the reported studies on biodynamic responses of seated occupants to horizontal vibration.

Reported studies	*Fairley and Griffin [6]*	*Holmlund and Lundström [7]*	*Mansfield and Lundström [8]*	*Nawayseh and Griffin [5]*	*Coronel [10]*	*Present Study*
Year	1990	1998	1999	2005	2005	2004-2005
Objective	APMS along *x*- and *y*- axis	DPMI along *x*- and *y*- axis	APMS along *x, y* and 3 non-orthogonal- axes	APMS along *x*- axis motion	APMS along *x*- and *y*- axis motion	APMS along *x*- and *y*- axis motion
Sample size	8 males	15 male / 15 female	15 male / 15 female	12 males	7 males	8 males
Age (years) M, SD(min, max)	27.87, 4.61(24, 38)	37, 11 (22, 59)	37, 14 /39, 13	30.8, (24-47)	34.86(25-50)	28.5, 9.38 (23, 50)
Height (m) M,SD (min, max)	1.79,0.09(1.6, 1.4)	1.72, 0.07, (1.6, 1.88)	1.79, 0.07/ 1.65, 0.07	1.79, (1.68-1.91)	1.75(1.7-1.83)	1.73, 2.5 (1.7, 1.78)
Weight (kg) M, SD (min, max)	71.87,10.37(57, 85)	69, 10 (54, 93)	75.8, 9.3/ 62, 7.2	76.1, (63, 103)	77.11(61.2-88.1)	71.2, 10.6 (59.4, 92)
Magnitudes of Vibration	0.5, 1.0, 2.0 m/s^2 rms (NB) 1.0 m/s^2 rms (Wb0)	0.25, 0.35, 0.5, 0.7, 1.0, 1.4 m/s^2 rms	0.25, 0.5, 1.0 m/s^2 rms	0.125, 0.25, 0.625 and 1.25 m/s^2 rms	Random: 0.25,0.5,1.0 Sine: 1, 1.5, 2	Random: 0.25, 0.5,1.0 m/s^2 rms Sine: 1, 2 m/s^2 (*x*) 2, 3 m/s^2 (*y*) *
Excitation type Exposure time	Random 128s	Discrete sine 20 sine cycles	Random 60s	Random 60s	Random/sine 128s/ 512 s	Random/sine 128s/ 512 s
Frequency range	0.25-20 Hz	1.13-80 Hz	1.25-20 Hz	0.25-10 Hz	0.25-10 Hz	0.5-10 Hz
Backrest	Vertical	Not used	Not used	Vertical	Vertical	Vertical/ inclined
Sitting posture	Upright	Upright(erect and relaxed)	Upright	Upright	Upright/ inclined	Upright/ inclined
Feet vibrated	Yes	No	---	Yes	Yes	Yes
Hands and arms	On lap	On lap	Arms folded	On lap	On lap	On lap

* peak acceleration



(a)



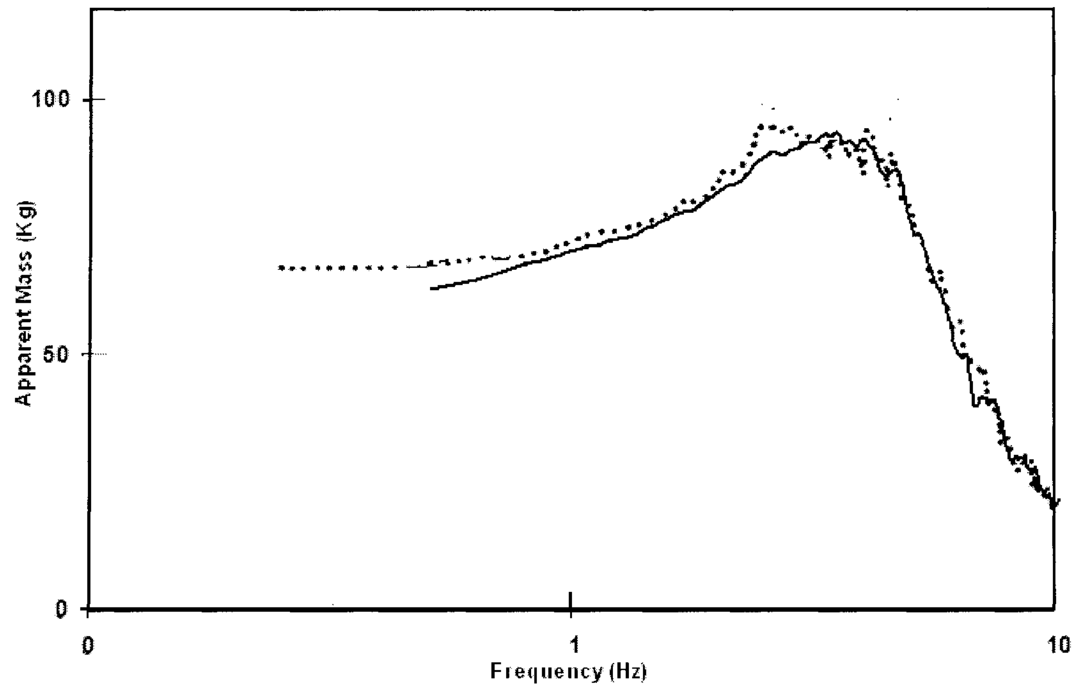
(b)

Figure 3.11: Comparisons of mean seat pan APMS responses measured in this study under 0.5 m/s^2 rms acceleration —— to those with reported data (— — Fairley and Griffin [6] under 0.5 m/s^2 rms random excitation; —— Mansfield and Lundström[8] under 0.5 m/s^2 rms random excitation and — —Holmlund and Lundström[7] using sinusoidal excitation at 0.5 m/s^2 rms).

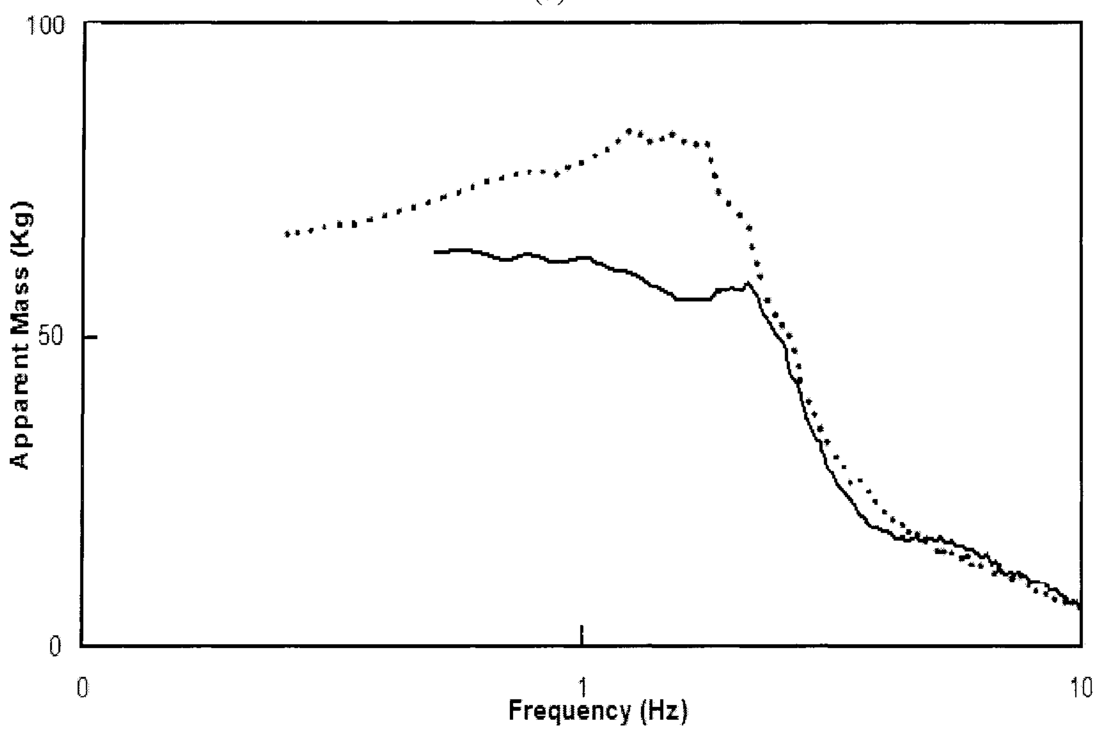
studies are comparable with the range of the frequencies obtained in the measured data. The measured data with NB posture revealed three peak resonance responses under both x- and y- axes random vibration, which are comparable with the corresponding frequencies in the reported studies. The peak magnitudes obtained with NB posture under x- and y-axes, in the vicinity of 0.7 Hz, agree well with those reported by Fairley and Griffin [6], as shown in Figures 3.11(a) and (b). The observed variations in the peak magnitudes can be attributed to the differences in the test conditions and the anthropometric features of the test subjects. The other studies [14, 17] have reported the similar responses at frequencies well above the primary resonant frequency, and thus could not be compared. Good agreements in the magnitude responses around the second and third modes, however, were observed.

Figure 3.12 presents the comparisons of mean seat pan APMS magnitude measured with the Wb0 posture under 1.0 m/s^2 fore-and-aft and lateral excitations with the data reported data by Fairley and Griffin [6]. The seat pan APMS magnitude response, reported for the Wb0 posture under x-axis agrees well with that of the present study, as evident in the figure, while the response along y-axis shows lower peak magnitude. This is most liked attributed differences in the anthropometric factors of the subjects and the experimental conditions.

The median seat pan magnitude responses measured under different magnitudes of x-axis excitations (0.125, 0.25, 0.625 and 1.25 m/s^2 rms acceleration) reported in a recent study [5] are also compared with the mean responses attained under three excitations levels in Figure 3.13. While the comparisons show similar trends in the seat pan magnitude responses, the magnitudes of the reported data tend to be considerably lower than those



(a)



(b)

Figure 3.12: Comparisons of mean seat pan APMS magnitude responses measured with the Wb0 posture under 1.0 m/s^2 rms along (a) fore-and-aft (b) lateral excitation, with the reported data. (········ Fairley and Griffin [6] ——— Present study).

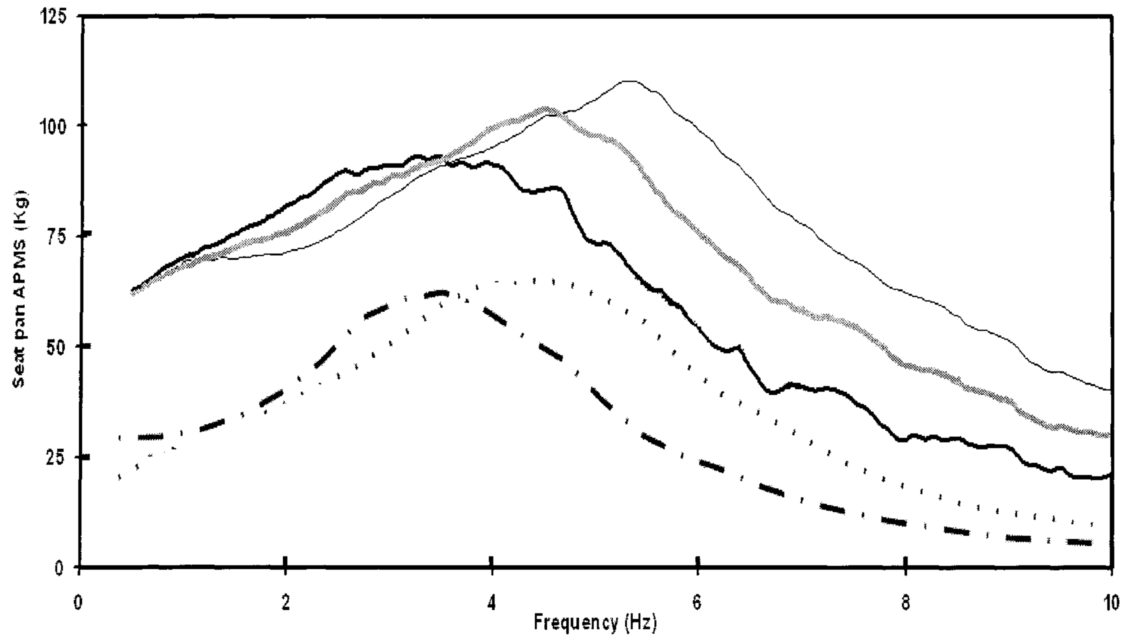


Figure 3.13: Comparisons of mean seat pan APMS magnitude responses measured with Wb0 posture under different magnitude fore-and-aft excitations (Nawayseh and Griffin[5]:········ 0.25 m/s^2; ▬ ▪ 0.625 m/s^2 rms; Present study: —— 0.25 m/s^2; ········ 0.5 m/s^2; ▬▬ 1.0 m/s^2 rms).

of the present study in the entire frequency range.

The reported data also show low frequency magnitude of approximately 25 kg, while the mean body weight of the test subject population (76.1 kg) is comparable with that of the present study (72.2 kg). The magnitudes of the reported data are also significantly lower than those reported by Fairley and Griffin [6]. The frequencies corresponding to the peak magnitudes of the reported data sets are also considerably lower than those observed from the data acquired in this study. The backrest APMS magnitude responses measured in the study, however, agree reasonably well with the reported data, as illustrated in Figure. 3.14.

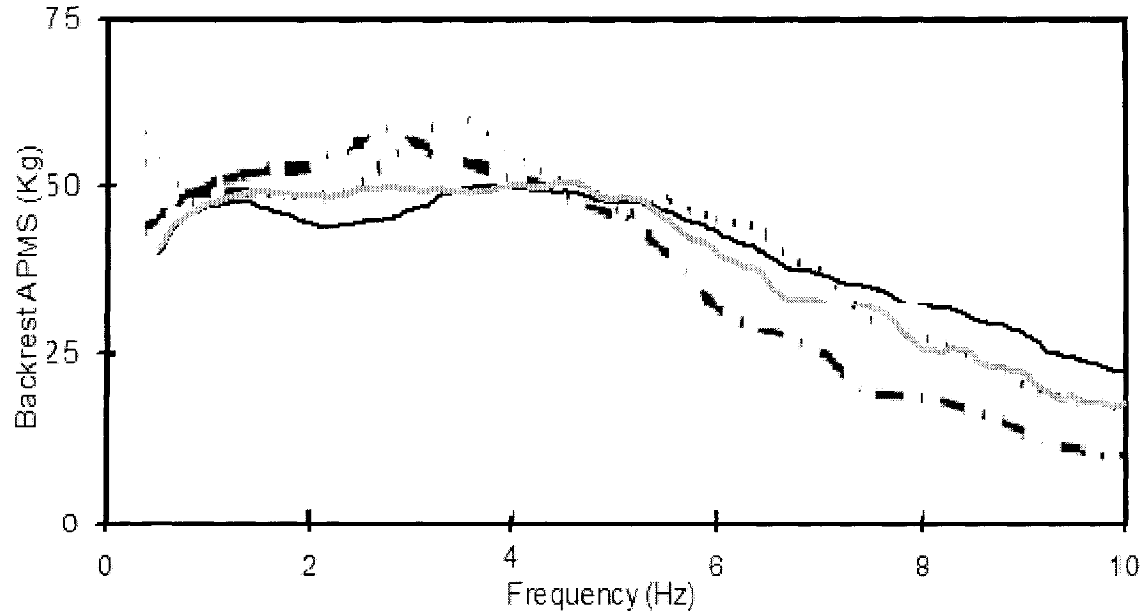


Figure 3.14: Comparisons of mean backrest APMS magnitude measured with Wb0 posture measured under different magnitudes of fore-and-aft excitations (Present study: —— 0.25 m/s^2; —— 0.5 m/s^2 rms; Nawayseh and Griffin [5]:······· 0.25 m/s^2; — · 0.625 m/s^2 rms).

3.6 Summary

The biodynamic response of seated occupants exposed to horizontal vibration, in different back supported postures and seat height are derived from the measured data. The data revealed high inter-subject variability, which was partly attributed to the anthropometric factors. The APMS magnitude responses revealed highly nonlinear behaviour of the seated occupant which was attributed to the involuntary movements of the subjects to realise stable sitting posture under vibration. The normalised mean responses are presented and the trends are discussed to emphasize the effects of back supported conditions, seat height, and magnitude and axis of vibration. The measured data are compared with the reported results with respect to peak magnitudes and corresponding frequencies. The present study has identified all the three important modes that are collectively identified in the reported studies. The considerable difference in peak magnitudes are is attributed to significant differences in the test conditions employed in different studies. The peak APMS magnitude revealed good correlation with the body mass, while the corresponding frequencies showed poor correlation. The measured data are further analysed to derive the power absorbed by the seated occupant, and the results are discussed in the following chapter.

Chapter 4

ABSORPTION OF ENERGY DURING WHOLE-BODY VIBRATION

4.1 Introduction

In addition to the apparent mass characterising the human body response to vibration, a measure based upon absorption of vibration energy by the exposed body has been proposed to asses the severity of the exposure [11, 12, 16]. The absorbed power has been suggested as a better measure of the exposure and the biodynamic response, and while it also relates the same quantities: the dynamic force response and vibration acceleration. The amount of vibration energy, absorbed and / or exchanged between the source and the body, could be considered as a measure of the physical stress on the body, as it considers the interchange between the vibrating surface and the human body [40]. The reported studies reveal that the absorbed power can also account for the effects of variations in the seat geometry [1] and sitting posture that are not addressed by the defined frequency weighting functions. The concept of energy absorbed by seated human body exposed to seat-transmitted vibration, first evolved in the sixties, when Lee and Pradko [40] proposed this measure for evaluating the safety and comfort of occupants of military vehicles.

Many epidemiologic studies have suggested a strong association between the exposure to WBV and the low back pain [1, 40, 55, 61, 62]. A few studies have suggested that the stress could be lessened by reducing the magnitude of motion or by changing the characteristics of the motion such that the vibration energy occurs at frequencies where the body is less responsive to the motion [1, 40, 62]. A number of studies have investigated the absorbed power in the hand-arm system exposed to hand-transmitted vibration arising from hand power tools[57, 60, 62, 63] and that of the seated human body exposed to whole-body vertical vibration [1, 11, 12]. A single study, however, has investigated the power absorbed by the seated body under exposure to horizontal vibration, with another study being done very recently at Concordia University [10]. Lundström [11] measured the absorbed power characteristics of seated subjects exposed to vibration along the *x*- and *y*- axis with back un-supported and reported the strong influence of magnitude, gender and direction of excitation. It was speculated that the absorbed portion of the total power is proportional to the injury, and the power which is not absorbed may have a negative effect on the body. It was also speculated that absorbed power is related to the musculo-skeletal disorder and effects on comfort and perception would be related to non-absorbed component of the power, while another possible assumption was relating severity of the injury to the total absorbed power.

In this study, the measured force-motion responses of the seated human subjects are analysed to derive the absorbed power characteristics under both fore-and-aft and lateral vibration. The results are evaluated to study the roles of various contributory factors, namely the postural condition, seat height, and magnitude and direction of horizontal vibration.

4.2 Absorbed power response to horizontal vibration

It was revealed that absorption of energy along horizontal direction is greater than that observed under vertical vibration exposure [11]. While prolonged exposure to whole-body vibration has been associated with an array of health and safety risks, the detrimental effects of the exposure with respect to vibration magnitude and frequency, and the daily and life time exposure are yet to be explored to reduce the associated safety risks. The vibration transmitted is expected to cause relative motions of various tissues, muscles and organs of the human body. The measure of absorbed energy per unit time is expected to be proportional the effort by the human body to resist vibration and thus the risk of vibration injuries or reduction in the comfort [14]. However, the elastic component of power for most of the practical cases has been considered insignificant and thus not considered for to assessment of risk of injuries. This could be more significant, in cases when the elastic limits of the soft tissues, organs and muscles, and bones and joints, are exceeded.

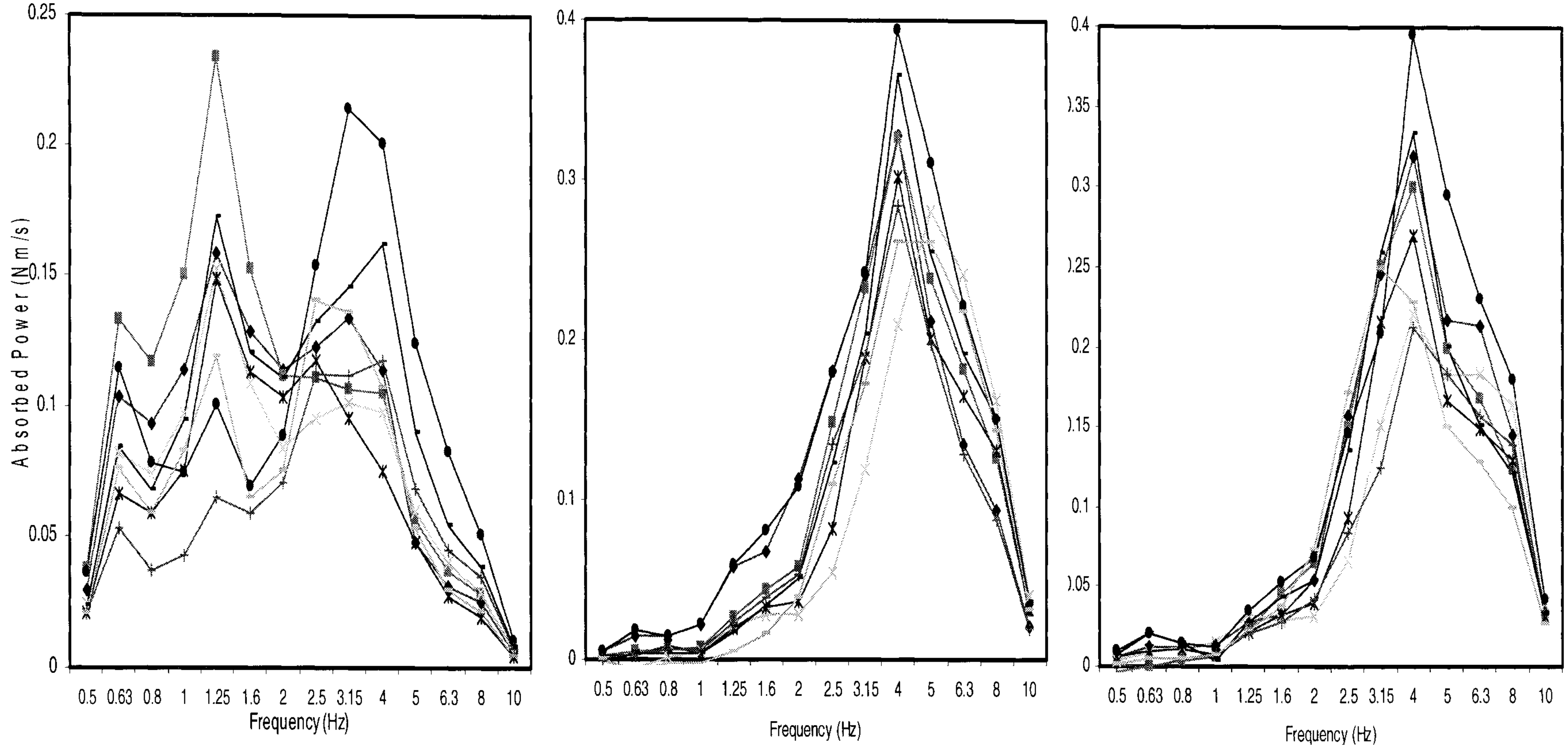
The absorbed power can be expressed by single scalar quantity that could facilitate the analyses on the contribution of variations in the individual characteristics, sitting postures (back supported conditions and seat heights), etc. The measured force and acceleration excitations due to horizontal vibrations are analysed to derive the cross-spectrum of the dynamic force and driving point velocity, as described in the section 2.3. The real part of the cross spectrum is used to realise the absorbed power characteristics of the occupants under vibration exposure. The absorbed power spectra obtained from the real component of the cross spectrum of force and velocity under defined experimental conditions, reveal considerable sensitivity to the excitation in frequency. However, the absorbed power responses reveal characteristic peak magnitudes and their corresponding frequencies similar to those observed from the APMS responses. The absorbed power responses corresponding to each experimental condition are further evaluated at the centre frequencies of the one-third octave bands in the 0.5-10 Hz frequency range to compute the total power absorbed.

The results attained for the 8 subjects considered in the study showed comparable trends in terms of frequencies corresponding to the peak magnitude of absorbed power, with considerable differences in the peak magnitudes. The results obtained are synthesised to present the influence of magnitude of vibration, the back supported conditions and various seat heights with respect to the absorbed power properties.

