

DEVELOPMENT OF BIODYNAMIC MODELS FOR A SEATED HUMAN BODY SUBJECTED TO HARMONIC VIBRATIONS

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of the requirement for the award of the degree of

DOCTOR OF PHILOSOPHY

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CERTIFICATE

I, Ishbir Singh hereby certify that the work presented in this thesis report entitled **“DEVELOPMENT OF BIODYNAMIC MODELS FOR A SEATED HUMAN BODY SUBJECTED TO HARMONIC VIBRATIONS”** in fulfillment of requirement for the award of the degree of **Doctor of Philosophy** submitted in Mechanical Engineering Department, Thapar University, Patiala is an authentic record of my own work carried out under the supervision of **Dr. S.P. Nigam** (Visiting Professor, Mechanical Engineering Department, Thapar University, Patiala) and **Dr. V.H. Saran** (Associate Professor, Mechanical and Industrial Engineering Department, IIT Roorkee, Roorkee) from July 2009 to July 2016. The matter presented in this thesis has not been submitted either in part or full to any other University or Institute for the award of any other degree.



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ABSTRACT

Humans are most sensitive to Whole Body Vibrations (WBV) under low-frequency excitation. As a result, biodynamic responses of seated human subjects when exposed to vibrations have been a topic of interest over the years. Knowledge of the biodynamic responses is required for designing, analysis and testing of transport vehicles with an aim to improve passenger and driver comfort.

In the present research work biodynamic models based on anthropometric data of Indian male subjects have been obtained. For this study, seated human subjects in different postures: without backrest and with backrest (inclined at 0° , 15° and 30° to the vertical) for rigid as well as cushioned seats have been considered. STHT values have been evaluated and the effect of different vibration magnitudes and excitation frequencies on it has been obtained.

Experimental investigations have been conducted on twelve subjects for all the above cases and mean STHT values were determined. Validation of analytically obtained STHT values and experimentally determined ones has been attempted.

In order to assess the transmission of vibrations through different human body segments, common subjective response studies were also conducted on human subjects for all the cases mentioned above and their common responses were obtained and discussed.

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NOMENCLATURE

a_i	Semi-axes of the ellipsoid along X-axis
$a_{head}(f)$	Acceleration at head measured in vertical direction
$a_{seat}(f)$	Acceleration at seat measured in vertical direction
A	Arms, Cross-sectional area
Ab	Abdomen
AM	Apparent mass
b_i	Semi-axes of the ellipsoid along Y-axis
B	Back
BMI	Body mass index
c_i	Original length
c_i	Semi-axes of the ellipsoid along Z-axis
C	Chest
C_{eq}	Equivalent damping coefficient/constant
C_{iv}	Damping coefficient of vertical dashpot connected to i^{th} mass
C_{ih}	Damping coefficient of horizontal dashpot connected to i^{th} mass
$C_{21}, C_{32}, C_{42},$ C_{43h}, C_{43v}, C_{54}	Damping coefficient of dashpots connecting various body segments
C_i	Damping coefficient of i^{th} segment
C_{eq}	Equivalent damping coefficient/constant
C_{BC}	Damping coefficient of back cushion
C_{SC}	Damping coefficient of seat cushion
CT	Central Torso
d_i	Truncated length
D_1, D_2	Cushion density
DOF	Degree of freedom
DPMI	Driving point mechanical impedance
E	Elastic modulus of ellipsoidal segments
E_b	Elastic modulus of bones
EOM	Equations of motion
E_t	Elastic modulus of tissues
F	Frequency
F	Feet
H	Head

Hp	Hips
HP	Head Pivot
I_i	Integral factor
K	Stiffness of connecting spring
K_{1v}	Stiffness of vertical and horizontal springs connected to m_1
K_{1h}	Stiffness of horizontal springs connected to m_1
$K_{21}, K_{32}, K_{42},$ K_{43h}, K_{43v}, K_{54}	Stiffness of springs connecting various body segments
K_{2v}, K_{2h}	Stiffness of vertical and horizontal springs connected to m_2
K_{eq}	Equivalent stiffness of K_{2v} and K_{sc}
K_{sc}	Stiffness of seat cushion
K_{BC}	Stiffness of back cushion
L_i	Anthropometric dimensions of Indian male in sitting posture
LA	Lower Arm, Left Ankle
LBP	lower back pain
LF	Left Foot
LH	Left Hip
LK	Left Knee
LL	Lower Leg
LPM	Lumped parameter model
LS	Left Shoulder
LUA	Left Upper Arm
LUL	Left Upper Leg
m_1	Lower legs and feet
m_2	Lower torso and upper legs
m_3	Central torso
m_4	Upper torso (including both arms and hands)
m/s^2	Meter per second square
m_{BC}	Mass of back cushion
m_s	Mass of springs connecting human body segments
m_{eq}	Equivalent mass
m_{sc}	Mass of seat cushion
M_i	Mass of ellipsoidal body segments

N	Neck
NP	Neck Pivot
P	Pelvis
Rms	Root mean square
RA	Right Ankle
RE	Right Elbow
RF	Right Foot
RH	Right Hip
RK	Right Knee
RLA	Right Lower Arm
RLL	Right Lower Leg
RS	Right Shoulder
RUA	Right Upper Arm
RUL	Right Upper Leg
S_i	Stiffness of individual (i^{th}) body segment
S_{ih}	Horizontal stiffness
S_{iv}	Vertical stiffness of human body segments
STHT	Seat to Head Transmissibility
t_r^i	Truncation factor
UA	Upper Arm
UL	Upper Leg
UT	Upper Torso
W	Waist
WBV	Whole body vibration
*	Moderate to severe vibrations experienced
H	Loss coefficient
ξ	Damping ratio
ξ_i	Damping ratio
A	Inclined backrest angle

CHAPTER 1

INTRODUCTION

Vibrations provoke sensations and responses varying from pleasure or displeasure, to interference with activities, injury, and disease. Human responses to vibration may be predicted if the vibration is measured, evaluated, and assessed using understanding derived from studies of human response to vibrations. Understanding comes from laboratory experimental exposures, from tests in real environments, from vibration exposures at work and during leisure, and from analytical studies (Griffin 2007).

1.1 Human body vibration

Humankind has always had the desire to build, create, and explore. Each of these activities has involved exposure to vibration, whether the source comes from handsaws or riding in carts, from using power tools, industrial machines, or riding in planes, trains, and automobiles. As modern man has harnessed power sources in more efficient ways, the apparatus used to build, create, and explore have used more energy and as a result, increased quantities of energy have been dissipated in the form of vibration, some of which has been transmitted to people (Mansfield 2005). Human body vibrations can be classified into two major categories:

1. Whole Body Vibration (WBV)
2. Hand Arm Vibration (HAV)

1.2 Whole body vibration

Whole body vibration (WBV) occurs when the body is supported on the surface which is vibrating. Local vibration occurs when one or more limbs (or the head) are in contact with a vibrating surface. Both whole body and local vibration can cause vibration throughout the body (Griffin 1990). Seated persons exposed to whole body vibration are also often simultaneously exposed to local vibration of the head (e.g. from a head-rest), the hands (e.g. on a steering wheel), and the feet (e.g. on the floor). Vibration may also enter the body as a result of contact with the backrest of a seat.

1.2.1 Factors affecting WBV

There are number of factors on which whole body vibration depends. Some of them are listed below:

1. Posture:
 - i. Seated
 - ii. Standing
 - iii. Recumbent Position
2. Vibration Axis:
 - i. Translational Vibrations:
 - a. x-axis (Fore-and-aft in spine)
 - b. y-axis (Lateral in Shoulder-to-shoulder)
 - c. z-axis (Foot to head)
 - ii. Rotational Vibrations:
 - a. Rotation about x-axis (Roll)
 - b. Rotation about y-axis (Pitch)
 - c. Rotation about z-axis (Yaw)
3. Frequency of Whole Body Vibrations
4. Amplitudes of Whole Body Vibrations
5. Duration of Whole Body Vibration Exposures
6. Confounding Factors

Figure1.1 illustrates the axes of vibration used to measure and evaluate exposures to whole body vibration.

1.2.2 Effects of WBV

Human response to whole body vibration has five separate effects:

1. Impaired health
2. Degraded comfort
3. Interference with activities
4. The occurrence of motion sickness and
5. Perception of low magnitude vibration.

These consequences of vibration exposure are not simple: the perception of motion, the sensations it produces and the interference with health and activities are all complex phenomena (Griffin 1990).

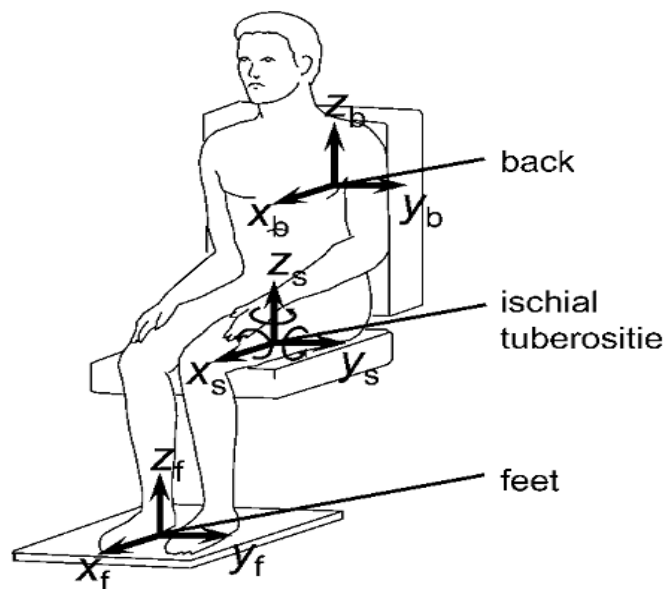


Figure 1.1 Axes of vibration used to measure and evaluate exposures to whole body vibration (Griffin 1990)

1.3 Hand arm vibration

The term hand arm vibration (HAV) is frequently used to refer vibration from power tools, but it does not clearly indicate whether the hand and arm are the origins of the vibration or the limits of its effects. The expression ‘local vibration’ suggests that the effects are localised near to the point of contact with a source of vibration. While some effects can, by definition, only occur in the fingers or hand, the vibration is transmitted into the body and the effect it produces may be of interest.

The principal causes of severe HAV are the tools and processes in industry, agriculture, mining and construction where the hands and fingers grasp or push vibrating objects. Figure 1.2 illustrates the axes of vibration used to measure and evaluate exposures to hand-arm vibration.

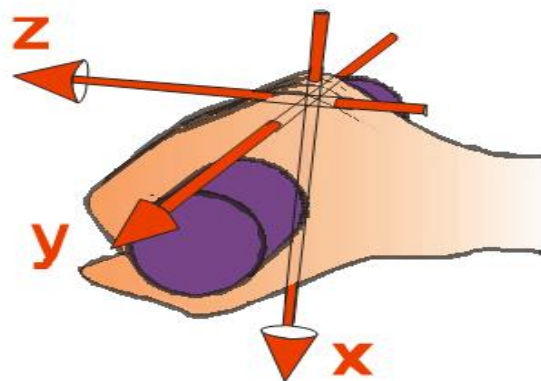


Figure 1.2 Axes of vibration used to measure and evaluate exposures to hand arm vibration (Griffin 1990)

1.3.1 Factors affecting HAV

There are number of factors on which HAV depends. Some of them are listed below:

1. Vibration Axis
2. Vibration Duration
3. Vibration Frequency
4. Vibration Magnitude
5. Confounding Factors

1.3.2 Effects of HAV

A wide range of disorders could occur as a result of vibration exposure. Effect of HAV on human body can be of five types:

1. Vascular disorders
2. Bone and joint disorders
3. Neurological disorders
4. Muscle disorders
5. Other disorders

1.4 Biodynamics

The human body is a complex mechanical system that does not, in general, respond to vibration in the same manner as a rigid mass. There are relative motions between the body parts that vary with the frequency and the direction of the applied vibration. The dynamics of the body affect all human responses to vibration. However, the discomfort, the interference with activities, and the health effects of vibration cannot be predicted solely by considering the body as a mechanical system.

1.4.1 Biodynamic modelling

Some investigators of human response to vibration adopt the philosophy that the ultimate objective is the definition of an engineering model of the response of the body. In an age, when robots are being in the image of man it is perhaps natural to attempt to represent the responses of the body by masses, dampers and springs. For the prediction of the movements and forces in the body this approach is challenging because of the complex structure of the body, the need to model non-linearities in the system, the influence of the active voluntary and involuntary muscular control over body posture and the difficulty of

obtaining empirical data needed for the parameters in the models. Some of the large differences between and within subjects might be modelled but, again, the mechanisms of their actions are not yet fully understood. It would therefore, be understood not to expect comprehensive models of the dynamic response of the body from the meagre data currently available.

The prediction of forces and movements in the body is only the first step towards predicting the effects of vibration on comfort, performance or health. For example, the discomfort produced by vibration may originate in all areas of the body from feet to the head. A very small amount of movement causes considerable discomfort at some locations on the body while a lot of movement at other locations is variously pleasant or unpleasant.

At each location the transduction from movement to sensation is complex; it may involve time-dependent effects, the summation over body areas and ‘masking’ phenomena (Griffin 1990). A mechanical analogue with masses, dampers and springs would seem to be the optimum approach to modelling such phenomena.

1.4.2 Importance of biodynamics and mathematical models

Humans are most sensitive to whole body vibration under low-frequency excitation in seated posture. As a result, biodynamics of seated human subjects has been a topic of interest over the years, and a number of mathematical models have been established. Most of the existing mathematical models are based on the results obtained from the experimental investigations. When using such models it should not be forgotten that the model is only a representation of reality and errors have been introduced in approximating the model to limited experimental data.

Biodynamics of the human system is one of the important foundations for understanding mechanisms of whole body vibration induced disorders and for developing better standards for assessing risk of vibration exposure. Knowledge of the biodynamic responses is also required for designing and assessing vibration isolation methods and developing whole body vibration simulators for analysis and testing of vehicles in automotive industry.

1.4.3 Applications of biodynamic modelling

Biodynamic modelling has a wide range of applications. Some of the important applications are:

1. To predict movement or forces caused by situations too hazardous for an experimental determination.
2. To predict movement or forces caused by situations too numerous and varied for experimental determination.
3. To understand the nature of body movements.
4. To provide information necessary for the optimisation of isolation systems and the dynamics of other systems coupled to the body.
5. To determine standard impedance conditions for the vibration testing of systems used by man.
6. To provide a convenient method of summarizing average experimental biodynamic data.
7. To predict the influence of variables affecting biodynamic response.
8. Mathematical models of the human body have been used for estimating and predicting human vibration response and may be useful tools for optimizing civilian and military vehicle seated system designs for vibration mitigation.

1.4.4 Complications in biodynamic modelling

The human body has a complex non-linear dynamic response which varies greatly between and within individuals. Some of the complications encountered while developing biodynamic models are:

1. Although, there are some data showing the transmission of vibration to the body (point mechanical impedance) and transmission of vibration through the body (transmissibility), the complexity of the phenomena and factors which influence the vibration in the body are not well understood.
2. Curves showing the dynamic responses of the body are mere shadows of the true responses; biodynamic models have been formed from the superposition of a few such shadows.
3. Most studies of the transmissibility of the body have concerned the transmission of vertical vibration from a seat to head. It has been shown that the magnitudes of

translational head vibration vary with position on the head: vertical head vibration may increase or decrease from front to back while for-and-aft vibration increases from bottom to the top of the head.

4. There are large variations in transmissibility between subjects: change in back posture and head orientation can result in very considerable alterations in the translational and rotational motions of the head. A useful value for the transmissibility of the body cannot be specified without specifying the body posture and seated conditions.

1.5 Human response to vibration

Exposure to certain vibration frequencies may have profound effects on specific parts and systems of the body, particularly if the frequency of vibration corresponds to the resonant frequency of that body part or system. In such cases, vibration in that area is likely to be amplified and therefore may have more pronounced effects on that area as compared to other parts of the body.

The magnitude of vibration is usually expressed in terms of acceleration, velocity and displacement. The International Organization for Standardization (ISO) has provided the following guide lines relating the magnitude to comfort for passengers on public transport as tabulated in table 1.1.

Table 1.1 ISO guidelines on magnitude and comfort relation

S. No.	Magnitude of vibration (m/s^2)	Comfort level
1.	<0.315	Not uncomfortable
2.	0.315-0.63	Little uncomfortable
3.	0.5-1	Fairly uncomfortable
4.	0.8-1.6	Uncomfortable
5.	1.25-2.5	Very uncomfortable
6.	>2	Extremely uncomfortable

Passengers' perception of comfort would also depend on the expectations (e.g., the activities they would expect to accomplish), as well as other characteristics of the vibration such as frequency and duration (ISO 2631/1, 1997).

It has been generally accepted that discomfort increases with exposure time, although the exact relationship is not straightforward. Direction of vibration is the most important characteristic and includes three linear translational and rotational axes. Point of entry is a major influence on how vibration is transmitted through the body.

Vibration is complicated enough motion, though, a full understanding of its nature and how it will be transmitted through the human body requires consideration of numerous different types of vibration characteristics (i.e., of varying frequency, direction and magnitude).

1.6 Discomfort due to vibration

The effect of vibration on the human body is presently being widely studied. Vibrations cause a sensation of discomfort, irritation, nausea and other unpleasant phenomena; when applied briefly, pain in the stomach and back, headache, general fatigue, difficulty in breathing, itching, deafness, etc. For study convenience effects of whole body vibration is categorized into four principal parts and considered to be: degraded health, impaired activities, impaired comfort and motion sickness.

1.7 Effects on health

Any part of the body may be injured by exposure to a significant magnitude of vibration. The parts of the body most likely to be injured during exposure to whole-body vibration will depend on the distribution of motion within the body and this will depend on the vibration frequency and axis and the coupling of the body to the vibrating source.

The probabilities and extents of particular health effects from prolonged exposures to whole-body vibration have not been established. There is a shortage of conclusive evidence relating specific injuries to definite causes. Therefore, it is not yet possible to provide a definitive dose-effect relationship between whole-body vibration and injury or health damage.

Bio-dynamic models and knowledge of the physical properties of body tissue may be used to predict injury. Subjective data concerning vibration magnitudes which cause discomfort and pain may give some indication of the possibility of injury for various conditions, although it is recognized that sensations may not necessarily correlate with pathological damage.

1.8 Effect on activities

Vibration of the body may affect the acquisition of information via senses, information processing, levels of arousal (stimulation), motivation or fatigue, intentional actions. Vision is the perceptual mechanism most easily affected by vibration since even small movements of an image on the retina of the eye can degrade visual acuity (insight). There is little evidence that whole-body vibration directly affects cognitive processes. It is

often difficult to separate direct effects from those caused by changes in arousal or motivation.

Arousal, motivation and fatigue are aspects of the behavioural state of an individual and, although they are not readily quantifiable, their effects can be very great. Vibration has been observed both to improve and to reduce task performance. This may be because it fatigues or arouses or, because of increased task difficulty, motivates (Griffin 1990).

Actions performed by a person are often accomplished by speech or movements of hands or feet. Whole-body vibration may cause a modulation of speech but under normal listening conditions this does not degrade intelligibility. Where an activity requires fine movements of the limbs, whole-body vibration can have a large effect on proficiency.

1.9 Effects on Comfort

The complex distribution of oscillatory motion and force within the body during whole-body vibration produces complex sensations. The location and character of the sensations vary greatly according to the vibration frequency, axis and other factors. This effect will be widely assessed using experimental and bio-dynamic response study through the years.

1.10 Whole body vibration standards

Standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines, or definitions of characteristics, to ensure that materials, products, processes, and services are fit for their purpose (Mansfield 2005). The standards and guidelines concerning whole-body vibration are designed to reduce vibration to a level where most workers can perform job tasks without discomfort.

Whole body vibration standards are developed by national, regional, and global committees representing bodies such as the International Organization for standardization, European committee for standardization, and national bodies such as the British standards institution. Standards directly related to the present research work are described in the next sections.

1.10.1 ISO 2631: Evaluation of human response to whole body vibration

The primary purpose of ISO 2631 is to define methods of quantifying whole body vibration relation to

- i. Human health and comfort

- ii. The probability of vibration perception
- iii. The incidence of motion sickness

ISO 2631 includes the guidance on effects of vibration and rotational motion on passenger and crew comfort in fixed-guide way transport systems (ISO 2631-4: 2001). The ISO 2631-1: 1997 gives the methods for measuring periodic, random, and transient whole-body vibration, and annexes providing guidance on the interpretation of the measurements (Mansfield 2005 and ISO 2631-1: 1997).

Three annexes provide current information on the possible effects of vibration on health (annex B), comfort and perception (annex C) and on the incidence of motion sickness (annex D). This guidance is intended to take into account all the available data and to satisfy the need for the recommendations which are simple and suitable for general application (Mansfield 2005).

Guide to the evaluation of human exposure to whole body vibration (ISO 2631) gives three different types of exposure limits:

- i. A reduced-comfort boundary
- ii. The fatigue-decreased proficiency boundary
- iii. An exposure limit

The reduced-comfort boundary is for the comfort of people travelling in airplanes, boats, and trains. Exceeding these exposure limits makes it difficult for passengers to eat, read or write when travelling. The fatigue-decreased proficiency boundary is a limit for time-dependent effects that impair performance. For example, fatigue impairs performance in flying, driving and operating heavy vehicles. The exposure limit is used to assess the maximum possible exposure allowed for whole body vibration.

These were recommended in the earlier version of ISO 2631 and are no longer used in ISO 2631-1: 1997.

1.10.2 ISO 13090-1: Guidance on safety aspects of test and experiment with people

Exposure to whole body vibrations and repeated shock, guidance is provided on the safety aspects of equipment or procedures which are particular to experiments involving mechanical vibration and repeated shock, and which affect the safety of those involved. It aims to reduce the chance of the subjects, or those monitoring or conducting the experiments, being exposed to undue risk of injury or impaired health arising from such exposure, or of injury attributed to the malfunction or poor operation of the equipment used to generate the mechanical vibration and shock (Mansfield 2005).

1.11 Present scenario

In recent years, people have become more concerned about the vibrations seeking better and comfortable environment. As travelling increases, the driver is more exposed to vibrations mostly originating from the interaction between road and vehicle. Vibration induces discomfort and fatigue and sometimes leads to an injury. So, it is imperative to know how the vibrations are transmitted through the human body before trying to manage it (Cho and Yoon 2001).

According to Kim, Kim, and Yoon (2005), there are many factors that lead to discomfort in a driving vehicle, such as pressure at seat interface, sitting posture, vibration, noise, visual effects, humidity, etc. Whole-body vibration causes many problems in human health, comfort and performance. So many researchers have studied the cause-effect relationship between whole-body vibration and related problems as published in the International standard ISO 2631 (1997) and others: Osborne (1978), Parson and Griffin (1983), BS 6841 (1987) and Griffin (1990).

While travelling in a seated posture, human subjects are exposed to low frequency vibrations and as a result need of mathematical modelling of seated human body while travelling has attracted researchers. Human body is a complex dynamic system, the properties of which vary from time to time and from one individual to another and poses a lot of challenge in modelling.

While much research has been carried out on building up specific biodynamic models based on certain experimental data under prescribed testing conditions, a thorough investigation of mathematical human models has not yet received the same level of attention (Liang and Chiang 2006).

The biodynamic responses of the human body influence the manner in which vibration causes discomfort and injury, and interferes with activities. Purely numerical considerations of body dynamics have been reported, but the complexity of the human body dictates a vital role for experimentation in the development of understanding of human responses to vibration.

There are currently insufficient data to derive a 'complete' mathematical model of the movement of the body during exposure to vibration and also insufficient information to fully justify the form of complex models of body responses. The development of complex models of the responses of the body requires an understanding of the modes of oscillation of the body (Wei and Griffin 1998).

According to Kim, Kim, and Yoon (2005), discomfort estimation using experimental methods is time-consuming and needs much effort. The mechanical response of human body can be predicted well by using biomechanical modelling in vibrating environment. So, the simulation of the mechanical human models would be a better option to estimate dynamic characteristics of human body.