4.3 Inter-subject variability

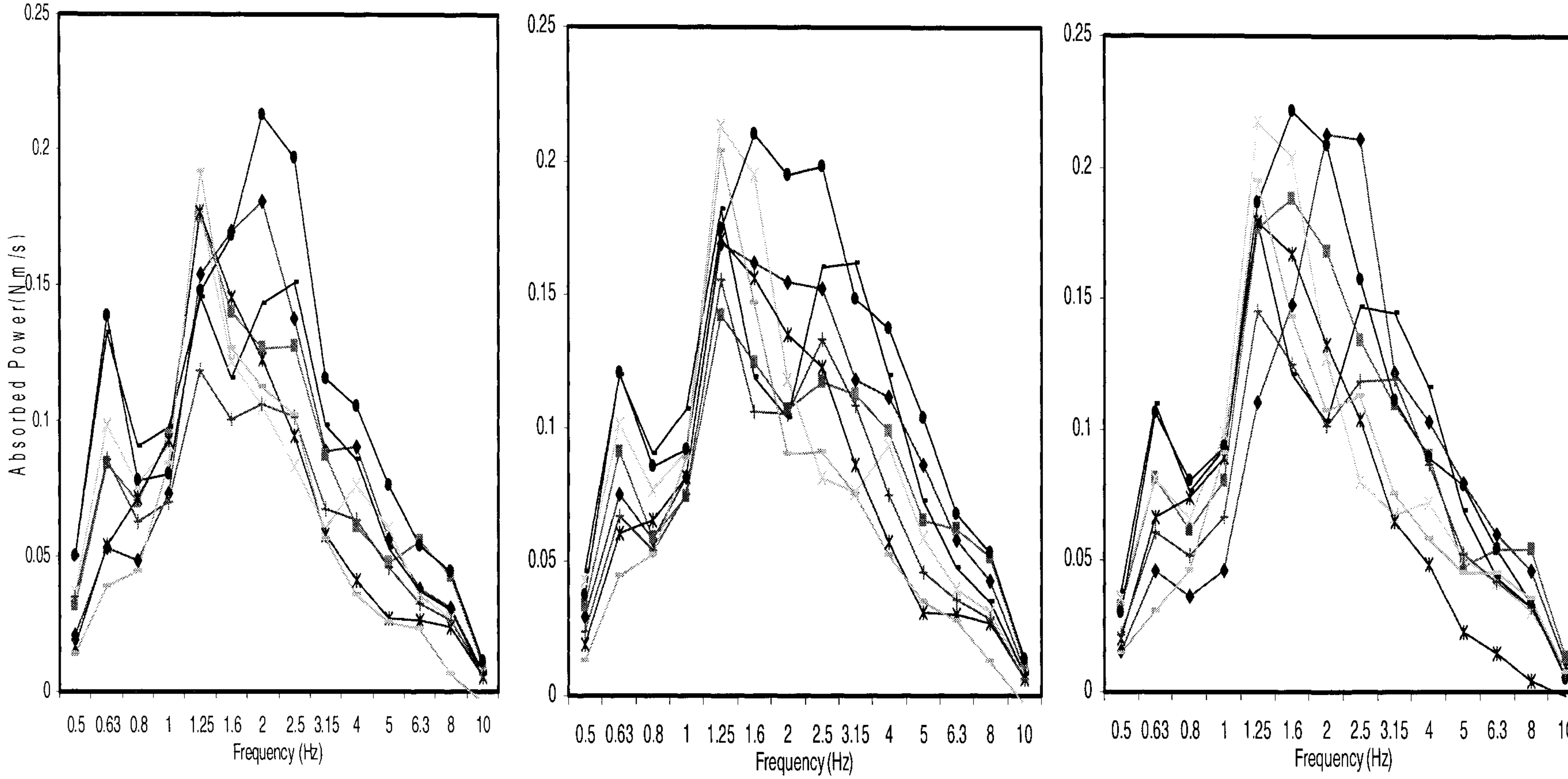
The previous studies in both APMS and absorbed power, suggest the inter-subject differences to be among the most important factors that affect the absorbed power response. It is essential to understand the source of variations in the responses derived from the experiments. The measurement system and methodology are generally considered to be sufficiently reliable, such that the variations observed under controlled experimental conditions can be mostly related to intra- and inter-subject variations, and the effects of magnitudes and direction of vibration, different back supported postures and different seat heights.

Relatively higher intra-subject variations in absorbed power have been reported irrespective of the magnitude of vibration [11]. The repeatability of the measured data acquired under different trials of the same conditions is initially investigated in this study to estimate the intra-subject variability. Owing to the high repeatability of the measured data acquired under different trials of the same experimental condition, and contrary to the high intra-subject variability reported in [11], the intra-subject variation in the present study was observed to be insignificant. The mean responses of the data acquired during two trials are thus computed to examine the inter-subject variability. Figures 4.1 and 4.2 suggest significant inter-subject variability in the absorbed power responses obtained



(a) (b) (c)

Figure 4.1: Variations in the absorbed power responses of the eight subjects exposed to 1.0 m/s^2 rms fore-and-aft excitation at the seat pan of height H1: (a) NB posture; (b) Wb0 posture; and (c) WbA posture.



(a) (b) (c)

Figure 4.2: Variations in the absorbed power responses of the eight subjects exposed to 1.0 m/s^2 rms lateral excitation at the seat pan of height H1: (a) NB posture; (b) Wb0 posture; and (c) WbA posture.

with unsupported and supported back postures, at the centre frequencies of the third octave bands under 1.0 m/s^2 vibration magnitude, along fore-and-aft and lateral excitations, respectively.

The results obtained from the measurements acquired at the seat pan reveal comparable trends in terms of frequencies corresponding to the peak magnitude of absorbed power, while large variations in the peak magnitudes of power due to different participants is evident. Despite the considerable dispersion of the magnitude data in Figure 4.1, the absorbed power characteristics of all subjects seated with back unsupported posture and exposed to fore-and-aft excitations consistently reveal three distinct peaks in bands with center frequencies at about 0.63, 1.25 and 2.5-4. The addition of inclined back support revealed a small peak in 0.63 Hz band, while the principal resonant peak shifts towards higher frequency bands centered in the 2.5-4 Hz range. The vertical back support posture also reveals similar trends. These frequencies corresponding to important absorbed power magnitudes correspond reasonably well with those observed from the APMS responses in the section 3.4.2. The peak magnitude of absorbed power in case of inclined back support is observed to be larger than that obtained for the NB posture, but lower than that for the vertical back support.

Unlike the behaviour under fore-and-aft excitations, the absorbed power responses under lateral excitations are observed to be similar in magnitude and corresponding frequency for the unsupported and supported back postures, as shown in the Figure 4.2. The absorbed power responses under lateral excitations also reveal two distinct peaks in the 0.63 and 1.25 Hz frequency bands similar to the APMS responses presented in chapter 3.

The absorbed power responses at the backrest along the fore-and-aft direction, as shown in the Figure 4.3 reveal similar trends in magnitude and corresponding frequency as those observed for the seat pan. All the subjects reveal peak magnitudes in the 4Hz band with the WB0 and WbA postures. Unlike the absorbed power response at the backrest along *x*- axis, the responses under *y*- axis excitation at the backrest reveal substantial dispersion in the data, as shown in the Figure 4.4, which could be attributed to the sliding or intermittent loss of contact between the upper body and the backrest. However, the data attained for all subjects show consistent resonant peak in absorbed power magnitude in the frequency bands of 0.63, 1.25 and 2-3.15 Hz. Under fore-and-aft excitations, the peak magnitude of the absorbed power obtained at the backrest is around 50-60% of that observed at the seat pan.

The absorbed power response of seated occupants with the NB posture in *x* and *y* directions are relatively similar and reveal principal peaks in the comparable frequency bands. These frequency bands corresponding to the principal resonances account for nearly 70% and 90% of the total absorbed power in the 0.5-10 Hz frequency range, along the *x*- and *y*- vibration, respectively. The low magnitudes of absorbed power in a number of frequency bands, however, yield significant values of CoV, even though the standard deviations of the mean could be small. The reported studies in horizontal and vertical vibration report large inter-subject variations [10, 11, 64]. The values of CoV in absorbed power magnitudes in the frequency bands with in the concerned frequency range were observed to be very high (>100%) at frequencies below 1 Hz. This is observed mainly due to the negative values of power absorbed power in the low frequency bands most likely caused by phase errors between force and velocity. Owing to the low magnitudes

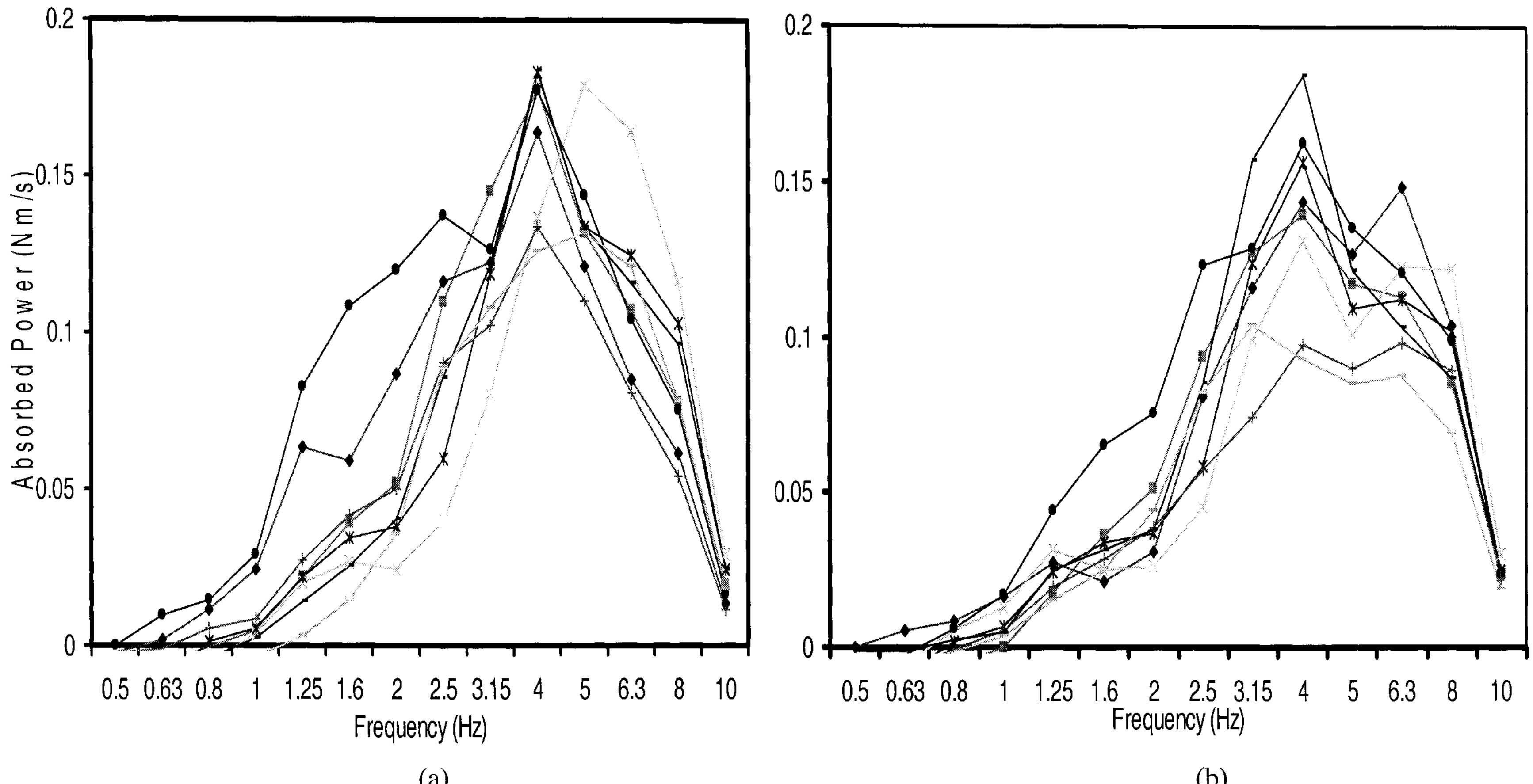


Figure 4.3: Variations in the absorbed power responses of the eight subjects measured at the backrest, when exposed to 1.0 m/s^2 rms fore-and-aft excitation (seat height H1): (a) Wb0 posture and (b) WbA posture.

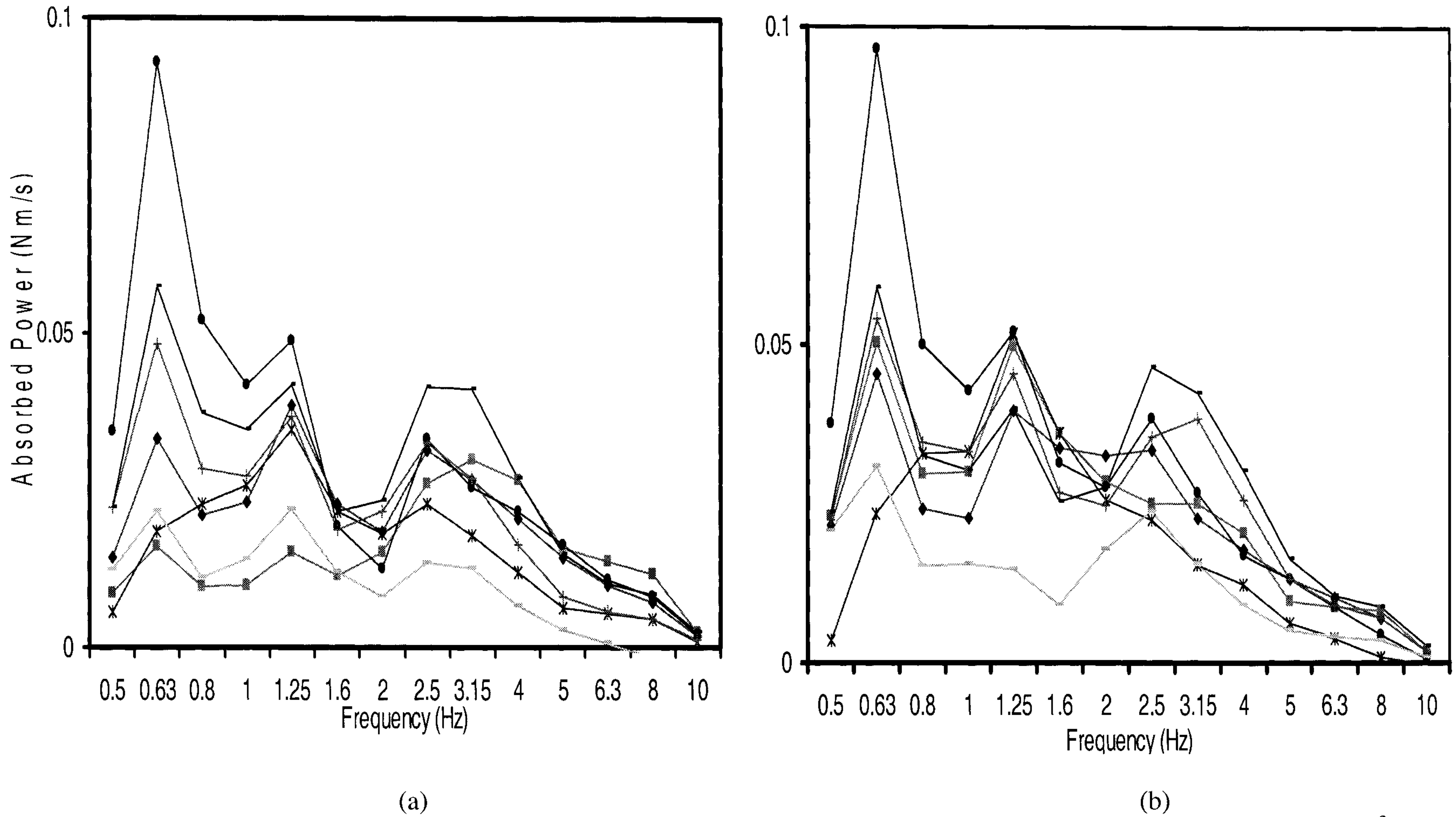


Figure 4.4: Variations in the absorbed power responses of the eight subjects measured at the backrest, when exposed to 1.0 m/s^2 rms lateral excitation (seat height H1): (a) Wb0 posture and (b) WbA posture.

of absorbed power, the smaller deviations lead to higher values of CoV. The peak absorbed power and the total absorbed power have been suggested to account for a better measure of the variability [10].

In the present study, CoV values of the total absorbed power data were computed to analyse the inter-subject variability. Table 4.1 summarises the coefficient of variation (CoV) derived from the data sets attained for 8 subjects corresponding to different combinations of sitting posture, seat height, excitation level and axis of vibration. The CoV values for the absorbed power data obtained at the seat pan were observed to be near 20% for all the experimental conditions considered. However, data measured at the backrest showed relatively higher values of CoV, which can be attributed to the intermittent loss of contact or sliding at the backrest interface. The values of CoV did not suggest any particular trend with respect to the magnitude of excitation, sitting posture, seat height or direction of excitation. Large variations in the magnitude of absorbed power responses in the vicinity of resonant frequencies under both *x*- and *y*- axis excitations, however, are evident, which causes excessive values of CoV that have been mostly attributed to variability in the subjects' body mass, height and body mass index [1, 10, 11-13].

The absorbed power data revealed significant effect of the backrest and also the effect of inclination of the back support under fore-and-aft vibration. The absorbed power responses of all the subjects consistently reveal lower peak magnitudes in case of inclined back support compared to the vertical back support. An inclined back support would improve relatively less vibration along direction normal to the contact surface, and could thus yield slightly lower absorbed power. The absorbed power responses at the backrest along fore-and aft direction also reveal similar characteristics. The absorbed power responses obtained at the backrest under fore-and-aft excitations yield peak magnitudes in the 3.5-4 Hz bands, as shown in Figure 4.3, for the Wb0 and WbA postures. The results reveal additional peak in the 6.3 Hz band for WbA posture, which was also observed in the APMS response. The absorbed power responses at the backrest under lateral direction reveal extremely low values, which can be attributed to the sliding or intermittent loss of contact at the human body and the backrest interface.

Table 4.1: Coefficient of variation for the total power absorbed data measured at the seat base and the backrest.

Axis	*Seat Height*	*Vibration Level*	*Coefficient of Variation (%)*				
			Seat Pan			Backrest	
			NB	Wb0	WbA	Wb0	WbA
x	425mm	$0.25 m/s^2$	17.50	20.62	17.88	23.52	17.32
		$0.5 m/s^2$	14.18	18.74	17.15	18.58	16.63
		$1.0 m/s^2$	18.16	16.50	16.5	16.83	16.26
	390mm	$0.25 m/s^2$	13.73	22.18	17.15	20.04	19.28
		$0.5 m/s^2$	18.26	22.25	15.88	19.46	17.10
		$1.0 m/s^2$	16.42	20.28	17.13	19.82	19.84
	350mm	$0.25 m/s^2$	18.09	19.31	18.83	21.70	25.62
		$0.5 m/s^2$	17.13	19.62	19.44	19.33	23.97
		$1.0 m/s^2$	19.6	19.14	19.20	18.04	19.48
y	425mm	$0.25 m/s^2$	19.12	17.90	15.89	19.05	21.85
		$0.5 m/s^2$	20.67	16.21	15.35	28.47	25.07
		$1.0 m/s^2$	18.19	18.77	13.95	28.48	17.56
	390mm	$0.25 m/s^2$	18.81	16.42	16.17	21.70	17.88
		$0.5 m/s^2$	16.38	16.36	13.84	26.87	24.91
		$1.0 m/s^2$	17.31	14.59	13.69	30.52	29.12
	350mm	$0.25 m/s^2$	19.68	15.65	16.15	23.17	19.97
		$0.5 m/s^2$	16.85	14.52	14.99	30.82	21.27
		$1.0 m/s^2$	18.09	15.69	16.34	27.67	29.91

4.4 Influence of anthropometric factors

The body mass has been identified to be the most significant factor influencing the absorbed power characteristics of the seated occupant under both horizontal and vertical vibration [1, 10, 11-13], which was clearly evident from the APMS responses presented in Chapter 3. Owing to the rotation of the upper body under horizontal motions, the upper body or the overall subject height has also been identified as an important factor affecting the absorbed power response [10]. The total absorbed power in this study is evaluated with respect to the individual body masses and the coefficient of determination (r^2) is computed to illustrate the dependence of total absorbed power on the body mass.

The total absorbed power of 8 subjects is calculated individually in the 0.5-10 Hz frequency range, as described in the Equation (2.8). Figures 4.5 and 4.6 illustrate the total absorbed power of the subjects in three different sitting postures, and the influence of subject body mass on the absorbed power under vibration along *x*- and *y*- axes, respectively. The magnitudes of the total absorbed power reveal superior correlation with the body mass under all the experimental conditions, irrespective of the axis of vibration.

Higher dependency of the total absorbed power derived from the seat pan measurements on the body mass is observed ($r^2 > 0.8$) in most of the conditions considered, under fore-and-aft motions especially for back supported postures, and NB posture under lower magnitudes of vibration. The back supported postures reveal higher r^2 values in both lower and higher magnitudes of fore-and-aft vibration. The total absorbed power derived from measurements at the backrest-body interface under fore-and-aft vibration revealed fairly lower r^2 values with body mass, but the values are observed to be in excess of 0.7. This can be attributed to the subject's intermittent loss of contact with the backrest interface. The absorbed power measured at the backrest may be associated with absorption of vibration energy within the upper body in contact with the backrest, while that measured at the seat base would relate to that absorbed by entire

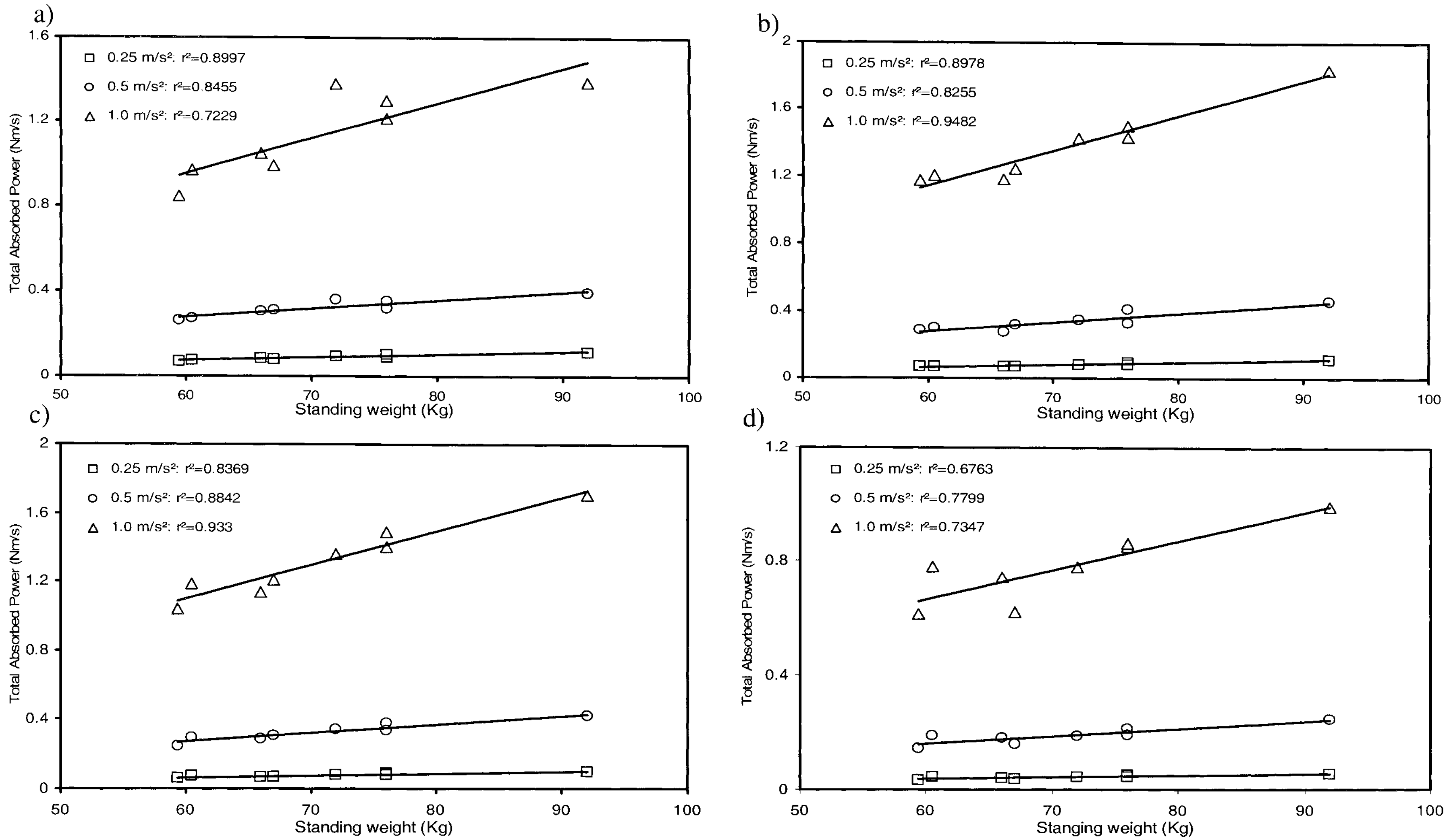


Figure 4.5: Linear dependence of the total absorbed power derived from the seat pan data on the subjects' body mass under fore-aft vibration: a) NB posture; b) Wb0 posture; and c) WbA posture; d) total power derived from the backrest data under WbA posture.

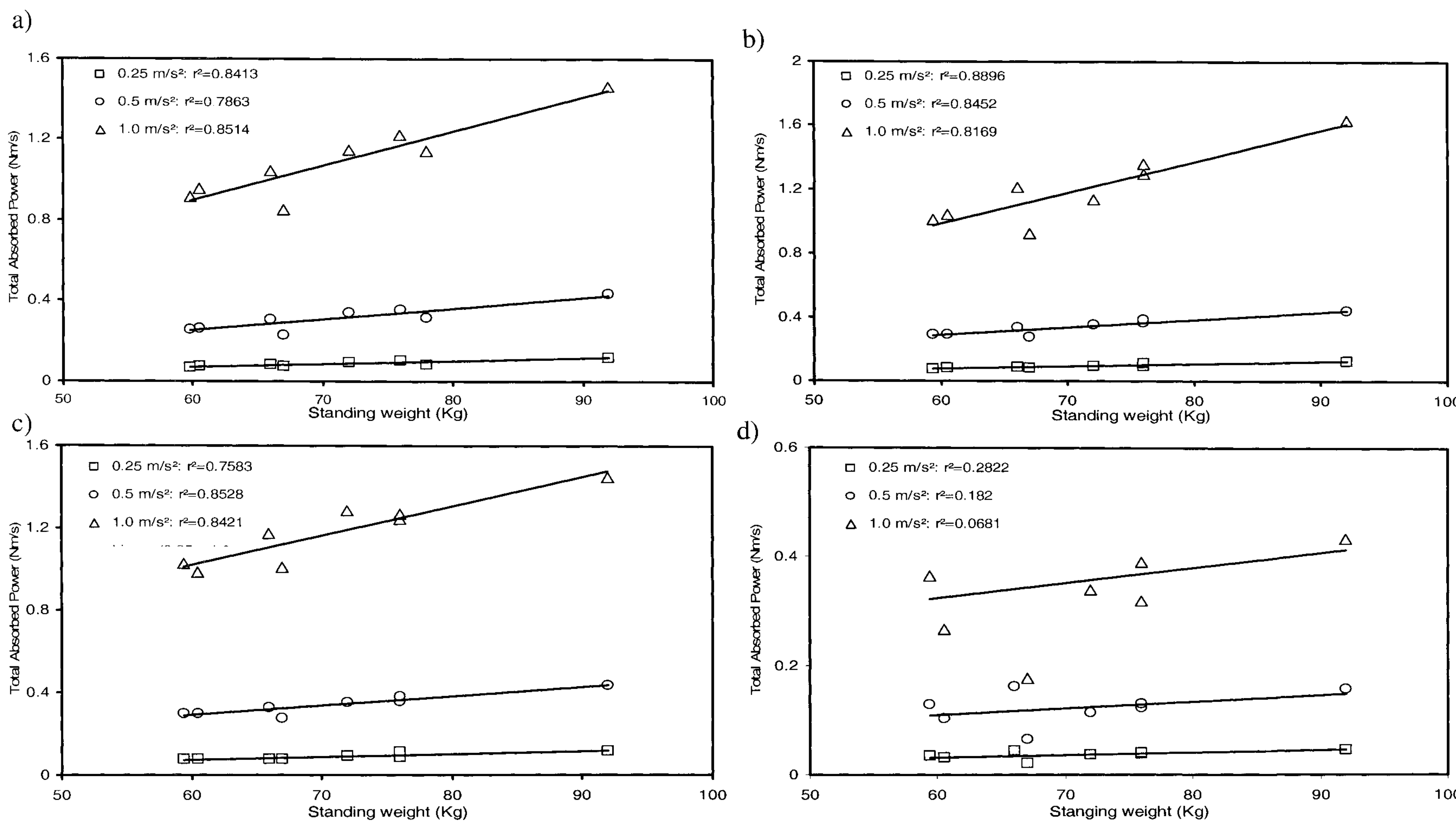


Figure 4.6: Linear dependence of the total absorbed power derived from the seat pan data on the subjects' body mass under lateral vibration: a) NB posture; b) Wb0 posture; and c) WbA posture; d) total power derived from the backrest data under WbA posture.

seated body. The magnitude of total power absorbed by the upper body alone, as derived from the backrest measurements, is thus considerably smaller than that derived from the seat pan measurements. The changes in seat height reveal relatively smaller effect on the correlation of total absorbed power and the body mass. The results obtained under *y*-axis vibration reveal comparable degree of correlation for the seat-pan measured absorbed power, where r^2 values in excess of 0.75 are obtained for the back supported and NB postures. The measurements based on the backrest force, however, reveal extremely poor correlation with the body mass, which is related to relatively small upper body force along y-axis and sliding of the upper body against the backrest. Similar trends were also observed with different seat heights, as it is evident from the r^2 values summarised in the Table 4.2 for both axes of vibration.

Table 4.2: Coefficient of determination for the influence of body mass on the total absorbed power data measured at the seat base and the backrest.

Axis	*Seat Height*	*Vibration Level*	*Coefficient of of determination (r^2)*				
			Seat Pan			Backrest	
			NB	Wb0	WbA	Wb0	WbA
x	425mm	0.25m/s^2	0.8997	0.8978	0.8369	0.713	0.6763
		0.5m/s^2	0.8455	0.8255	0.8842	0.6996	0.7799
		1.0 m/s^2	0.7229	0.9482	0.933	0.7753	0.7347
	390mm	0.25m/s^2	0.7728	0.5212	0.7704	0.7808	0.8466
		0.5m/s^2	0.8232	0.7218	0.7486	0.8569	0.9468
		1.0 m/s^2	0.862	0.8079	0.7396	0.7763	0.9037
	350mm	0.25m/s^2	0.8807	0.8064	0.9415	0.7948	0.7377
		0.5m/s^2	0.8929	0.8692	0.8769	0.7247	0.7533
		1.0 m/s^2	0.8561	0.97	0.9392	0.7383	0.8113
y	425mm	0.25m/s^2	0.8413	0.8733	0.7321	0.2156	0.2844
		0.5m/s^2	0.7863	0.8432	0.8446	0.0427	0.185
		1.0 m/s^2	0.8514	0.8155	0.8377	0.0626	0.0691
	390mm	0.25m/s^2	0.9107	0.9489	0.9489	0.1372	0.2292
		0.5m/s^2	0.9064	0.945	0.9563	0.034	0.2035
		1.0 m/s^2	0.8662	0.9694	0.9606	0.089	0.1441
	350mm	0.25m/s^2	0.9282	0.9599	0.9703	0.2651	0.2855
		0.5m/s^2	0.8621	0.9727	0.9689	0.1915	0.2518
		1.0 m/s^2	0.9322	0.9323	0.9192	0.1331	0.014

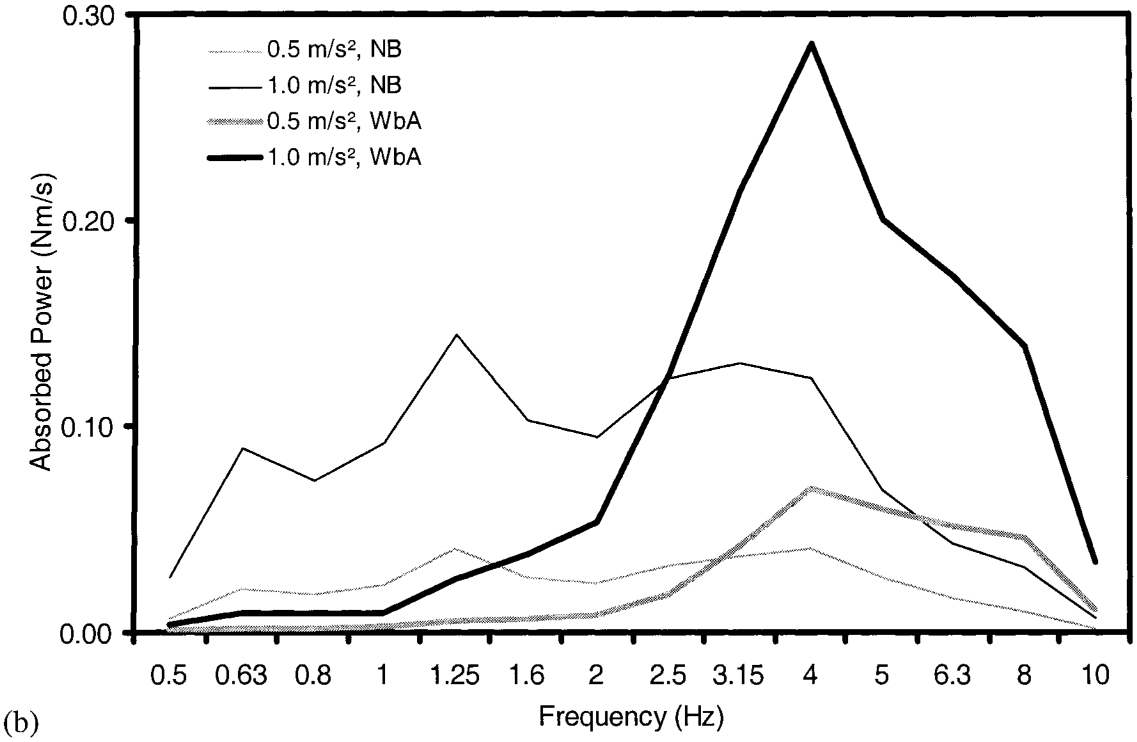
The trends observed in the absorbed power responses suggest that the value of total absorbed power increases with increasing body mass as illustrated in previous chapter with peak magnitudes of the APMS data. The value of total absorbed power, however, reveals relatively higher r^2 values compared to those obtained from the magnitudes of APMS data. Thus, the absorbed power data could be considered as a better measure of the human response to vibration in view of the body mass than compared to the peak APMS magnitude.

4.5 Factors influencing absorbed power response

Both the absorbed power and APMS response characteristics suggest strong influences of direction, magnitude, frequency and type of excitation, and the sitting posture. Despite the large inter-subject variability in the responses, the mean responses are considered to provide important information on the influences of excitation, magnitude and sitting posture on the absorbed power responses to fore-and-aft and lateral vibration. The mean total power reflected at the seat pan and the backrest, are thus computed from the data attained for eight subjects for different conditions of experimental conditions. The mean responses are then analysed in an attempt to quantify the role of contributing factors considered. The mean results are presented in the following sections to emphasize the trends observed under different postures and excitation conditions.

Figures 4.7(a) and (b) illustrate the mean absorbed power characteristics derived from the data acquired at the seat pan with unsupported and supported back conditions,

(a)



(b)

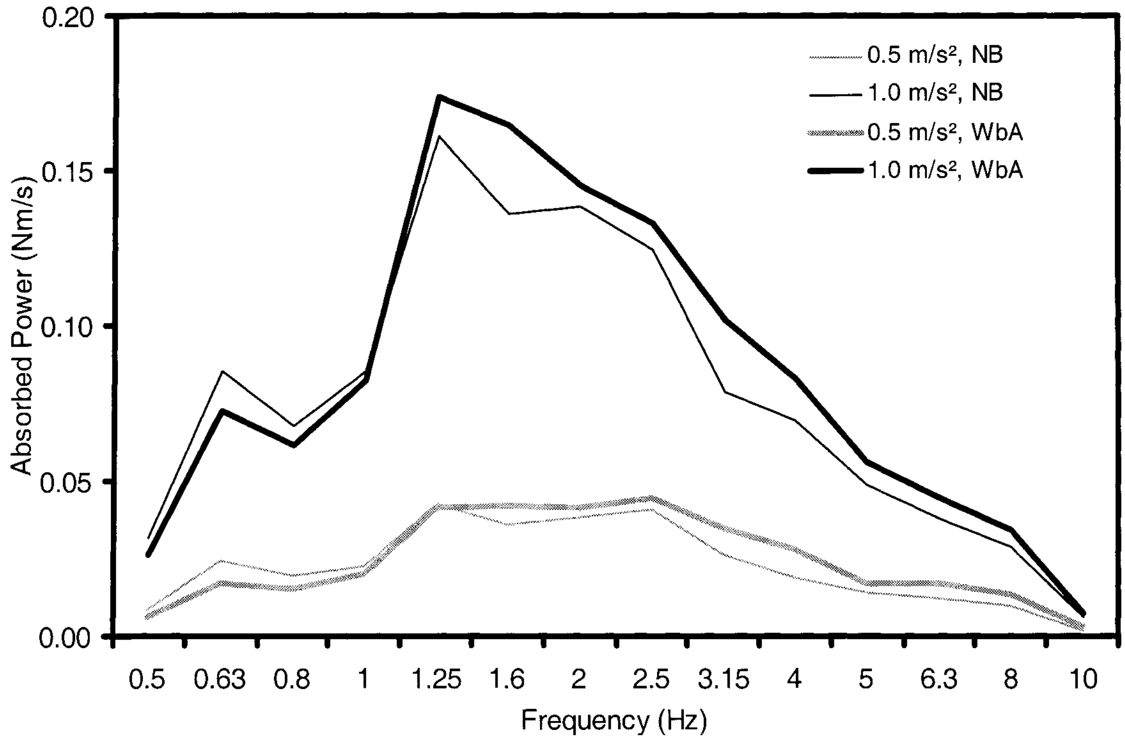


Figure 4.7 Mean absorbed power characteristics attained at the seat pan under different magnitudes of excitation and postures: a) fore-and-aft vibration; b) lateral vibration.

under 1.0 m/s^2 fore-and-aft and lateral excitations, respectively. The results show most significant effect of excitation magnitude on the absorbed power, which is not evident from the APMS response. Moreover, the back supported posture (WbA) yields considerably different response, when compared with that obtained with unsupported back postures, irrespective of the magnitude of excitation. The effect of back support condition on the total power measured under *y*-axis vibration, however, is very small, as illustrated in Figure 4.7 (b). Both the NB and WbA postures yield comparable total power response measured at the seat pan under lateral vibration. The absorbed power responses measured at the backrest reveal comparable trends for both Wb0 and WbA postures under the fore-and-aft and lateral excitations, as illustrated in the Figures 4.8(a) and 4.8(b), respectively. The absorbed power obtained at the backrest in both Wb0 and WbA postures reveal peak magnitudes in the frequency band centered near 4 Hz. However, absorbed power with WbA postures, generally yield higher values over entire frequency range considered. Owing to the intermittent loss of contact or sliding at the upper body and backrest interface, the absorbed power response measured at the backrest along y-axis reveal opposite trends in terms of the back supported posture.

Statistical analyses are performed for the absorbed power responses measured at the seat pan and the backrest at discrete frequencies over the concerned frequency range to identify the significant contributing factors. 'With-in subjects' statistical analysis are performed to analyse and state the significance of variation in the magnitude of absorbed power due to different experimental conditions, as described in section 3.4 for APMS data. Single factor ANOVA is performed to identify the significant effects due to main contributing factors individually and two-factor ANOVA is also performed to analyse the

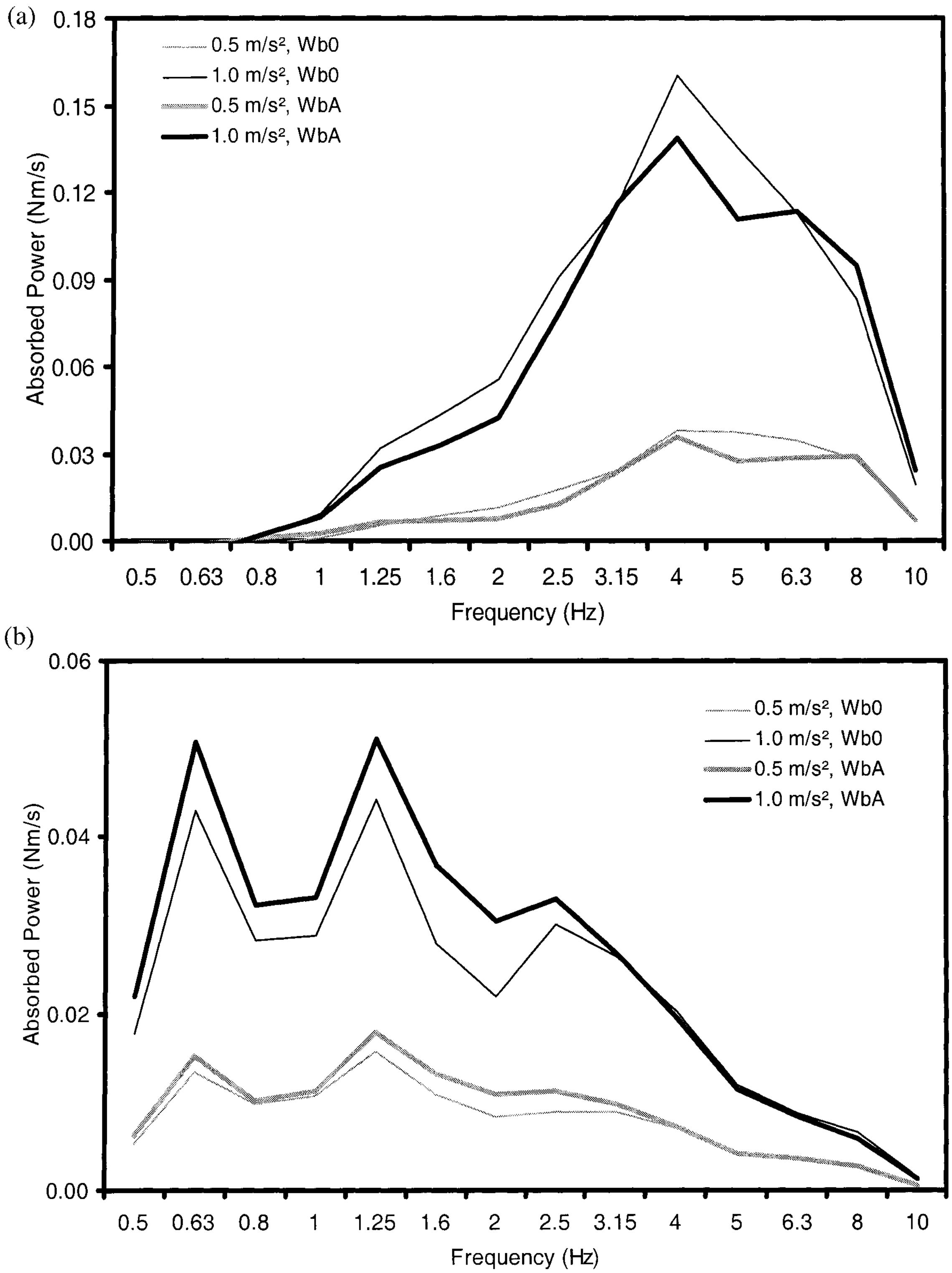


Figure 4.8: Mean absorbed power characteristics attained at the backrest under different magnitudes of excitation and postures: a) fore-and-aft vibration; b) lateral vibration.

significance of interaction between the two contributing factors on the absorbed power responses measured at seat pan and backrest. The significance of the contributing factors is stated based on the p values less than 0.05.

The p-values attained for the absorbed power data measured at seat pan, at selected discrete frequencies, considering each of the three levels of excitation magnitude and seat height, and their interactions, for each sitting posture along x- and y-axis vibration are summarized in Tables 4.3 and 4.4 respectively.

Table 4.3: p-values attained from single and two-factor ANOVA performed on the absorbed power magnitude measured at the seat pan under fore-aft vibration.

Factor	Excitation (.25, .5, 1.0 m/s^2)			Height (H_1, H_2, H_3)			Excitation*Height		
Frequency(Hz)	NB	Wb0	WbA	NB	Wb0	WbA	NB	Wb0	WbA
0.63	0.000	0.000	0.000	0.054	0.294	0.005	0.031	0.319	0.006
0.75	0.000	0.000	0.000	0.223	0.508	0.017	0.005	0.365	0.011
1	0.000	0.000	0.000	0.142	0.569	0.101	0.898	0.318	0.153
1.13	0.000	0.000	0.000	0.386	.557	0.335	0.532	0.756	0.546
2	0.000	0.000	0.000	0.235	0.806	0.628	0.605	0.54	0.495
3	0.000	0.000	0.000	0.597	0.176	0.392	0.929	0.371	0.372
4	0.000	0.000	0.000	0.716	0.008	0.064	0.905	0.004	0.007
5	0.000	0.000	0.000	0.401	0.054	0.070	0.792	0.076	0.053
6	0.000	0.000	0.000	0.299	0.513	0.016	0.69	0.68	0.039
8	0.000	0.000	0.000	0.899	0.504	0.007	0.915	0.782	0.000

Table 4.4: p-values attained from single and two-factor ANOVA performed on the absorbed power magnitude measured at the seat pan under lateral vibration.

Factor	Excitation (.25, .5, 1.0 m/s^2)			Height (H_1, H_2, H_3)			Excitation*Height		
Frequency(Hz)	NB	Wb0	WbA	NB	Wb0	WbA	NB	Wb0	WbA
0.63	0.000	0.253	0.008	0.322	0.785	0.965	0.437	0.657	0.879
0.75	0.000	0.000	0.000	0.382	0.178	0.747	0.811	0.25	0.568
1	0.000	0.000	0.000	0.756	0.811	0.698	0.392	0.992	0.838
1.13	0.000	0.000	0.000	0.081	0.927	0.861	0.051	0.962	0.976
2	0.000	0.000	0.000	0.013	0.581	0.378	0.96	0.532	0.277
3	0.000	0.000	0.000	0.381	0.215	0.302	0.616	0.035	0.216
4	0.000	0.000	0.000	0.024	0.028	0.798	0.340	0.001	0.938
5	0.000	0.000	0.000	0.001	0.226	0.669	0.009	0.153	0.931
6	0.000	0.000	0.000	0.000	0.757	0.377	0.000	0.714	0.682
8	0.000	0.000	0.000	0.000	0.036	0.313	0.000	0.088	0.746

The statistical analyses reveal highly significant ($p<0.008$) effect of vibration magnitude on the absorbed power responses obtained at the seat pan, irrespective of the direction of excitation, postural condition and seat height, in the entire frequency range. The significant differences between the magnitudes of absorbed power measured at the seat pan obtained for the two back-supported postures (Wb0 *vs* WbA) and all three postures are summarized in Table 4.5, for both axes of vibration. The analyses with the absorbed power data at backrest under fore-and-aft excitation also reveal information and trends similar to those derived for the seat pan data. However, the results suggest insignificant effect of vibration magnitude below 1 Hz. The results summarized in the Tables 4.3-4.6 illustrate the strong influence of the back support and magnitude of excitation, relatively small effect of seat height and almost negligible interaction effect of magnitude of excitation and seat height on the absorbed power response measured at both the seat pan and the backrest.

Table 4.5: Effect of posture shown by the p-values derived from single-factor ANOVA performed on the absorbed power magnitude measured at the seat pan under Fore-and-aft and lateral excitations.

Axis	Frequency (Hz)	0.63	0.75	1	1.13	2	2.75	4	5	6	8
x-	Wb0*Vs*WbA	0.003	0.121	0.388	0.830	0.054	0.495	0.000	0.000	0.027	0.038
	3 Postures	0.000	0.000	0.702	0.036	0.157	0.004	0.000	0.000	0.000	0.000
y-	Wb0*Vs*WbA	0.064	0.001	0.278	0.094	0.004	0.009	0.906	0.000	0.000	0.250
	3 Postures	0.000	0.000	0.000	0.000	0.000	0.125	0.000	0.000	0.000	0.000

Table 4.6: *p*-values attained from single and two-factor ANOVA performed on the absorbed power magnitude measured at the backrest under fore-aft vibration.