Modelling techniques can be grouped as lumped parameter modelling (LPM), finite element modelling and multi-body dynamic modelling. LPM considers the human body as several concentrated masses interconnected by springs and dampers. This type of modelling is simple to analyse and easy to validate with the experiments.

But, the disadvantage is its limitation to one-directional analysis (Liang and Chiang 2006) and its applicability to low frequency vibrations (Harris and Piersol 2002). LPM is one of the most popular methods used by researchers, and its validity has been established in low frequency range below 100 Hz (Harris and Piersol 2002).

Knowledge of the human responses to vibrations requires an understanding of the cause-effect relationships among the transmission of vibrations through the body and its health, comfort and performance. These responses have been widely assessed in terms of seat to head transmissibility (STHT), driving point mechanical impedance (DPMI) and apparent mass (AM).

The first function refers to the transmission of motion through the body; whereas the other two pertain to the force and motion at the point of vibration input. The human body is a very sophisticated dynamic system whose mechanical properties vary from one moment to another and from one individual to another. From the results of a large amount of experimental data, various biodynamic models have been developed to describe human motion.

While travelling, passengers experience a range of sinusoidal motions while seated on a soft seat. It is observed that seat can greatly increase or decrease the motion depending on the vibration frequency, magnitude and direction.

Study of human subjects in sitting posture is important for comfort evaluation of drivers and passengers. Therefore, it is important to study the phenomenon through analytical modelling and its validation with experimental investigations.

1.12 Organization of thesis

From the study carried out in this research work, thesis has been organized in the following chapters:

Chapter 1: Introduction

This chapter deals with introduction to human response to vibrations under different sitting postures when exposed to Whole Body Vibration (WBV), biodynamic modelling and biodynamic response.

Chapter 2: Literature Review

Background and literature survey regarding analytical studies and experimental investigations have been presented in this chapter

Chapter 3: Evaluation of Eigen Values and Eigen Vectors

In this chapter, biodynamic model suitable for vibration studies for seated human subjects under WBV has been developed. Assumptions made for modelling and evaluation of mass and stiffness of individual segments and connecting springs using anthropometric data have been presented. A new concept of slippage force term has been developed for writing equations of motion in a vibratory system.

Chapter 4: Determination of STHT using Analytical Modelling

In this chapter, STHT for Indian male subjects has been evaluated analytically for seated human subjects when subjected to vertical vibrations in different sitting postures.

Chapter 5: Evaluation of STHT through Experimental Investigations

This chapter describes the experimental set-up, physical data of the test subjects, evaluation of seat to head transmissibility without and with backrest for rigid and cushioned seats at different backrest inclinations. Validation of developed mathematical model with experimental investigations has also been done.

Chapter 6: Assessment of Subjective Response

Subjective response of the human subjects when exposed to different vibrating conditions has been discussed in this chapter.

Chapter 7: Conclusions and Scope of Future Work

This chapter summarises the conclusions of the research work undertaken along with the future scope of work.

CHAPTER 2

LITERATURE REVIEW

2.1 Literature review

After an extensive literature review, it was observed that the biodynamic response study of human body vibration is mainly divided in the following directions:

- i. **Analytical studies:** involve development of mathematical models (LPM, FEM & MBD). The researchers have used many assumptions and arrived at different degree of freedom (DOF) vibrating systems representing human body in sitting or standing posture. A wide variety of models ranging from 1 DOF to 15 DOF are reported in literature. In some cases, validation through available experimental investigations has been attempted. Some of the important work is given in the following section.
- ii. **Experimental investigations:** involve in-situ applications of the forces on humans (male/female & children) in vertical direction for seated subjects subjected to harmonic vibrations. The response parameters like apparent mass (AP), transfer function, transmissibility and driving point mechanical impedance (DPMI) were measured. Some of the important research work accomplished in this area has been reported in the coming section.

2.1.1 Analytical studies

Equations of motion for a model of the human body were developed by Huston and Passerello (1971). Basically, the model consisted of an elliptical cylinder representing the torso, together with a system of frustums of elliptical cones representing the limbs. They were connected to the main body and each other by hinges and ball and socket joints. Vector, tensor, and matrix methods provided a systematic organization of the geometry. The equations of motion were developed from the principles of classical mechanics. The solution of these equations then provided the displacement and rotation of the main body when the external forces and relative limb motions were specified.

A digital computer program was developed by Bartz and Gianotti (1975) to calculate dimensional and inertial properties of the human body. The program was designed so that the user may either select a data set from a program library, or compute a data set from a geometric man-model. From primary program inputs of sex, standing height, seated height and weight, the routines compute body segment link lengths, contact surface dimensions, masses and moments of inertia from input sets of anthropometric data. Overall validity of the formulation and techniques was established by comparing computed results with measurements on the human body reported by various investigators.

A lumped-parameter model of the human body in the sitting position was formulated by Muksian and Nash (1974) which included head, vertebral column, upper torso, abdomen-thorax viscera, pelvis and legs. The differential equations of motion for the rigid-body representation of the isolated masses were written for nonlinear springs and dashpots which represented the elasticity and damping, respectively, of the physical system. Additionally, in agreement with the frequency dependency of muscle forces, the possibility of frequency dependent damping coefficients was implied.

Muksian and Nash (1976) formulated and programmed a 3 DOF model of the human body, which included both vertebral and visceral paths between the seat and head, for solution using the IBM Continuous System Modelling Program. The parameters representing spring stiffness and damping coefficients were varied until the body-to-seat or head-to-seat acceleration ratios converged to existing experimental data at corresponding input frequencies. For input frequencies between 10 and 30 Hz, visceral damping was found to vary parabolically with input frequency.

Nigam and Malik (1987) developed a model of the human body considering it as a spring mass system. Based on certain assumptions, an analysis for evaluating the mass and stiffness values of the model was developed. As an illustration of the modelling procedure, a 15 DOF of a male body was considered. The computed natural frequencies of the model were found to be within the range of available experimental values.

Martin (1991) predicted that the mechanical properties of bones were governed by the same principles as those of man-made load-bearing structures, but the organism is able to

adapt its bone structure to changes in skeletal loading. In this overview of the determinants of the strength and stiffness of bone, a continuum approach was taken, in which the behaviour of a macroscopic structure depends on its shape and size, and on the mechanical properties of the material within. The latter were assumed to depend on the composition (porosity and mineralization) and organization (trabecular or cortical bone architecture, collagen fibre orientation, fatigue damage) of the bone and the effects of each of these factors were reviewed.

Nigam and Malik (1991) dealt with the problem of mode shape and frequency response analysis of a human body through analytical modelling. 7 DOF spring mass system was considered as a representative of male human body in standing postures. The stiffness matrix for the model was evaluated and the characteristic frequency equations were formed and frequency response was evaluated by modal matrix method. Eigen values and Eigen vectors were computed by generalised Jacobi method.

Nigam and Malik (1991) evaluated the natural frequencies of a seven degree of freedom model of a human body. The dimensional properties of a 50th percentile male were computed from the available anthropometric data and the characteristic frequency equation was formed. The computed natural frequencies were found to be within their expected range.

Lumped mass human model was used by Amirouche et al. (1994) to minimize the energy absorption at the feet/hip level when the body is subjected to vertical vibration. The contact forces were assumed unknown. By coupling the dynamic response of the body with certain objective criteria, the optimum damping and stiffness coefficients of shoes/chairs were sought. The criteria of acceleration, displacement and internal forces response area swept for a range of 0-15 Hz formed the basis of simulation study. In the seated/standing postures it was found that for each criterion the frequency response shifts the peak of resonance of each body segment response from 4.5/3.67 Hz to 2.5/2.255 Hz.

Vertical and horizontal vibrations of a 100kg human were investigated by Qassem et al. (1994). A new mechanical model was developed, and an analogous electric simulation was carried out, which in turn was analysed using computer software (MICRO-CAP II). The vibration force came from (a) hand, (b) seat and (c) a combination of the two. The theoretical results obtained were tabulated and were presented in a graphical manner.

Chen et al. (1996) presented a frequency-domain method for estimating the mass, stiffness and damping matrices of the model of a structure. The developed method was based on their previous work on the extraction of normal modes from the complex modes of a structure. A transformation matrix was obtained from the relationship between the complex and the normal frequency response functions of a structure. The transformation matrix was employed to calculate the damping matrix of the system. The mass and the stiffness matrices were identified from the normal frequency response functions by using the least squares method.

Paddan and Griffin (1998) reviewed published studies of the transmission of translational seat vibration to the heads of seated subjects in order to determine the variations in transmissibility. The review was restricted to vibration having the same direction at the seat and the head: (a) transmission between fore-and-aft seat vibration and fore-and-aft head motion, (b) transmission between lateral seat vibration and lateral head motion, and (c) transmission between vertical seat vibration and vertical head motion. Only studies reporting transmissibilities from six or more subjects were included in the review. The studies involved a wide range of experimental conditions, including different sitting postures, various types of subject and various locations for measuring vibration on the head.

Wei and Griffin (1998) developed alternative mathematical models of the vertical apparent mass of the seated human body. The optimum parameters of four models (two 1 DOF models and two 2 DOF models) were derived from the mean measured apparent masses of 60 subjects (24 men, 24 women, 12 children) previously reported. The best fits were obtained by fitting the phase data with 1 DOF and 2 DOF models having rigid support structures. For these two models, curve fitting was performed on each of the 60 subjects (so as to obtain optimum model parameters for each subject), for the averages of each of the three groups of subjects, and for the entire group of subjects. The values obtained were tabulated. It was concluded that the 2 DOF model provided an apparent mass similar to that of the human body.

Martin (2000) described a model in which 27 rigid bodies with 103 DOF represent the segments of the human body. 106 force elements imitate the muscles of the trunk and the legs. At first, the model parameters were varied so that for the simulated sitting posture the model fits the seat-to-head transmissibility given in the literature and in ISO/CD 5982. For

the standing posture, the transfer functions between the ground acceleration and the oscillating forces in the ankle, the knee, the hip, and the motion segment L3-L4 were computed. According to the moduli of these functions the forces in the ankles were higher than those in the knees or the hips and they nearly come up to the forces in the lumbar spine. Further the results of the simulation indicated that under equal vibration stress in the standing and the sitting posture the differences between the compressive forces in the lumbar spine are small.

Smith (2000) described the effectiveness of a modified 5 DOF model in simulating the major resonance behaviours observed in the population using representative data from a 56 kg female and 75 kg male. In addition, the model was also evaluated for its ability to predict the effects of selected seat cushions. The modified lumped-parameter model improved the peak chest and spine transmissibility simulations. The model was effective in simulating both the lower impedance peak observed in the primary resonance region (4-8 Hz) and the prevalent impedance peak observed in the second resonance region (7-10 Hz) in the smaller subjects. However, the model was not effective in predicting the dampening observed in the second resonance peak with the use of cushions.

V.P. Tregoubov (2000) studied and proved several theorems relative to existence and uniqueness of an identification problem solution. In particular, was shown that even if a mechanical model structure is given, one can find several sets of model parameters which result in one and the same amplitude frequency characteristic, conventionally used as a criterion. At the same time, it was shown that the different parameter values bring to different results when constructing a vibroprotection system. It was established that the mechanical model parameters determined uniquely if both transfer function and an input mechanical impedance of a human body are known. Besides, mechanical models of a new class, that is systems, possessing the multi-joint deformable links, were proposed to use and some advantages of such models for reproduction of experimental characteristics were illustrated.

Matsumoto and Griffin (2001) developed simple lumped parameter models with rotational degrees-of-freedom using previously obtained experimental data. The models provide reasonable explanations for the dynamic responses of the seated body exposed to vertical whole body vibration. The principal resonance of the apparent mass at about 5 Hz is attributed to a vibration mode consisting of vertical motion of the pelvis and legs and pitch

motion of the pelvis, both of which cause vertical motion of the upper body, bending of spine and vertical motion of the viscera. Vertical motion due to deformation of buttocks tissue, and vertical motion of the viscera, both made a dominant contribution to the apparent mass resonance. The contribution of bending motions of the spine to the principal resonance of the apparent mass may be small, even though bending is observed at the resonance frequency in experimental data.

Rosen and Arcan (2003) developed a multi DOF lumped parameter model of the human body in a sitting posture, incorporating global dynamics in terms of apparent mass and local dynamics of the body/seat contact interaction. This model was further used for simulating different vibration axes, body posture, seat configuration, and input vibration magnitudes. Moreover, simulating the contact force distribution at the human/seat inter-face with various cushion configurations provided guidelines for designing cushions from the materials composition and structural/geometry perspective.

Matsumoto and Griffin (2003) developed linear lumped parameter models of the apparent masses of human subjects in standing positions when exposed to vertical whole body vibration. Simple models with a 1 DOF and with 2 DOF were considered for practical use. Model parameters were optimized using both the mean apparent mass of 12 male subjects and the apparent masses of individual subjects measured in a previous study. The calculated responses of 2 DOF models with a mass less support structure showed best agreement with the measured apparent mass and phase. The model parameters obtained with the mean measured apparent masses of the 12 subjects were similar to the means of the 12 sets of parameters obtained when fitting to the individual apparent masses. It was found that the effects of vibration magnitude and postural changes on the measured apparent mass could be represented by changes to the stiffness and damping in 2 DOF models.

Kim *et al.* (2005) developed a biomechanical model of the human body for evaluating the vibration transmissibility and dynamic response to vertical vibrations in sitting posture. The biomechanical model consists of several lumped masses connected by linear spring and dampers. This model was selected from eight structural models after fitting measured data of apparent mass, vertical and rotational vibration transmissibility to the head of five individuals

on a vertical exciter vibrating under random signals. The proposed model describes the experimental data much better than the Matsumoto-Griffin model.

Dong *et al.* (2006) studied considerable differences among the reported data of the biodynamic response (BR) of the hand arm system. A significant portion of the differences were believed to have resulted from instrumentation problems and computational algorithm errors. To help establish a reliable and accurate methodology for BR measurement, this study addressed the fundamental instrumentation issues. Specifically, the general theory of the driving-point BR was reviewed and summarized. An accurate mass cancellation method for BR measurement was identified and further developed. A set of methods was proposed to systematically examine and calibrate the BR measurement system. Based on the experimental results and theoretical analyses, several instrumentation and algorithm problems were identified.

Teng *et al.* (2006) established a seated human body vibration model using the multi-body dynamics method. The dynamic equations of motion of the mechanical structure were based on Kane's equations as formulated by Huston *et al.* (1971). The equations were then coded into a computer program and solved using fourth-order Runge-Kutta methods. The developed human body model was employed to examine the biodynamic response of the human body under vertical vibration and to measure the natural frequency and input-output acceleration ratio (transmissibility) of each individual segment received. The multi-body dynamics results closely corresponded to the experimental results. The analysis cost of multi-body dynamics method was very low. The procedures described herein contributed efforts to optimize seat design and analyse human body comfort.

Stein *et al.* (2007) measured accelerations and forces in x-direction at the seat base during whole body vibration in the fore-and-aft direction (random signal in the frequency range between 0.3 and 30 Hz, vibration magnitudes 0.28, 0.96, and 2.03 ms⁻² un-weighted rms). 13 male subjects with body masses between 62.2 and 103.6 kg were chosen for the tests. They were made to sit on a cushioned driver seat with hands on a support and backrest contact in the lumbar region only. Based on these laboratory measurements, a linear model of the system-seated human body and cushioned seat in the fore-and-aft direction was developed. The model accounted for the reaction from the steering wheel.

Griffin (2007) identified opportunities to improve current standardised methods of predicting vibration discomfort from increased understanding of human sensitivity to variations in the magnitudes, frequencies, directions, and durations of vibration in transport, and the interactions between responses to vibration and other stimuli. The methods of predicting discomfort were seen to provide useful guidance, greater unification of the methods of measuring, evaluating and assessing human responses to vibration in the different forms of transport.

Dong *et al.* (2007) developed analytical models for simulating driving-point biodynamic responses distributed at the fingers and palm of the hand under vibration along the forearm direction (z_h -axis). The variations in the identified model parameters under different hand actions were further discussed in view of the biological system behaviour. The proposed models were considered to serve as useful tools for design and assessment of vibration isolation methods, and for developing a hand-arm simulator for vibration analysis of power tools.

Liang and Chiang (2008) investigated two multi-body models (representative of the automotive postures found in the literature), one with and the other without a backrest support. Both models were modified to suitably represent the different automotive postures with and without backrest supports and validated by various experimental data from the published literature pertaining to the same postural conditions. On the basis of the analytical study and the experimental validation, the 14 DOF model proposed in the research was found to be best fitted to the test results and was recommended for studying the bio-dynamic responses of a seated human body exposed to vertical vibrations in various automotive postures.

Subashi *et al.* (2008) developed lumped parameter mathematical models representing anatomical parts of the human body to represent body motions associated with resonances of the vertical apparent mass and the fore-and-aft cross-axis apparent mass of the human body standing in five different postures: upright, lordotic, anterior lean, knees bent, and knees more bent. The inertial and geometric parameters of the models were determined from published anthropometric data. Stiffness and damping parameters were obtained by comparing model responses with experimental data obtained previously.

Dong *et al.* (2009) directly compared the arithmetically averaged response with the response derived from a property-based method proposed in this study. Two sets of reported mechanical impedance data measured at the fingers and the palms of the hands were used to derive the models required for the comparison. This study found that the response-based arithmetic averaging could generate some systematic errors. The range of the subject's natural frequencies in each resonance mode, the mode damping ratio, and the number of subjects participating in the experiment were among the major factors influencing the level of the errors. An effective and practical approach for reducing the potential for error was to increase the number of subjects in the BR measurement.

2.1.2 Experimental investigations

The experiment described by Griffin and Whitham (1978) was designed to evaluate the differences in discomfort and body transmissibility between and within different population groups and to attempt to discover physical causes of the differences. The responses of one hundred-and-twelve seated subjects to vertical (z-axis) sinusoidal vibration at 4 Hz and 16 Hz were investigated. The subjects were in three groups (56 men, 28 women and 28 children) and were of varied demography. The large differences found between the responses of individual subjects were presented as frequency distributions. The subjective responses from each of the three populations were well approximated by log-normal distributions.

Zimmermann and Cook (1997) evaluated the effects of changes in pelvic orientation and vibration frequency on the seated human's response to WBV. Seat-to-trunk and seat-to-head acceleration transmissibility, peak-to-peak pelvic motion and erector spinae EMG and mean erector spinae EMG was collected across three pelvic orientations (9° anterior pelvic tilt, neutral pelvis, and 9° posterior pelvic tilt) and frequencies ranging from 4.5 to 16 Hz. Subjects included 30 healthy males between the age of 18 and 35. Ensemble averages, two vibration cycles in length, were produced for each subject within each frequency-pelvic orientation combination. Group ensemble averages within each frequency-pelvic orientation combination were then compared using ANOVA. Thus, vibration frequency and pelvic orientation were shown to have significant interactive effects on the seated human's response to WBV.

Harazin and Grzesik (1998) investigated the effects of body postures in standing position on the transmission of whole body vibration to body segments. The magnitude acceleration in the Z-axis direction of six body segments: the metatarsus, ankle, knee, hip, shoulder and head were measured during exposure to random vibration. 10 male subjects exposed to floor vibration stood in ten postures described as: relaxed standing, legs stiffened, legs bent, standing on the toes, and standing on one leg with or without support of the other foot and standing in steps. The transmissibility of random vibration from the floor to the body points was calculated at frequencies ranging from 4-250 Hz in 1/3 octave bands.

The power absorbed by 12 male subjects during exposure to vertical whole body vibration at six magnitudes of random vibration (0.25, 0.5, 1.0, 1.5, 2.0 and 2.5 ms⁻² rms) was measured by Mansfield and Griffin (1998). All subjects showed greatest absorbed power at about 5Hz but the frequency of this peak in the absorbed power reduced with increasing vibration magnitude. Comparing the characteristics of this absorbed power weighting to standard frequency weightings showed substantial differences, especially at high frequencies. It was concluded that the differences from currently accepted frequency weightings are so great that the absorbed power is unlikely to yield good general predictions of the discomfort or risks of injury from whole body vertical vibration.

Boileau and Rakheja (1998) measured the vertical driving-point mechanical impedance characteristics applicable to seated vehicle drivers the 0.625-10 Hz frequency range with excitation amplitudes ranging from 1.0 to 2.0 ms⁻² using a whole body vehicular vibration simulator. The measurements were performed for seated subjects with feet supported and hands held in a driving position. Variations in the seated posture, backrest angle, and nature and amplitude of the vibration excitation were introduced within a prescribed range of likely conditions to illustrate their influence on the driving-point mechanical impedance of seated vehicle drivers. From the model, the main body resonant frequencies computed on the basis of both biodynamic response functions were found to be within close bounds to that expected for the human body.

Apparent masses of 15 male and 15 female subjects were measured by Mansfield and Lundstrom (1999) during exposure to various directions of horizontal vibration. Twenty vibration conditions were used in the experiment. In each of five directions (0°, 22.5°, 45°, 67.5° and 90° to the mid-sagittal plane) subjects were exposed to random vibration in the frequency range of 1.5-20 Hz at 0.25, 0.5 and 1.0 ms⁻² rms. The five remaining conditions

were selected to give measurements whereby the magnitude of the x-component of the vibration was fixed and the y-component changed and vice-versa. Two peaks were observed in the apparent masses. Predictions of the response at 45° by applying the principle of superposition to data measured at 0° and 90° showed that the response of the body with direction was not linear. This implies that the apparent mass in non-orthogonal axes cannot be predicted from the apparent masses measured in orthogonal directions.

Mansfield and Griffin (2000) exposed 12 subjects to six magnitudes, 0.25-2.5 ms⁻² rms, of vertical random vibration in the frequency range 0.2-20 Hz. The apparent masses of the subjects were determined together with transmissibilities measured from the seat to various locations on the body surface: the upper and lower abdominal wall, at L3, over the posterior superior iliac spine and the iliac crest. There were significant reductions in resonance frequencies for both the apparent mass and the transmissibilities to the lower abdomen with increases in vibration magnitude. The apparent mass resonance frequency reduced from 5.4-4.2 Hz as the magnitude of the vibration increased from 0.25-2.5 ms⁻² rms. Vertical motion of the lumbar spine and pelvis showed resonances at about 4 Hz and between 8 and 10 Hz. When exposed to vertical vibration, the human body showed appreciable non-linearities in its biodynamic responses.

Matsumoto and Griffin (2000) compared the dynamic responses of the human body in standing and sitting positions. The apparent mass and transmissibilities to the head, six locations along the spine, and the pelvis were measured with 8 male subjects exposed to vertical whole body vibration. In both postures, the principal resonance in the apparent mass occurred in the range 5-6 Hz, with slightly higher frequencies and lower apparent mass in the standing posture. There was greater transmission of vertical vibration to the pelvis and the lower spine and greater relative motion within the lower spine in the standing posture than in the sitting posture at the principal resonance and at higher frequencies. Transmissibilities from the supporting surface (floor or seat) to the thoracic region had similar magnitudes for both standing and sitting subjects.

According to Hinz *et al.* (2001) the seat-to-head transfer function of the human body reflects the biodynamic response. Based on measured data, biodynamic models were proposed to reflect this response. An experimental study was performed with 39 male subjects sitting on a hard seat without back rest and with supported feet. They were exposed

to random whole body vibration at three intensities with a relaxed and an erect posture. The accelerations in the z-direction were measured at the seat and head. The seat-to-head transfer functions with the associated coherence functions were calculated. The biodynamic response characterised by the maximum of seat-to-head transmissibility and the frequency of its occurrence was influenced by the posture of the subjects in a dominant way and showed an individual variability of considerable extent. The mean responses suggested missing effect of vibration intensity, but individually effects of the intensity were found. Repeated measurements confirmed this result.