Factor	Excitation (.25, .5, 1.0 m/s^2)		Height (H_1, H_2, H_3)		Excitation*Height		Posture (Wb0 *vs* WbA)
Frequency(Hz)	Wb0	WbA	Wb0	WbA	Wb0	WbA	---
0.63	0.003	0.000	0.003	0.448	0.000	0.529	0.052
0.75	0.303	0.139	0.873	0.390	0.566	0.063	0.011
1	0.000	0.000	0.004	0.704	0.038	0.782	0.794
1.13	0.000	0.000	0.145	0.926	0.130	0.844	0.272
2	0.000	0.000	0.658	0.465	0.361	0.417	0.001
3	0.000	0.000	0.413	0.285	0.362	0.313	0.002
4	0.000	0.000	0.088	0.514	0.058	0.359	0.033
5	0.000	0.000	0.827	0.284	0.133	0.477	0.000
6	0.000	0.000	0.579	0.389	0.177	0.693	0.000
8	0.000	0.000	0.038	0.336	0.022	0.345	0.020

4.5.1 Effect of vibration magnitude on the absorbed power response

A vast number of studies on biodynamic responses to vertical vibration have reported relatively small effects of vibration magnitudes on the APMS response, but the effects on the absorbed power are most significant [12]. This suggests that the variation in the absorbed power response the seated occupant system responds to vibration in a highly non linear manner. This further supports the assertion that absorbed power could serve as a more effective measure of the exposure severity. The variations in the vibration magnitudes tend to affect the magnitude of absorbed power in a significant manner, while little or no effect is observed in the corresponding frequencies associated with the peak magnitudes of absorption of energy by the seated occupant system, as illustrated in Figures 4.7 and 4.8, irrespective of the excitation direction and sitting posture. The peak magnitudes of absorbed power occur in three frequency bands, which agree well with the reported natural frequencies of the seated human body with out a back support [12].

While majority of the reported study concern with analysis of absorbed power of seated occupant under vertical vibration, only two studies have investigated the absorbed power characteristics under horizontal vibration [10, 11]. These studies have revealed strong effects of vibration magnitude, which is partly attributed to the relatively large movements in the upper body, legs, and involuntary movement of the subjects to realize a stable sitting posture. Figure 4.9 further illustrates a comparison of the absorbed power spectra attained under 0.5 and 1.0 m/s^2 fore-and-aft excitation of occupants seated with un-supported back posture. The figure shows scaled absorbed power responses under two excitations to demonstrate that variation in the excitation magnitude would alter the predominant response frequencies only slightly.

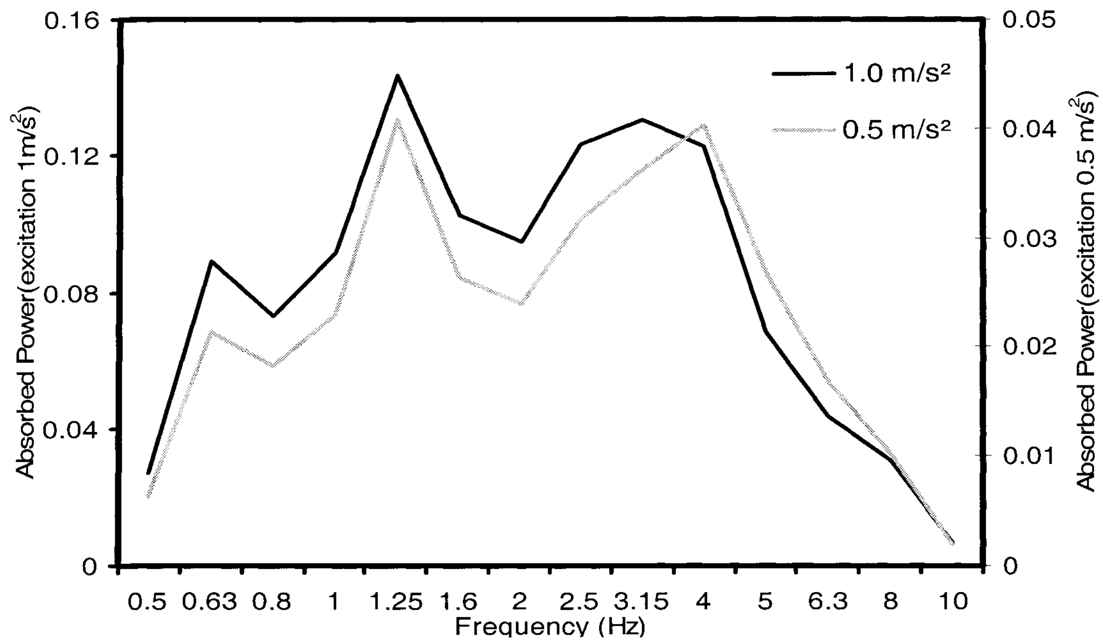


Figure 4.9: Frequency dependency of the mean absorbed power magnitude response measured under 0.5 and 1.0 m/s^2 fore-and-aft excitation (Posture-NB; Height H1).

Absorbed power responses of seated occupant under fore-and-aft excitations obtained in this study, generally show similar characteristics in terms of frequency irrespective of the magnitude of vibration. Similar to the phenomena reported for vertical biodynamic responses, the peak absorbed power occurs at slightly lower frequencies, when exposed to higher magnitude of vibration. This tendency has been widely attributed to the softening effect of the human body due to excessive upper body movements [1].

The total power absorbed for un-supported and supported back postures computed with respect to different levels of vibration are illustrated in the Table 4.7. The effect of magnitude of excitation was observed in all the conditions of seat height, sitting posture and direction of excitation, considered in the study. The absorbed power data obtained at the backrest also reveal strong effect of excitation magnitude. The significant effect of vibration magnitude on the absorbed power response is also suggested by the statistical analysis: single factor ANOVA revealed p <0.008 for discrete frequencies considered in the 0.5-10 Hz frequency range, irrespective of the experimental conditions.

Table 4.7: The total absorbed power measured at the seat pan and the backrest, under the influence of various unsupported and supported back postures, and magnitudes of vibration at various seat heights.

Axis	*Seat Height*	*Vibration Level*	*Total absorbed power (Nm/s)*				
			Seat Pan			Backrest	
			NB	Wb0	WbA	Wb0	WbA
x	425mm	0.25m/s^2	0.0885	0.0806	0.0749	0.0483	0.0435
		0.5m/s^2	0.3224	0.3399	0.3246	0.2061	0.1881
		1.0 m/s^2	1.1401	1.3766	1.3166	0.8511	0.7803
	390mm	0.25m/s^2	0.0908	0.0940	0.0854	0.0483	0.0457
		0.5m/s^2	0.3152	0.3763	0.3586	0.2075	0.1973
		1.0 m/s^2	1.0768	1.4308	1.4701	0.8428	0.7898
	350mm	0.25m/s^2	0.0921	0.0757	0.0747	0.0478	0.0455
		0.5m/s^2	0.3359	0.3252	0.3023	0.2055	0.1892
		1.0 m/s^2	1.1627	1.3493	1.2077	0.8503	0.7660
y	425mm	0.25m/s^2	0.0881	0.0930	0.0900	0.0358	0.0365
		0.5m/s^2	0.3136	0.3443	0.3393	0.1078	0.1223
		1.0 m/s^2	1.0893	1.2037	1.1777	0.3112	0.3550
	390mm	0.25m/s^2	0.0853	0.0934	0.0932	0.0352	0.0384
		0.5m/s^2	0.3177	0.3475	0.3400	0.1064	0.1164
		1.0 m/s^2	1.0996	1.2127	1.1173	0.3270	0.3244
	350mm	0.25m/s^2	0.0907	0.0947	0.0936	0.0368	0.0347
		0.5m/s^2	0.3265	0.3547	0.3482	0.1130	0.1170
		1.0 m/s^2	1.1135	1.2262	1.2300	0.3477	0.3417

Similar trends are also observed from the absorbed power responses of seated occupant exposed to lateral vibration, as illustrated in Figures 4.10 and 4.11. The total absorbed power suggests a strong and nearly quadratic relation with the magnitude of vibration under both fore-and-aft directions of vibration, which may be expressed in the form:

$$\overline{P} = \alpha \ddot{X}_{rms}^{\beta} \qquad (4.1)$$

Where β is the exponent of the overall rms acceleration $\ddot{X}_{rms}$ due to excitation and α is proportionality constant. The reported studies on whole-body vibration have suggested that the increase in the amount of absorbed power is proportional to approximately mean square value of the acceleration due to vibration [12, 16, 19]. Studies on energy absorbed by the human hand-arm system exposed to hand transmitted vibration have also concluded that the total absorbed power is proportional to the square of the level of vibration exposure expressed in terms of the rms acceleration magnitude [1, 12, 60]. The absorbed power data acquired in this study is further analysed to study the effect of levels of vibration on the total absorbed power as a function of the posture, seat height and direction of vibration. The variations in the magnitudes of total absorbed power measured at the seat pan and the backrest with the magnitudes of acceleration are illustrated in Figures 4.10-4.13 for various back supported postures under both fore-and-aft and lateral vibration. The correlation coefficient (r^2) values exceeded 0.9 for all the experimental conditions considered and the regression analysis suggests nearly quadratic relationship between the level of vibration and the total absorbed power and thus the non-linear dependence on the magnitude of vibration.

Table 4.8 summarises the constant and the exponent values obtained under different excitation and postural conditions. The exponent values range from 1.84-2.08 and 1.56-1.86 for the absorbed power data obtained at the seat pan and the backrest, respectively. The values of constant range from 1.09-1.39 for the absorbed power data obtained at the seat pan under both *x*- and *y*-axis motions, and considerably lower values with the absorbed power data obtained at the backrest. Higher exponent values are observed for the absorbed power data with Wb0 and WbA postures at the seat pan and the backrest, particularly under fore-and-aft excitations. The exponent values under *y*-axis excitation, however, yield lower magnitudes of absorbed power, which can be attributed to the

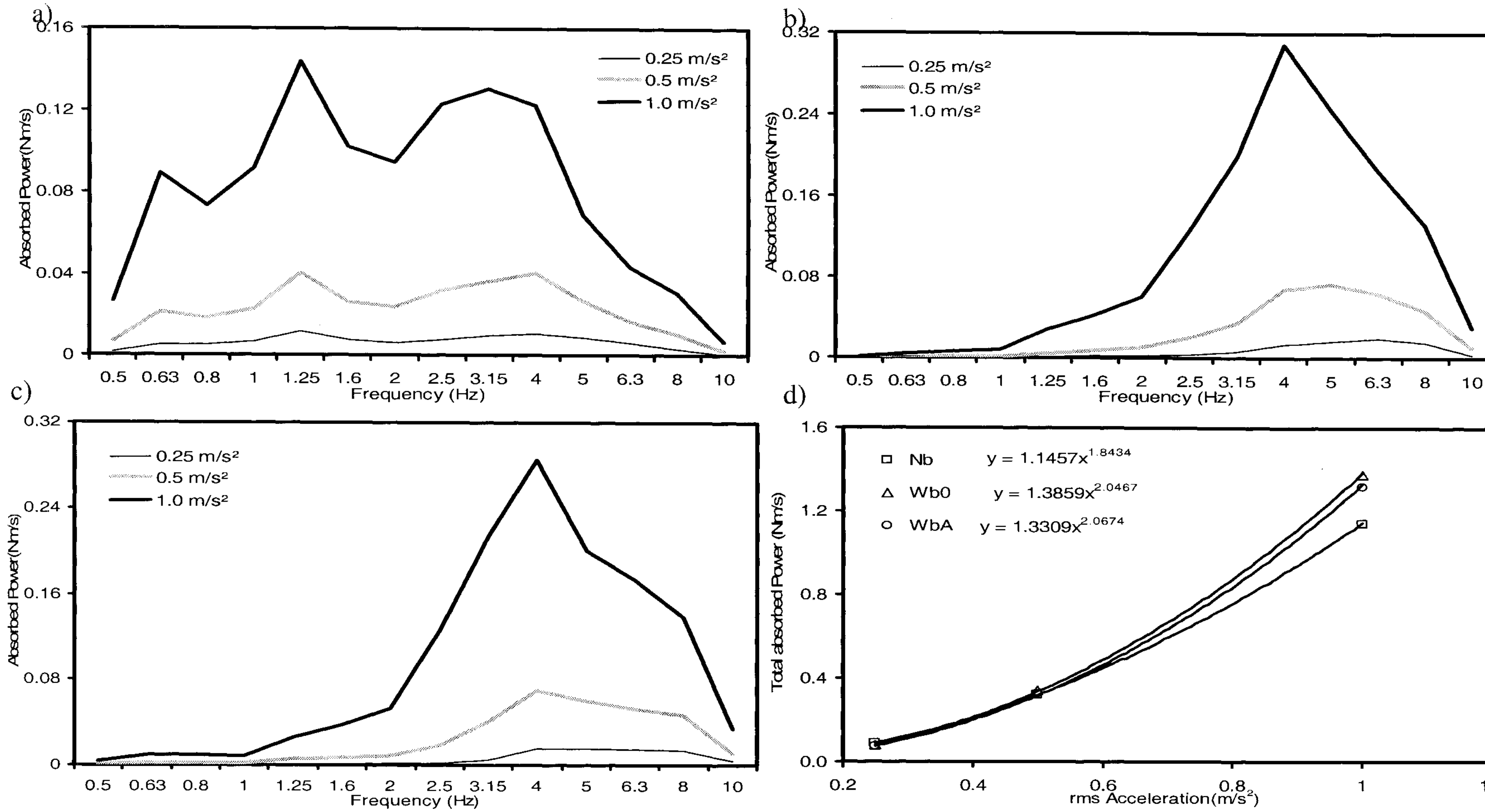


Figure 4.10: Mean Absorbed Power of eight subjects measured at the seat pan under different magnitudes of fore-aft vibration and postures (seat height: H1), and variations in total absorbed power with excitation magnitude: a) NB posture; b) Wb0 posture; c) WbA posture.

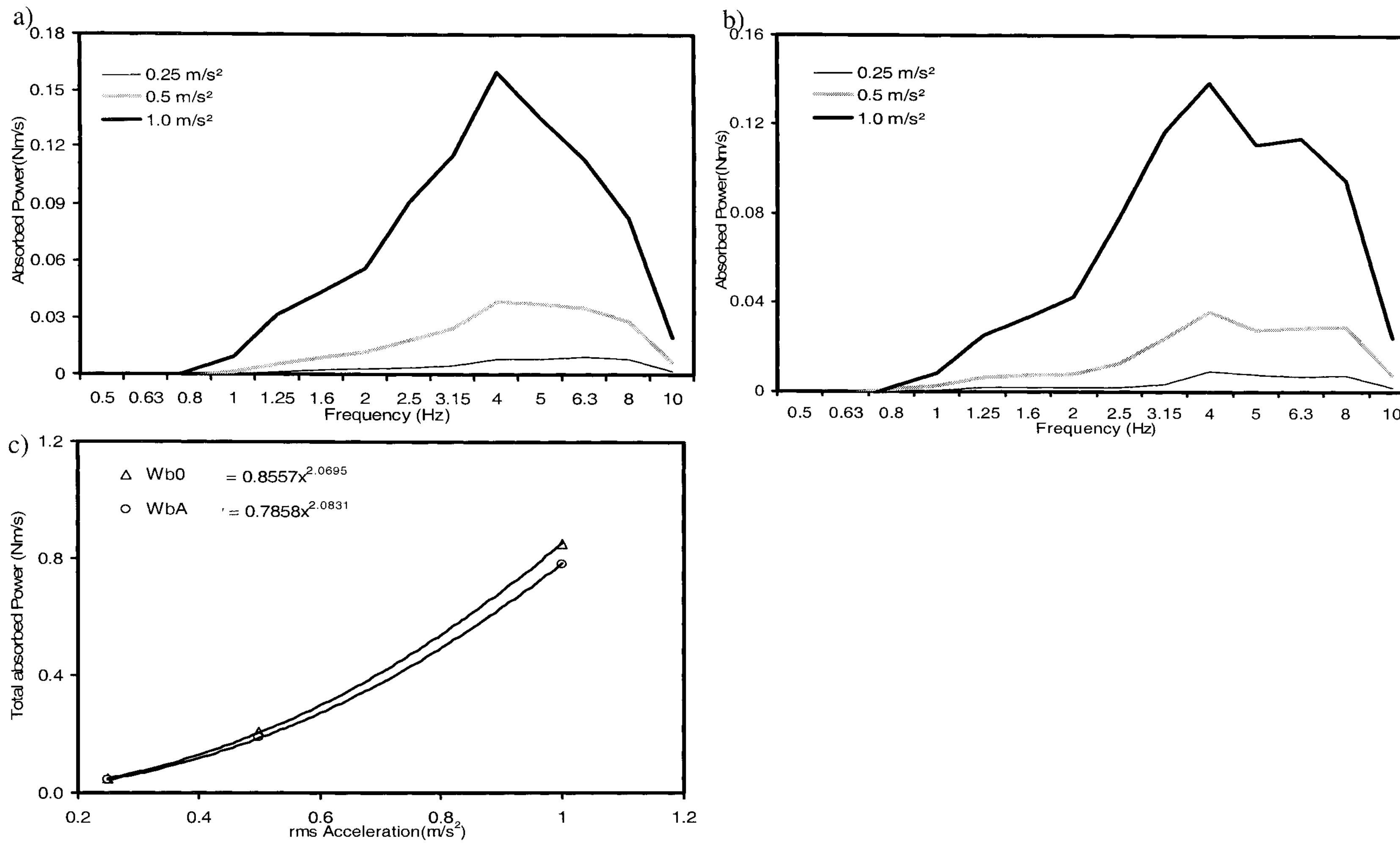


Figure 4.11: Mean Absorbed Power of eight subjects measured at the backrest under different magnitudes of fore-aft vibration and postures (seat height: H1), and variations in total absorbed power with excitation magnitude: a)Wb0 posture; b) WbA posture; and c) dependence of total absorbed power on the magnitude of excitation acceleration.

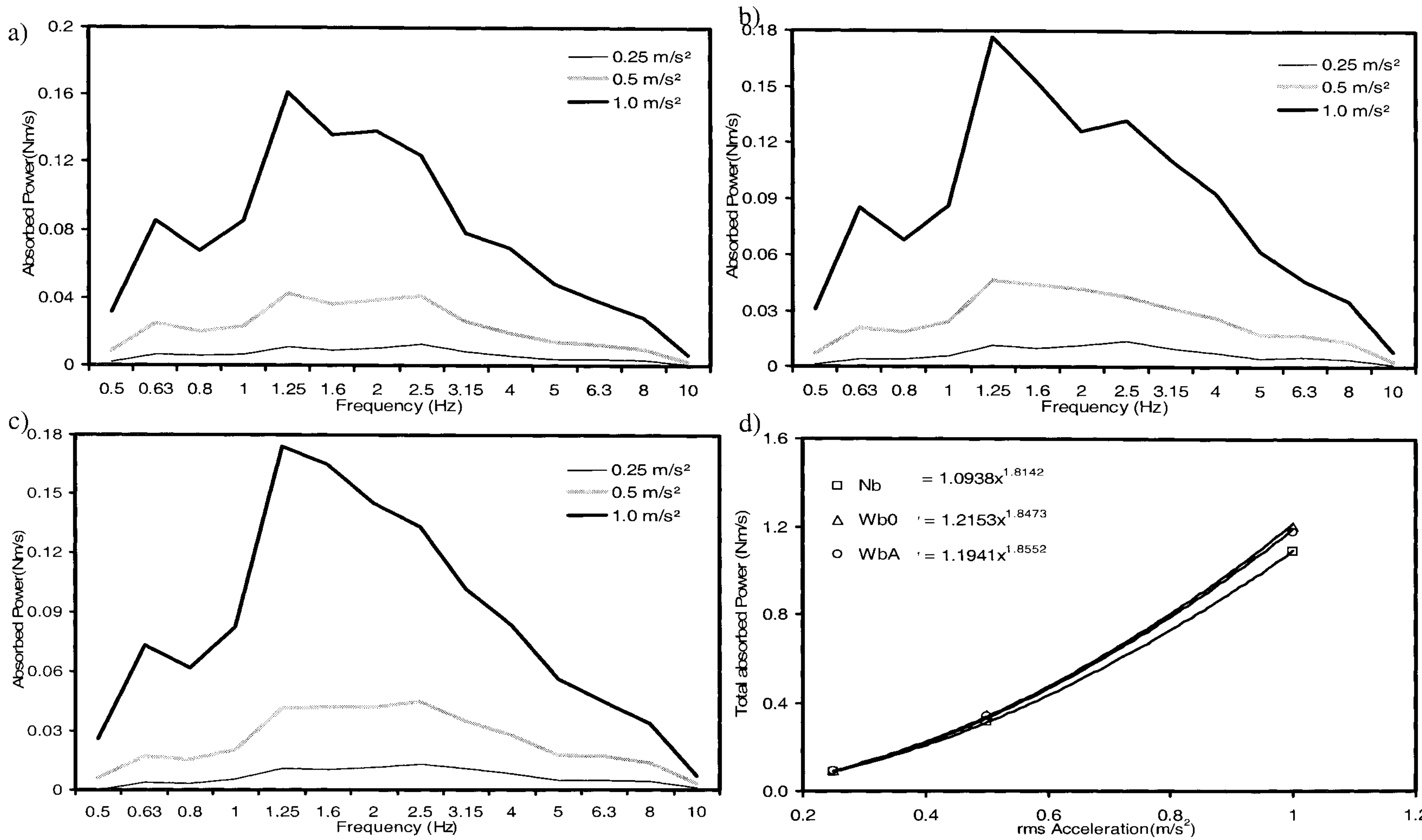


Figure 4.12: Mean Absorbed Power of eight subjects measured at the seat pan under different magnitudes of lateral vibration and postures (seat height: H1), and variations in total absorbed power with excitation magnitude: a) NB posture; b) Wb0 posture; c) WbA posture; and d) dependence of total absorbed power on the magnitude of excitation acceleration.

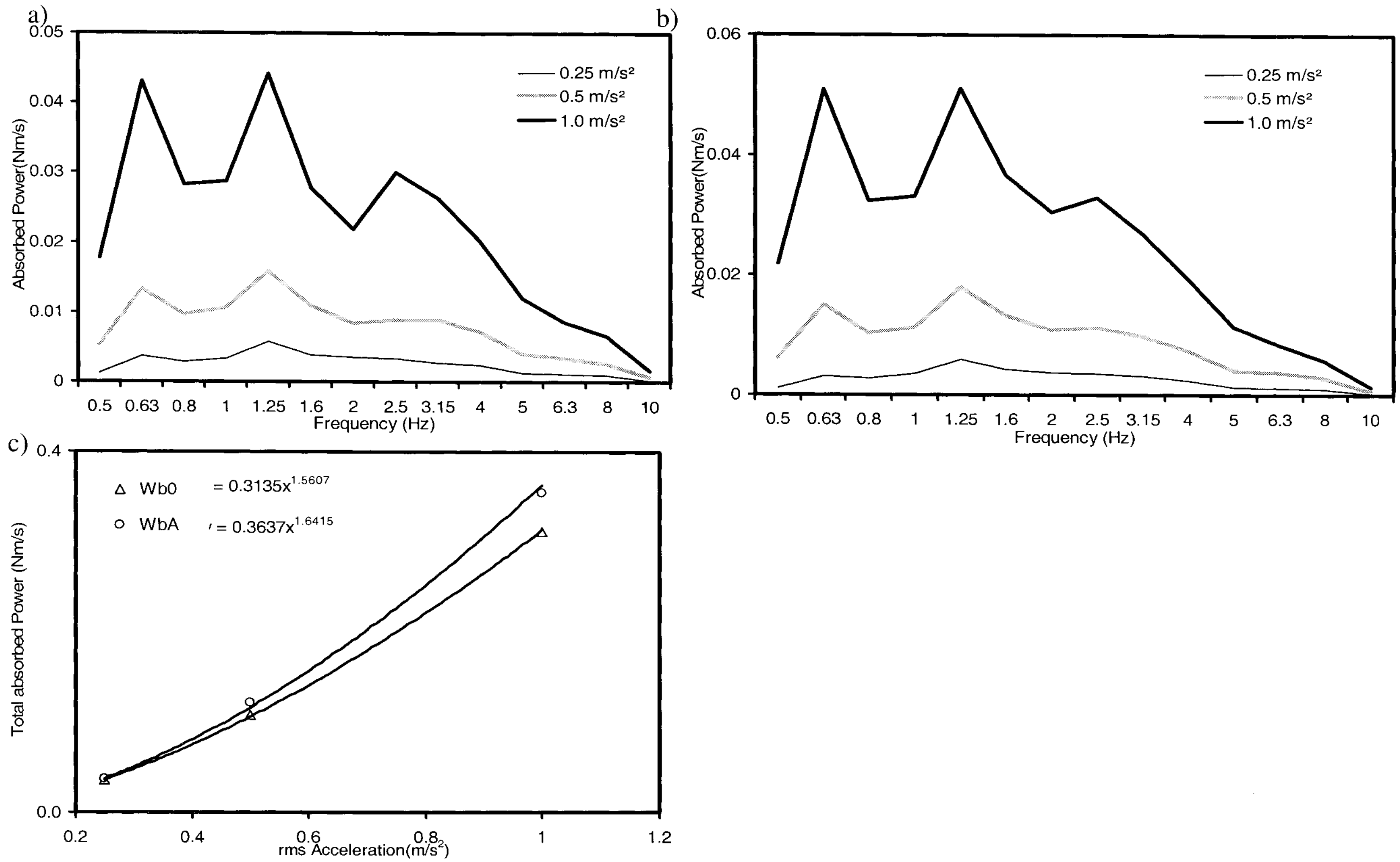


Figure 4.13: Mean Absorbed Power of eight subjects measured at the backrest under different magnitudes of lateral vibration and postures (seat height: H1), and variations in total absorbed power with excitation magnitude: a)Wb0 posture; b) WbA posture; and c) dependence of total absorbed power on the magnitude of excitation acceleration.

smaller forces along the y-axis. The exponent values along y-axis obtained for Wb0 and WbA postures are comparable to those obtained fore the with NB posture, which could be attributed to lower resistance provided by the backrest under lateral excitations. Furthermore, constant values are also observed to be low for the data measured at the backrest under lateral motions.