Nawayseh and Griffin (2003) exposed seated human subjects to vertical whole body vibration so as to investigate the non-linearity in their biodynamic responses and quantify the response in directions other than the direction of excitation. Twelve males were exposed to random vertical vibration in the frequency range 0.25-25 Hz at four vibration magnitudes (0.125, 0.25, 0.625 and 1.25 ms⁻² rms). The subjects sat in four sitting postures having varying foot heights so as to produce differing thigh contact with the seat (feet hanging, feet supported with maximum thigh contact, feet supported with average thigh contact, and feet supported with minimum thigh contact). Forces were measured in the vertical, fore-and-aft, and lateral directions on the seat and in the vertical direction at the footrest.

Nawayseh and Griffin (2004) measured forces in the fore-and-aft, lateral and vertical directions at the seat and backrest during exposure of seated subjects to vertical whole body vibration. The responses at the seat were compared with those measured previously on a seat without a backrest. 12 male subjects were exposed to random vertical vibration in the frequency range 0.25-20 Hz. The subjects sat on a rigid seat with a rigid backrest and were exposed to a fannted 16 different conditions: four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 ms⁻²rms) and four sitting postures (with varying thigh contact with the seat). The presence of the backrest modified the forces on the seat in both the vertical and fore-and-aft directions: in all four postures there was an increase in the resonance frequency of the apparent mass when using the backrest. The effect of the backrest on fore-and-aft forces on the seat depended on whether the feet were supported or not. The results show the importance of considering the backrest when studying the response of the human body to whole body vertical vibration.

Wang *et al.* (2004) characterized the biodynamic response characteristics of 13 male and 14 female seated subjects, exposed to vertical vibration, under different postural conditions. The measurements were performed for a total of thirty six different sitting postural configurations realized through variations in hands position (in lap and on steering wheel), three seat heights (510, 460 and 410 mm), and seat design factors involving two different pan orientations (0° and 7.5°) and three different back support conditions (no support, and support with vertical and inclined backrest). The results suggested that the hands in lap posture yields larger primary resonant frequency and considerably higher APMS magnitude response in the vicinity of primary resonant frequency than the hands on the steering wheel posture, when the back is supported with an inclined backrest.

In an experimental study conducted by Hinz *et al.* (2006) pressure distributions on a seat cushion were measured during whole body vibration in z-direction (random signal in the frequency range between 0.3 and 20 Hz, vibration magnitudes 0.25, 0.8, and 1.6 ms^{-2} un-weighted root mean square measured at the seat base) with a sampling rate of 32 ms. The apparent masses were calculated by the forces derived from the pressure distributions and accelerations measured at one point of the seat cushion near the buttocks. The data of this study indicated the possibility and necessity to consider the contact conditions at the interface when deriving target functions for the model development. Recommendations for technical improvements and further experimental studies with driver seats were derived.

Hinz *et al.* (2006) performed an experimental study with 13 male subjects sitting on a rigid seat without backrest, and with a hand resting on a support. They were exposed to random whole body vibration with root mean square (rms) values of about 0.25, 1.0 and 2.0 ms^{-2} in vertical, fore-and-aft, and lateral direction, and additionally in two horizontal vibration axes and all three vibration axes simultaneously. The forces and accelerations were measured in x-, y-, and z-directions for each condition tested. The method of the modal description was applied to all individual apparent mass functions in order to obtain representative target functions. Recommendations for the revision of ISO 5982 were summarized.

Mansfield and Maeda (2006) performed a study wherein 15 male subjects were exposed to single-axis whole body vibration in the x-, y- and z-directions and dual-axis vibration in the xy-, xz-, and yz-directions using a 6 DOF vibration simulator. All vibration magnitudes were 0.4 ms^{-2} rms in each axis. Acceleration and force was measured in the x-, y-,

and z-direction during all trials. Subjects sat in two postures ('back-on' and 'back-off') on a flat rigid seat. Apparent masses measured using single-axis and dual-axis vibration stimuli showed comparable results; similarly, cross-axis apparent masses (i.e. the ratio of the force in one direction to the acceleration in another direction) were almost identical for the single- and dual-axis vibration stimuli. All results were in agreement with data previously published using single-axis vibration.

Mansfield and Maeda (2007) measured apparent masses of 15 subjects whilst exposed to single-axis and tri-axial whole body vibration. Each subject was exposed to 28 vibration conditions comprising every combination of single-axis and tri-axial vibration with magnitudes of 0.4 and 0.8 ms⁻² rms in each direction, once with backrest contact and once without backrest contact. Results showed that increasing the magnitude of vibration affected the apparent mass, causing a reduction in the resonance frequency as the total magnitude of vibration increased. It was demonstrated that the apparent mass resonance frequency was a function of the total vibration magnitude in all axes rather than a function of the vibration magnitude in the direction being measured. It was concluded that more complex biomechanical models were required in order to simulate human response to multi-axis vibration.

Shibata and Maeda (2010) performed whole-body vibration experiments with subjects under vertical vibration to examine and evaluate the effects of backrest inclination on vibration transmitted through seats to the human body. The biodynamic response parameters of twelve male subjects, exposed to vertical random vibration at 0.8 m/s² r.m.s., were characterized under three different backrest support conditions, with the upper body supported against backrest inclined at angles of 0° (vertical), 10° and 30° with respect to the vertical axis. An increased backrest inclination angle resulted in reduction of the total power absorption calculated particularly the frequency range of 1-20 Hz. Normalized AP magnitudes showed a principal resonance at about 5 Hz for each subject for a backrest supported vertically.

Basri and Griffin (2011) designed an experimental study to determine how back rest inclination and the frequency of vibration influence perception thresholds and vibration discomfort when the vibration is applied normal to the back (i.e. fore-and-aft vibration when seated upright and vertical vibration when fully reclined). Absolute thresholds for the

perception of vibration were determined with four back rest inclinations: 0° (upright), 30°, 60° and 90° (recumbent). As the backrest inclination became more horizontal, the thresholds increased at frequencies between 4 and 8 Hz. With an upright backrest, the discomfort caused by vibration acceleration tended to be greatest at frequencies less than about 8 Hz. With inclined backrests (at 30°, 60°, and 90°), the equivalent comfort contours were broadly similar to each other.

Dewangan *et al.* (2013) measured apparent mass responses of human body seated on elastic seat, without and with a vertical back support using a seat pressure sensing mat under three levels of vertical vibration (0.25, 0.50 and 0.75 m/s² rms acceleration) in 0.50-20 Hz frequency range. The responses were also measured with a rigid seat using the pressure mat and a force plate. The responses revealed lower peak magnitude and corresponding frequency compared to those measured with rigid seat, irrespective of back support and excitation considered.

Toward and Griffin (2009) designed a study to quantify the effect of foam and rigid backrests on the vertical apparent mass of the human measured at the seat surface supporting the body. The apparent masses of 12 subjects were measured during exposure to random vertical vibration (1.0 ms² rms from 0.125 to 40 Hz) in a seat with a rigid backrest at different inclinations and with different foam thickness. With all vertical backrests (0° inclination), there were resonances in the apparent mass of the body around 5 and 10 Hz.

It has been well-established that the upper body support conditions affect the seat-to-head vibration transmissibility most significantly (Wang *et al.* 2006 and Paddan and Griffin 1988). The human body biodynamic responses have been invariably characterized with body seated on a rigid seat in order to attain uncoupled body responses to vibration (Hinz *et al.* 2006). This condition is not at all representative of vehicle seats because a viscoelastic seat can alter the body-seat contact area, sitting posture and body mass distribution on the seat (Boileau *et al.* 1998). An elastic seat cushion is thus expected to substantially alter the biodynamic response of the seated body under vertical vibration.

Car seats have inclined backrests and inclined seat-pans, but there has been little study on how the inclinations of seat influence the vibration through the backrest. Investigations were conducted for two seats (a car seat and a rigid seat with solid foam backrest). With 12

subjects, each seat was exposed to vibration in the frequency range 0.25-20 Hz with a vibration magnitude of 0.4 ms^{-2} . It was concluded that both the backrest inclination and the seat inclination affect the transmission of vibrations through backrests. But, with moderate changes of inclination, the effects are not large (Jalil and Griffin 2007).

According to Zhang *et al.* (2015) the perception of vehicle ride comfort is influenced by the dynamic performance of full-depth foam used in many vehicle seats. The effects of the thickness of foam on the dynamic stiffness (i.e., stiffness and damping as a function of frequency) of foam cushions with three thicknesses (60, 80, and 100 mm), and the vibration transmitted through these cushions at the seat pan and the backrest were measured with 12 subjects (6 males and 6 females). With increasing thickness, the stiffness and the damping of the foam decreased. With increasing thickness of foam at the seat pan, the resonance frequencies around 4 Hz in the vertical in-line and fore-and-aft cross-axis transmissibilities of the seat pan cushion and the backrest cushion decreased. For the conditions investigated, it was concluded that the thickness of foam at a vertical backrest has little effect on the vertical in-line or fore-and-aft cross-axis transmissibilities of the foam at either the seat pan or the backrest. Compared to sitting on a rigid seat pan with a foam backrest, sitting with foam at both the seat pan and the backrest reduced the resonance frequency in the vertical in-line transmissibility of the backrest foam while the fore-and-aft cross-axis transmissibility of the backrest was little affected.

Several studies have shown that the transmission of vertical vibrations to the head of seated subjects is influenced by backrest (Paddan and Griffin 1988; Hinz *et al.* 2006; Boileau *et al.* 1998 and Griffin 1990). The presence of a backrest vibrating vertically with the seat often increases the magnitude of vibration at the head. Change in body posture when leaning against a backrest may alter the transmission of vibrations through the body. The effects of vertical vibration can be further complicated by resonances in the backrest. A backrest can reduce vertical vibration in the body when the magnitudes of vertical backrest vibration are less than those at the back of the body. This may occur when seat cushions have high amplifications at resonance (Boileau *et al.* 1998).

Nawayseh (2015) investigated the effect of different seating conditions on the transmission of vibration through a car seat. Ten male subjects were made to sit on the passenger seat of a sedan car driven at 60 km/h adopting one of six conditions at a time. The

VDV was measured on the seat and backrest. Backrest contact affected the VDV measured on the seat pan in the z- and y-axis only. Increasing the backrest angle increased the VDV at the backrest in the x-direction and reduced the VDV at the backrest in the z-direction. With the increase in the backrest angle, the total VDV at the backrest became higher than the total VDV on the seat pan. The study showed no effect of foot position and contact with a headrest on the VDV.

Paddana *et al.* (2012) investigated the effects of reclined backrest angles on cognitive and psycho-motor tasks during exposure to vertical whole-body vibration. Twenty participants were each exposed to three test stimuli of vertical vibration: 2-8 Hz; 8-14 Hz and 14-20 Hz, plus a stationary control condition whilst seated on a vibration platform at five backrest angles: 0° (recumbent, supine) to 90° (upright). The vibration magnitude was 2 ms⁻² rms. Apart from 22.5° seat backrest angle for the tracking task, backrest angle did not adversely affect the performance during vibration. However, participants required increased effort to maintain performance during vibration relative to the stationary condition. These results suggest that undertaking tasks in an environment with vibration could increase workload and risk earlier onset of fatigue.

Tarabini (2014) analysed the apparent mass of standing subjects using the conditioned response techniques in order to understand the causes of the non-linear behaviour. The conditioned apparent masses were derived considering models of increasing complexity. The multiple coherence function was used as a figure of merit for the comparison between the linear and the non-linear models. The apparent mass of eight male subjects was studied in six configurations (combinations of three vibration magnitudes and two postures). The contribution of the non-linear terms was negligible and was endorsed to the change of modal parameters during the test. Since the effect of the inter-subject variability was larger than that due to the increase in vibration magnitude, the biodynamic response should be more meaningfully modelled using a linear estimator with uncertainty rather than looking for a non-linear modelling.

In an attempt to define how train vibration and motion affect passenger comfort, Bhiwapurkar *et al.* (2016) conducted an experimental study to show the effect of variations in posture and vibration magnitude on head motion in three translational directions (fore-and-aft, lateral and vertical) with seat vibration in lateral direction. The data results were analysed

in terms of seat-to-head-transmissibility response, phase and coherence for head motions in two sitting postures (backrest and forward lean). The seat-to-head-transmissibility response registered maximum head motion in lateral direction with single peak at 2 Hz in both the sitting posture. The response also reported an additional peak near 6 Hz in forward lean postures. The broad peak converged to a single peak at 2 Hz with reduction in seat-to-head-transmissibility response under the higher magnitude of lateral vibration, which was attributed to the softening effect of the human body.

2.2 Problem formulation

Existing literature reveals that human body is a complex structure and developing biodynamic model and evaluating its biodynamics response is a challenging task. A large number of experimental studies have been conducted. Need and importance of modelling in human body vibration research studies and their experimental validation are well documented.

It is observed that a large number of research activities are based on experimental investigations leading to measurements of seat to head transmissibility/driving point mechanical impedance/apparent mass. The development of analytical models and its parameters are then deduced from these experimental results.

A need is therefore felt that an alternate methodology for determining the model parameters based only on anthropometric data would be a useful research outcome. This will obviate the need of costly and time consuming experimentation all together.

In the present work, an attempt has been made in this direction and the anthropometric data of Indian male subjects has been used for deriving the models. The biodynamic models have been formulated for seated human subjects without backrest and with different backrest inclinations for rigid as well as cushioned seats.

STHT values have been evaluated through analytical modelling for different vibration magnitudes and excitation frequencies. The experimental investigations have been conducted for all the above mentioned cases and STHT values determined. The developed models have been validated with the experimental results.

Realising the importance of the role played by cushions and their inclinations in transmission of vibrations for the seated subjects, an attempt has also been made to assess the transmission of vibration through the body seated on rigid and cushioned seats by obtaining the subjective response of human subjects.

2.3 Objectives

The objectives of the present research work are:

1. To develop the biodynamic model, suitable for vibration studies under different sitting postures for Whole Body Vibration (WBV) studies.
2. To evaluate the transmissibility response parameters for different sitting postures, with and without cushions, under different sinusoidal excitation conditions.
3. To validate the developed mathematical models with experimental investigations (performed at IIT Roorkee).

CHAPTER 3

EVALUATION OF EIGEN VALUES AND EIGEN VECTORS

3.1 Introduction

A lot of work has been reported in the literature regarding biodynamic modeling using the anthropometric data for US and European subjects. The stiffness and damping values have mostly been estimated by researchers based on the reported experimental data available in literature based on Seat to Head Transmissibility (STHT), Driving Point Mechanical Impedance (DPMI) and Apparent Mass (AM) results. A limited work has been reported in the literature considering 50th percentile anthropometric data of Indian subjects.

Objective of the present study is not to obtain a new model and compare it with the existing models. However, the aim is to establish an alternate methodology for determining the model parameters like stiffness and mass of the model 'based only on anthropometric data' thus obviating the need of experimentation. The present investigation is an attempt to obtain eigen values and eigen vectors through 50th percentile anthropometric data for 54 kg Indian male subjects under sitting posture without backrest for un-damped free vibrations. The model parameters have been derived from the anthropometric data available in the literature. The effect of spring mass which has been neglected in the earlier studies has been taken into consideration while determining the eigen values and eigen vectors. This has resulted into eigen values which are closer to those reported in literature. Decoupling of vertical and fore and aft vibrations has been clearly established which conforms to the actual physical behavior of human beings.

3.2 Methodology

Based on ellipsoidal mass segments shown in Figure 3.1, Nigam and Malik (1987) established a technique for evaluating the stiffness of body segments shown (Figure 3.2), which has been used by Gupta (2007) and others, and has also been followed in the present study.

3.2.1 Assumptions

In the present study, following assumptions have been made:

- i. Free un-damped human body vibratory model has been considered.

- ii. Subject is considered to be sitting erect without backrest, with hands resting on the laps.
- iii. Each body segment is considered to be of ellipsoidal shape.
- iv. Though a human body in reality is not a homogeneous mass, the bulk (average) densities of different body segments are nearly the same ($\rho=1.062 \times 10^3 \text{ kg/m}^3$) (Kimberly *et al.* 2010). The density of each segment is therefore taken to be the same and equal to the average density of the whole body.

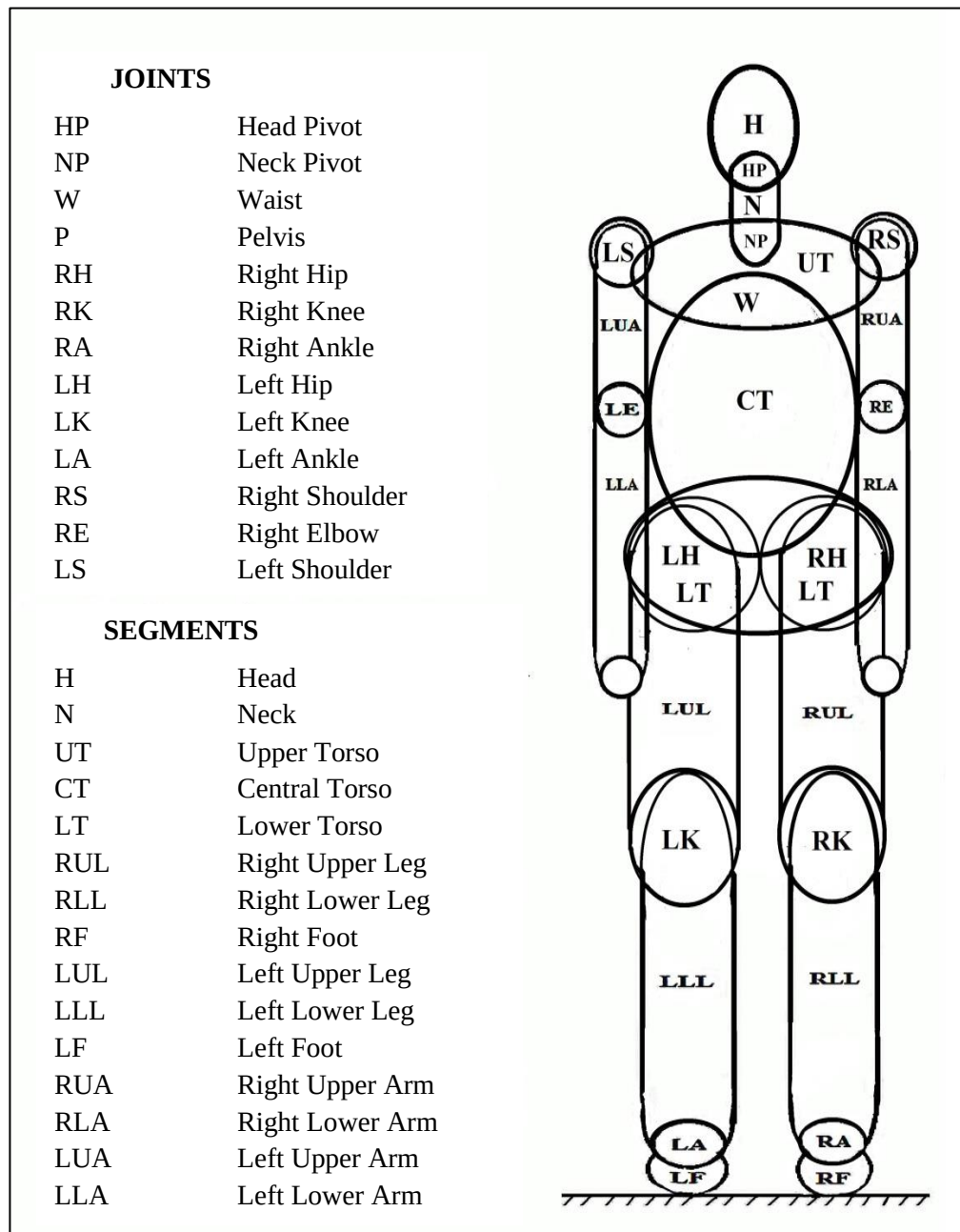


Figure 3.1 Anthropometric model of a human body (Bartz and Gianotti 1975)

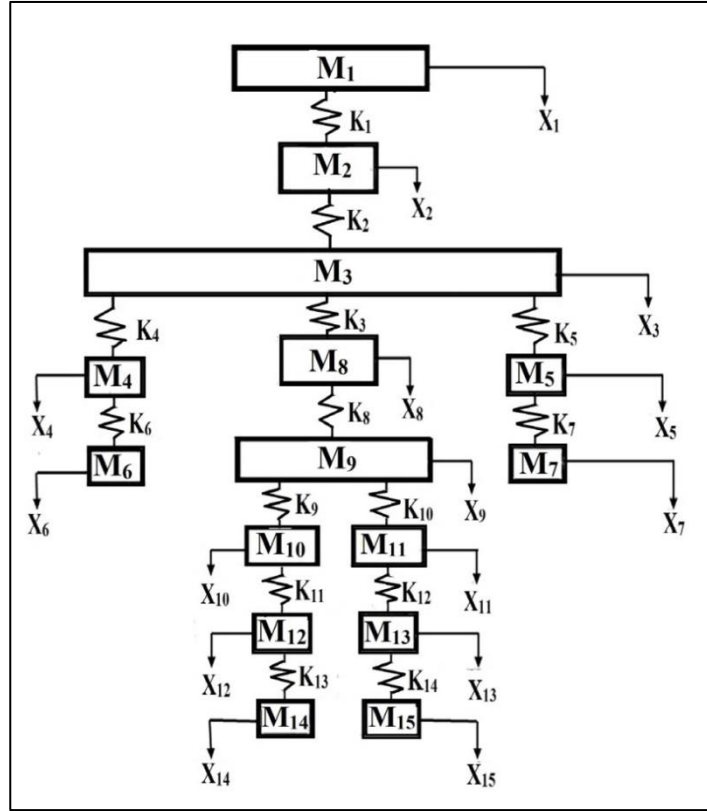


Figure 3.2 Vibratory model of human body (Nigam and Malik 1987)

3.2.2 Description of model

This study deals with the human subjects in sitting posture for which anthropometric data of Indian male subjects has been taken from Chakrabarti (1997). A nine degree of freedom lumped parameter model has been developed by Harsha *et al.* (2014) in order to study the response of seated human body to the vertical and horizontal whole body vibrations. This LPM study consists of five segments of masses interconnected by four vertical and two horizontal springs such that seat and feet are fixed with respect to floor with the help of two vertical and two horizontal springs with hands resting on the lap. This model has been modified as per need of the present study.

The essential difference between the model developed in the present work and the model of Harsha *et al.* (2014) is in the manner the clubbing of mass segments has been done, to make the model more realistic. In the present model (Figure 3.3), lower legs and feet have been clubbed together to represent mass m_1 since, both vibrate more or less together as a

single mass when subjected to external vibrations which are transmitted through the feet in direct contact with the floor.

Similarly, the lower torso and upper legs have been clubbed to represent mass m_2 , since both exhibit motions together due to vibrations transmitted through the seat. Further, damping has not been considered in the present model in order to facilitate evaluation of the eigen values and eigen vectors under free vibration conditions. Symbolic representation of human body model parameters is given in Table 3.1.

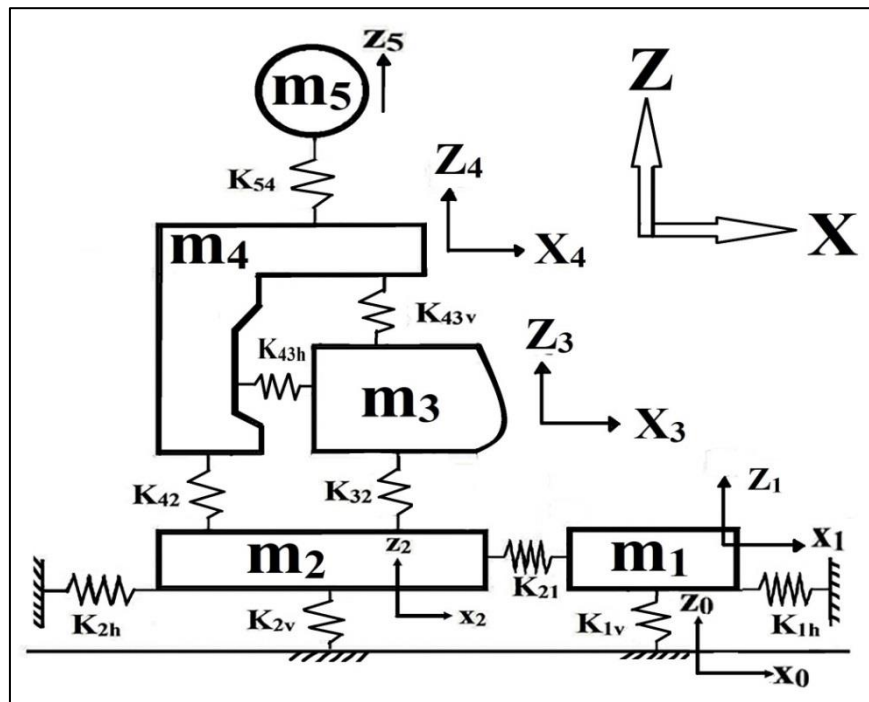


Figure 3.3 Nine DOF lumped parameter model for sitting posture without

Table 3.1 Symbolic representation of human body model parameters

S. No.	Parameter	Representation
1.	m_5	Head and neck
2.	m_4	Upper torso (including both arms and hands)
3.	m_3	Central torso
4.	m_2	Lower torso and upper legs
5.	m_1	Lower legs and feet
6.	K_{1v}, K_{1h}	Stiffness of vertical and horizontal springs connected to m_1
7.	K_{2v}, K_{2h}	Stiffness of vertical and horizontal springs connected to m_2
8.	$K_{21}, K_{32}, K_{42}, K_{43h}, K_{43v}, K_{54}$	Stiffness of springs connecting various body segments

For computing the stiffness of various body segments, the ellipsoids are considered to be truncated at the ends (Figures 3.4 and 3.5). The ratio of truncated length (d_i) to the original length (c_i) of the ellipsoidal segment is defined as truncation factor. This assumption is for the reason that in a realistic model, as shown in Figure 3.1, the adjacent ellipsoids should have an overlapping area of contact. An ellipsoid with point contact would in fact be fragile, while overlapping provides rigidity to the model. Further, in order to evaluate the Integral factor I_i , appearing in the equations 3.6 for evaluating stiffness of springs, truncating the ellipsoid is a mathematical necessity for evaluating this integral.

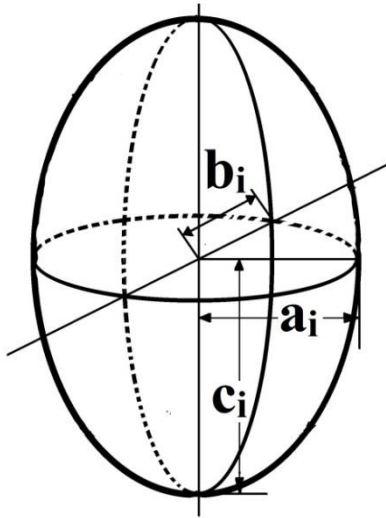


Figure 3.4 An ellipsoidal segment (Nigam and Malik 1987)

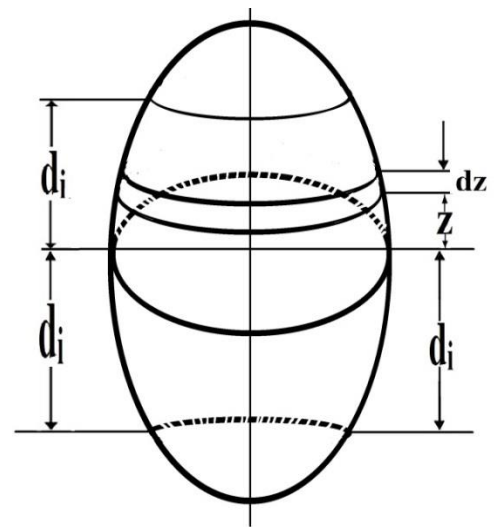


Figure 3.5 Truncated ellipsoid (Nigam and Malik 1987)

Obviously, the smaller the value of truncation factor, more appropriate would be the compromise between the mathematical necessity and overlapping of the connected ellipsoidal segments. 5% truncation factor was used by Nigam and Malik (1987) however, in the present work 1% truncation factor has been used as a matter of conjecture for arriving at a better compromise. The modeling of human body like any other lumped parameter modeling involves following steps:

- i. Segmentation of human body
- ii. Evaluation of mass and stiffness values of individual segments (S_i)
- iii. Evaluating the stiffness of connecting springs (K)

3.2.3 Segmentation of human body

In this model human body has been divided into five segments:

- i. Head and neck have been considered as one segment (m_5)

- ii. Upper torso, upper arms, lower arms and both hands have been incorporated together to form upper body (m_4) and is assumed to be connected with m_5 with a vertical spring having spring stiffness K_{54} .
- iii. Central torso i.e. viscera (m_3) has been considered as an individual segment and is assumed to be connected to m_4 through one vertical and one horizontal spring having spring stiffness of K_{43v} and K_{43h} , respectively.
- iv. Lower torso and upper legs have been considered as integral part (m_2) for a sitting human body and is assumed to be connected to m_4 and m_3 through two vertical springs having stiffness of K_{42} and K_{32} , respectively.
- v. Mass (m_1) consists of a combination of lower legs and feet and m_1 is connected to m_2 through a horizontal spring having stiffness K_{21} .

3.2.4 Evaluation of mass of individual segments

Most of the work reported in the literature shows that for biodynamic modeling, 50th percentile anthropometric data has been taken either for US or European subjects. Likewise, in this study 50th percentile anthropometric data for Indian male subjects (Chakrabarti, 1997) has been considered and is listed in Table 3.2.

The mass of an individual segment is proportional to its volume and can be expressed as a fraction of total body mass. According to Nigam and Malik (1987), if a_i , b_i , and c_i are the semi-axes of an i^{th} ellipsoid, then its mass M_i can be obtained as follows:

$$M_i = M a_i b_i c_i / (\sum_{i=1}^n a_i b_i c_i) \quad (3.1)$$

where, M_i is the mass of an individual (i^{th}) segment, M is the total mass of the body, n is the total number of segments (15) and a_i , b_i , c_i are the semi-axes of the ellipsoid (as shown in Figure 3.4). Formulae used by Nigam and Malik (1987), have been applied on the 50th percentile anthropometric data for Indian male subjects (Chakrabarti, 1997) for evaluating the physical dimensions of the ellipsoids representing body segments a_i , b_i and c_i and are tabulated in Table 3.3. The mass of each ellipsoidal segment for a 15 DOF model is given in Table 3.4 and mass of the segments for the nine DOF model derived after clubbing of masses is given in Table 3.5.

Table 3.2 Anthropometric data (50th Percentile) of Indian male in sitting posture (Chakrabarti 1997)

S. No.	Dimensional data (L _i)		Measurement (mm)
1.	L ₁	Standing height	1648
2.	L ₂	Shoulder height (from seat)	576
3.	L ₃	Armpit height	417
4.	L ₄	Waist height	213
5.	L ₅	Seated height (from seat)	837
6.	L ₆	Head depth	187
7.	L ₇	Head breadth	147
8.	L ₈	Head to chin height	243
9.	L ₉	Neck breadth	112
10.	L ₁₀	Shoulder breadth	380
11.	L ₁₁	Chest depth	209
12.	L ₁₂	Chest breadth	298
13.	L ₁₃	Waist depth	192
14.	L ₁₄	Waist breadth	259
15.	L ₁₅	Buttock circumference	957
16.	L ₁₆	Hip breadth (sitting)	331
17.	L ₁₇	Shoulder to elbow length	312
18.	L ₁₈	Forearm length	243
19.	L ₁₉	Biceps circumference	244
20.	L ₂₀	Elbow circumference	273
21.	L ₂₁	Forearm circumference	228
22.	L ₂₂	Wrist circumference	156
23.	L ₂₃	Knee height seated	519
24.	L ₂₄	Thigh breadth	129
25.	L ₂₅	Upper leg length	127
26.	L ₂₆	Knee circumference	351
27.	L ₂₇	Calf circumference	319
28.	L ₂₈	Ankle circumference	239
29.	L ₂₉	Ankle height outside	61
30.	L ₃₀	Foot breadth	94
31.	L ₃₁	Foot depth	248
32.	L ₃₂	Neck height	43
33.	L ₃₃	Upper leg length (buttock to knee length)	558
34.	L ₃₄	Neck length	86
35.	L ₃₅	Lower lumbar length	101
36.	L ₃₆	Abdomen depth	217
37.	L ₃₇	Elbow to elbow (closed)	409
38.	L ₃₈	Abdomen breadth	260
39.	L ₃₉	Elbow rest	188
40.	L ₄₀	Lower leg height	425
41.	L ₄₁	Foot height	61
42.	L ₄₂	Head circumference	544
43.	L ₄₃	Head height	219
44.	L ₄₄	Hand length	180

Table 3.3 Formulae for physical dimensions of the ellipsoids representing body segments

S. No.	Body segments	Symbol	Mass elements	Depth (X) a_i (mm)		Breadth (Y) b_i (mm)		Height (Z) c_i (mm)	
				Formula	Value	Formula	Value	Formula	Value
1.	Head	H	M_1	$L_6/2$	93.50	$L_7/2$	73.50	$L_{43}/2$	106.50
2.	Neck	N	M_2	$L_9/2$	56.00	$L_9/2$	56.00	$(L_5-L_2-L_{43})/2$	24.00
3.	Upper Torso	UT	M_3	$L_{11}/2$	104.50	$L_{12}/2$	149.00	$(L_{17})/2$	156.00
4.	Central Torso	CT	M_8	$L_{36}/2$	108.50	$L_{38}/2$	13.00	$(L_{17}+L_{18}+L_{44})/4$	183.75
5.	Lower Torso	LT	M_9	$L_{15}/2\pi$	152.30	$L_{16}/2$	165.50	$(L_{18}+L_{44})/4$	105.75
6.	Upper Arm	UA	M_4, M_5	$L_{19}/2\pi$	38.80	$L_{19}/2\pi$	38.80	$L_{17}/2$	156.00
7.	Lower Arm	LA	M_6, M_7	$L_{21}/2\pi$	38.80	$L_{21}/2\pi$	38.80	$(L_{18} + L_{44})/2$	211.50
8.	Upper Leg	UL	M_{10}, M_{11}	$(L_{33}/2)$	279.00	$L_{25}/2$	63.50	$L_{25}/2$	63.50
9.	Lower Leg	LL	M_{12}, M_{13}	$L_{27}/2\pi$	50.77	$L_{27}/2\pi$	50.77	$(L_{40})/2$	212.50
10.	Feet	F	M_{14}, M_{15}	$L_{31}/2$	124.00	$L_{30}/2$	47.00	$L_{41}/2$	30.50

Table 3.4 Mass of ellipsoidal segments for a 15 DOF model

S. No.	Body segment	Symbol	Mass elements	Value (kg)
1.	Head	H	M_1	2.97
2.	Neck	N	M_2	0.29
3.	Upper Torso	UT	M_3	9.86
4.	Right Upper Arm	RUA	M_4	0.95
5.	Left Upper Arm	LUA	M_5	0.95
6.	Right Lower Arm	RLA	M_6	1.29
7.	Left Lower Arm	LLA	M_7	1.29
8.	Central Torso	CT	M_8	10.52
9.	Lower Torso	LT	M_9	10.82
10.	Right Upper Leg	RUL	M_{10}	4.57
11.	Left Upper Leg	LUL	M_{11}	4.57
12.	Right Lower Leg	RLL	M_{12}	2.23
13.	Left Lower Leg	LLL	M_{13}	2.23
14.	Right Foot	RF	M_{14}	0.72
15.	Left Foot	LF	M_{15}	0.72

Table 3.5 Mass of ellipsoidal segments for a 9 DOF model

S. No.	Body segments	Clubbed mass	Formulae	Value (kg)
1.	H+N	m_5	$M_1 + M_2$	3.26
2.	UT+RUA+LUA +RLA+LLA	m_4	$M_3 + M_4 + M_5 + M_6 + M_7$	14.35
3.	CT	m_3	M_8	10.52
4.	LT+RUL+LUL	m_2	$M_9 + M_{10} + M_{11}$	19.96
5.	RLL+LLL+RF+LF	m_1	$M_{12} + M_{13} + M_{14} + M_{15}$	5.90

3.2.4.1 Consideration of mass segments as rigid body

The mass segments have been considered to be rigid elements, though human body is quite a complex structure. A plausible explanation for this could be seen as the longitudinal wave velocity $(E/\rho)^{1/2}$ flowing through a human body under vertical vibrations comes out to be of the order of 110 m/s.

where, elastic modulus of ellipsoidal segments, $E = (E_b E_t)^{1/2} = 13 \text{ MN/m}^2$ (Nigam and Malik 1987), elastic modulus of bones, $E_b = 22.6 \text{ GN/m}^2$ and elastic modulus of tissues, $E_t = 7.5 \text{ kN/m}^2$, (Goldman and Gierke 1961) and bulk average density of different body segments, $\rho = 1.062 \times 10^3 \text{ kg/m}^3$ (Kimberly *et al.* 2010).

Vibration frequencies of less than 100 Hz, would then correspond to a wavelength of over 1m which would normally pass through an average human being without causing any vibratory effect since the wavelength is larger than the human segment dimensions. Thus, it can be easily conjectured that human body can be treated as consisting of rigid body segments up to a frequency of 100 Hz as enunciated in literature (Harris 2002) justifying the lumped parameter modelling.

3.2.4.2 Evaluation of the mass of connecting spring elements (m_s)

Rigid mass and mass-less spring modeling is universally used mostly in all mechanical systems. LPM used by various researchers for analysis of human body vibrations also treat masses as perfectly rigid and springs as mass-less, as per the classical vibration approach. However, it appears reasonable to consider springs to have mass in case of human body vibratory model, as the human body is a complex system with interconnecting tissues, muscles, bones, fats, skin etc.

Therefore, it is hypothesized that considering springs to be mass-less in human body vibration model may not be a right assumption and it would be prudent to take mass of the springs into analysis. In order to take mass of the springs into account, standard vibration text (Grover and Nigam 2009) indicate that one-third of the spring mass need to be added to the mass of the corresponding segment, while evaluating the natural frequency.

Anatomical studies indicate that about 40% of the total mass of human body consists of bones and tissues (Gale Encyclopedia of Food and Culture 2003). These bones and tissues have been considered to provide stiffness to the body segments. So, it can be assumed that mass of each connecting spring (m_s) would be 40% of the mass of corresponding body segment and can be given as

$$m_s = 0.40 \times M_i \quad (3.2)$$

3.2.5 Evaluation of the stiffness of individual segments (S_i)

According to Nigam and Malik (1987), stiffness of individual (i^{th}) segment can be calculated as

$$S_i = (\pi E a_i b_i) / (c_i I_i) \quad (kN/m) \quad (3.3)$$

In this study, to evaluate vertical (S_{iv}) & horizontal stiffness (S_{ih}) of individual (i^{th}) human body (ellipsoidal) segments the above equation has been modified as under:

$$S_{iv} = (\pi E a_i b_i) / (c_i I_i) \quad (kN/m) \quad (3.4)$$

$$S_{ih} = (\pi E b_i c_i) / (a_i I_i) \quad (kN/m) \quad (3.5)$$

Figure 4.4 shows a_i , b_i and c_i , represent x-axis, y-axis and z-axis, respectively. Equation 3.4 has been derived from equation 3.3 in this way. But, when we transform equation from vertical to horizontal axis, 90° transformation takes place. As a result in equation 3.5, a_i becomes b_i , b_i becomes c_i and c_i becomes a_i .

where, E = Elastic modulus of ellipsoidal segments; a_i , b_i , c_i = semi-axes of the ellipsoid (as shown in Figure 3.4) and integral factor I_i is given by

$$I_i = c_i \int_{-d_i}^{d_i} dz / (c_i^2 - z^2) = \log(c_i + d_i) / (c_i - d_i) \quad (3.6)$$

$$= \log((2 - t_r^i) / t_r^i) \quad (3.7)$$

Here, truncation factor is given as

$$t_r^i = 1 - d_i / c_i \quad (3.8)$$

where, d_i = half length of the truncated ellipsoid (as shown in Figure 3.5).

Using equations 3.2 and 3.3, values of vertical (S_{iv}) and horizontal stiffness (S_{ih}) of individual (i^{th}) human body (ellipsoidal) segments for a 15 DOF vibratory model have been evaluated and are given in Table 3.6 and Table 3.7, respectively.

For evaluating vertical (S'_{iv}) and horizontal stiffness (S'_{ih}) of individual body segments for a nine DOF model from (S_{iv}) and (S_{ih}) of a 15 DOF model, the various segments in the human body have been assumed to be physically connected in a series manner and have been tabulated in Table 3.8 and Table 3.9, respectively.

Table 3.6 Vertical stiffness of the segments in vibratory model (15 DOF)

S. No.	Segment stiffness (S_{iv}) (kN/m)	
1.	S_{1v}	498.16
2.	S_{2v}	1052.60
3.	S_{3v}	770.54
4.	S_{4v}	74.49
5.	S_{5v}	74.49
6.	S_{6v}	54.95
7.	S_{7v}	54.95
8.	S_{8v}	592.60
9.	S_{9v}	1840.07
10.	S_{10v}	2153.88
11.	S_{11v}	2153.88
12.	S_{12v}	93.75
13.	S_{13v}	93.75
14.	S_{14v}	1475.15
15.	S_{15v}	1475.15

Table 3.7 Horizontal stiffness of the segments in vibratory model (15 DOF)

S. No.	Segment stiffness (S_{ih}) (kN/m)	
1.	S_{1h}	646.31
2.	S_{2h}	117.56
3.	S_{3h}	1717.16
4.	S_{4h}	1204.32
5.	S_{5h}	1204.32
6.	S_{6h}	1632.78
7.	S_{7h}	1632.78
8.	S_{8h}	1699.64
9.	S_{9h}	887.15
10.	S_{10h}	111.57
11.	S_{11h}	111.57
12.	S_{12h}	1640.50
13.	S_{13h}	1640.50
14.	S_{14h}	89.25
15.	S_{15h}	89.25

Table 3.8 Vertical stiffness of the segments in vibratory model (9 DOF)

S. No.	Segment stiffness (S_{iv}) (kN/m)		
1.	S'_{5v}	$(S_{1v} * S_{2v}) / (S_{1v} + S_{2v})$	338.13
2.	S'_{4v}	$(1 / S'_{4v}) = (1 / S_{3v}) + (1 / \alpha_v) + (1 / \beta_v)$ where, $\alpha_v = (S_{4v} * S_{6v}) / (S_{4v} + S_{6v})$ $\beta_v = (S_{5v} * S_{7v}) / (S_{5v} + S_{7v})$	15.49
3.	S'_{3v}	S_{3v}	770.54
4.	S'_{2v}	$(1 / S'_{2v}) = (1 / S_{9v}) + (1 / S_{10v}) + (1 / S_{11v})$	679.34
5.	S'_{1v}	$(S'_v * S''_v) / (S'_v + S''_v)$ where, $S'_v = (S_{12v} * S_{14v}) / (S_{12v} + S_{14v})$ $S''_v = (S_{13v} * S_{15v}) / (S_{13v} + S_{15v})$	44.07

Table 3.9 Horizontal stiffness of the segments in vibratory model (9 DOF)

S. No.	Segment stiffness (S_{ih}) (kN/m)		
1.	S'_{5h}	$(S_{1h} * S_{2h}) / (S_{1h} + S_{2h})$	139.29
2.	S'_{4h}	$(1 / S'_{4h}) = (1 / S_{3h}) + (1 / \alpha_h) + (1 / \beta_h)$ where, $\alpha_h = (S_{4h} * S_{6h}) / (S_{4h} + S_{6h})$ $\beta_h = (S_{5h} * S_{7h}) / (S_{5h} + S_{7h})$	288.35
3.	S'_{3h}	S_{3h}	1717.16
4.	S'_{2h}	$(1 / S'_{2h}) = (1 / S_{9h}) + (1 / S_{10h}) + (1 / S_{11h})$	52.48
5.	S'_{1h}	$(S'_h * S''_h) / (S'_h + S''_h)$ where, $S'_h = (S_{12h} * S_{14h}) / (S_{12h} + S_{14h})$ $S''_h = (S_{13h} * S_{15h}) / (S_{13h} + S_{15h})$	42.32

3.2.6 Evaluation of stiffness of connecting springs (K_i)

The stiffness (K_i) of springs connecting various body segments (m_1 , m_2 , m_3 , m_4 and m_5) in a nine DOF lumped parameter model (Figure 3.3) have been derived from vertical (S'_{iv}) and horizontal stiffness (S'_{ih}) of individual body segments for a nine DOF model (Table 3.8 and Table 3.9) using suitable combination of stiffness of adjacent body segments and have been presented in Table 3.10.

Table 3.10 Spring stiffness for 9 DOF lumped parameter model

S. No.	Spring element designation	Spring stiffness (K_i) (kN/m)
1.	$K_{54} = (S'_{5v} * S'_{4v}) / (S'_{5v} + S'_{4v})$	14.81
2.	$K_{43v} = (S'_{4v} * S'_{3v}) / (S'_{4v} + S'_{3v})$	15.19
3.	$K_{42} = (S'_{4v} * S'_{2v}) / (S'_{4v} + S'_{2v})$	15.14
4.	$K_{32} = (S'_{3v} * S'_{2v}) / (S'_{3v} + S'_{2v})$	361.04
5.	$K_{2v} = S'_{2v}$	679.34
6.	$K_{1v} = S'_{1v}$	44.07
7.	$K_{43h} = (S'_{4h} * S'_{3h}) / (S'_{4h} + S'_{3h})$	246.89
8.	$K_{2h} = S'_{2h}$	52.49
9.	$K_{21} = (S'_{2h} * S'_{1h}) / (S'_{2h} + S'_{1h})$	23.43
10.	$K_{1h} = S'_{1h}$	42.32

3.2.7 Equations of motion using slippage force term concept

Nine Equations of Motion (EOM's) have been formulated using slippage force term concept which is an offshoot of Free Body Diagram/Newton's Law. Generalized equation using slippage force term concept can be written as:

Inertia force term (for a mass under consideration) + spring force term (corresponding to the end of the spring(s) attached to the mass under consideration (ends of the spring(s) for mass m_1 are: b and c; for m_2 : d and e; for m_3 : f as shown in Figure 3.6)) - slippage force term (corresponding to the far end of the spring(s) attached to the mass under consideration (far ends of the spring(s) for mass m_1 are: a and d; for m_2 : d and e; for m_3 : f as shown in Figure 3.6)) = 0

For a three DOF model (shown in Figure 3.6), as an illustration, the three equations can be developed as:

$$m_1 \ddot{x}_1 + k_1 x_1 + k_2 x_1 - k_1 0 - k_2 x_2 = 0 \quad (3.9)$$

$$m_2 \ddot{x}_2 + k_2 x_2 + k_3 x_2 - k_2 x_1 - k_3 x_3 = 0 \quad (3.10)$$

$$m_3 \ddot{x}_3 + k_3 x_3 - k_3 x_2 = 0 \quad (3.10 \text{ a})$$

The advantage of slippage force term concept is that one need not draw the free body diagrams for a complex multi-degree of freedom system and equations of motion can directly be written by inspection making derivations much simpler.