Table 4.8: Constant and exponent values for different excitation and postural conditions.

Location	*Axis of vibration*	*exponent β*			*constant α*		
		NB	Wb0	WbA	NB	Wb0	WbA
Seat pan	x	1.84	2.05	2.07	1.15	1.39	1.33
	y	1.81	1.85	1.86	1.09	1.21	1.19
Backrest	x	-	2.07	2.08	-	0.86	0.79
	y	-	1.56	1.64	-	0.31	0.36

4.5.2 Effect of posture on the absorbed power response

Only a few reported studies have considered back supported posture for characterising the horizontal biodynamic response and concluded that the back support strongly affects the occupants response to horizontal vibration [5, 6, 10]. A number of studies have also reported the effect of back supported posture on the biodynamic response to vertical vibration [28, 52, 65]. The back supported posture is suggested to strongly effect the biodynamic response particularly under fore-and-aft vibration. Contact between the upper body and the backrest forms another source of vibration and encourages rotational motions of the upper body. With the exception of a single study [10], which considered an inclined back support, the absorbed power characteristics of seated occupants exposed to horizontal vibration, under different back supported conditions have not been investigated.

Figure 4.14 illustrates the influence of different back supported conditions considered in this study, on the mean absorbed power responses in the 0.5-10 Hz frequency range under fore-and-aft vibration of magnitude of 0.25 m/s^2. The frequencies corresponding to the resonance peaks are comparable to those observed in the APMS responses, illustrated in chapter 3. Moreover, the total absorbed power in the 0.5-10.0 Hz frequency range is computed to estimate the effect of back supported postures. Figures 4.14 and 4.15 further compare the absorbed power responses with occupants seated with NB, Wb0 and WbA postures and exposed to 1.0 m/s^2 magnitude of vibration along the *x*- and *y*- axis, respectively.

ANOVA-'within subjects' method was used to study the significance of the NB, Wb0 and WbA postures, and also the inclination of the backrest individually. The results attained for the seat pan and backrest data have been presented in Tables 4.5 and 4.6, respectively. The significance factor of about $p<0.05$ were observed, indicating the significance effect of unsupported and supported back conditions under both directions of vibration. As suggested in literature, the amount of total absorbed power can serve as measure of the potential of occupational injury and the comfort perception of vibration-exposed occupants. The majority of the absorbed power in NB posture could be due to the motion of the upper body; the results revealed that about 50% of the total absorbed power appears in the lower frequency range of 0.5-2.19 Hz. It has also been reported that the primary resonance occurring at lower frequencies is due to pitch motion of the upper body [6]. The restrained upper body with vertical or inclined backrest revealed peak magnitudes of the absorbed power at higher frequencies and were higher compared to the total absorbed power obtained with NB postures.

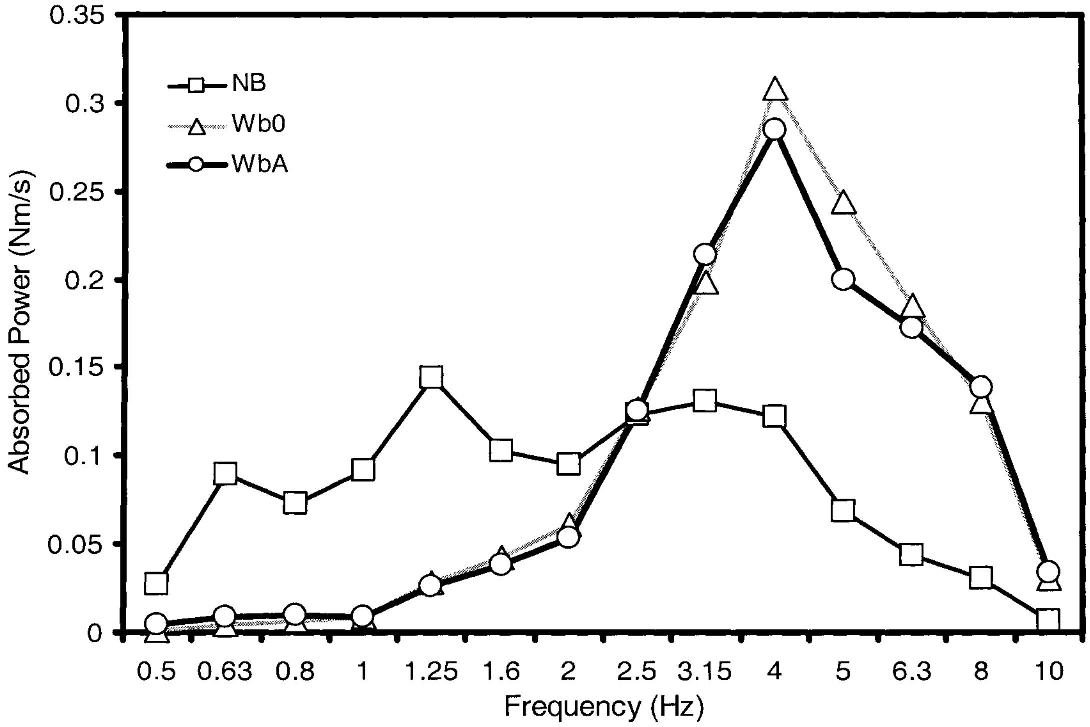


Figure 4.14: Mean Absorbed Power of subjects seated with NB, Wb0 and WbA- under fore-and-aft excitation (0.25 m/s^2).

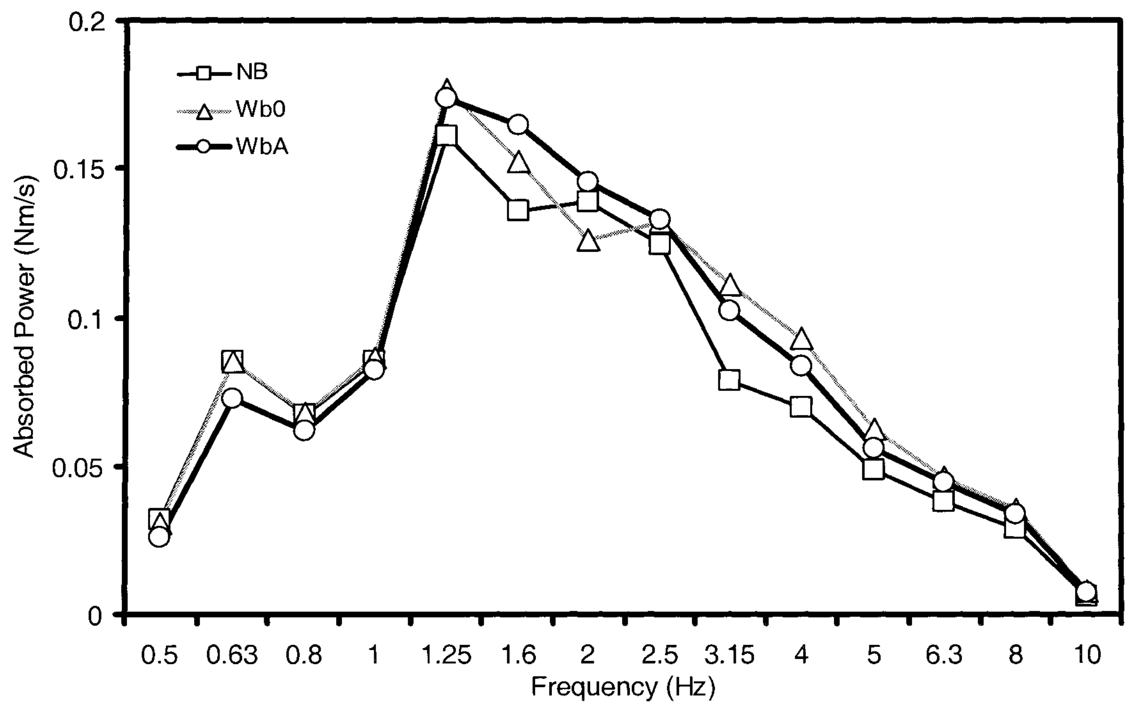


Figure 4.15: Mean Absorbed Power of subjects seated with NB, Wb0 and WbA- under lateral excitation (0.25 m/s^2).

The back support restraints the movement of the upper body, irrespective of the direction of vibration, and it forms additional source of vibration transmitted to the seated occupant. A more comprehensive single resonant peak is revealed under the Wb0 and WbA postures, compared to the three principal peak responses observed under the NB posture. The single resonant peak is observed to occur at a higher frequency in the fore-and-aft axis compared to that along the lateral axis. In addition to the seat pan, the backrest, armrest, head rest, footrest and hands on the steering wheel also transmit vibration to the seated occupant. It has been reported that sitting with a back supported posture could be annoying, or even effect the posture and the balance, which is related mainly to the human response to low-frequency WBV, as evident from the vertical biodynamic studies [22, 29, 48]. However, a backrest reduces the loads on the lumbar spine by transmitting part of the gravity forces due to the upper body to the backrest [41]. The backrest tends to support and stiffen the upper body and thus affects the human response to perceived vibration [65], which is also evident from the results obtained in this study.

The seated occupant with the WbA posture showed less absorbed power compared to that of the Wb0 posture, which can be attributed to the more stable upper body posture in the WbA posture. An inclined back support tends to limit the backward upper body motion, while the forward motion is limited by the weight of the subject resting against the back support. Therefore, adequate contact of upper body with back rest is expected. The data attained at the seat pan with the supported back conditions generally show about 20 % power absorption higher than those under the NB postures.

The absorbed power responses measured at the backrest in both Wb0 and WbA postures under fore-and-aft and lateral motions reveal peak magnitudes at frequencies comparable to those observed in the seat pan data. Figure 4.16 illustrates a comparison of the mean absorbed power response of seated occupant measured at the seat pan and the backrest under fore-and-aft motions, with WbA posture. To quantify the effect of the backrest, the ratio of the power absorbed at the backrest to that at the seat pan is computed, such that:

$$P_{\gamma} = \frac{P_{backrest}}{P_{seatpan}} \qquad (4.2)$$

Where P_{γ} is the absorbed power ratio, $P_{backrest}$ and $P_{seatpan}$ are the total absorbed powers derived from the data acquired at the backrest and seat pan, respectively. Table 4.9 summarises the power ratios for both axes of vibration, and different seat heights and excitation magnitudes. Higher percentages of backrest absorbed power are observed along the x-axis, the values range from 51-63%, while those for the y-axis range from 25-40%. Generally, the ratio of powers obtained with the Wb0 postures tend to be slightly higher than those with the WbA postures. The trend, however, is opposite in the results attained under y-axis vibration. These results show the strong contributions due to backrest to the total power absorbed by the seated occupants' exposed to horizontal vibration. Higher values of total absorbed power obtained at both the seat pan and the backrest, with Wb0 posture than those with WbA posture under fore-and-aft motions suggests that a WbA posture would be relatively more comfortable in view of vibration exposure. The influence of supported back postures on absorbed power response of seated occupant was observed to be less prominent under lateral vibration, as illustrated in the Figure 4.15. Further, the total absorbed power values illustrated in Table 4.7 reveal

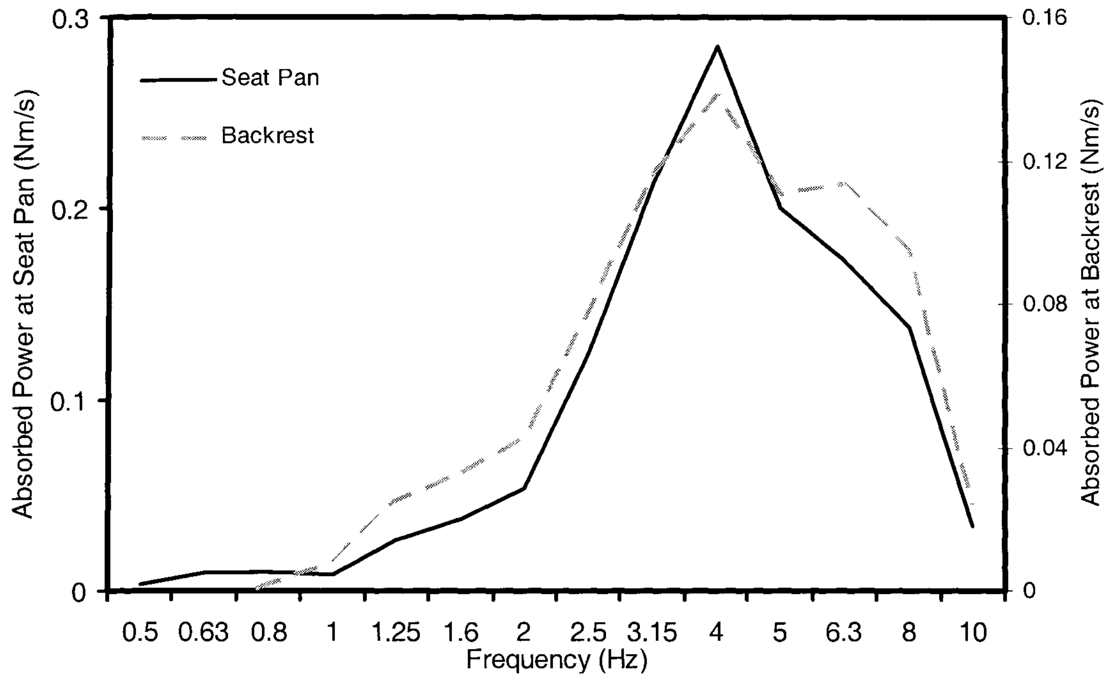


Figure 4.16: Comparison of mean absorbed power response measured at the seat pan and the backrest under fore-and-aft vibration (Posture-WbA, Seat height-H1).

Table 4.9: Ratio of the total absorbed power measured at the backrest to that at seat pan, under the experimental conditions considered in the study.

Axis	*Seat height*	*Excitation magnitude*	*% Ratio P_Y*	
			Wb0	WbA
x	425mm	0.25m/s^2	59.93	58.08
		0.5m/s^2	60.64	57.95
		1.0 m/s^2	61.83	59.27
	390mm	0.25m/s^2	51.38	53.51
		0.5m/s^2	55.14	55.02
		1.0 m/s^2	58.90	53.72
	350mm	0.25m/s^2	63.14	60.91
		0.5m/s^2	63.19	62.59
		1.0 m/s^2	63.02	63.43
y	425mm	0.25m/s^2	38.49	40.56
		0.5m/s^2	31.31	36.04
		1.0 m/s^2	25.85	30.14
	390mm	0.25m/s^2	37.69	41.20
		0.5m/s^2	30.62	34.24
		1.0 m/s^2	26.96	29.03
	350mm	0.25m/s^2	38.86	37.07
		0.5m/s^2	31.86	33.60
		1.0 m/s^2	28.36	27.78

small effect of the back support along lateral axis, particularly with higher magnitudes of excitation.

4.5.3 Effect of seat height on the absorbed power response

The measured data are analysed to assess the effect of the seat height on the power absorption characteristics of the seated human occupants exposed to horizontal vibration. The seat height tends to alter the thigh contact with the seat pan, which could cause variations in the subject's efforts to realise stable seated posture under horizontal vibration. Figures 4.17 and 4.18 illustrate the effect of seat height on the mean absorbed power response of 8 subjects measured at the seat pan and backrest, respectively, under 1.0 m/s^2 rms excitation along both the x and y axis independently. The results show relatively small effect of seat height on the absorbed power response. Irrespective of the axis of excitation, only small effects of seat height on the absorbed power response could be observed for the NB posture compared to with the supported back postures. Very little or no effect of seat height was observed in the absorbed power responses with WbA posture, measured at the seat pan, compared to that with the Wb0 posture.

Figure 4.18 illustrated the absorbed power responses obtained at the backrest under both fore-and-aft and lateral excitations, which reveal minor effects of the seat height with both Wb0 and WbA postures. Table 4.7 illustrates comparisons of the total absorbed power values obtained at the seat pan and backrest as a function of the seat height. The total absorbed power measured at the seat pan with the supported back postures tends to be higher under higher magnitudes of vibration. However, the effect of seat height on the absorbed power of the seated occupant exposed to horizontal vibrations was observed to be very small, particularly at low frequencies.

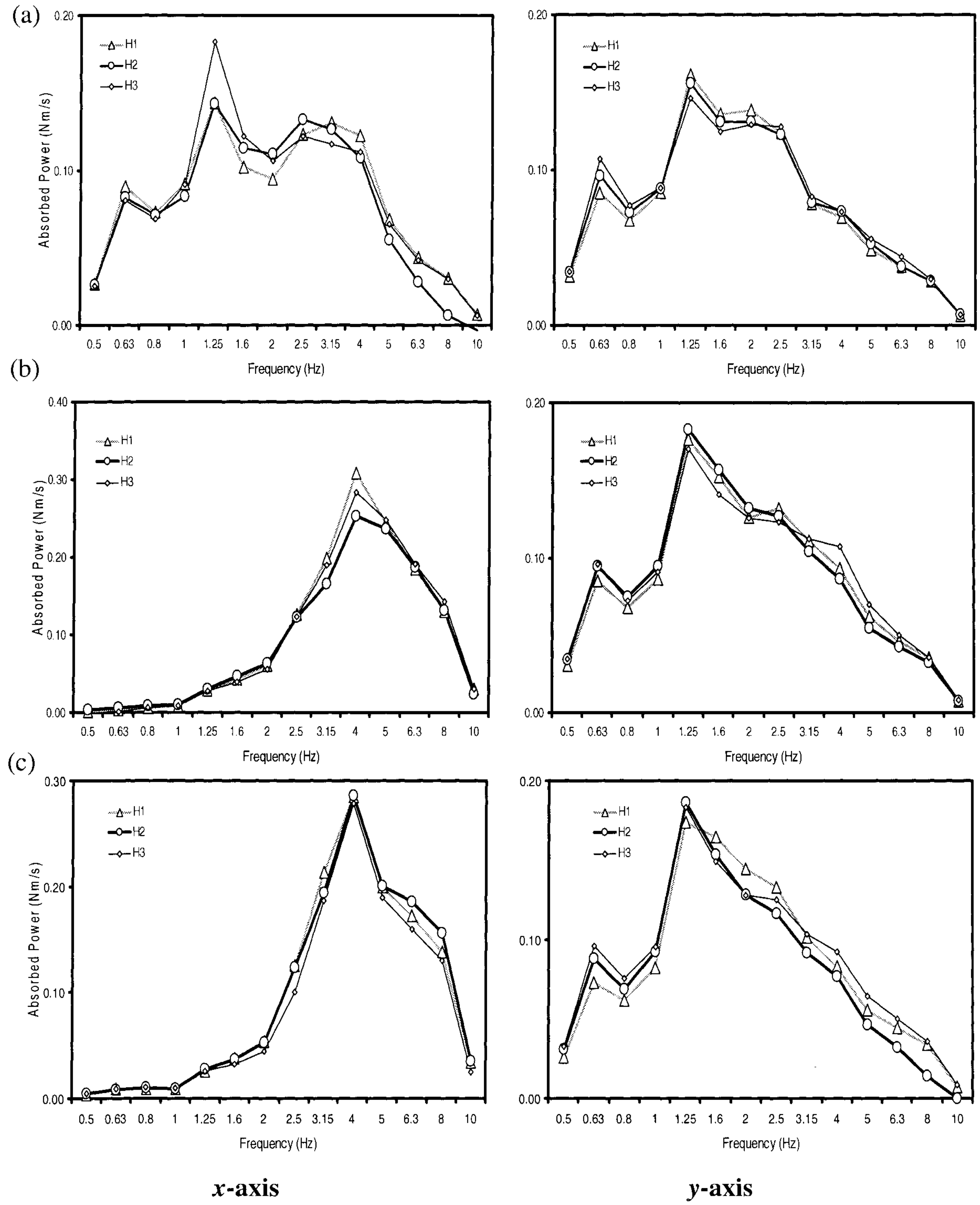
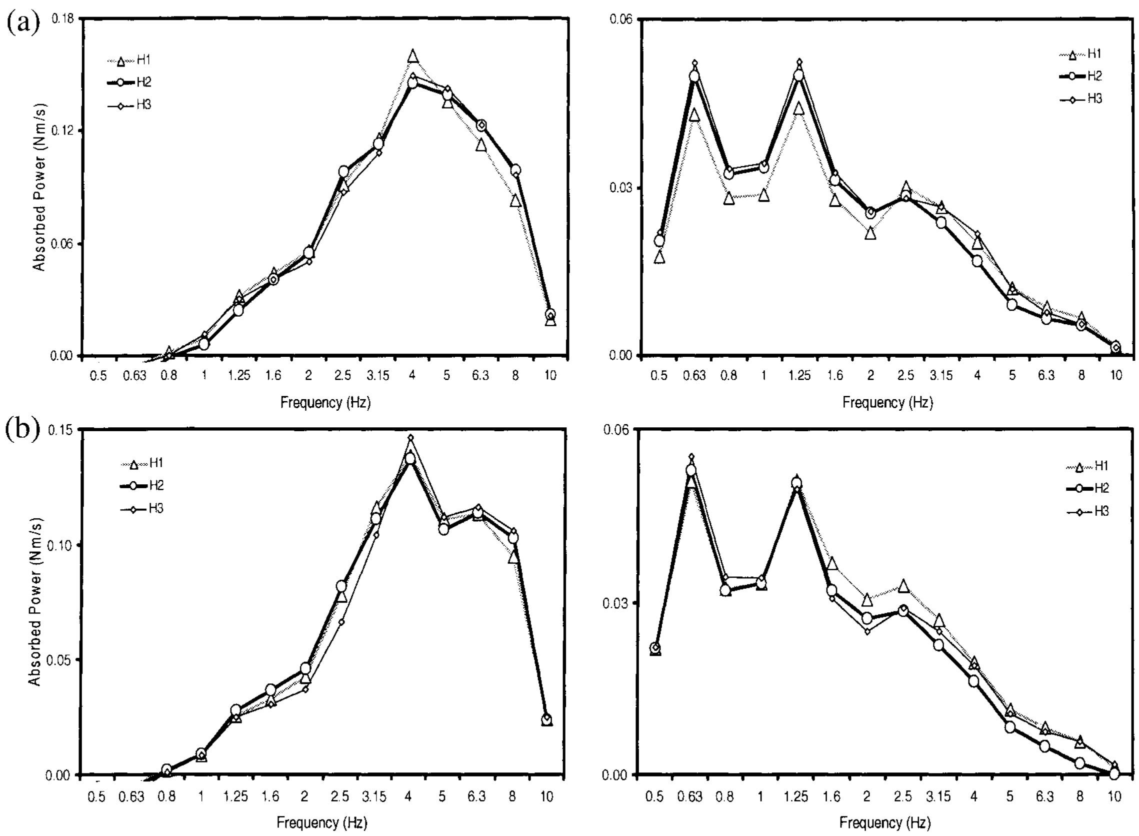


Figure 4.17: Effect of seat height on the mean absorbed power responses measured at the seat pan for different back conditions (excitation 1.0 m/s^2 rms) (a) NB; (b) Wb0; (c) WbA posture.



***x*-axis** ***y*-axis**

Figure 4.18: Effect of seat height on the mean absorbed power response measured at the backrest (excitation 1.0 m/s^2 rms). (a) Wb0 and (b) WbA posture.