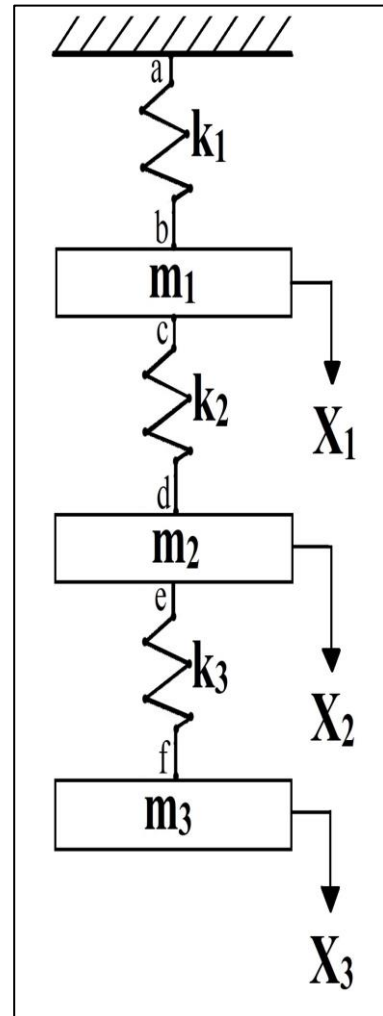


Figure 3.6 Three DOF system

For a nine DOF lumped parameter model of human body for a sitting posture without backrest (shown in Figure 3.3), corresponding 9 EOM's developed are:

$$m_5 \ddot{z}_5 + k_{54}(z_5 - z_4) = 0 \quad (3.11)$$

$$m_4 \ddot{z}_4 + k_{42}(z_4 - z_2) + k_{54}(z_4 - z_5) + k_{43v}(z_4 - z_3) = 0 \quad (3.12)$$

$$m_4 \ddot{x}_4 + k_{43h}(x_4 - x_3) = 0 \quad (3.13)$$

$$m_3 \ddot{z}_3 + k_{32}(z_3 - z_2) + k_{43v}(z_3 - z_4) = 0 \quad (3.14)$$

$$m_3 \ddot{x}_3 + k_{43h}(x_3 - x_4) = 0 \quad (3.15)$$

$$m_2 \ddot{z}_2 + k_{2v}(z_2 - z_0) + k_{32}(z_2 - z_3) + k_{42}(z_2 - z_4) = 0 \quad (3.16)$$

$$m_2 \ddot{x}_2 + k_{2h}(x_2 - x_0) + k_{21}(x_2 - x_1) = 0 \quad (3.17)$$

$$m_1 \ddot{z}_1 + k_{1v}(z_1 - z_0) = 0 \quad (3.18)$$

$$m_1 \ddot{x}_1 + k_{1h}(x_1 - x_0) + k_{21}(x_1 - x_2) = 0 \quad (3.19)$$

Mass matrix obtained from above equations is given below:

$$[M] = \begin{bmatrix} m_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_4 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & m_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_1 \end{bmatrix}$$

Similarly, stiffness matrix is given as:

$$[K] = \begin{bmatrix} K_{54} & -K_{54} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -K_{54} & K_{42} + K_{43v} + K_{54} & 0 & -K_{43v} & 0 & -K_{42} & 0 & 0 & 0 \\ 0 & 0 & K_{43h} & 0 & -K_{43h} & 0 & 0 & 0 & 0 \\ 0 & -K_{43v} & 0 & K_{32} + K_{43v} & 0 & -K_{32} & 0 & 0 & 0 \\ 0 & 0 & -K_{43h} & 0 & K_{43h} & 0 & 0 & 0 & 0 \\ 0 & -K_{42} & 0 & -K_{32} & 0 & K_{2v} + K_{32} + K_{42} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & K_{2h} + K_{21} & 0 & -K_{21} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & K_{1v} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -K_{21} & 0 & K_{1h} + K_{21} \end{bmatrix}$$

The EOM's developed for the present model have been solved using MATLAB programming platform and the matrices obtained for eigen values and eigen vectors are:

Eigen Values:

$$\begin{bmatrix} 16049 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 5353 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1305 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 62542 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 35987 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2846 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10393 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 6618 \end{bmatrix}$$

Eigen Vectors:

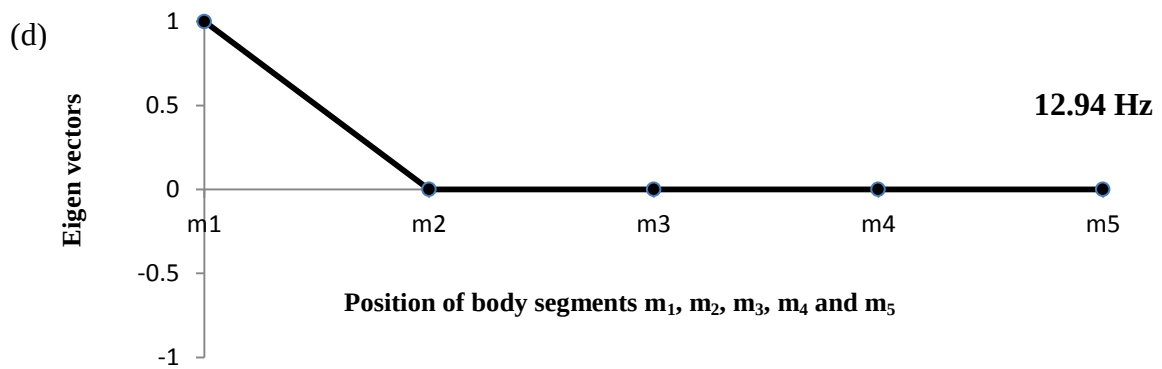
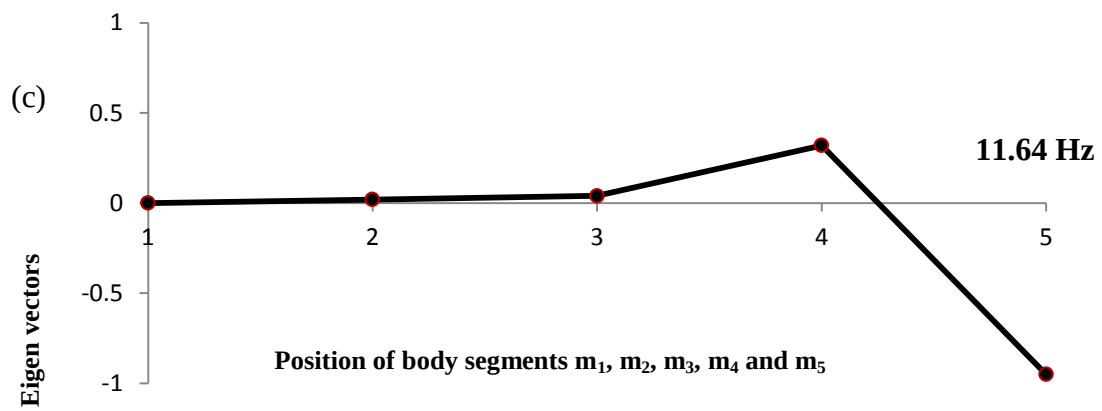
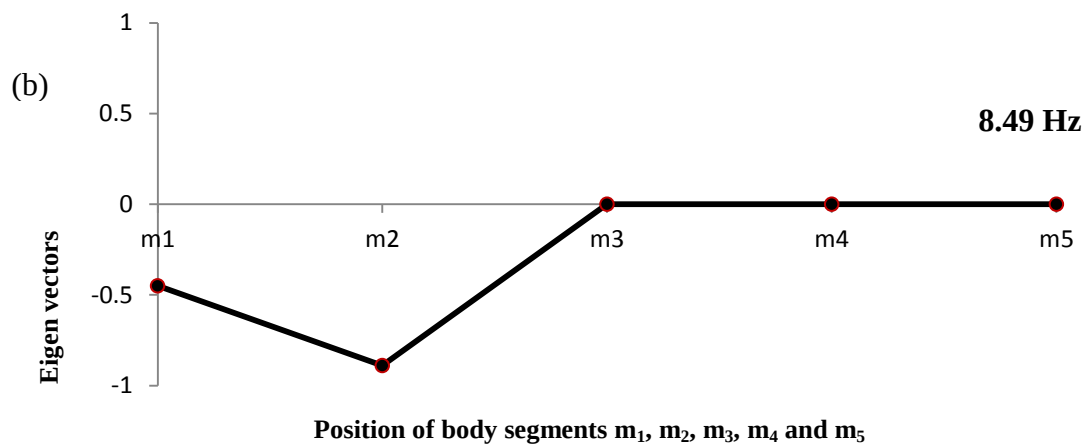
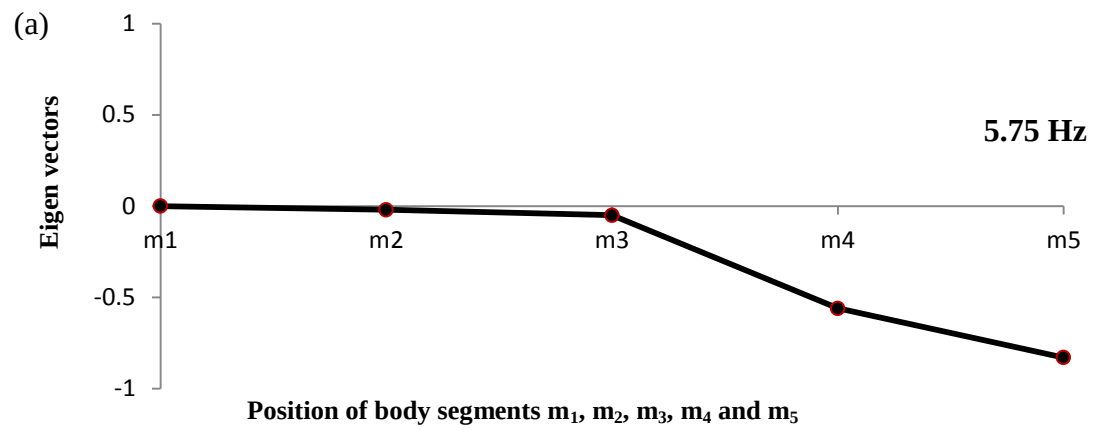
	20.16 Hz	11.64Hz	5.75Hz	39.80 Hz	0 Hz	30.19 Hz	8.49 Hz	16.22 Hz	12.94 Hz
Z ₅ →	-0.03	-0.95	-0.83	0	0	0	0	0	0
Z ₄ →	0.09	0.32	-0.56	0	0	0	0	0	0
X ₄ →	0	0	0	0	0.70	0.59	0	0	0
Z ₃ →	-0.88	0.04	-0.05	-0.70	0	0	0	0	0
X ₃ →	0	0	0	0	0.70	-0.81	0	0	0
Z ₂ →	-0.46	0.02	-0.02	0.71	0	0	0	0	0
X ₂ →	0	0	0	0	0	0	-0.89	0.15	0
Z ₁ →	0	0	0	0	0	0	0	0	1
X ₁ →	0	0	0	0	0	0	-0.45	-0.99	0

Vertical motion
Fore-and-aft motion

In the eigen vector matrix, values in the first four columns indicate the presence of vertical motions (Z₂ to Z₄) in different body segments. In the next five columns it is observed that segments move only in fore and aft direction (X₁ to X₄).

1. From the eigen value and eigen vectors matrices it is clearly seen that a rigid body mode is obtained at a frequency of 0 Hz which indicates that a combination of central torso (m₃)

- and upper torso, upper arms, lower arms and hands (m_4) behave as a single rigid mass in fore and aft direction and the interconnecting spring has no effect on the motion.
2. At fundamental frequency of 5.75 Hz, lower torso and upper legs (m_2), central torso (m_3), combination of upper torso, upper arms and lower arms including hands (m_4) and head and neck (m_5) show vertical motion in same direction only, whereas no motion is observed in lower legs and feet (m_1) resulting into the first mode shape. Motions in m_4 and m_5 are significant whereas m_2 and m_3 show negligible motion (Figure 3.7(a)).
 3. At a frequency of second harmonic 8.49 Hz (Figure 3.7(b)), motion is observed only in lower torso and upper legs (m_2) and lower legs and feet (m_1). Both move along same horizontal direction and no node is observed.
 4. When the body is vibrating under third harmonic vibration (11.64 Hz) all the body segments except lower legs and feet (m_1) show significant motion along vertical direction (Figure 3.7(c)). Head and neck (m_5) move in opposite direction in comparison to lower torso and upper legs (m_2), central torso (m_3) and upper torso, upper arms, lower arms and hands (m_4) and as a result single node is obtained between m_4 and m_5 such that m_4 and m_5 are out of phase by 180° . Magnitude of motion of m_4 and m_5 is quite large as compared to that of m_2 and m_3 .
 5. At 12.94 Hz (Figure 3.7(d)) only vertical motion of lower legs and feet (m_1) is observed and rest of the body motion in vertical and fore and aft direction is absent.
 6. Frequency of 16.22 Hz (Figure 3.7(e)) corresponds to motion along horizontal direction only. Both lower legs and feet (m_1) and lower torso and upper legs (m_2) move in opposite direction resulting in one intermediate node. This clearly indicates that during fore and aft motion when lower legs and feet (m_1) move forward, lower torso and upper legs (m_2) move backwards and vice-versa. Magnitude of m_1 is larger in comparison to that of m_2 .
 7. Two intermediate nodes are obtained at 20.16 Hz (Figure 3.7(f)) resulting in third mode shape indicating that lower torso and upper legs (m_2), central torso (m_3) and head and neck (m_5) move in same vertical direction whereas lower torso and upper legs (m_4) move in opposite vertical direction. This clearly indicates that during vertical motion at about 20 Hz, combination of upper torso, upper arms, lower arms and hands (m_4) and a combination of head and neck (m_5) move relatively in opposite direction. Similarly, m_2 and m_3 move in opposite direction to m_4 . Magnitude of vibration in m_2 and m_3 is quite large as compared to that of m_4 and m_5 .



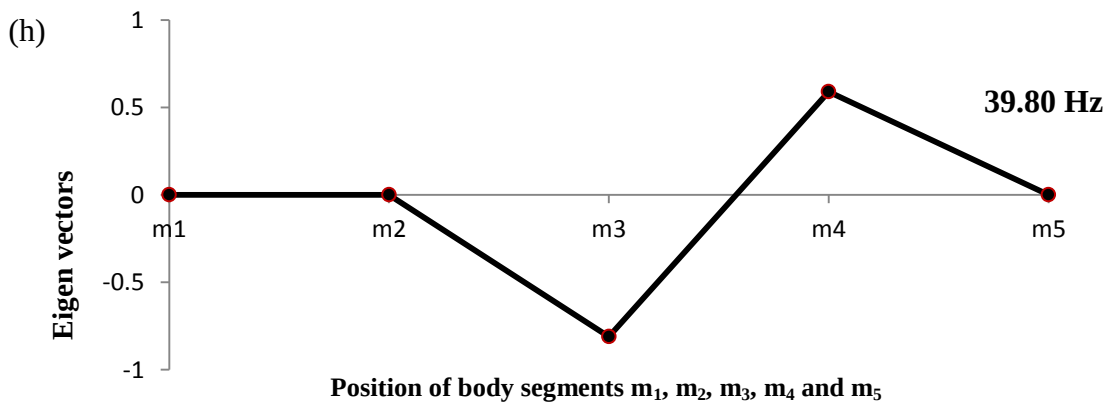
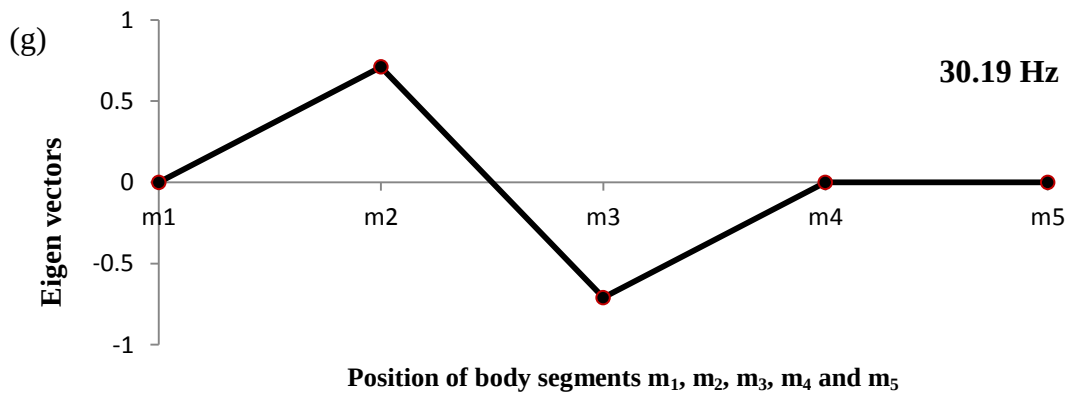
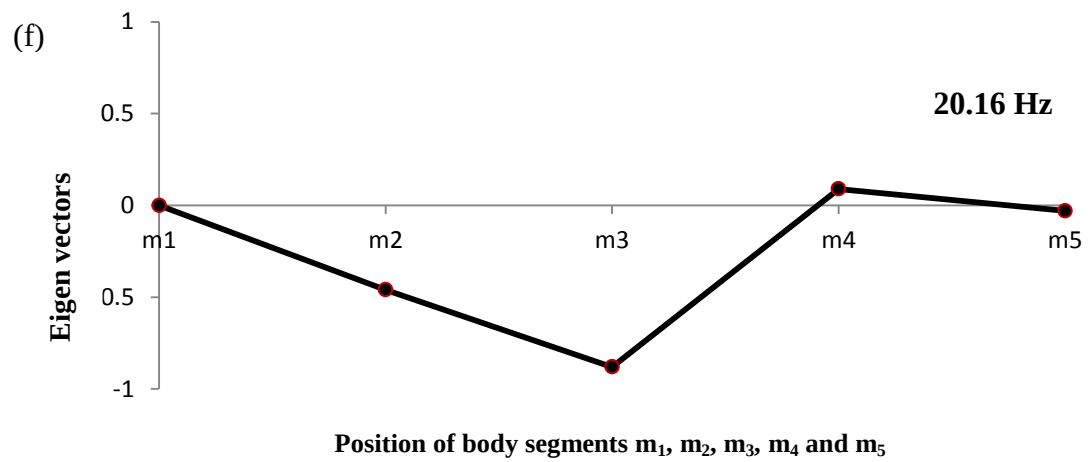
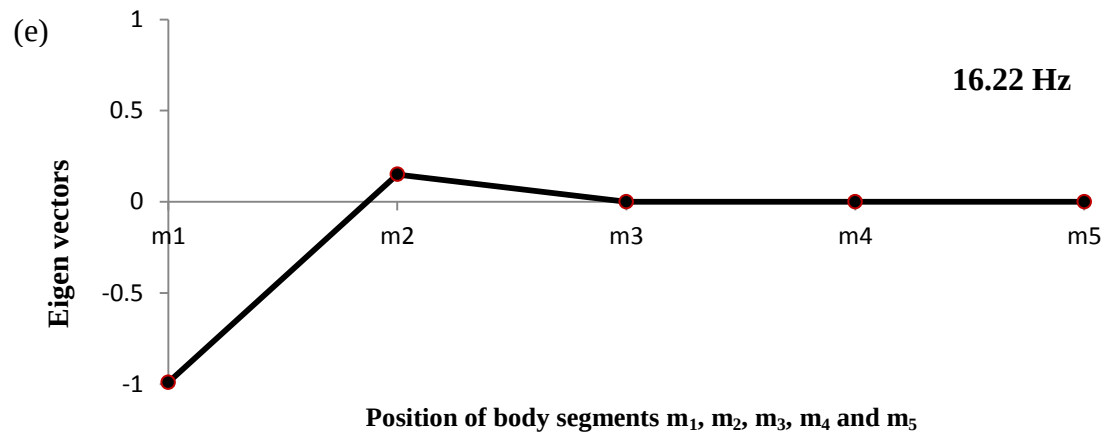


Figure 3.7 Eigen vectors w.r.t. position of body segments

At 30.19 Hz, a single intermediate node is obtained (Figure 3.7(g)) resulting into the second mode shape. Vertical motion is absent and a significant motion occurs along horizontal direction between central torso (m_3) and a combination of upper torso, upper arms, lower arms and hands (m_4). This clearly depicts that during fore and aft motion m_3 and m_4 move along opposite horizontal direction with m_3 is having more magnitude of vibration than m_4 .

8. At 39.80 Hz, second mode shape is obtained resulting in one intermediate node (Figure 3.7(h)) between lower torso and upper legs (m_2) and central torso (m_3) which can be physically interpreted such that m_2 and m_3 show significant motion along vertical axis but always move in opposite direction to each other with almost the same magnitude.

From the above discussion and the shaded region in eigen vector matrix (vertical motion) it is clearly understood that at low frequencies combination of upper torso, upper arms, lower arms and hands (m_4) and head and neck (m_5) show significant motion along vertical direction and with increase in frequency, vibration magnitudes of m_4 and m_5 decrease and finally becomes zero. But, in the same vertical motion block in eigen vector matrix, segments m_2 and m_3 exhibit opposite behaviour, that is, lower torso and upper legs (m_2) and central torso (m_3) have small motion at low frequencies and with increase in frequency their magnitude increases.

As far as fore and aft motion is concerned column five clearly indicates the rigid mode oscillations, since combination of upper torso, upper arms, lower arms and hands (m_4) and central torso (m_3) move in the same direction with same magnitude. At a frequency of 8.49 Hz lower legs and feet (m_1) and lower torso and upper legs (m_2) have substantial motion in same direction but at frequency of 12.94 Hz the only motion is in lower legs and feet (m_1) which is having unity magnitude being the normalising element in this matrix. At the frequency of 16.22 Hz the lower legs and feet (m_1) and lower torso and upper legs (m_2) move in opposite direction with an intermediate node in between. As the frequency further increases to 30.19 Hz the central torso (m_3) and combination of upper torso, upper arms, lower arms and hands (m_4) have a fore and aft motion with an intermediate node.

A look into this matrix clearly indicates decoupling of vertical and fore and aft oscillations. This is typical behaviour of the human subjects in the sitting posture as a frequency dependent phenomenon which can be easily related to the relative motion of the different body segments separately into vertical and fore and aft vibrations.

The results have been compared with the values available in the literature and it was found that the eigen values evaluated in the present work are comparable with the resonant frequency peaks obtained from the experimental data (Harsha *et al.* 2014, Gupta 2007), Kitazaki and Griffin 1997, 1998 and Rutzel *et al.* 2006).

In comparison to the experimental values, frequencies calculated in this study seem to be slightly on higher side, as damping has not been included in the present free vibration analysis.

CHAPTER 4

DETERMINATION OF STHT USING ANALYTICAL MODELLING

4.1 Introduction

A lot of work has been reported in the literature regarding modelling based on 50th percentile anthropometric data. Subsequently, 50th percentile anthropometric data reported by Chakrabarti (1997) for Indian subjects was used for determining eigen values and eigen vectors in the previous chapter. Analytical modelling of 95th percentile anthropometric data from Chakrabarti (1997) which pertains to 76 kg weight of Indian male subjects was done in order to validate it with the experimental investigations.

In this chapter, STHT of seated human male subjects has been determined analytically for the following cases:

1. Without backrest
2. With backrest (inclined at 0°, 15° and 30° to the vertical)
3. With backrest (without and with cushions)

Nine DOF lumped parameter model for a sitting posture without backrest is shown in Figure 3.3 and the corresponding assumptions for the same have been given in section 3.2.1 in the previous chapter. First assumption of the previous model has been modified and damping has been considered in this chapter. Methodology adopted in section 3.2 has been adopted in this chapter to evaluate mass of ellipsoidal segments, spring stiffness and damping coefficients of connecting springs and dashpots for a nine DOF model of a seated human body (without backrest) shown in Figure 4.1. Nomenclature used in this figure is given in Table 4.1.

4.2 Evaluation of mass of individual segments

Anthropometric data for a 76 kg Indian male subject (95th percentile) has been tabulated in table 4.2. Physical dimensions and mass of the ellipsoidal segments for 76 kg Indian male subject have been calculated as per the methodology followed in section 3.2.4 and are given in table 4.3, table 4.4 and table 4.5.

Table 4.1 Symbolic representation of human body model parameters

S. No.	Parameter	Representation
1.	m_5	Head and neck
2.	m_4	Upper torso (including both arms and hands)
3.	m_3	Central torso
4.	m_2	Lower torso and upper legs
5.	m_1	Lower legs and feet
6.	K_{iv}, K_{ih}	Stiffness of vertical and horizontal springs connected to i^{th} mass
7.	C_{iv}, C_{ih}	Damping coefficient of vertical and horizontal dashpots connected to i^{th} mass
8.	$K_{21}, K_{32}, K_{42}, K_{43h}, K_{43v}, K_{54}$	Stiffness of springs connecting various body segments
9.	$C_{21}, C_{32}, C_{42}, C_{43h}, C_{43v}, C_{54}$	Damping coefficient of dashpots connecting various body segments

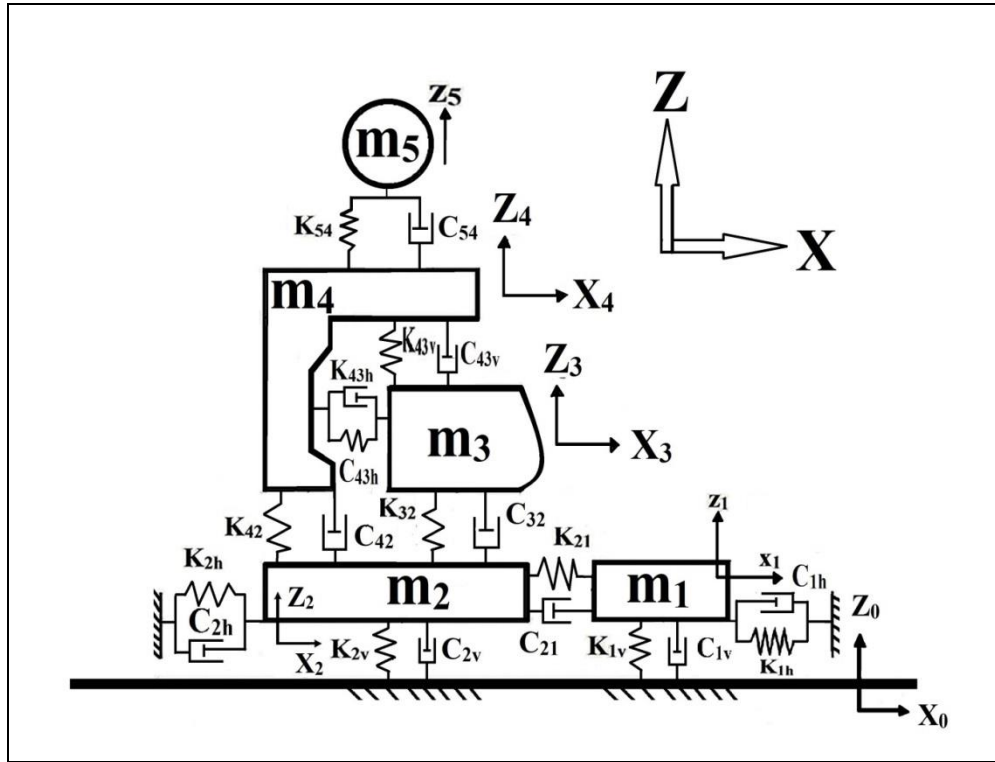


Figure 4.1 Nine DOF lumped parameter model for sitting posture without backrest

Table 4.2 Anthropometric data (95th Percentile) of Indian male in sitting posture (Chakrabarti 1997)

S. No.	Dimensional data (L _i)		Measurement (mm)
1.	L ₁	Standing height	1781
2.	L ₂	Shoulder height (from seat)	634
3.	L ₃	Armpit height	476
4.	L ₄	Waist height	270
5.	L ₅	Seated height (from seat)	905
6.	L ₆	Head depth	199
7.	L ₇	Head breadth	157
8.	L ₈	Head to chin height	257
9.	L ₉	Neck breadth	128
10.	L ₁₀	Shoulder breadth	422
11.	L ₁₁	Chest depth	254
12.	L ₁₂	Chest breadth	356
13.	L ₁₃	Waist depth	275
14.	L ₁₄	Waist breadth	317
15.	L ₁₅	Buttock circumference	1164
16.	L ₁₆	Hip breadth (sitting)	405
17.	L ₁₇	Shoulder to elbow length	356
18.	L ₁₈	Forearm length	289
19.	L ₁₉	Biceps circumference	301
20.	L ₂₀	Elbow circumference	320
21.	L ₂₁	Forearm circumference	264
22.	L ₂₂	Wrist circumference	177
23.	L ₂₃	Knee height seated	567
24.	L ₂₄	Thigh breadth	164
25.	L ₂₅	Upper leg length	158
26.	L ₂₆	Knee circumference	414
27.	L ₂₇	Calf circumference	377
28.	L ₂₈	Ankle circumference	274
29.	L ₂₉	Ankle height outside	71
30.	L ₃₀	Foot breadth	122
31.	L ₃₁	Foot depth	274
32.	L ₃₂	Neck height	80
33.	L ₃₃	Upper leg length (buttock to knee length)	615
34.	L ₃₄	Neck length	121
35.	L ₃₅	Lower lumbar length	156
36.	L ₃₆	Abdomen depth	302
37.	L ₃₇	Elbow to elbow (closed)	489
38.	L ₃₈	Abdomen breadth	327
39.	L ₃₉	Elbow rest	221
40.	L ₄₀	Lower leg height	471
41.	L ₄₁	Foot height	71
42.	L ₄₂	Head circumference	574
43.	L ₄₃	Head height	226
44.	L ₄₄	Hand length	198

Table 4.3 Physical dimensions of the ellipsoids representing body segments

S. No.	Body segment	Symbol	Mass elements	Depth (X) a_i (mm)	Breadth (Y) b_i (mm)	Height (Z) c_i (mm)
1.	Head	H	M_1	99.50	78.50	113.00
2.	Neck	N	M_2	64.00	64.00	22.50
3.	Upper Torso	UT	M_3	127.00	178.00	178.00
4.	Central Torso	CT	M_8	151.00	163.50	210.75
5.	Lower Torso	LT	M_9	185.25	202.50	121.75
6.	Upper Arm	UA	M_4, M_5	47.90	47.90	178.00
7.	Lower Arm	LA	M_6, M_7	42.01	42.01	243.50
8.	Upper Leg	UL	M_{10}, M_{11}	307.50	79.00	79.00
9.	Lower Leg	LL	M_{12}, M_{13}	60.00	60.00	235.50
10.	Feet	F	M_{14}, M_{15}	137.00	61.00	35.50

Table 4.4 Mass of ellipsoidal segments for a 15 DOF model

S. No.	Body segment	Symbol	Mass elements	Value (kg)
1.	Head	H	M_1	2.97
2.	Neck	N	M_2	0.31
3.	Upper Torso	UT	M_3	13.54
4.	Right Upper Arm	RUA	M_4	1.37
5.	Left Upper Arm	LUA	M_5	1.37
6.	Right Lower Arm	RLA	M_6	1.45
7.	Left Lower Arm	LLA	M_7	1.45
8.	Central Torso	CT	M_8	17.52
9.	Lower Torso	LT	M_9	15.38
10.	Right Upper Leg	RUL	M_{10}	6.46
11.	Left Upper Leg	LUL	M_{11}	6.46
12.	Right Lower Leg	RLL	M_{12}	2.85
13.	Left Lower Leg	LLL	M_{13}	2.85
14.	Right Foot	RF	M_{14}	0.99
15.	Left Foot	LF	M_{15}	0.99

Table 4.5 Mass of ellipsoidal segments for a 9 DOF model

S. No.	Body segments	Clubbed mass	Formulae	Value (kg)
1.	H+N	m_5	$M_1 + M_2$	3.28
2.	UT+RUA+LUA +RLA+LLA	m_4	$M_3 + M_4 + M_5 + M_6 + M_7$	19.19
3.	CT	m_3	M_8	17.51
4.	LT+RUL+LUL	m_2	$M_9 + M_{10} + M_{11}$	28.30
5.	RLL+LLL+RF+LF	m_1	$M_{12} + M_{13} + M_{14} + M_{15}$	7.70

4.3 Evaluation of the stiffness of individual segments (S_i)

Based on the methodology adopted in section 3.2.5 both vertical and horizontal stiffness of the ellipsoidal segments (S_{iv} and S_{ih}) have been evaluated analytically and are tabulated in table 4.6 and table 4.7.

Table 4.6 Vertical and horizontal stiffness of the segments in vibratory model (15 DOF)

S. No.	Segment stiffness (S_{iv}) (kN/m)		Segment stiffness (S_{ih}) (kN/m)	
1.	S_{1v}	533.62	S_{1h}	688.24
2.	S_{2v}	1405.38	S_{2h}	173.70
3.	S_{3v}	980.44	S_{3h}	1925.98
4.	S_{4v}	99.53	S_{4h}	1374.16
5.	S_{5v}	99.53	S_{5h}	1374.16
6.	S_{6v}	55.97	S_{6h}	1879.82
7.	S_{7v}	55.97	S_{7h}	1879.82
8.	S_{8v}	904.36	S_{8h}	1761.67
9.	S_{9v}	2378.74	S_{9h}	1027.39
10.	S_{10v}	2373.90	S_{10h}	156.68
11.	S_{11v}	2373.90	S_{11h}	156.68
12.	S_{12v}	118.02	S_{12h}	1818.06
13.	S_{13v}	118.02	S_{13h}	1818.06
14.	S_{14v}	1817.35	S_{14h}	122.02
15.	S_{15v}	1817.35	S_{15h}	122.02

Table 4.7 Vertical and horizontal stiffness of the segments in vibratory model (9 DOF)

S. No.	Segment stiffness (S_{iv}) (kN/m)		Segment stiffness (S_{ih}) (kN/m)	
1.	S'_{5v}	386.76	S'_{5h}	138.69
2.	S'_{4v}	17.59	S'_{4h}	329.10
3.	S'_{3v}	980.44	S'_{3h}	1925.99
4.	S'_{2v}	791.84	S'_{2h}	72.79
5.	S'_{1v}	55.41	S'_{1h}	57.18

4.4 Evaluation of damping of individual segments (C_i)

Damping ratio (ξ) values in the present study have been taken from the existing literature (Gupta 2007) and have been iterated to obtain a best fit response and are tabulated in table 4.8.

According to classical theory of vibration for a single degree of freedom (SDOF) system, relationship between damping coefficient, damping ratio, stiffness and mass is given by equation 4.1.

$$C_i = 2\xi_i\sqrt{S_iM_i} \quad (4.1)$$

where, C_i is damping coefficient, ξ_i is damping ratio, S_i is stiffness and M_i = mass of individual (i^{th}) human body segment.

Using this relation, the vertical and horizontal damping coefficients (C_{iv} and C_{ih}) of the individual human body (ellipsoidal) segments, have been evaluated and are given in tables 4.9 and 4.10.

Table 4.8 Damping ratio of ellipsoidal segments for a 15 DOF model

S. No.	Body segment	Symbol	Mass elements	Damping Ratio (ξ)
1.	Head	H	M_1	0.004
2.	Neck	N	M_2	0.015
3.	Upper Torso	UT	M_3	0.015
4.	Right Upper Arm	RUA	M_4	0.01
5.	Left Upper Arm	LUA	M_5	0.01
6.	Right Lower Arm	RLA	M_6	0.01
7.	Left Lower Arm	LLA	M_7	0.01
8.	Central Torso	CT	M_8	0.4
9.	Lower Torso	LT	M_9	0.8
10.	Right Upper Leg	RUL	M_{10}	1.0
11.	Left Upper Leg	LUL	M_{11}	1.0
12.	Right Lower Leg	RLL	M_{12}	1.25
13.	Left Lower Leg	LLL	M_{13}	1.25
14.	Right Foot	RF	M_{14}	1.25
15.	Left Foot	LF	M_{15}	1.25

Table 4.9 Vertical and horizontal damping coefficients of the segments in vibratory model (15 DOF)

S. No.	Segment damping (C_{iv}) (kNs/m)		Segment damping (C_{ih}) (kNs/m)	
1.	C_{1v}	0.32	C_{1h}	0.36
2.	C_{2v}	0.62	C_{2h}	0.22
3.	C_{3v}	3.46	C_{3h}	4.84
4.	C_{4v}	0.23	C_{4h}	0.87
5.	C_{5v}	0.23	C_{5h}	0.87
6.	C_{6v}	0.18	C_{6h}	1.04
7.	C_{7v}	0.18	C_{7h}	1.04
8.	C_{8v}	100.69	C_{8h}	140.54
9.	C_{9v}	306.01	C_{9h}	201.11
10.	C_{10v}	247.69	C_{10h}	63.63
11.	C_{11v}	247.69	C_{11h}	63.63
12.	C_{12v}	45.88	C_{12h}	180.09
13.	C_{13v}	45.88	C_{13h}	180.09
14.	C_{14v}	106.51	C_{14h}	27.60
15.	C_{15v}	106.51	C_{15h}	27.60

Table 4.10 Vertical and horizontal damping coefficients of the segments in vibratory model (9 DOF)

S. No.	Segment damping (C_{iv}) (kNs/m)		Segment damping (C_{ih}) (kNs/m)	
1.	C_{5v}	0.21	C_{5h}	0.14
2.	C_{4v}	0.05	C_{4h}	0.43
3.	C_{3v}	3.46	C_{3h}	4.84
4.	C_{2v}	88.17	C_{2h}	27.47
5.	C_{1v}	16.04	C_{1h}	11.97

4.5 Evaluation of stiffness of connecting springs and damping of connecting dashpots

The stiffness of springs connecting various body segments (m_1 , m_2 , m_3 , m_4 and m_5) in a nine DOF lumped parameter model (Figure 4.1) have been evaluated using the methodology adopted in section 3.2.6. Same methodology has been adopted for evaluating damping coefficients of connecting dashpots also and has been presented in table 4.11. Sensitivity analysis indicated that C_{54} , C_{42} and C_{2v} affect STHT more critically. Non-linearity associated and lack of ability to determine actual values of damping coefficients corresponding to the human body affect STHT plots in some cases.

Table 4.11 Model parameters for a seated human subject (without backrest)

Mass (kg)		Spring Stiffness (kN/m)		Damping Coefficient (kNs/m)	
Symbol	Value	Symbol	Value	Symbol	Value
m_5	3.28	K_{54}	16.83	C_{54}	0.12
m_4	19.19	K_{43v}	17.28	C_{43v}	0.05
m_3	17.51	K_{42}	17.21	C_{42}	0.60
m_2	28.30	K_{32}	438.05	C_{32}	3.33
m_1	7.70	K_{2v}	791.84	C_{2v}	28.16
		K_{1v}	55.41	C_{1v}	16.04
		K_{43h}	281.07	C_{43h}	0.39
		K_{2h}	72.79	C_{2h}	27.47
		K_{21}	32.02	C_{21}	8.34
		K_{1h}	57.17	C_{1h}	11.97

4.6 Equations of motion

A nine degree of freedom lumped parameter model for a seated human body without backrest has been shown in Figure 4.1 and symbolic representation of the corresponding parameters is given in Table 4.1. Each mass has its own local coordinates in terms of vertical and fore and aft axis. Complete model has its own coordinate system which may be called as a global coordinate system. Figure 3.3 shows the same model for the case of free vibrations whereas, in the lumped parameter model shown in Figure 4.1 damping has been included for analytical determination of seat to head transmissibility in case of forced vibrations.

Damping coefficients have been introduced in all the equations of motion. Damping matrix and force matrix have been introduced to include the effect of damping and force for determination of STHT. Seated human male subject sitting erect (without backrest) is exposed to vertical harmonic vibrations at different vibration magnitudes and excitation frequencies. All human body segments considered in the study are connected with each other by interconnecting springs and dashpots.

Vertical harmonic vibrations were given to seat and the corresponding response at head was determined analytically in terms of vibrations transmitted to head through the body.

Nine equations of motion describing the system dynamic behavior have been derived for all the models using slippage force term concept. General equation of motion representing multi degree of freedom lumped parameter model can be given as:

$$[M] [\ddot{Z}] + [C] [\dot{Z}] + [K] [Z] = [F] \quad (4.2)$$

where, $[M]$, $[C]$ and $[K]$ are mass, damping and stiffness matrices, respectively, $[\ddot{Z}]$, $[\dot{Z}]$ and $[Z]$ are acceleration, velocity and displacement vectors for each segment and $[F]$ is the force matrix. $[M]$, $[C]$, $[K]$ and $[F]$ matrix obtained in this case are as under:

Mass Matrix, [M] =

$$\begin{bmatrix} m_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & m_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & m_5 \end{bmatrix}$$

Damping Matrix, [C] =

$$\begin{bmatrix} a_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_1 & 0 & -C_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & c_1 & 0 & C_{32} & 0 & -C_{42} & 0 & 0 \\ 0 & -C_{21} & 0 & d_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -C_{32} & 0 & e_1 & 0 & -C_{43v} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & f_1 & 0 & -C_{43h} & 0 \\ 0 & 0 & -C_{42} & 0 & -C_{43v} & 0 & g_1 & 0 & -C_{54} \\ 0 & 0 & 0 & 0 & 0 & -C_{43h} & 0 & h_1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -C_{54} & 0 & i_1 \end{bmatrix}$$

where, $a_1 = C_{1v}$, $b_1 = C_{21} + C_{1h}$, $c_1 = C_{2v} + C_{42} + C_{32}$, $d_1 = C_{21} + C_{2h}$, $e_1 = C_{32} + C_{43v}$, $f_1 = C_{43h}$, $g_1 = C_{42} + C_{4v} + C_{54} + C_{43v}$, $h_1 = C_{4h} + C_{43h}$, $i_1 = C_{54}$

Stiffness Matrix, [K] =

$$\begin{bmatrix} a_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & b_2 & 0 & -K_{21} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & c_2 & 0 & -K_{32} & 0 & -K_{42} & 0 & 0 \\ 0 & -K_{21} & 0 & d_2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -K_{32} & 0 & e_2 & 0 & -K_{43v} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & f_2 & 0 & -K_{43h} & 0 \\ 0 & 0 & -K_{42} & 0 & -K_{43v} & 0 & g_2 & 0 & -K_{54} \\ 0 & 0 & 0 & 0 & 0 & -K_{43h} & 0 & h_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -K_{54} & 0 & i_2 \end{bmatrix}$$

where, $a_2 = K_{1v}$, $b_2 = K_{21} + K_{1h}$, $c_2 = K_{2v} + K_{42} + K_{32}$, $d_2 = K_{21} + K_{2h}$, $e_2 = K_{32} + K_{43v}$, $f_2 = K_{43h}$, $g_2 = K_{42} + K_{43v} + K_{54}$, $h_2 = K_{43h}$, $i_2 = K_{54}$

External Excitation, [F] =

$$\begin{bmatrix} 0 \\ 0 \\ F \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

4.7 Determination of STHT for sitting posture without backrest

Seat to Head Transmissibility (STHT) is a measure of vibration flowing through the body and is the ratio of acceleration at the head $a_{head}(f)$ to the acceleration at the seat $a_{seat}(f)$ at a particular frequency (f) in vertical direction (Griffin 1990) and is given by Eq. 4.3.

$$STHT = \frac{a_{head}(f)}{a_{seat}(f)} \quad (4.3)$$

where,

$a_{head}(f)$ = acceleration at head measured in vertical direction

$a_{seat}(f)$ = acceleration at seat measured in vertical direction

STHT is a complex ratio between the vertical acceleration at head (output) to the vertical acceleration at the seat (input) and has been determined analytically using MATLAB programming platform. Model parameters evaluated (table 4.11) and equations of motion and matrices have been given as input in MATLAB for analytical determination of STHT and the plot obtained is shown in Figure 4.2.

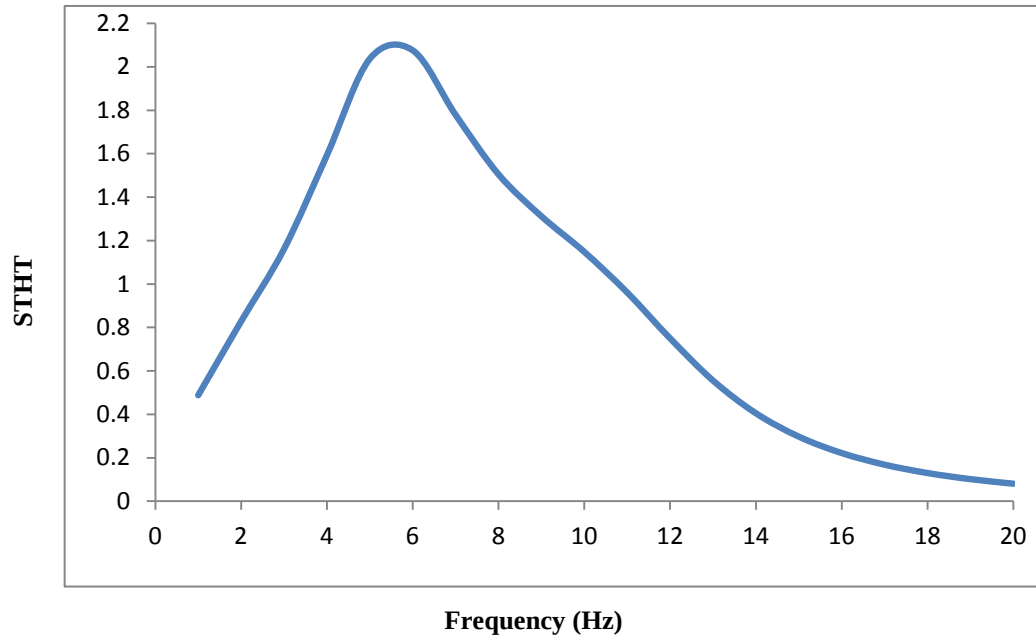


Figure 4.2 STHT of lumped parameter model for sitting posture without backrest

4.7.1 Effect of vibration magnitude

For a lumped parameter model sitting without backrest (erect posture), seat to head transmissibility values were determined analytically when vertical harmonic vibrations were applied at seat. It was clearly noticed that for the three vibration magnitudes (0.5, 1.0 and 1.5 m/s^2) STHT values evaluated were same. For all the vibration magnitudes given at seat as input the corresponding change in absolute acceleration values determined at head as output was almost the same. So, with increase in vibration magnitude at seat, almost the same increase was noticed at head. Since STHT is a ratio of two vibration magnitudes in terms of acceleration, the net result came out to be nearly same. As a result, STHT plots obtained for all the three vibration magnitudes considered in the study overlap with each other.

4.7.2 Effect of excitation frequency

STHT peak value of 2.12 occurs at a frequency of 5 Hz which corresponds to the primary natural frequency of the human body. Beyond 11 Hz attenuation in STHT is observed with a progressive decrease in STHT as frequency increases.

4.8 Determination of STHT for sitting posture with backrest

Lumped parameter model for a seated posture with backrest inclined at 0° with the vertical axis is shown in Figure 4.3.

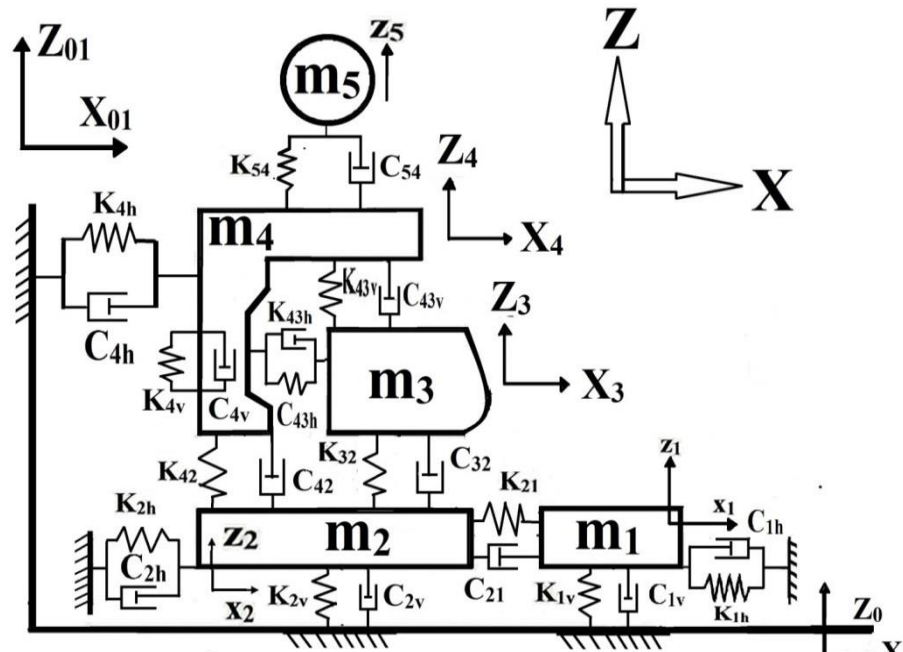


Figure 4.3 Nine DOF lumped parameter model for sitting posture with backrest

Table 4.12 Model parameters for a rigid seat with backrest inclined at 0° to the vertical

Mass (kg)		Spring Stiffness (kN/m)		Damping Coefficient (kNs/m)	
Symbol	Value	Symbol	Value	Symbol	Value
m_5	3.28	K_{54}	16.83	C_{54}	0.12
m_4	19.19	K_{43v}	17.28	C_{43v}	0.05
m_3	17.51	K_{42}	17.21	C_{42}	0.60
m_2	28.30	K_{32}	438.05	C_{32}	3.33
m_1	7.70	K_{2v}	791.84	C_{2v}	38.17
		K_{1v}	55.41	C_{1v}	16.04
		K_{43h}	281.07	C_{43h}	0.39
		K_{2h}	72.79	C_{2h}	27.47
		K_{21}	32.02	C_{21}	8.34
		K_{1h}	57.17	C_{1h}	11.97
		K_{4v}	17.59	C_{4v}	0.05
		K_{4h}	329.10	C_{4h}	0.43

Due to addition of backrest in this model, one additional set of spring and dashpot each in vertical as well as horizontal direction needs to be considered along with the back and backrest. Effect of K_{4v} , K_{4h} , C_{4v} and C_{4h} was taken into account and corresponding changes were made in the respective equations of motion, stiffness matrix and damping matrix. Addition of backrest in the model resulted in addition of two new spring-dashpot combinations K_{4v} , C_{4v} and K_{4h} , C_{4h} and the corresponding values are given in table 4.12.