4.5.4 Effect of vibration direction on the absorbed power response.

The absorbed power and APMS responses of the seated occupants with back supported postures are strongly dependent upon the direction of the vibration [10, 11]. Figure 4.19 illustrates comparisons of mean absorbed power responses obtained for the seated occupants with NB Wb0 and WbA postures, and exposed to fore-aft (*x*) and lateral (*y*) vibration. The results attained from the seat pan data suggest reasonable similarity between the responses under fore-and-aft and lateral motions for the NB posture, while significant difference can be observed for the back-supported (Wb0 and WbA) postures. The exposure to fore-aft vibration transmits significance vibration vibration to

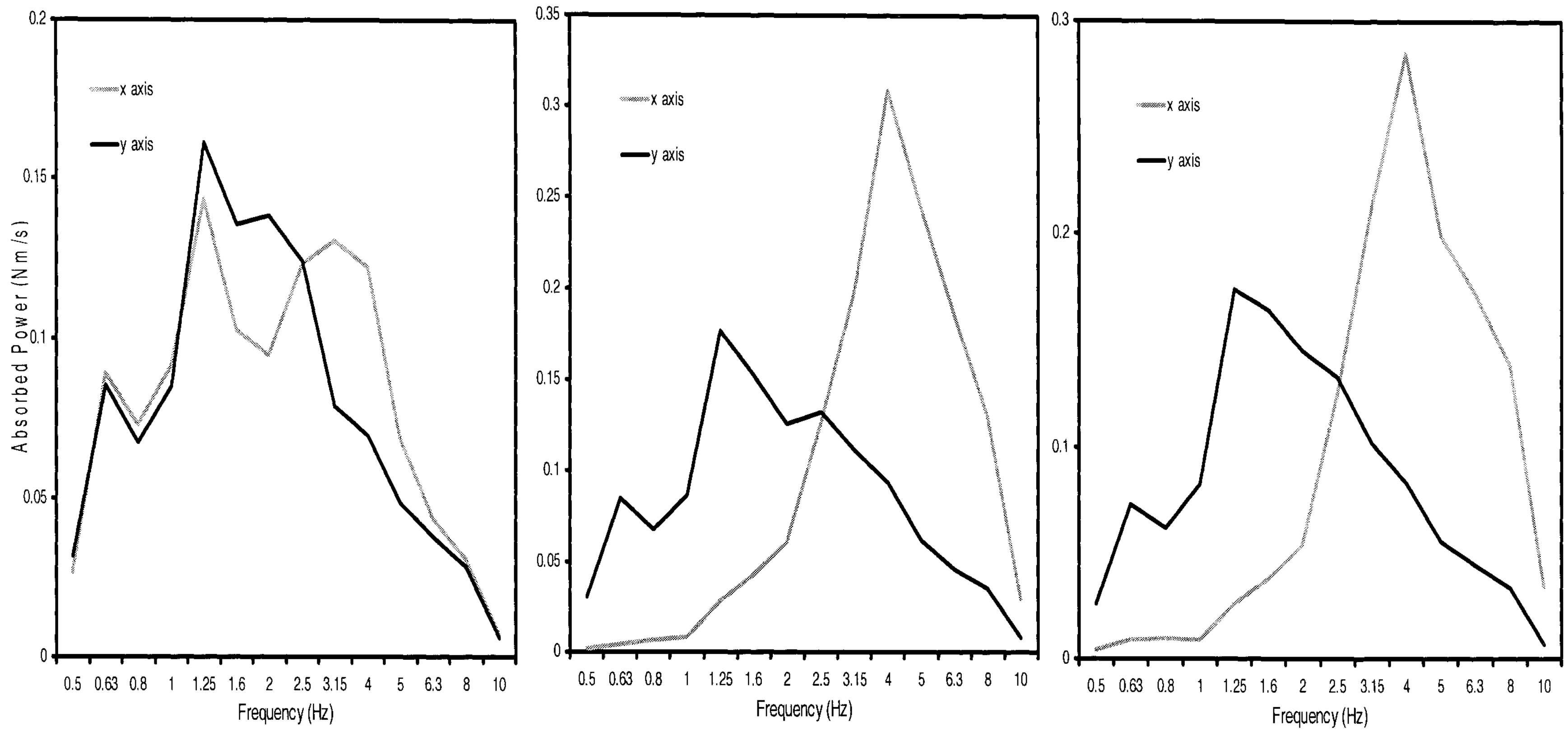


Figure 4.19: Comparisons of mean absorbed power responses obtained at the seat pan under 1.0 m/s^2 acceleration excitation: (a) NB; (b) Wb0; and (c) WbA posture.

the upper body, while that to lateral vibration causes the sliding between the upper body and the backrest. The power absorbed under x-axis motion thus tends to considerably larger than that attained under y-axis vibration. Moreover, the back support serves as an important restraint for the upper body under *x*-axis motions, and thus yields peak responses at significantly higher frequencies, as shown in Figure 4.19.

4.6 Relationship between APMS and absorbed power

The power absorbed by the vibration-exposed seated occupant can also be related to the APMS response, since both responses are based upon force motion relationships at driving point. A few studies have proposed two different methods for computing the absorbed power based upon the direct and indirect approaches [60]. The direct method computes the absorbed power as the real component of cross-spectrum of the driving-point force and velocity, as described in Equations (2.4) to (2.8). The indirect approach relates the absorbed power to the driving-point mechanical impedance [62] or the apparent mass [66]. The absorbed power can be indirectly computed from the real component of the driving-point mechanical impedances such that:

$$P_{Abs} = \mathrm{Re}[Z(j\omega)]\dot{X}^2(\omega) \tag{4.3}$$

Where *Re* represents the real component of the complex driving point mechanical impedance $Z(j\omega)$, and $\dot{X}(\omega)$ is the velocity. Considering that $Z(j\omega) = j\omega\ M(j\omega)$, the absorbed power may also be expressed in terms of the apparent mass as follows

$$P_{Abs} = -\mathrm{Im}\,ag[M(j\omega)]\frac{\ddot{X}^2(j\omega)}{\omega} \tag{4.4}$$

Where Imag represents the imaginary component of the apparent mass $M(j\omega)$ and $\ddot{X}(j\omega)$ is the acceleration. Equation (4.4) is applied to compute the absorbed power from the apparent mass. The resulting power spectra are compared to those derived using the direct method. Figure 4.20 illustrates the comparisons of the absorbed power spectra obtained under different levels of fore-aft excitations (0.25, 0.5 and 1.0 m/s^2 rms acceleration). The results clearly show that both methods yield identical absorbed power, irrespective of the excitation magnitude.

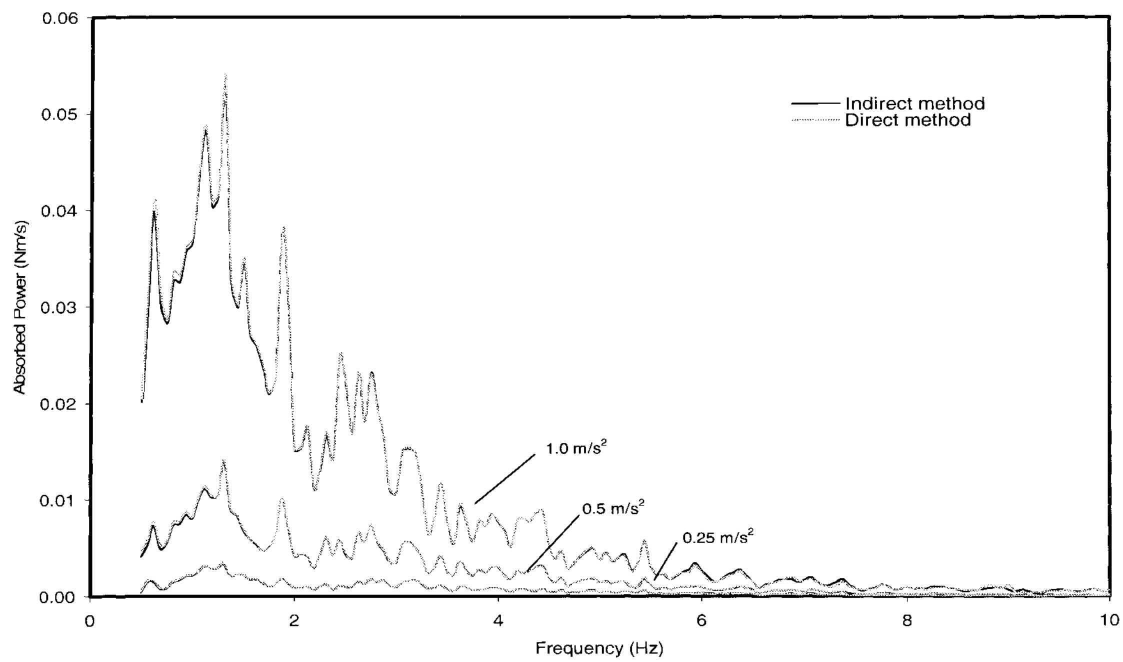


Figure 4.20: Comparisons of absorbed power spectra derived using direct and indirect methods (fore-aft excitation).

4.7 Comparison with the literature

Only two studies have characterised the seated occupant responses under horizontal vibration in terms of absorbed power. These include a study by Lundström and Holmlund [16] involving measurements of absorbed power of subjects seated without a back support, and a recent study by Coronel [10]. The experimental conditions employed in these studies are thoroughly reviewed and compared with those considered in the present study, as summarised in Table 4.10. Study by Lundström [11] has considered only NB posture with feet rested on the floor but not vibrated, which is not a representative of the vehicular environment. The study also considered different magnitudes of sinusoidal fore-aft and lateral vibration (0.25-1.4 m/s^2) in the 1.13-80 Hz range. Coronel performed measurements using a typical automotive seat with an inclined seat pan (13° with respect to a horizontal axis) and inclined back support (24°) with respect to a vertical axis, while the vibration excitations involved different levels of white noise and sinusoidal excitation in the 0.25-10 Hz frequency range. The study reported the absorbed power characteristics for NB and WbA (24°) postures. The present study considers the NB, Wb0 and WbA postures, and various seat heights which are quite representative of the off-road vehicle environment. The mean mass and height of the test subjects in the reported study are relatively high, and the magnitudes of excitation fall within the commonly used ranges. The mean absorbed power responses measured at the seat pan with the NB and WbA postures in this study under 0.5 m/s^2 rms acceleration are comparable with those reported in [10] for both fore-and-aft and lateral axes excitations, as illustrated in Figure 4.21. The absorbed power responses obtained in the present study, under both fore-and-aft and lateral excitations reveal lower peak magnitudes compared with those reported in the previous study, which can be attributed to relatively lower mean values of body mass and height of the test participants in the present study. The small variations observed in the absorbed power responses over the entire frequency range can also be attributed to the difference in the seat geometry. The frequencies

Table 4.9: Comparisons of experimental conditions employed in reported studies on absorbed power.

Reported studies	*Lundström and Holmlund [11]*	*Pena Cornel [10]*	*Present Study*
Year	1998	2003-2004	2004-2005
Objective	Time-averaged absorbed power(horizontal and vertical)	Absorbed power density	Absorbed power
Sample size	15 male / 15 female	7 males	8 males
Age (years) M, SD(min, max)	38, 12/35, 10 (24, 59)/ (22, 51)	34.8, 9.62 (25, 50)	28.5, 9.38 (23, 50)
Height (m) M,SD (min, max)	1.72, 0.07, (1.6, 1.88)	1.75, 0.04(1.7-1.83)	1.73, 2.5 (1.7, 1.78)
Weight (kg) M, SD (min, max)	69, 10 (54, 93)	77.11, 9.41(61.2, 88.1)	71.2, 10.6 (59.4, 92)
Magnitudes of Vibration	0.25, 0.35, 0.5, 0.7, 1.0, 1.4 m/s^2 rms	Random: 0.25, 0.5,1.0 m/s^2 rms (*x*) 0.75 m/s^2 rms (*y*) Sine: 1, 1.5, 2 m/s^2	Random: 0.25, 0.5,1.0 m/s^2 rms Sine: 1, 2 m/s^2 (*x*) 2, 3 m/s^2 (*y*) *
Excitation type	Sinusoidal, increased in steps of 1/6 octaves	Random/sine	Random/sine
Exposure time	180 s	128s / 512 s	128 s (random) / 512 s (sine)
Frequency range	1.13-80 Hz	0.25-1.0 Hz	0.5-1.0 Hz
Seat pan	Flat	Inclined (13°)	Flat
Backrest	Not used	Inclined (24°)	Vertical/ inclined
Sitting posture	Upright(erect and relaxed)	Upright / Inclined	Upright/ Inclined
Feet	On the floor	On the vibrator table	On the vibrator table
Hands and arms	On lap	On lap	On lap

* peak acceleration

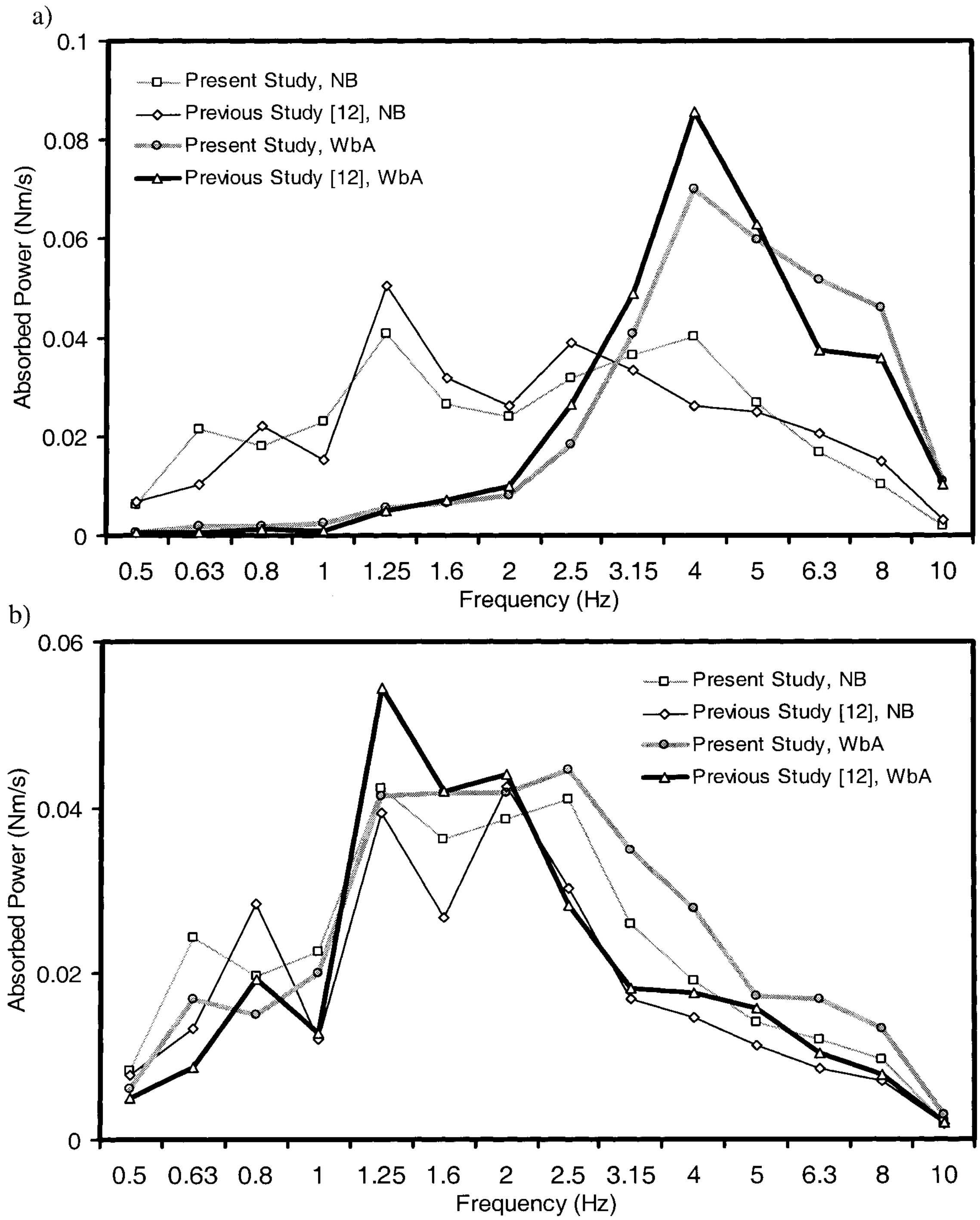


Figure 4.21: Comparisons of mean absorbed power responses measured at the seat pan with the NB and WbA postures under 0.5 m/s^2 rms acceleration with those reported in literature [10]: (a) fore-and-aft; (b) lateral excitations.

corresponding to the peak responses observed in both studies, are however, are quite comparable.

4.8 Summary

Absorbed power characteristics of seated occupants exposed to whole-body horizontal vibration are investigated through analysis of force-motion data at both the seat pan and the backrest interfaces. The results show that the absorbed power is strongly influenced by the excitation magnitude, body mass, direction of excitation, and back supported conditions, while the effect of variations in seat height is very small. The results suggest that the power absorbed by the vibration-exposed seated occupants is significantly affected by the magnitude and direction of excitation, and back supported condition. Owing to the periodic (expected displacement) motions and the human body sensitivity to harmonic vibration, the response is reported to change considerably due to the involuntary adaptation of the human body. The effect of type of excitation is further discussed in the following chapter.

Chapter 5

COMPARISON OF BIODYNAMIC RESPONSES MEASURED USING RANDOM AND SINUSOIDAL EXCITATION

5.1 Introduction

Several studies have reported seated occupants' responses to WBV using measurement of driving-point force-motion relationships, under discrete sinusoidal, swept sine or random excitations [3-9, 11-14]. Although these studies generally reveal similar trends in responses, attained under different types of excitations, the effects could not be quantified by comparing the data reported in different studies, as the different studies employ varying experimental conditions, particularly the excitation magnitudes, frequency range and sitting posture. The influence of the type of excitation on the driving-point responses can be more appropriately evaluated using the data attained under identical conditions and comparable magnitudes. Only two studies have presented systematic comparisons of the driving-point responses to random and sinusoidal excitations along the vertical axis obtained under identical experimental conditions [18, 67]. Only a single study has performed measurements under random and sinusoidal excitation along the horizontal direction, but did not attempt to provide a systematic comparison of responses to different types of excitations [10]. The reported studies on vertical biodynamics have shown very little influence of type of excitation on the driving-point impedance and apparent mass responses. The results attained under horizontal vibration, however, point to some differences in the responses attained under random and sinusoidal vibration [10]. Under harmonic excitations, energy at an instant occurs at a discrete frequency, while under random excitations the energy is spread over all the frequencies within the range of excitation frequency. The magnitude of excitation could be one of the possible contributing factors influencing the biodynamic responses under different types of excitations. The study under vertical vibration revealed nominally identical modulus of APMS irrespective of random or sinusoidal excitation, while the phase response also revealed similar values in majority of the frequency range. This could be perhaps attributed to relatively small influence of the vertical excitation magnitude on the biodynamic responses, and thereby nearly linear behaviour of the human system. However, the comparison of horizontal biodynamic responses under harmonic and random excitations are expected to reveal considerable differences because the horizontal biodynamic responses are considerably influenced by the magnitude of excitation as evident from the results presented in sections 3.4.1 and 4.5.1.

Recent study on horizontal biodynamics suggests that apart from the differences in the magnitudes of sinusoidal and random excitations, the responses reflect different perception of the subjects to deterministic and random excitations [10]. Moreover, the amplitudes of sinusoidal excitations employed in these study need to be varied with frequency to ensure reasonable levels of displacement at low frequencies, and low acceleration at higher frequencies. This study had employed constant displacement sinusoidal excitation in the 0.25-1.0 Hz frequency range; the displacement amplitude was gradually decreased at frequencies above 1 Hz to ensure constant level of acceleration. The relatively high displacement at lower frequencies was easily perceived by the subjects. The observed differences in the responses at lower frequencies could thus be attributed to the higher perception of subjects of the repetitive sinusoidal motion. Owing to discrete and continuous natures of the sinusoidal and random vibration, it is stated that the biodynamic responses attained under two excitations cannot be directly compared even though both types yield similar values of rms acceleration [7]. The absorbed power responses are expected to show considerable variation with the type of excitation as shown by the APMS data, since the power reflects the change in the human responses due to the contributing factors as presented in chapter 4.

This chapter presents the seated human responses to harmonic vibration along the x and y axes for the two back postures. The APMS and absorbed power responses of the seated occupant to horizontal vibrations are compared with those observed under random excitations of comparable magnitude of excitations. The comparisons are further reported for the NB and WbA postures.

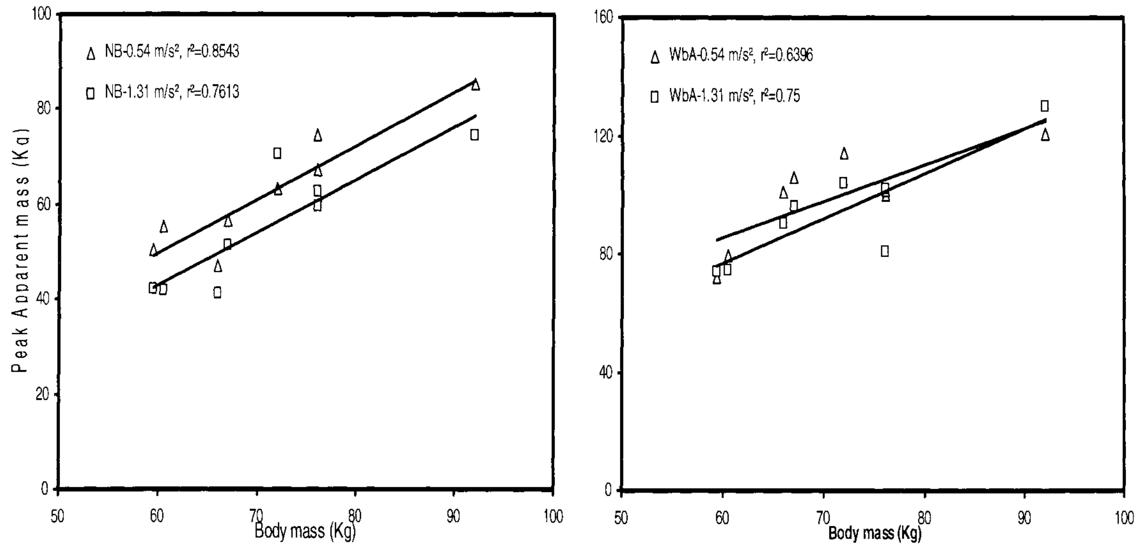
5.2 Inter-subject variability

The seated occupants APMS and absorbed power responses to harmonic excitations revealed considerable scatter in the magnitude responses as observed for random excitations, which are mostly attributed to variation in the individuals mass. The measured data, however, revealed fairly consistent trends with respect to the frequency of peak response, which could be considered as the resonant frequency of the occupant as described in section 3.2. Peak magnitudes of APMS responses attained under fore-and-aft axis vibration reveal good correlation with the body mass, irrespective of the magnitude of excitation and the sitting posture, as illustrated in Figure 5.1. The results suggest trends similar to those observed under random excitations, presented in section 3.3.1. the figure shows the relationship between the peak APMS magnitude and the body mass for the NB and WbA postures, and two different magnitudes sinusoidal vibration (0.54 and 1.34 m/s^2). Nearly linear variations in the peak magnitude with the body mass are observed, particularly for the NB posture. The results further suggest lower peak magnitude under high level of sinusoidal excitation.

The variability in the peak magnitudes of the APMS and total absorbed power with the body mass were also examined for both axes and magnitudes of vibration. Table 5.1 summarises the coefficients of determination for the peak APMS magnitude and total absorbed power under two different postures and different excitations. The table also presents the r^2 values attained for the data acquired at the backrest. The results generally show high degree of correlation between the measured responses under x-axis vibration with the body mass, with the exception of the peak backrest APMS magnitude, which also revealed low r^2 value under random excitations. The total absorbed power data reveals good correlation with body mass for both the seat pan and the backrest, as presented in the Table 5.1. However, both the APMS and absorbed power responses of the seated human body exposed to lateral harmonic excitations suggest poor correlation with body mass, although the inclined back support posture yields some what better correlation. Such trends were also observed from the data attained under random excitations.

Table 5.1: Coefficient of determination of the peak APMS magnitude and total absorbed power measured at the seat base and the backrest with respect to the body mass.

Axis	Vibration Level	Coefficient of Determination (r^2)					
		APMS			Total absorbed power		
		Seat pan		Backrest	Seat pan		Backrest
		NB	WbA	WbA	NB	WbA	WbA
x	0.54m/s^2	0.8543	0.6396	0.0132	0.6473	0.9501	0.8753
	1.31 m/s^2	0.7613	0.75	0.0002	0.6609	0.9266	0.9288
y	1.31m/s^2	0.4339	0.27	0.0114	0.4861	0.588	0.0225
	2.17 m/s^2	0.1877	0.8028	0.0027	0.2659	0.5489	0.0038



(a) (b)

Figure 5.1: Dependency of peak seat-pan-APMS magnitude and corresponding resonant frequency on the body mass, when exposed to fore-and-aft harmonic vibration under tow sitting postures: (a) NB posture and (b) WbA posture.