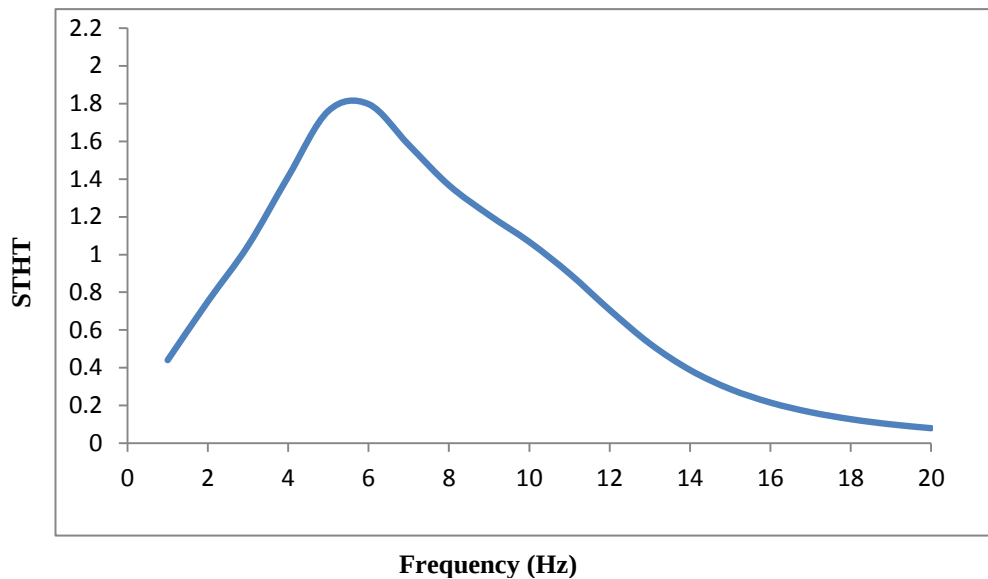


Figure 4.4 STHT of lumped parameter model for sitting posture with backrest

Variation of seat to head transmissibility with respect to frequency of lumped parameter model for a sitting posture seated on a rigid seat with backrest inclined at 0° to the vertical is shown in Figure 4.4.

Effect of variation in vibration magnitude on STHT over the frequency range 1 to 20 Hz is nearly the same for all the cases considered as explained in section 4.7.1. STHT peak value of 1.83 occurs at a frequency of 5.5 Hz which lies in the range of 4 to 6 Hz corresponding to the primary natural frequency of human body. Attenuation in STHT is observed beyond 10 Hz with a progressive decrease in STHT as frequency increases.

The comparison of STHT without and with backrest support indicates a considerable decrease in its value. From Figure 4.2 and 4.4, it was observed that STHT value decreases by 13.68 % when backrest is used.

4.9 Determination of STHT for seated subjects with inclined (α) backrest

Lumped parameter model for a seated posture with inclined backrest (α) with the vertical axis is shown in Figure 4.5. Due to backrest inclined in the anticlockwise direction w.r.t. vertical axis, both vertical and horizontal combinations of springs and dashpots are also inclined at same angle and in the same direction. Component of K and C in the direction of motion are to be accounted for as $K \cos^2 \alpha$ and $C \cos \alpha$, respectively in both vertical and horizontal direction. Backrest inclination angles considered in the study are 15° and 30° with the vertical axis.

These two backrest inclination angles were selected based on the fact during travelling backrest of passengers is inclined in the range of 0° to 30° with the vertical axis. Mathematical models in the existing literature consider only spring and dashpot combination (i.e. K_{4v} , K_{4h} , C_{4v} and C_{4h}) attached directly between upper torso (m_5) and backrest to be inclined. The mathematical model undertaken in the present research work for inclined backrest in case of rigid and cushioned seats, considers springs and dashpots attached to the head and neck (m_5), upper torso (m_4) and central torso (m_3) as inclined to get a more realistic model. Accordingly, necessary changes were made in the respective equations of motion, stiffness matrix and damping matrix.

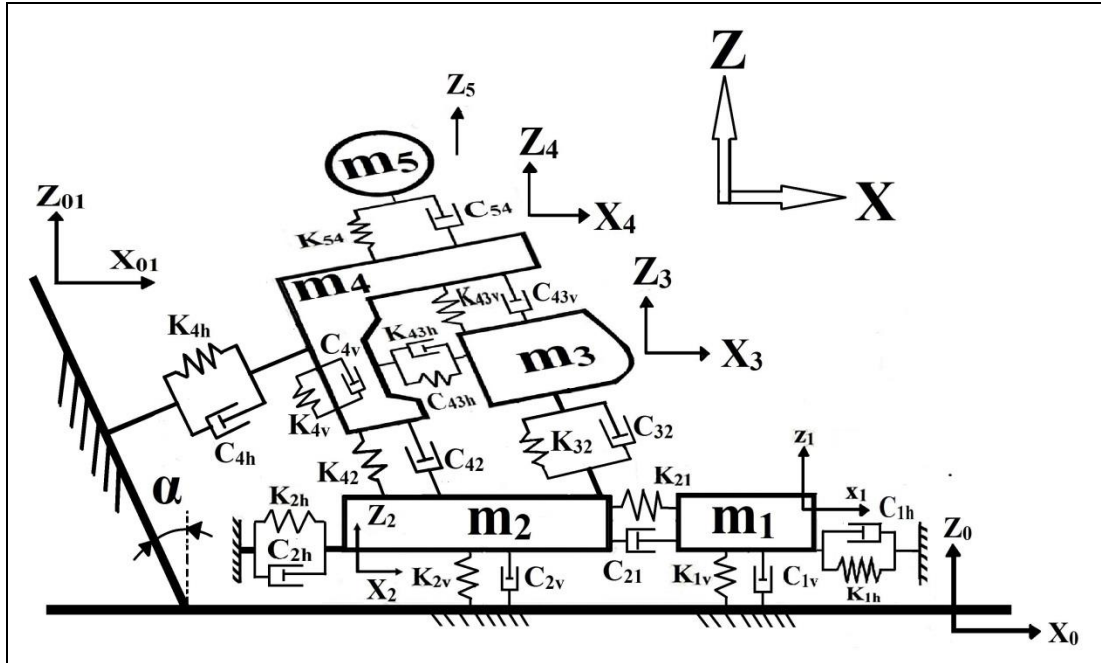


Figure 4.5 Nine DOF lumped parameter model for sitting posture with inclined (α) backrest

With backrest inclined at an angle α with the vertical, m_3 , m_4 and m_5 are inclined and the corresponding values of spring-dashpot combinations have been calculated and are given in table 4.13.

Table 4.13 Model parameters for a rigid seat with backrest inclined at 15° and 30° to the vertical

Mass (kg)		Spring Stiffness (kN/m)			Damping Coefficient (kNs/m)		
Symbol	Value	Symbol	$\alpha = 15^\circ$	$\alpha = 30^\circ$	Symbol	$\alpha = 15^\circ$	$\alpha = 30^\circ$
m_5	3.28	K_{54}	15.70	12.62	C_{54}	0.12	0.12
m_4	19.19	K_{43v}	16.12	12.96	C_{43v}	0.05	0.04
m_3	17.51	K_{42}	16.06	12.90	C_{42}	0.50	0.50
m_2	28.30	K_{32}	408.70	328.54	C_{32}	3.21	2.88
m_1	7.70	K_{2v}	791.84	791.84	C_{2v}	58.17	53.17
		K_{1v}	55.41	55.41	C_{1v}	16.04	16.04
		K_{43h}	262.24	210.80	C_{43h}	0.37	0.34
		K_{2h}	72.79	72.79	C_{2h}	27.47	27.47
		K_{21}	32.02	32.02	C_{21}	8.34	8.34
		K_{1h}	57.17	57.17	C_{1h}	11.97	11.97
		K_{4v}	16.41	13.19	C_{4v}	0.05	0.04
		K_{4h}	307.05	246.82	C_{4h}	0.42	0.37

For a rigid seat with backrest inclined at 15° and 30° to the vertical, variation in seat to head transmissibility with respect to frequency is shown in Figure 4.6.

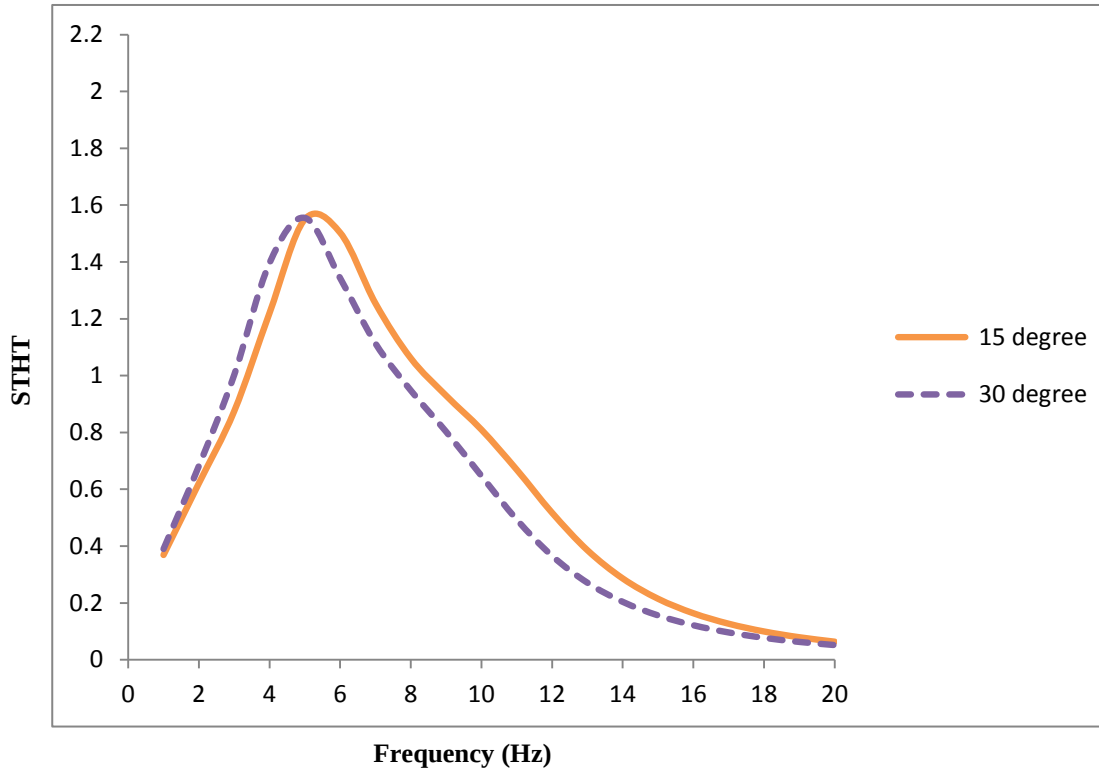


Figure 4.6 STHT of lumped parameter model for sitting posture with inclined (α) backrest

For backrest inclination angle of 15°, STHT peak value of 1.58 was observed at a frequency of 4.5 Hz and for backrest inclination angle of 30°, STHT peak value of 1.55 was observed, both at a frequency of 5 Hz which corresponds to the primary natural frequency of human body. Attenuation in STHT is observed beyond 8.5 Hz and 7.5 Hz in case of backrest inclination of 15° and 30°, respectively with a progressive decrease in STHT as frequency increases.

For a rigid seat, when the seat inclination was increased from 0° to 15° STHT decreased by 13.66 % and with increase in seat inclination from 0° to 30° STHT decreased by 15.3 %. STHT is more in case of 0° inclination in comparison to 15° and 30° inclination of backrest support irrespective of magnitudes of vibration. This clearly shows that comfort level is more in case of backrest inclined at 30° to the vertical.

4.10 Determination of SHT for seated subjects with cushioned seats

To study the effect of cushions on seat to head transmissibility two commonly used vehicle cushions each of 60 mm thickness having density of 32 kg/m^3 (D_1) and 40 kg/m^3 (D_2) were selected. Dimensions of seat cushion were $450 \times 450 \times 60 \text{ mm}$ and that of backrest cushion were $450 \times 60 \times 520 \text{ mm}$.

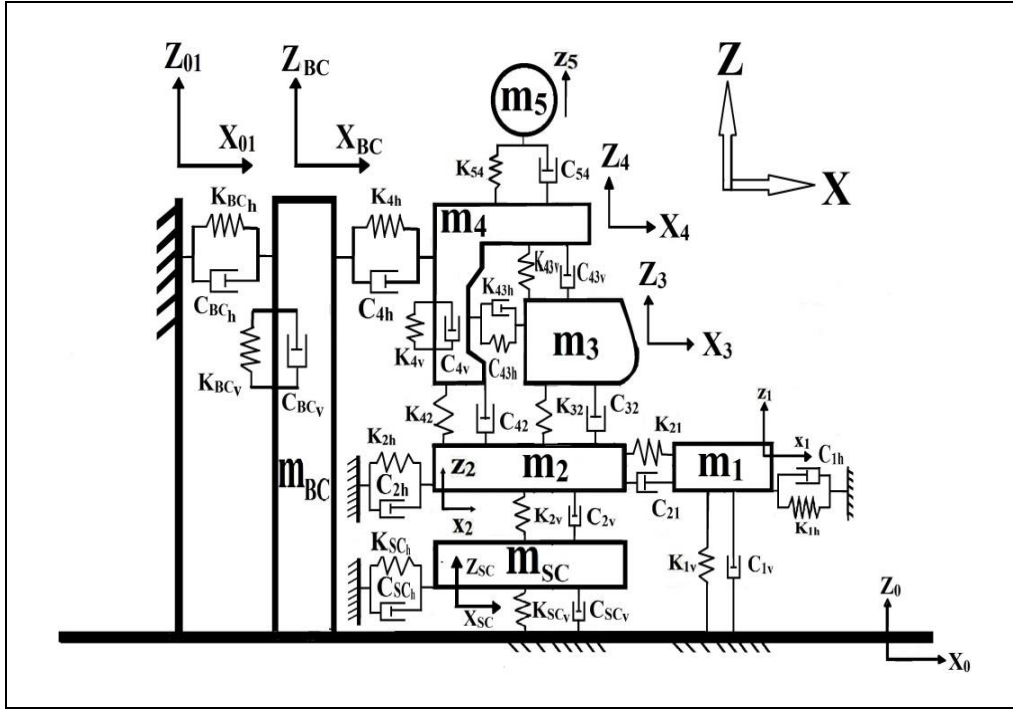


Figure 4.7 Nine DOF lumped parameter model for sitting posture with cushion at seat and backrest

For mathematical modelling, seat cushion was assumed to be placed on the seat in such a way that when a subject is sitting on the seat, the lower torso (m_2) is supported by the seat cushion and similarly the upper torso (m_4) is supported by the backrest cushion (shown in Figure 4.7).

With addition of cushion at seat and backrest, four new spring-dashpot combinations two along seat (K_{SCv} , C_{SCv} and K_{SCH} , C_{SCH}) and two along backrest (K_{SCv} , C_{SCv} and K_{SCH} , C_{SCH}) are added into the existing model. Symbolic representation of human model for cushioned seats is given in table 4.14. To account for the addition of spring-dashpot combinations in the mathematical model, equivalent spring stiffness and damping coefficient have been evaluated separately for each case and one representative case has been shown in Figure 4.8.

Table 4.14 Symbolic representation of human model for cushioned seats

S. No.	Symbol	Representation
1.	m_2	Lower torso and upper legs
2.	m_{SC}	Seat Cushion
3.	m_{BC}	Back cushion
4.	m_{eq}	Equivalent mass of m_2 and m_{SC} , Equivalent mass of m_4 and m_{BC}
5.	H	Loss coefficient
6.	K_{SC}, K_{BC}	Stiffness of seat cushion and back cushion, respectively
7.	C_{SC}, C_{BC}	Damping coefficient of seat cushion and back cushion, respectively
8.	K_{eq}	Equivalent stiffness of K_{2v} and K_{sc}
9.	C_{eq}	Equivalent damping C_{2v} and C_{sc}

4.10.1 Equivalent mass of cushions

Cushions have been considered mass-less in the previous studies but in the present model, the mass of cushions and cushion damping has been taken into consideration for arriving at better results. Using the density and dimensions of cushions, mass of seat cushion (m_{SC}) and back cushion (m_{BC}) have been calculated using the standard relation between mass, density and volume and are given in table 4.15. Equivalent mass m_{eq} has been calculated separately in each case. Equivalent mass in case of seat cushion has been calculated by adding m_2 and m_{SC} . Similarly, equivalent mass in case of back cushion has been calculated by adding m_4 and m_{BC} . Both these equivalent masses replace the previous values of m_2 and m_4 , respectively in the mass matrix and are given in table 4.15.

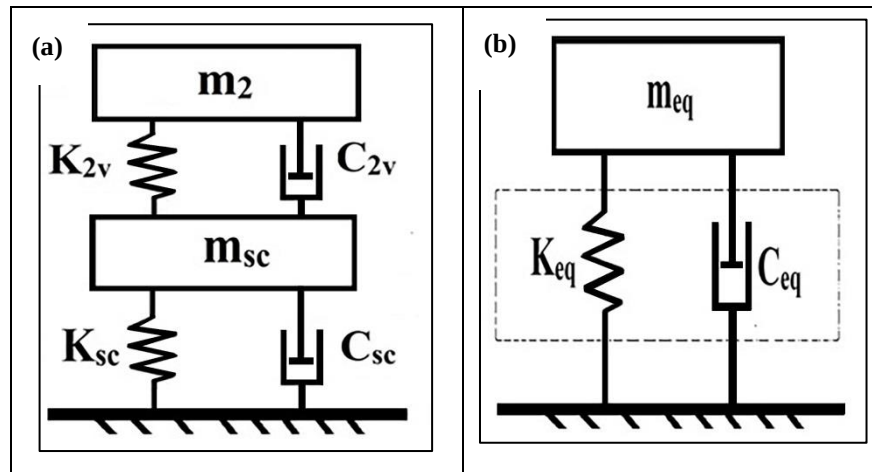


Figure 4.8 Schematic diagram showing (a) actual system and (b) equivalent system

4.10.2 Equivalent stiffness of cushions

Stiffness (K) of cushions springs has been calculated using equation 4.2.

$$K = (AE)/L \quad (4.2)$$

where, A = Cross-sectional area (in direction perpendicular to force)

E = Modulus of elasticity of PU foam = 1×10^6 N/m² (Ashby, 1999)

L = Length (in the direction of force)

Vertical and horizontal stiffness of seat cushion (K_{SCv} and K_{SCH}) and back cushion (K_{BCv} and K_{BCh}) have been calculated using this relation and are given in table 4.15. It is clearly seen from Figure 4.8 that K_{2v} and K_{SC} are considered to be in series to get the equivalent stiffness of the system (K_{eq}). Similarly, K_{BCh} and K_{4h} have been considered in series to get the equivalent stiffness of the system. Both these equivalent stiffness values replace the previous values of K_{2v} and K_{4h} , respectively in the stiffness matrix and are given in table 4.15.

Similarly, K_{SCH} and K_{2h} have been considered in parallel to get the equivalent stiffness and K_{BCv} and K_{4v} have been considered in parallel to get the equivalent stiffness. Both these equivalent stiffness values replace the previous values of K_{2h} and K_{4v} , respectively in the stiffness matrix and have been reported in table 4.15.

4.10.3 Equivalent damping of cushions

Damping ratio (ξ) of cushions has been calculated using equation 4.3.

$$\xi = \eta/2 \quad (4.3)$$

where, η = Loss coefficient = 0.4 for PU Cushions (Ashby, 1999)

Damping coefficient (C) of cushions has been calculated using equation 4.4.

$$C = 2 \xi \sqrt{KM} \quad (4.4)$$

where, K and M are stiffness and mass of respective cushions.

Using equations 4.3 and 4.4, vertical and horizontal damping coefficients of seat cushion (C_{SCv} and C_{SCH}) and back cushion (C_{BCv} and C_{BCh}) have been calculated. Same series and parallel combinations for connecting springs as considered in section 4.10.2 for evaluation of spring stiffness have been considered for evaluating of damping coefficients of connecting dashpots. Equivalent values replace the previous values of C_{2v} , C_{2h} , C_{4v} and C_{4h} for both D_1 and D_2 in the damping matrix and are reported in table 4.15.