Owing to the strong dependency of the measured biodynamic responses on the body mass, the measured APMS data are normalised as described in section 2.3.2 the normalised APMS responses attained under harmonic excitations also revealed considerably larger dispersion in the data compared to that observed from the data obtained under random excitations, corresponding to comparable rms acceleration magnitudes. Table 5.2 summarises the peak values of the coefficients of variation of the mean normalised APMS magnitude with in the considered frequency range for the two harmonic excitations and two postures. The table also summarises the CoV values of the total absorbed power. The results suggest peak CoV values in normalised APMS magnitude in the order of 45% and 58% under *x*- and *y*- axes of vibration. The peak values are comparable to those observed for random excitations, and generally occur in the vicinity of the resonant frequencies. The CoV values of the total absorbed power are relatively small and approach as high as 35% for the backrest-measured data. Although the observed peak CoV values seem to be excessive, they are considerably smaller than those observed by the reported studies [8, 64].

Table 5.2: Peak CoV values of the normalised APMS magnitudes and total absorbed power under each of the experimental conditions considered.

Axis	Vibration Level	Coefficient of Variation (%)					
		Normalised APMS			Total absorbed power		
		Seat pan		Backrest	Seat pan		Backrest
		NB	WbA	WbA	NB	WbA	WbA
x	$0.54 m/s^2$	24.11	16.30	22.31	13.23	23.10	22.17
	$1.31 m/s^2$	45.28	19.05	30.56	17.20	20.02	17.95
y	$1.31 m/s^2$	41.74	44.90	57.67	17.80	11.71	28.04
	$2.17 m/s^2$	36.05	33.89	49.46	15.89	15.50	35.09

5.3 Influence of back supported posture and magnitude of excitation

The normalised APMS magnitude and absorbed power data attained under particular magnitude of harmonic excitation and sitting posture are analysed to derive the mean responses. The trends in the mean responses are studies to enhance an understanding on the influences of excitation magnitude and back support condition. Figure 5.2 illustrates comparisons of mean normalized APMS magnitude and phase responses at the seat pan of the seated occupants exposed to two different magnitudes of x- and y-axes of sinusoidal excitations, for the NB and WbA postures. The results clearly show that variations in both the magnitude of vibration and posture strongly affect the APMS responses, particularly the peak magnitudes and the corresponding frequencies under fore-and-aft vibration. The strong effect of the back support posture is clearly evident under fore-and-aft vibrations. The magnitude of harmonic vibration also significantly affects the APMS magnitude and phase response under fore-and-aft excitations, while the effect is relatively small on the y-axis response an increase in y-axis excitation magnitude from 1.34 m/s^2 to 2.13 m/s^2 generally yields slightly lower magnitude in the entire frequency range, while the phase response remains nearly unaltered.

Under 0.54 m/s^2 fore-aft harmonic excitations, the Seat pan APMS magnitude response of the occupants with NB reveals two resonant peaks near 0.5 and 2.13 Hz, while WbA posture yields near 2.5 and 4.25Hz as shown in Figure 5.2. This effect of back support was also observed in response to broad band random vibration. An increase in magnitude of excitation, yields lower peak magnitude and the corresponding resonant frequency. This softening trend was also observed in responses to random vibration, and has been widely reported in studies on vertical as well as horizontal biodynamics. An increase in the fore-aft excitation magnitude yields considerably lower phase response in the entire frequency range. The back support posture on the other hand causes slightly higher phase response.

Figure 5.3 illustrates the influence of harmonic excitation magnitude on the APMS magnitude and phase responses reflected on the backrest. The results show trends similar to those observed in the seat-pan responses. An increase in excitation magnitude causes the fore-aft APMS magnitude to decrease, and the corresponding phase to increase in the entire frequency range. The response to lower magnitude (0.54 m/s^2) excitations show peaks near 2.5 and 4.25 Hz, as observed in the seat pan response. The peak near 4.25 tends to diminish under higher magnitude excitation. The y-axis response measured at the backrest reveals same trend in magnitude but insignificant effect on the phase response, as observed for the seat pan response.

The absorbed power response of seated occupant under different sitting postures and magnitudes of horizontal excitations are shown in Figure 5.4. The figures show the absorbed power with in the 1/3-octave frequency bands centered at frequencies from 0.5 to 10 Hz. The results show trends similar to those depicted in the APMS responses. The absorbed power responses of seated occupants with NB posture exposed to fore-and-aft excitations reveal a minor peak in the frequency band centered around 0.8 Hz and a principal peak value in the 2.5 Hz frequency band, irrespective of the excitation magnitude. However, the absorbed power response with WbA posture reveal principal peak in the 4 Hz frequency band. Similar to the APMS response measured under lateral excitations, the absorbed power responses measured at seat pan and backrest, reveal only little effect of the back supported condition. The results reveal peak values in the 1.25 Hz frequency bands, irrespective of the posture and excitation magnitude.

The influence of excitation magnitude on the mean absorbed power characteristics measured at the seat pan and the backrest is significant, as observed for the random vibration responses in section 4.5.1. An increase in excitation magnitude yields considerably higher magnitude of absorbed power. The mean absorbed power data measured at the backrest also reveals peak magnitudes in value in the 4 Hz and 1.25 Hz bands under x- and y- axis vibration, respectively, as evident in Figure 5.4. The total absorbed power was analysed as discussed in the Equation (4.1) and revealed α, β values in the order of 0.9 to 1.6 and 1.4 to 1.8, respectively.

5.4 Comparison of responses to random and harmonic excitations

In sinusoidal excitations the vibration, energy would generally occur at a discrete frequency at a given instant, while the broad-band random vibration energy with several spectral components. The inherent difference in the two excitations could yield

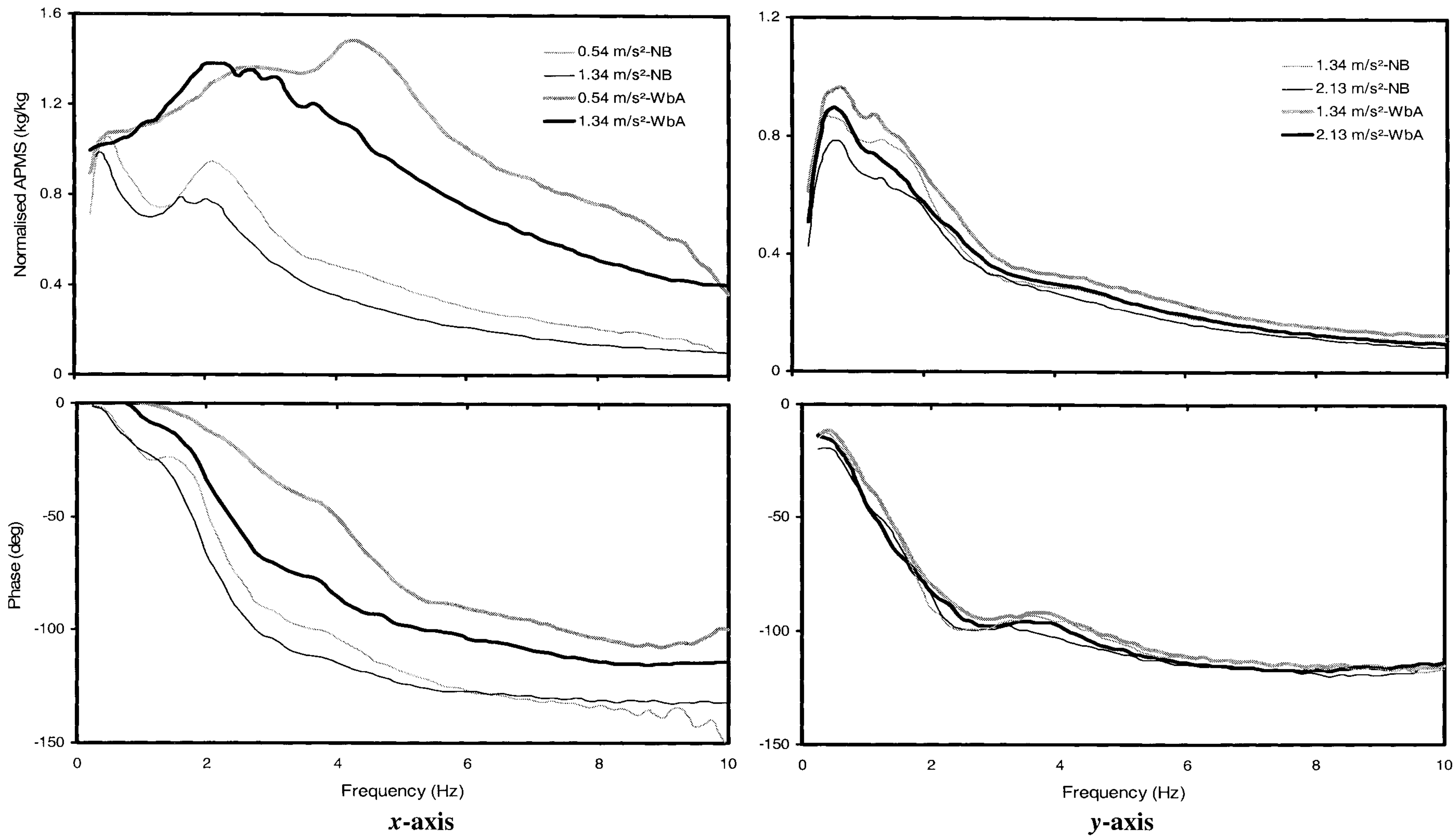
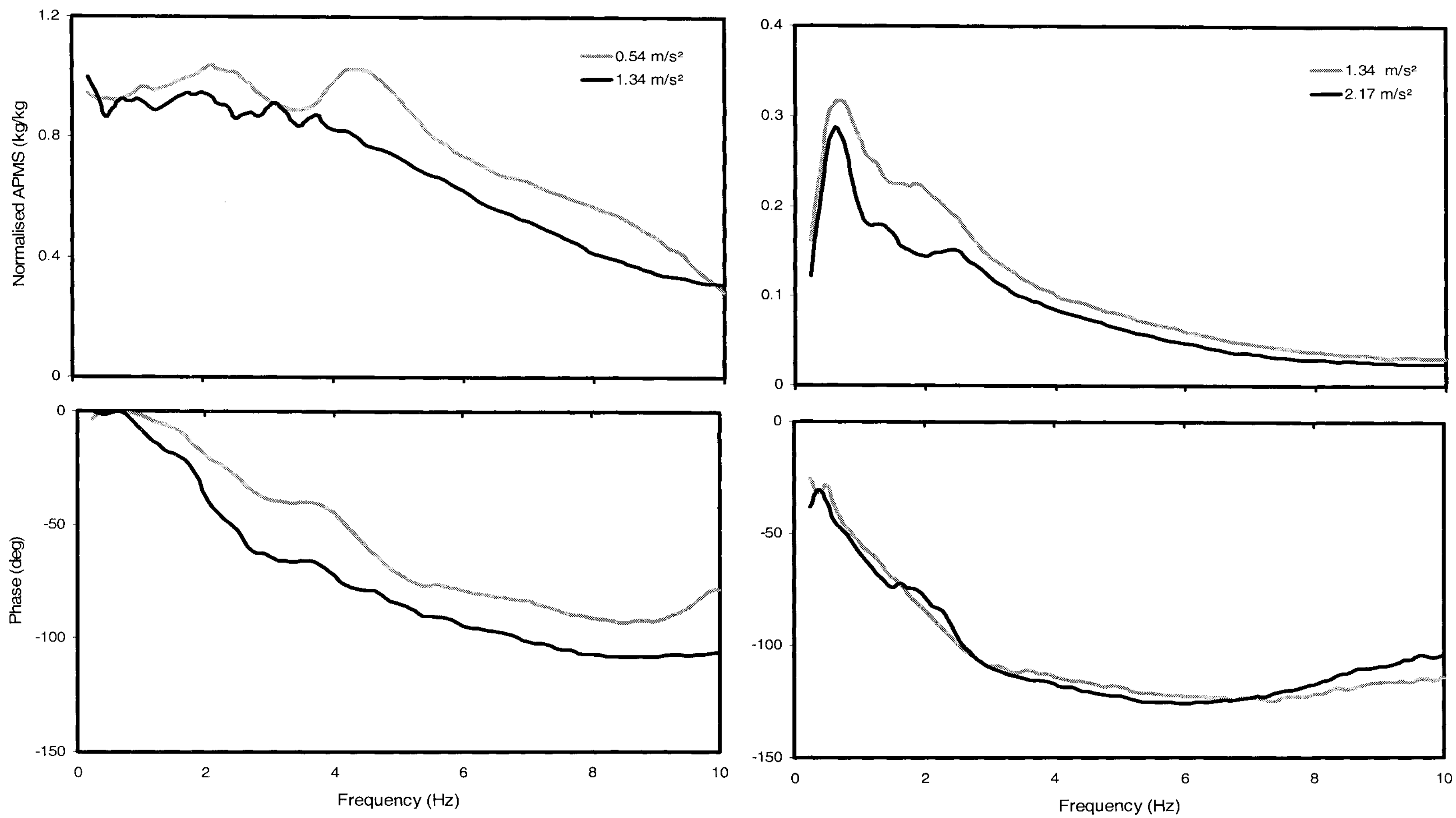


Figure 5.2: Mean normalized seat pan APMS magnitude and phase responses of seated occupants under different magnitudes of excitations and back support conditions.



***x*-axis** ***y*-axis**

Figure 5.3: Mean normalized backrest APMS magnitude and phase responses of seated occupants under different magnitudes of excitations

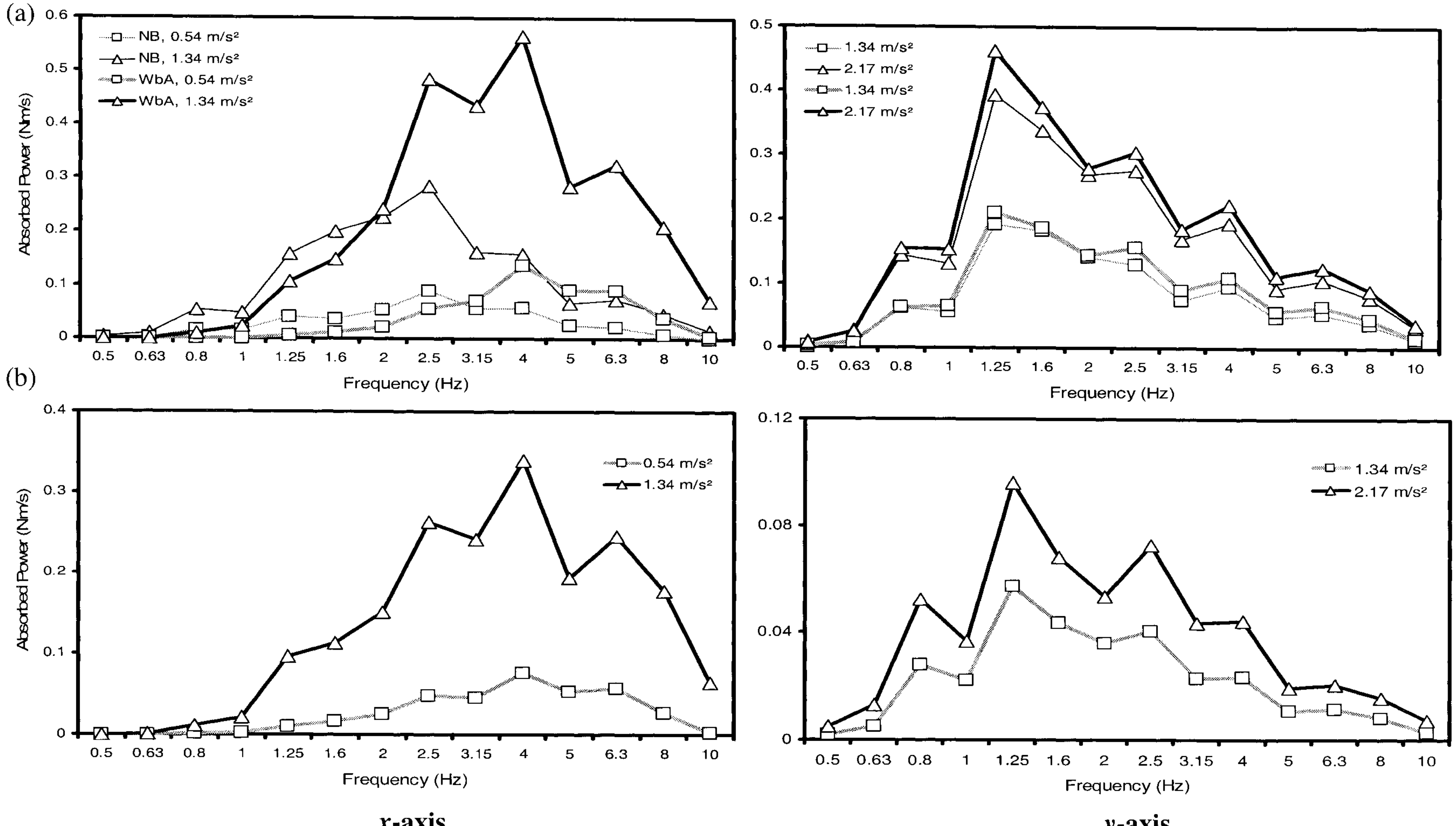


Figure 5.4: Mean seat pan absorbed power responses of the seated occupants exposed to different magnitudes of excitations and back support conditions: a) Seat pan and b) Backrest.

considerable difference in the biodynamic responses, which could possibly be attributed to two important factors. The first factor concerns with the human perception or anticipation of the motion, while the second factor is concerned with the intensity of different spectral components to each spectral component, while harmonic vibration synthesised in this study yield varying vibration intensity with frequency. In order to limit the exposure intensity, the sinusoidal waveform was synthesized to produce a constant displacement harmonic motion in the 0.5-1.0 Hz, range and constant acceleration in the 1-10 Hz range as discussed in section 2.2. The resulting vibration spectrum would thus yield different amount of energy in different frequency bands. Prior to comparing biodynamic responses as a function of type of excitation, it would be reasonable to examine the relative magnitudes of harmonic and random excitations in the third-octave frequency bands. The rms acceleration spectra of the harmonic and random excitations used in this study are shown in the Figure 5.5 corresponding to third-octave frequency bands. The overall rms accelerations due to the harmonic and random excitations shown in the figure are 0.54 and 0.5 m/s^2, respectively. It is evident that the harmonic excitation causes considerably larger energy that the random excitation at frequencies above 1 Hz, even though the over all magnitudes are quite comparable. The accelerations due to sinusoidal motion at lower frequencies, however, are lower. Owing to the strong effect of excitation magnitude on the human response to horizontal vibration, the differences in magnitudes of sine and random acceleration excitations are expected to yield considerable difference in the biodynamic responses.

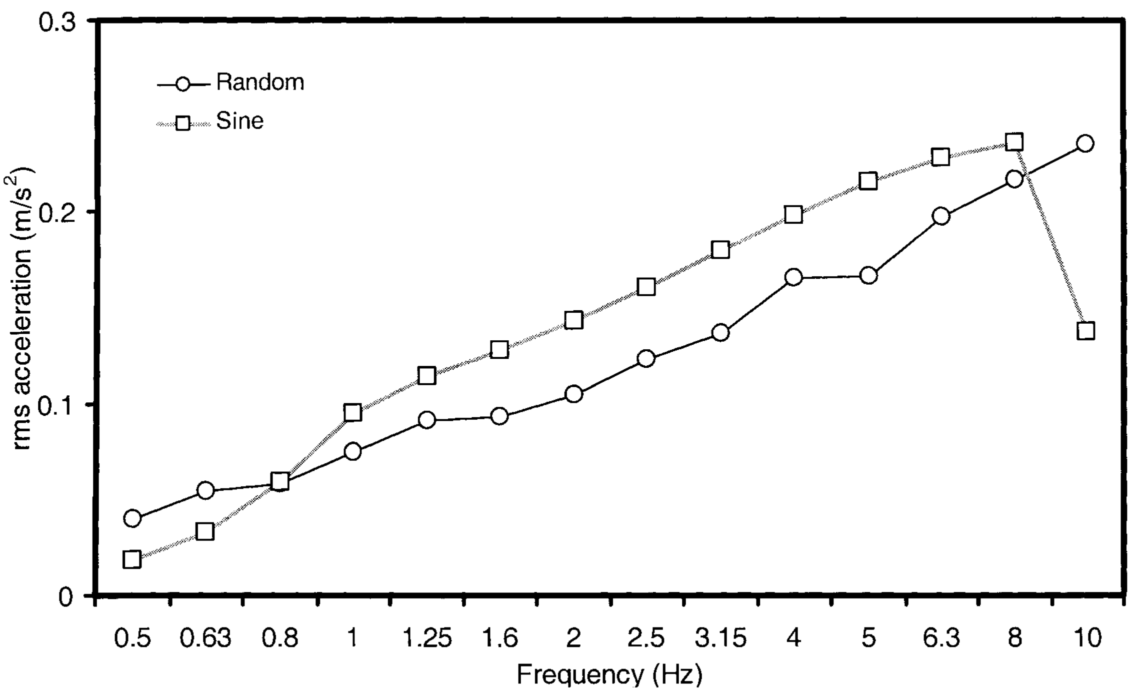


Figure 5.5: Comparison of acceleration spectra of the: harmonic and random excitations in the 1/3 octave band frequencies.

5.4.1 Comparison of APMS responses

Figure 5.6 illustrates comparisons of the mean seat pan APMS responses of the seated occupants exposed to both harmonic and random fore-aft excitations of comparable magnitudes of 0.54 and 0.5 m/s^2 rms, respectively. The comparisons reveal similar trends in the magnitudes as well as phase responses, while considerable differences could also be observed in the peak responses, particularly for NB posture. The APMS magnitude response of the seated occupants exposed to harmonic excitations reveal distinct secondary resonant peak around 2.13 Hz for the NB posture, which is not clearly evident from the response under random excitation. The human occupant tends to stiffen his body to minimise the rotational movement of the upper body, which is believed to contribute to higher peak magnitude. This is most likely attributed to higher perception of the human body of the harmonic excitation in the lower frequency bands, where the magnitude of displacement tends to be high. The APMS phase response under harmonic excitations in the lower frequency range is also lower than that observed under random excitations, which further suggests the stiffening of the body. The phase response at frequencies above 2 Hz tends to be greater for the harmonic excitation, which can be related to relatively lower displacement amplitude due to the excitation. The magnitude response to harmonic excitations at frequencies above 2.5 Hz tends to be lower than the corresponding random response. This may be attributed to relatively higher magnitudes of harmonic excitation in this frequency range. This trend of lower APMS magnitude under higher excitation has been observed in the responses presented in chapters 3 and 4. The mean APMS responses of the seated occupants with WbA posture under harmonic excitations reveal the peak magnitudes in 2.5-3 Hz range and near 4.2 Hz, while the response to random vibration exhibits a dominant peak magnitude near 3.3 Hz. This in part may be attributed to enhanced perception of the harmonic motion and high variability in the back support contact of the upper body. The phase response under random excitation tends to slightly lower when compared to that under harmonic excitations at frequencies above 1.6 Hz.

Figure 5.7 compares the mean backrest APMS responses attained under comparable magnitudes of harmonic and random excitations. The mean backrest APMS responses of the seated occupants exposed to harmonic and random excitations exhibits similar trends, while the frequencies corresponding to the peak magnitudes differ as observed in the seat pan responses. The APMS responses under harmonic and random excitations reveal peak magnitudes at 2.13 and 4.2 Hz, and near 1 and 3.3 Hz,

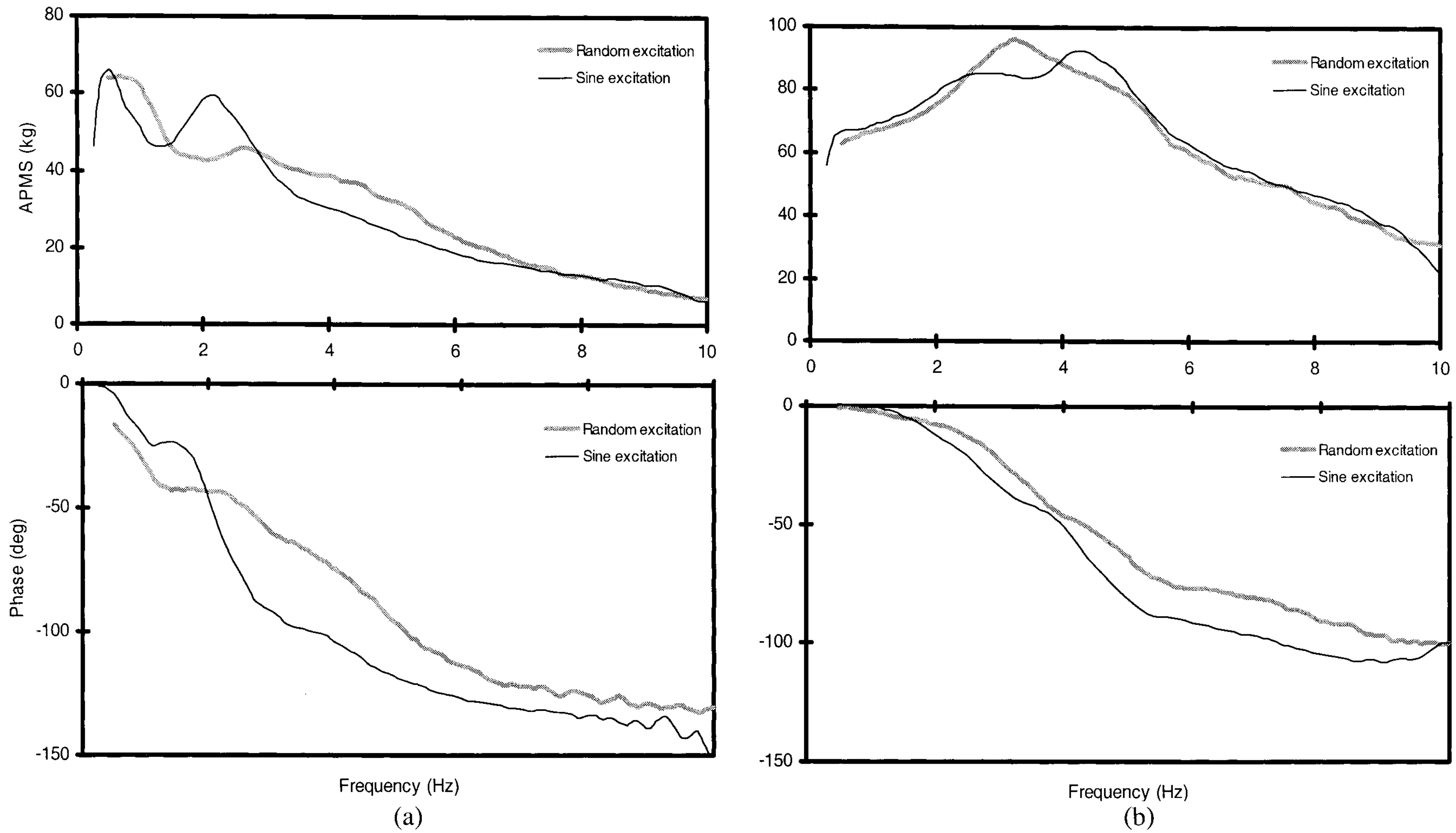


Figure 5.6: Effect of type of excitation on the mean Seat pan APMS and phase responses of the seated human subjects exposed to fore-and-aft and lateral vibrations. (a) No-back posture; (b) Inclined back supported posture.

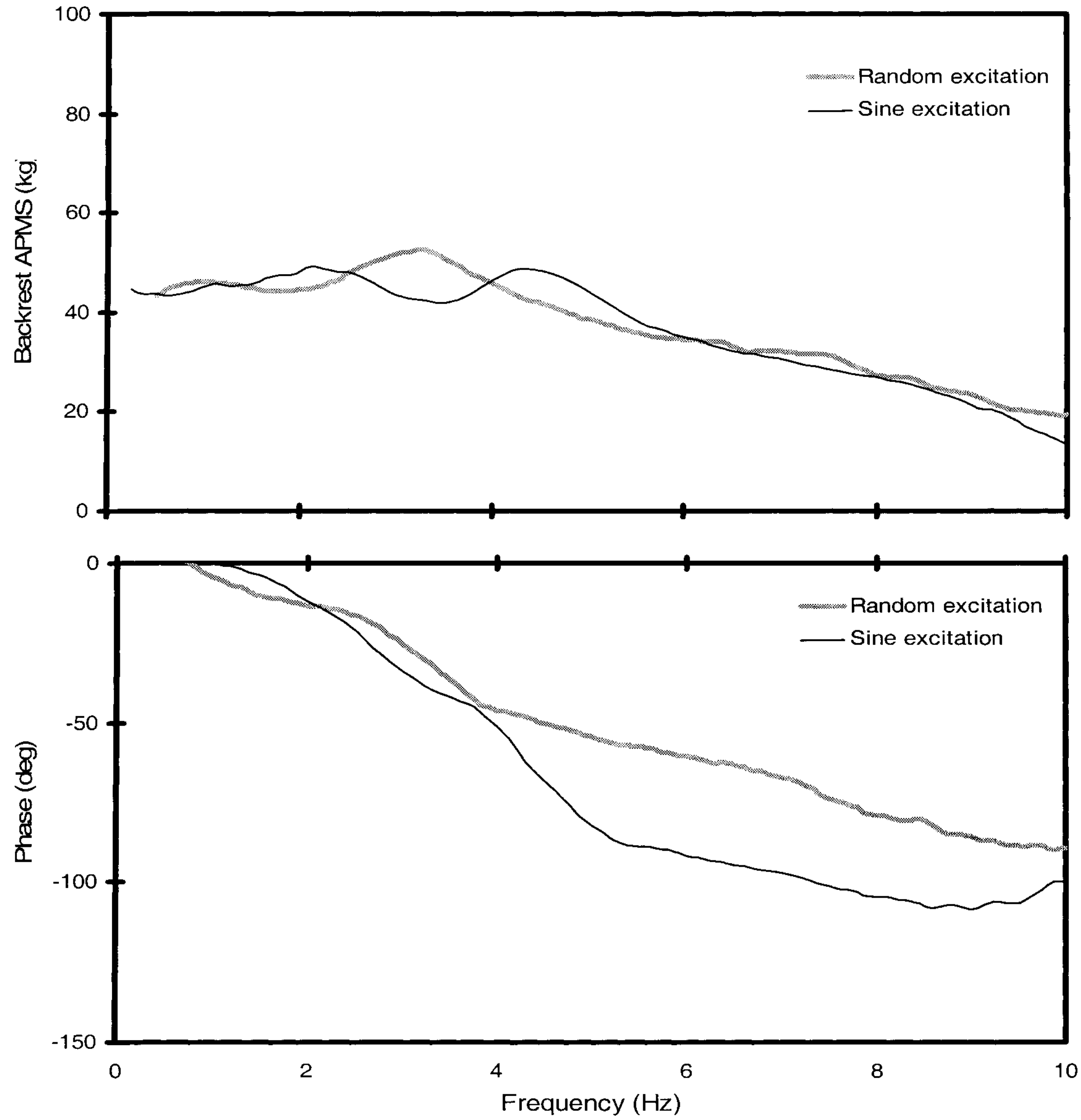


Figure 5.7: Effect of type of excitation on backrest APMS and phase responses of seated human exposed to fore-and-aft.

respectively. Similar to the phase response trends derived from the seat pan response, the backrest phase response under sine excitations tends to higher phase at frequencies above 2.13 Hz. Furthermore, the APMS and absorbed power responses of the seated human occupant under harmonic excitations show better correlations with body mass when compared to those attained for random excitations, as shown in Table 5.1.

5.4.2 Comparison of absorbed power

The occupant seated with NB and WbA postures and exposed to harmonic excitation exhibit considerably higher values of absorbed power at the seat pan in the frequency bands centered above 1.25 Hz. The higher values of absorbed power in the 2.5 Hz band for NB posture and harmonic excitation is attributed to the stiffening of the upper body and observed APMS magnitude peak near 2.13 Hz (Figure 5.6). The higher absorbed power under harmonic excitation in part is also attributed to its slightly higher magnitude at frequencies above 2 Hz, as shown in the Figure 5.8. The corresponding power at frequency below 1.25 Hz tends to be relatively lower due to the lower excitation magnitude at lower frequencies. The WbA posture also yields higher power absorption under harmonic excitation in the frequency bands ranging from 1.25 Hz to 6.3 Hz, which is attributed to slightly higher magnitude of excitation and vibrations in the contact between the upper body and the backrest, as observed for the APMS magnitude. The absorbed power characteristics derived from the backrest data show slightly higher values for the harmonic response, similar to the trends absorbed in the backrest APMS magnitude response.

5.5 Summary

The comparisons of biodynamic responses of the human occupant seated with NB posture and exposed to harmonic and random excitations along the fore-and-aft axis reveal comparable primary peak magnitudes in both the APMS magnitude and absorbed power. The exposure to harmonic excitation, however, causes a secondary peak in both the APMS and the absorbed power. This is mostly attributed to relatively higher perception of the harmonic vibration and stiffening tendencies of the occupant.

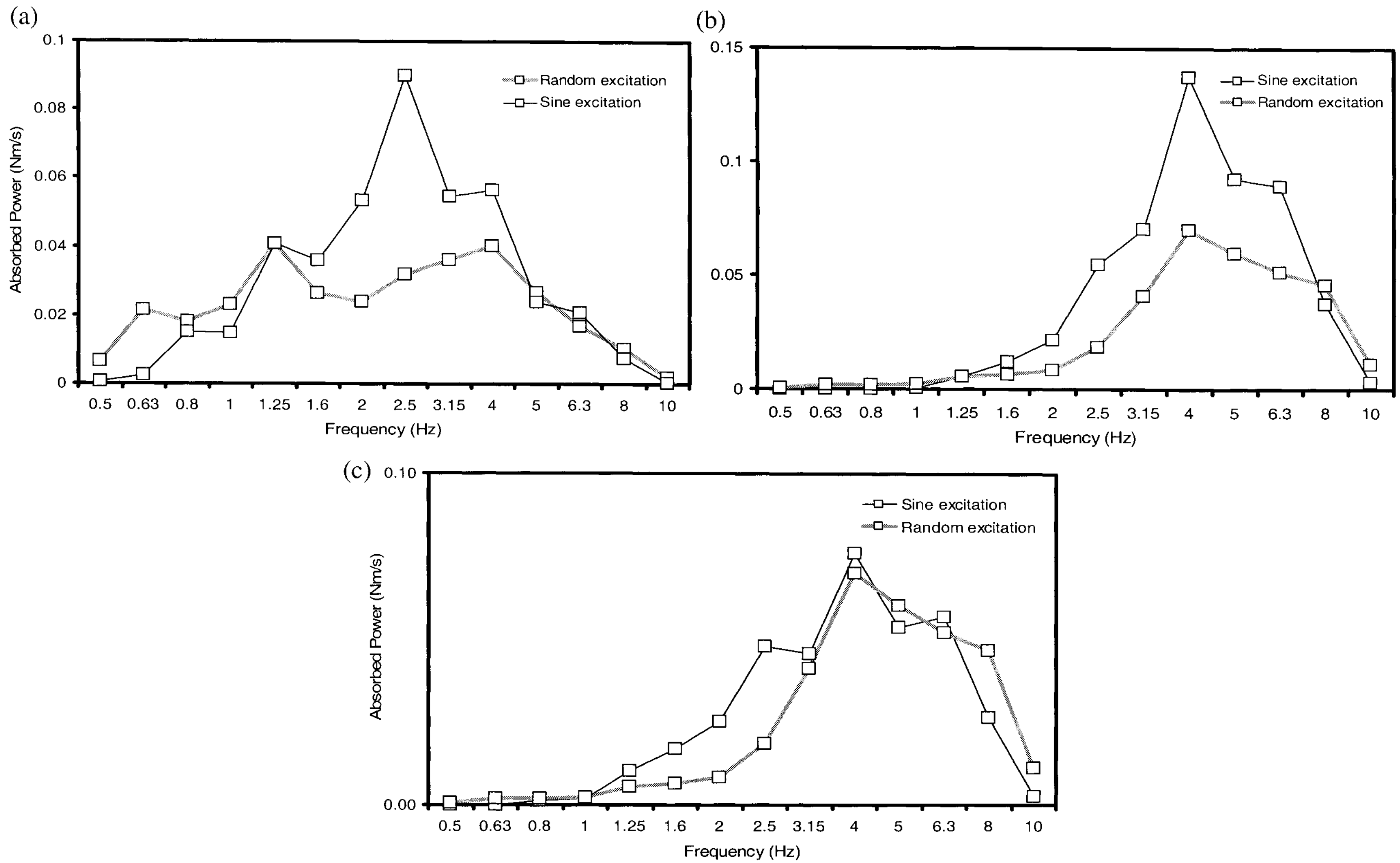


Figure 5.8: Effect of type of excitation on absorbed power responses of seated human exposed to fore-and-aft and lateral vibrations. (a) Seat pan -NB posture; (b) Seat pan -WbA posture and (c) Backrest absorbed power.

The harmonic and random responses of the occupant seated with a WbA posture under fore-aft motions, measured at the seat pan and backrest-interfaces, also revealed considerable differences in the peak APMS magnitude, resonant frequencies and the APMS phase. The observed divergence in the seated occupant's response owing to change in the type of excitation could be explained as an effect of different distribution of energies, minor differences in the magnitude of excitations, and the human perception to the change in the type of excitation.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS FOR FURTURE WORK

6.1 General

The magnitudes of vibration encountered in vehicles are generally believed to cause detrimental effects in view of driver's health and safety. Seated human occupants' responses to whole-body vertical vibration have been widely investigated in terms of force-motion relationships at the body-seat pan driving-point. The characterization of the responses of the seated occupant and the biodynamic forces under exposure to vibration could yield significant knowledge and insight into assessment of exposure and means to diminish the injurious effects related to the exposure. The majority of these studies focus on response analyses of seated body exposed to vertical vibration, while the nature of horizontal vibration transmitted along the horizontal-axes is also known to be quite severe, particularly for many off-road vehicles. Only a few studies have investigated the force-motion relationships under vibration along the longitudinal and lateral directions. The relatively low flexibility of tires of off-road vehicles coupled with high location of the operator, and presence of localized slopes and cross-slopes in the terrain, contribute to considerable motions at the operators' location along the x- and y-axes. The backrest is anticipated to contribute considerably to the seated occupants' response particularly under fore-and-aft vibration. The assessments, however, must take into consideration the contributions due to seat design and resulting postures, which could form the sources of extreme variations. This study concerns with characterization of biodynamic responses of seated occupants to horizontal vibration under varying postural and excitation conditions.

The major contributions and conclusions drawn from the study are summarized in this chapter.

6.2 Major contributions

The human response to horizontal vibration have been derived from force-motion relationships at the two driving-points, body-seat pan and upper body-backrest, and expressed in terms of apparent mass (APMS) and absorbed power, under different experimental conditions. Owing to the lack of data available for typical off-road vehicle sitting postures, the study emphasises the postural factors, such as back supported conditions and seat height. The dissertation research thus involved: (i) design of the experiment: synthesis of selected vibration excitations, instrumentation, data acquisition and analyses, and the measurement methodology; (ii) designs of horizontal vibration simulator and a test seat to simulate desired back supported conditions and various seat heights; (iii) computation of the mean values and ranges of the measured biodynamic responses, along with the analysis of the effects of nature of vibration, back support and seat height on the APMS response; (iv) analysis of absorbed vibration energy properties of the seated occupant, and effect of back supported condition, sitting height and nature of vibration; and (v) comparisons of the mean biodynamic responses to harmonic excitation with those obtained under random excitations. Owing to only a few reported works on the seated occupants response to horizontal vibration, particularly under different back supported conditions and seat heights, this dissertation research is expected to represent a major contribution to the subject. The major contributions of the dissertation research are summarised as follows:

- A comprehensive review of reported studies revealed significant magnitudes of horizontal vibration in off-road vehicles, which are comparable to those encountered along the vertical axis. The vast majority of the efforts on seated human responses to vibrations, however, focus on vertical vibration.
- Previous studies on biodynamic responses of seated occupants are thoroughly reviewed to establish the lack of data under horizontal vibration, specifically under typical off-road postures and multiple drive-points.
- An off-road vehicle seat coupled to a horizontal vibrator, operating under feasible and repeatable conditions, as well as capable of synthesising representative off-road vehicular vibration, including instrumentation and design signals, has been developed and used to conduct the desired experiments.
- Statistical analyses of the measured data were performed to identify significant contributing factors to the biodynamic responses.
- The apparent mass (APMS) responses of seated occupants are characterised in relation to several factors, which include anthropometric features, different back support conditions, seat heights, and nature of vibration (excitation type, magnitude and direction). The role of back supported postures, particularly under fore-and-aft revealed strong influence on the seated occupants' response. The measurements were taken at multiple points (seat pan and backrest), the anticipated sources of vibration transmitted to the seated occupant, which has not been addressed in the reported studies. Data analyses were performed to emphasis and quantify the effect of contributing factors on APMS data obtained at both the seat pan and the backrest.

- The vibration energy absorption properties of the seated occupants exposed to horizontal vibration are investigated, and the effects of anthropometric features, different back supported conditions, seat heights, and nature of vibration (excitation type, magnitude and direction) are illustrated and additionally corroborated by statistical data analysis. The results obtained are considered to form major contribution, since only two studies have reported absorbed power of seated occupants to horizontal vibration, assuming postures that are not representative of the automotive environment.
- The APMS and absorbed power responses of seated occupants under horizontal -harmonic and -random excitations are investigated systematically, and the observed differences are explained. The results are considered to chiefly portray the complexity of the seated occupant system; only one such study has been reported under vertical vibration.

6.3 Conclusions

This dissertation has provided the essential data on the seated occupant's response to horizontal vibrations in 0.5-10 Hz frequency range, in terms of apparent mass and absorbed power, which is expected to append to the available data under more realistic off-road vehicle simulation in experiments, such as the seat design factors, with different back supported conditions and seat heights. The major conclusions and observations obtained in the study are summarized below:

- From the review of reported studies on ride vibration environment of different vehicles, it is concluded that the magnitudes of low frequency horizontal vibration are comparable to those along the vertical axis, and may exceed the levels of vertical vibration for some off-road vehicles.

- From the review of studies on biodynamic characteristics of seated occupants exposed to horizontal vibration, it is concluded that the reported data is not applicable for typical vehicle seating postures, and lacks consideration of multiple driving-points, inclined back support, seat height variations and anthropometry.
- APMS measurements in this study revealed considerable inter-subject variability, which could be attributed to differences in anthropometric factors, involuntary movements of subjects to realise a more stable posture. The biodynamic data obtained at backrest reveal higher values of CoV compared to that at seat pan, which was attributed to the intermittent loss of contact or sliding at the upper-body and backrest interface.
- Unlike the widely reported responses of seated occupants under vertical vibration, the responses to horizontal vibration show strong effect of excitation magnitude. Higher excitation magnitudes yield considerably lower peak magnitudes of the seat pan APMS and the corresponding frequencies, irrespective of the posture and the direction of motion.
- The dynamic response characteristics of seated human subjects exposed to fore-aft (x-axis) and lateral (y-axis) vibration show considerable dynamic interactions between the upper body and the seat backrest, apart from those of the body-seat pan.
- The APMS and absorbed power responses measured at the seat pan and the backrest clearly show strong influences of the back support condition.

- Significance of inclination of the backrest under fore-and-aft excitations is illustrated by both the absorbed power and the APMS data obtained under all conditions considered in this study, at both the seat pan and the backrest, irrespective of type and direction of excitation.
- The seat pan APMS magnitude responses of occupants seated with NB posture dominate around the low frequency of 0.7 Hz, associated with the rocking and swaying motions of the upper body under fore-aft and lateral vibration, respectively.
- The addition of back support causes the seat pan APMS response to converge mostly to a single primary peak, resulting in a single-degree-of-freedom like behaviour, with peak occurring in the 2.7-5.4 and 0.9-2.1 Hz ranges under *x*- and *y*-axis motions, respectively.
- The peak seat pan APMS magnitude occurs in the 3.3-5.4 Hz range with occupants seated against a vertical backrest posture, depending upon the fore-and-aft excitation magnitude. The relaxed posture against inclined back support posture causes some softening of the body, resulting in peak magnitude response in the 2.7-4.1 Hz range.
- Under lateral vibration, the back support offers limited resistance against the body sway to help stabilize the sitting posture. The back-supported postures thus yield relatively higher frequency of the primary peak in the seat pan APMS response, when compared to that of the unsupported posture.
- A higher seat with NB posture generally encouraged the subjects to shift more weight towards the feet in an attempt to stabilize their posture. A lower seat

height provided a more stable posture, and the resulting stiffening effect caused the fundamental frequency and the magnitude to increase slightly. The peak magnitude response with back supported postures, however, decrease with the decrease in the seat height. However, these effects were evident only under lower magnitudes of excitation; under higher magnitudes the effects were relatively small.

- Absorbed power analyses revealed definite relationship between acceleration stimuli, body mass and biodynamic responses, respectively, with relatively high correlation. The absorbed power may thus serve as a better assessment method.
- Absorbed power spectra of seated occupant with back unsupported posture under *x*- axis excitations, revealed peak values in the 0.6, 1.25 and 4 Hz bands, irrespective of the magnitude of vibration.
- The majority of the power absorption in an unsupported back posture could be attributed to the motion of the upper body. The results further revealed that about 50% of the total absorbed power appears in the lower frequency range of 0.5-2.19 Hz.
- The back support posture resulted in peak absorbed power in a considerably higher frequency, the 4 Hz band, under fore-aft excitations.
- Absorbed power of seated occupant exposed to horizontal vibration increased significantly with the magnitude of transmitted vibration. The regression analyses suggest an approximately quadratic relation between the absorbed power and the acceleration magnitude.

- Irrespective of the axis of excitation, small effect of seat height was noticed on the absorbed power response with back unsupported posture compared to that with supported back postures. Very little or no effect of seat height was observed in the absorbed power responses with inclined back support posture, measured at the seat pan, compared to that with the vertical back posture.
- The mean APMS responses of the seated occupants with an inclined back posture under fore-aft harmonic excitations revealed the peak magnitudes in 2.5-3 Hz range and near 4.2 Hz, while the response to random vibration exhibits a dominant peak magnitude near 3.3 Hz.
- The responses of seated occupant with back unsupported posture, under to harmonic fore-and-aft excitation reveal an additional secondary peak in both the APMS and the absorbed power responses around 2.13 Hz. The harmonic and random responses of the occupant seated with an inclined back posture under fore-aft motions, measured at the seat pan and backrest-interfaces, also revealed considerable differences in the peak APMS magnitude, resonant frequencies and the APMS phase. These differences are attributed to higher perception of the subject of the harmonic excitations.

6.4 Recommendations for furture work

Owing to the complexities associated with the seated human system, the present study is believed to constitute a preliminary step to quantify the human response horizontal vibrations under typical off-road vehicle seating postures. Substantial, further efforts need to be under taken done to obtain reliable data in terms of both the APMS and absorbed power of seated occupant exposed to horizontal vibrations. The current study constitutes many limitations, which are put forward as the recommendations for further work as follows:

- Number of subjects: Current study considered only 8 subjects, it is recommended to consider a larger sample of subjects to enhance characterisation of biodynamic responses. This would be important considering the large inter-subject variability of the data, and strong dependence of the responses on the body mass.
- Normalisation factor: Current study has considered normalisation factor as 87.8% of the total body mass, which was judged to be in adequate for the data acquired for some of individuals, particularly under back unsupported posture. A more thorough study of the anthropometric data together with measurements at lower frequencies in the data of 0.25 Hz is thus recommended.
- Posture: The present study suggests strong contributions due to inclination of the backrest. It is recommended that the role of backrest under different inclinations of the backrest and pan be considered. The response analyses for the hands on the steering wheel posture are further recommended to attain data for typical driver postures.
- Biodynamic function: Further studies in characterising biodynamic responses in terms of absorbed power are suggested, since could effectively account for exposure in view of both critical measures, the vibration magnitude and exposure duration. Absorbed power data analyses revealed definite relationship between the acceleration stimuli, body mass and biodynamic responses, respectively, with considerably higher correlation. The absorbed power may serve thus as a better assessment method.

- Multi directional stimuli: Uncoupled excitations considered in this study do not represent the realistic occupational vibration environment, although the results are vital to enhance the response characteristics. Thus further studies are desirable under multi directional excitations. The simultaneous exposure to fore-aft and lateral vibration can be easily realised using the current simulator, by installing the seat at certain angle to the axis of vibration.
- Multi-axis and multi-interface measurements: The biodynamic measurements at different body segments is encouraged to understand precise limbs involved in resonant behaviour. The multi axis measurements at the body- seat interface are encouraged to enhance the understanding.
- EMG: The human exposed to vibration comprises diverse psychological and physiological reactions. The behaviour of human response in this study has been referred to voluntary or involuntary actions, particularly at the muscle level. To ascertain such anticipation, it is encouraged to measure the muscle-activity under vibration environment. Heart rate, muscle fatigue and other vital measures could also be performed to understand other complex reactions.
- Angular motion: Measurement of angular motion of the seated occupants is encouraged to further understand the dynamics of the system.
- Modelling: Biodynamic models satisfying the apparent mass response of the seated occupant at both the seat pan and the seat backrest along horizontal axes are required to analyse seated body system with respect to various contributing factors.

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