Table 4.15 Model parameters for cushioned seats (D_1 and D_2) with backrest inclined at 0°

Mass (kg)			Spring Stiffness (kN/m)			Damping Coefficient (kNs/m)		
Symbol	D_1	D_2	Symbol	D_1	D_2	Symbol	D_1	D_2
m_5	3.28	3.28	K_{54}	16.83	16.83	C_{54}	0.12	0.12
m_4	19.64	19.75	K_{43v}	17.28	17.28	C_{43v}	0.05	0.05
m_3	17.51	17.51	K_{42}	17.21	17.21	C_{42}	0.5	0.5
m_2	28.68	28.79	K_{32}	438.05	438.05	C_{32}	3.33	3.33
m_1	7.70	7.70	K_{2v}	641.36	641.36	C_{2v}	38.17	38.93
m_{SC}	0.38	0.49	K_{1v}	55.41	55.41	C_{1v}	16.04	16.04
m_{BC}	0.45	0.56	K_{43h}	281.07	281.07	C_{43h}	0.39	0.39
			K_{2h}	132.79	132.79	C_{2h}	29.38	29.64
			K_{21}	32.02	32.02	C_{21}	8.34	8.34
			K_{1h}	57.17	57.17	C_{1h}	11.97	11.97
			K_{4v}	69.51	69.51	C_{4v}	0.50	0.53
			K_{4h}	303.49	303.49	C_{4h}	0.42	0.42
			K_{SCv}	3375.00	3375.00	C_{SCv}	14.32	16.26
			K_{SCh}	60.00	60.00	C_{SCh}	1.91	2.17
			K_{BCv}	51.92	51.92	C_{BCv}	1.93	2.16
			K_{BCh}	3900.00	3900.00	C_{BCh}	16.76	18.69

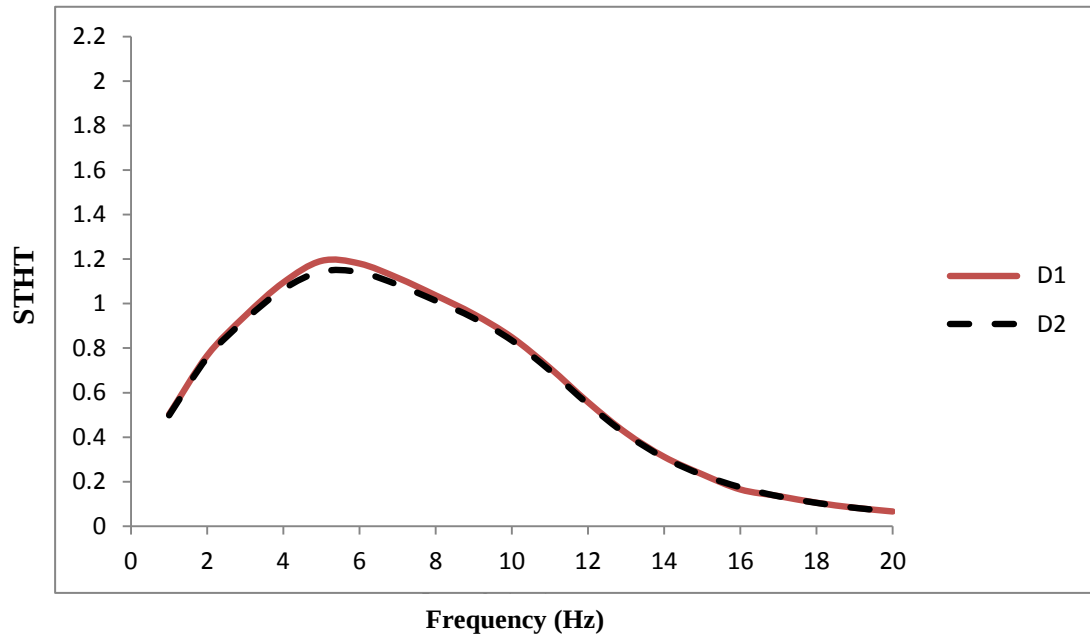


Figure 4.9 STHT for sitting posture with cushioned seats (D_1 and D_2) with backrest inclined at 0°

Seat to head transmissibility for sitting posture with cushioned seats (D_1 and D_2) with backrest inclined at 0° are shown in Figure 4.9. For D_1 , STHT peak value of 1.19 occurs at a frequency of 5.5 Hz and for D_2 , STHT peak value of 1.15 occurs at a frequency of 5.5 Hz corresponding to the primary natural frequency of human body. For both D_1 and D_2 attenuation in STHT is observed beyond 8 Hz with a progressive decrease in STHT as frequency increases.

Comparison of seat to head transmissibility for rigid and cushioned seats with backrest inclined at 0° with the vertical indicates a significant decrease in its value. From Figure 4.4 and 4.9, it was observed that for cushion D_1 , STHT value decreases by 34.97 % for cushion D_2 , STHT value decreases by 37.16 %. Results clearly indicate that cushioned seats provide more comfort to the passengers while travelling.

4.11 Determination of STHT for seated subjects with inclined cushioned seats

For cushioned seat when backrest is inclined at an angle α with the vertical m_3 , m_4 and m_5 and m_{BC} are also inclined at same angle and in same direction. The corresponding lumped parameter model is shown in Figure 4.10 and the corresponding values of spring-dashpot combinations have been given in table 4.16.

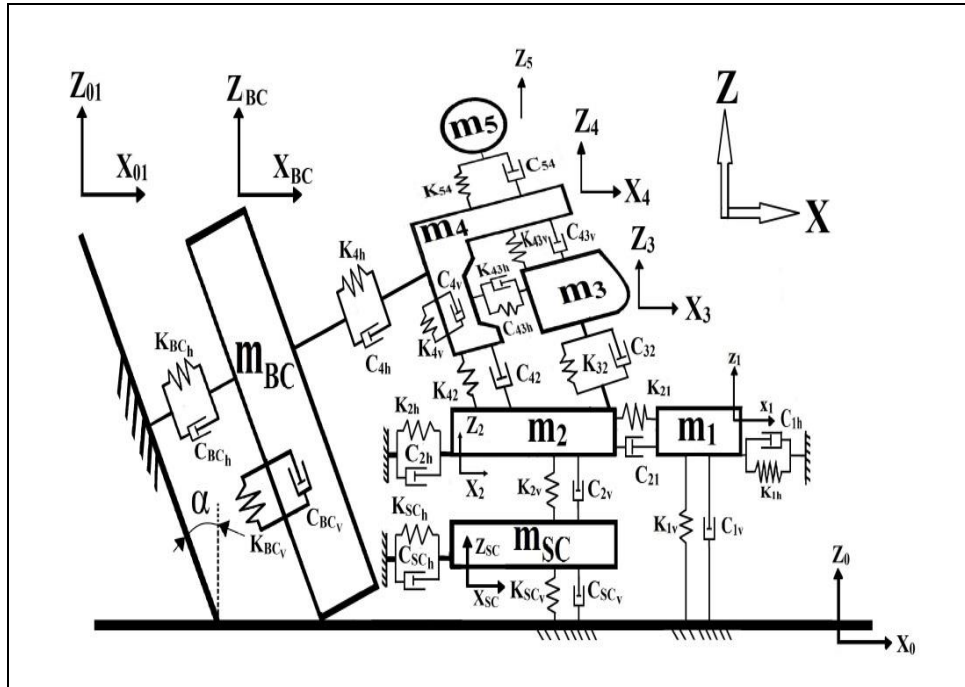


Figure 4.10 Nine DOF LPM for sitting posture with cushion at seat and backrest and inclined (α) backrest

Table 4.16 Model parameters for a cushioned seat with backrest inclined at 15° and 30°

Mass (kg)			Spring Stiffness (kN/m)					Damping Coefficient (kNs/m)				
m	D ₁	D ₂	K	D ₁		D ₂		C	D ₁		D ₂	
				15°	30°	15°	30°		15°	30°	15°	30°
m ₅	3.28	3.28	K ₅₄	15.70	12.62	15.70	12.62	C ₅₄	0.12	0.12	0.12	0.12
m ₄	19.64	19.75	K _{43v}	16.12	12.96	16.12	12.96	C _{43v}	0.05	0.04	0.05	0.04
m ₃	17.51	17.51	K ₄₂	16.06	12.91	16.06	12.91	C ₄₂	0.5	0.49	0.49	0.48
m ₂	28.68	28.79	K ₃₂	408.71	328.54	408.71	328.54	C ₃₂	3.22	2.88	3.22	2.88
m ₁	7.70	7.70	K _{2v}	641.36	641.36	641.36	641.36	C _{2v}	41.17	43.17	39.17	39.42
m _{SC}	0.38	0.49	K _{1v}	55.41	55.41	55.41	55.41	C _{1v}	16.04	16.04	16.04	16.04
m _{BC}	0.45	0.56	K _{43h}	262.24	210.80	262.24	210.80	C _{43h}	0.38	0.34	0.38	0.34
			K _{2h}	132.79	132.79	132.79	132.79	C _{2h}	29.38	29.38	29.38	29.38
			K ₂₁	32.02	32.02	32.02	32.02	C ₂₁	8.34	8.34	8.34	8.34
			K _{1h}	57.17	57.17	57.17	57.17	C _{1h}	11.97	11.97	11.97	11.97
			K _{4v}	64.85	52.13	64.85	52.13	C _{4v}	0.50	0.50	0.60	0.60
			K _{4h}	283.16	227.62	283.16	227.62	C _{4h}	0.41	0.36	0.41	0.36
			K _{SCv}	3375.00	3375.00	3375.00	3375.00	C _{SCv}	14.32	14.32	16.26	16.26
			K _{SCh}	60.00	60.00	60.00	60.00	C _{SCh}	1.91	1.91	2.17	2.17
			K _{BCv}	48.44	38.94	48.44	38.94	C _{BCv}	1.86	1.67	2.09	1.87
			K _{BCh}	3638.75	2925.00	3638.75	2925.00	C _{BCh}	16.19	14.51	18.05	16.19

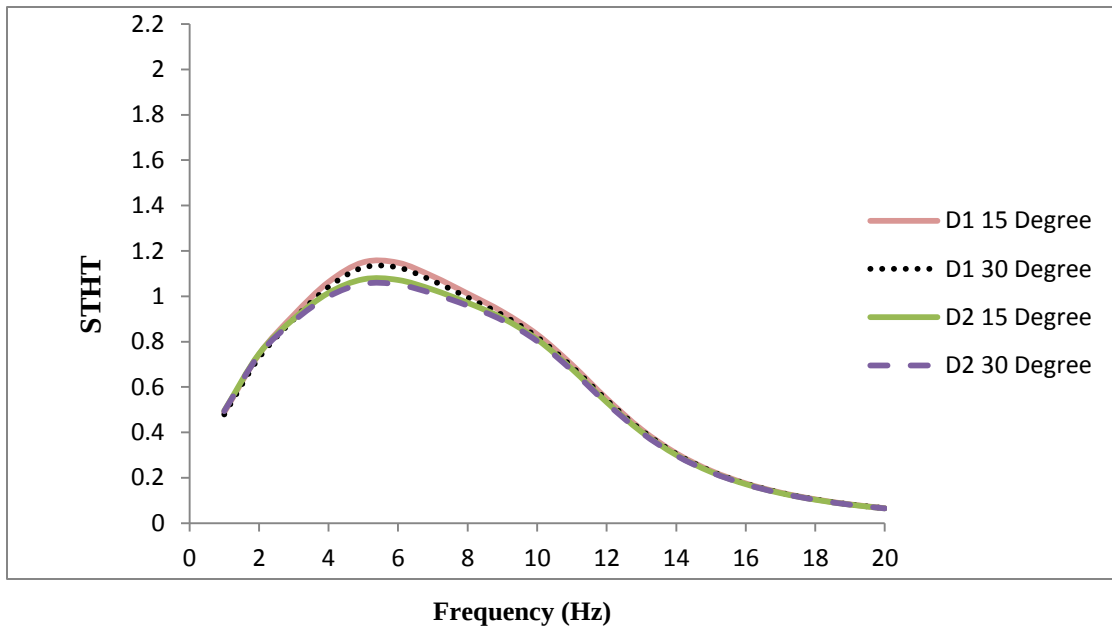


Figure 4.11 STHT for sitting posture with cushioned seats (D₁ and D₂) with backrest inclined at 15° and 30°

In case of cushioned seat (D_1), for backrest inclination angle of 15° , STHT peak value of 1.16 was observed and for backrest inclination angle of 30° , STHT peak value of 1.14 was observed, both at a frequency of 5.5 Hz which corresponds to the primary natural frequency of human body. In case of cushioned seat (D_2), for backrest inclination angle of 15° , STHT peak value of 1.08 was observed and for backrest inclination angle of 30° , STHT peak value of 1.06 was observed, both at a frequency of 5.5 Hz which corresponds to the primary natural frequency of human body.

For cushioned seat D_1 , attenuation in STHT is observed beyond 7.5 Hz and 8.0 Hz in case of backrest inclination of 15° and 30° , respectively with a progressive decrease in STHT as frequency increases.

For cushioned seat D_2 , attenuation in STHT is observed beyond 7.5 Hz and 7.0 Hz in case of backrest inclination of 15° and 30° , respectively with a progressive decrease in STHT as frequency increases.

For a cushioned seat (D_1), when the seat inclination was increased from 0° to 15° STHT decreased by 2.5 % and with increase in seat inclination from 0° to 30° STHT decreased by 4.2 %. STHT is more in case of 0° inclination in comparison to 15° and 30° inclination of backrest support at all magnitudes of vibration. This shows that comfort level is slightly more in case of cushioned seats (D_1) with backrest inclined at 30° to the vertical.

For a cushioned seat (D_2), when the seat inclination was increased from 0° to 15° STHT decreased by 6.1 % and with increase in seat inclination from 0° to 30° STHT decreased by 7.8 %. STHT is more in case of 0° inclination in comparison to 15° and 30° inclination of backrest support at all magnitudes of vibration. This shows that comfort level is slightly more in case of cushioned seats (D_2) with backrest inclined at 30° to the vertical.

For 0° backrest inclination, STHT value decreased by 3.36 % when density of cushions was increased from D_1 to D_2 . For 15° backrest inclination, STHT value decreased by 6.9 % when density of cushions was increased from D_1 to D_2 . For 30° backrest inclination, STHT value decreased by 7 % when density of cushions was increased from D_1 to D_2 .

Results clearly depict that 30° backrest inclination with cushion density 40 kg/m³ (D₂) provides the maximum comfort level to the passenger while travelling. It is noted that there is not much change in either the STHT values or in the peak resonant frequencies for the two cushion densities undertaken in this study for all the cases. It is probably due to the fact that there is not much difference in the cushion densities considered in this study.

CHAPTER 5

EVALUATION OF STHT USING EXPERIMENTAL INVESTIGATIONS

5.1 Introduction

Studies concerning human response to whole body vibration and various variables influencing a seated human being have been reported in the existing literature. In this chapter experimental work performed to investigate the effect of excitation frequency, magnitude, backrest inclination angle and cushion on dynamic response (transmissibility) of sitting human subjects under sinusoidal vertical whole body vibration is being presented.

The objective of performing this experimentation work was to provide the supportive information concerning the effect of vibration magnitude, frequency, back rest inclination angle and cushion on sitting posture. In addition, it was conducted to provide experimental data sets to validate the models developed and presented in subsequent chapters. Besides dynamic response, subjective response study has also been conducted to investigate the effect of vibration magnitude and frequency on human beings.

5.2 Experimental set-up

The study was conducted on the vibration simulator, available in Vehicle Dynamics Laboratory, Mechanical and Industrial Engineering Department (MIED), Indian Institute of Technology (IIT) Roorkee. This vibration simulator was developed as a mock-up of a train compartment, and has been used in many previous studies Bhiwapurkar *et al.* (2011), Desta *et al.* (2011), Harsha *et al.*, 2014 and V. Kumar and V.H. Saran (2014).

The vibration simulator consists of a platform (2m x 2m) made up of steel sheets, on which two rigid chairs and a table have been securely fixed (Figure 5.1). Three electrodynamic shakers were used to provide vibration stimuli to the platform along three axes: longitudinal (x-axis), lateral (y-axis) and vertical (z-axis). Each vibration exciter has a force capacity of 1 kN with a stroke length of 25 mm (peak-to-peak). An accelerometer is attached to each shaker for providing continuous motion feedback to the corresponding controller to form a closed loop motion feedback system.

In the present work, the subjects were exposed to sinusoidal vertical whole-body vibrations. The tri-axial accelerometers (PCB356A32 Piezoelectric) were placed at (i) seat-buttock interface, (ii) back and back support interface and (iii) on the bite-bar to measure the

vibration at seat, backrest and head, respectively. The vibration signals from the accelerometers were amplified using three signal conditioners (480B21) each having three channel amplifiers. The amplified signals were conveyed to the LabVIEW SignalExpress software via data acquisition card (NI cDAQ-9174). The experiment required the test subjects to sit comfortably on a chair rigidly mounted on the platform of vibration simulator which was excited with the same frequency as that of the platform (Figure 5.2).

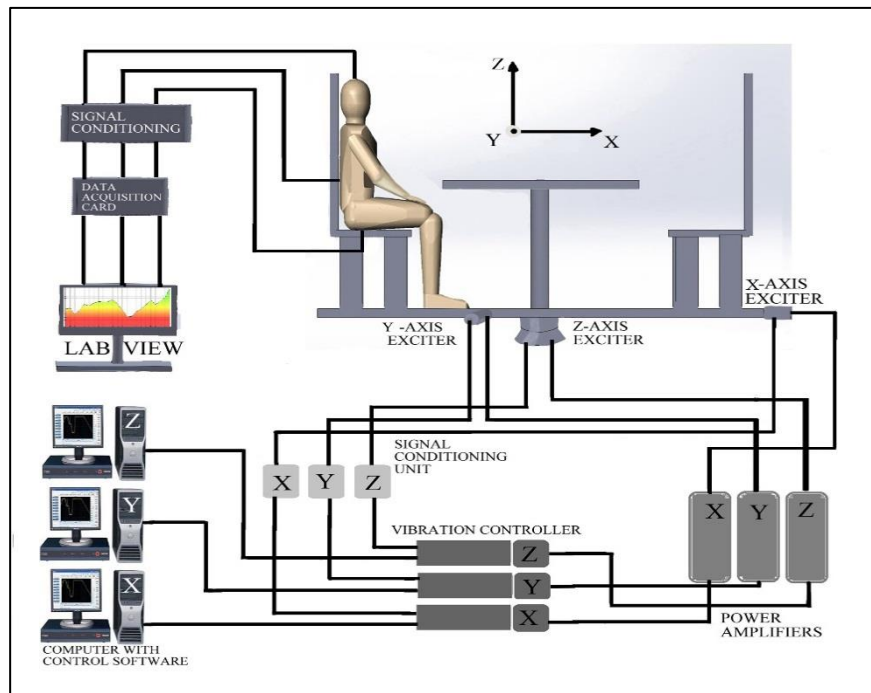


Figure 5.1 Schematic diagram of vibration simulator

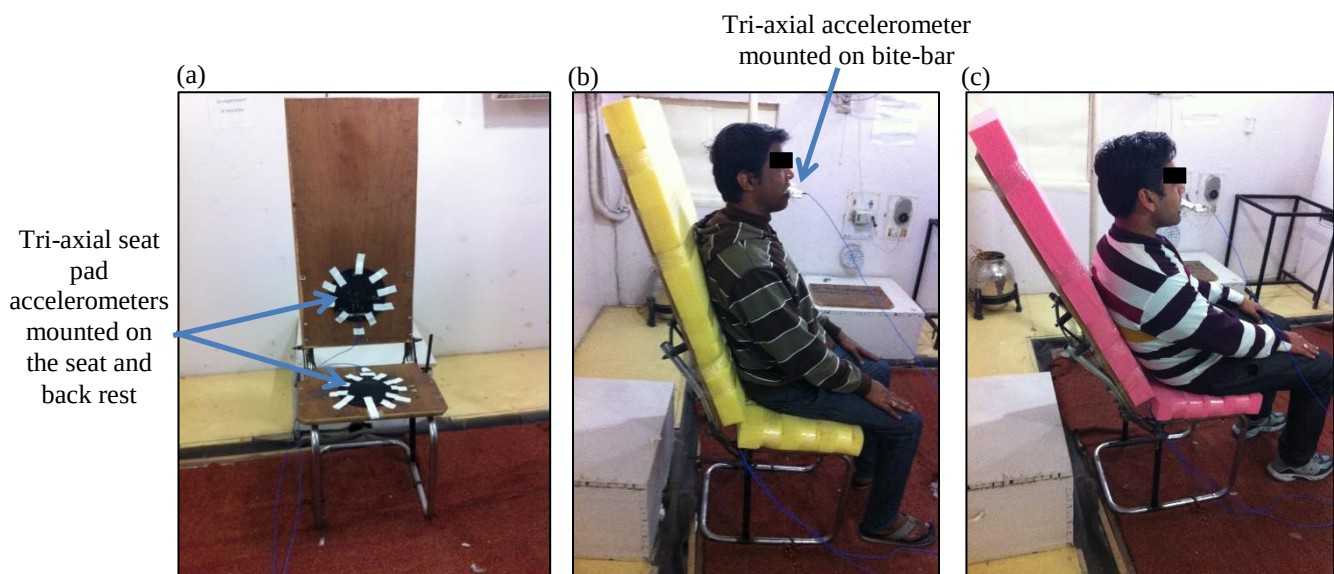


Figure 5.2 Sitting postures with backrest showing (a) rigid seat with tri-axial seat pad accelerometers mounted on the seat and back rest (b) cushioned seat with backrest inclined at 15° to the vertical (c) cushioned seat with backrest inclined at 30° to the vertical

No resonance was observed in seat, backrest, table and any other accessory attached to the vibrating platform in any of the three axes within the frequency range studied (1 to 20 Hz). The backrest of one chair is rigid, flat and vertical whereas backrest of the second chair can be inclined as per requirement.

5.2.1 Experimental conditions

Prior to the tests, each subject was informed about the purpose of the study, the experimental set-up and the effects of inconsistency in desired positions and orientations. Each subject was asked to sign a consent form approved by the Human Research Ethics Committee, IIT Roorkee.

Two widely used methods for measuring vibration at head are: (i) mounting an accelerometer on the outer surface of the helmet (ii) mounting an accelerometer on the bite-bar. Vibrations at head can be measured using helmet with accelerometers mounted over it. Securing a helmet on head with sufficient rigidity is itself a problem. Moreover, mounting an accelerometer over the curved surface of helmet and securing it intact is a challenging task. Comparatively, it is easier to measure vibration at the head using a bite-bar as the teeth are rigidly embedded in the skull in the frequency range of interest (Paddan and Griffin 1988). Thus, each subject was asked to hold a bite-bar in between the teeth and a light weight tri-axial accelerometer was mounted on the bite-bar to measure vibrations transmitted to the head.

Each subject was asked to sit comfortably with average thigh contact and upper legs comfortably supported on the seat and lower legs oriented vertically with feet on the vibrating platform. Each subject was asked to maintain a steady head position while the data were being recorded. Meanwhile, the subject's posture during each test was visually checked by the experimenter to ensure consistency. Experimentation was conducted under following conditions:

- i. Human subjects were sitting erect in case of subjects sitting without backrest; and with their back in contact with the backrest and hands resting on laps in case of subjects sitting with backrest
- ii. The feet were resting on the floor and thus vibrated
- iii. Data sets acquired under vibration excitations were constrained to be in the vertical direction
- iv. Each subject was exposed to vibration for 60 seconds

5.2.2 Sources of error

Some of the important sources of error which might have affected the measurement are:

- i. Improper mounting and calibration of accelerometers
- ii. Sinusoidal vibrations given as input along vertical (z-axis), might have contributed along fore and aft direction (x-axis) also which may lead to cross-coupling effects
- iii. Input values given in the computer might not have been exactly reproduced at the floor of the set-up.
- iv. Feedback sensors used in the closed loop might get loosened after some time as they are mounted on the vibrating exciter.

5.2.3 Physical data of test subjects

Physical data of test subjects, Body Mass Index (BMI), mean and standard deviation of the recorded data has been summarized in Table 5.1.

Table 5.1 Recorded data of test subjects

S. No.	Subject	Age (Yrs.)	Weight (kg)	Height (m)	BMI (kg/m ²)
1.	S1	21	76	1.77	24.26
2.	S2	21	71	1.70	24.56
3.	S3	24	67	1.81	20.45
4.	S4	26	92	1.77	29.36
5.	S5	20	69	1.72	23.32
6.	S6	24	63	1.64	23.42
7.	S7	21	65	1.71	22.23
8.	S8	23	83	1.66	30.12
9.	S9	23	79	1.79	24.66
10.	S10	25	73	1.72	24.68
11.	S11	24	87	1.70	30.10
12.	S12	26	76	1.80	23.46
Mean		23.17	75.08	1.73	25.05
Standard Deviation		1.95	8.56	0.05	3.00

Twelve healthy male subjects (20 to 26 years of age) with no prior history of back injuries or lower back pain (LBP) were selected for this study. The standing height of subjects ranged from 1.64 to 1.81m with mean height 1.73 m and standard deviation of 0.05 m, while the standing weight varied from 63 kg to 92 kg with mean weight 75.08 kg and standard deviation of 8.56 kg.

5.2.4 Range of stimuli

Each subject was exposed to three sinusoidal vibration magnitudes of 0.5, 1.0 and 1.5 m/s^2 (rms) over the frequency range of 1 to 20 Hz in different postures. The postures considered in this study were intended to represent the postures of seated human body while travelling: without backrest; with backrest inclined at 0°, 15° and 30° to the vertical (both without and with cushions). Figure 5.2 shows sitting postures with backrest showing (a) rigid seat with tri-axial seat pad accelerometers mounted on the seat and back rest; (b) cushioned seat with backrest inclined at 15° to the vertical and (c) cushioned seat with backrest inclined at 30° to the vertical.

5.2.5 Cushions used

Two commonly used vehicle cushions with different densities D_1 and D_2 were selected. Dimensions of seat cushion and backrest cushion have been given in section 4.10. Nowadays, commonly used cushions in automotive industry are full depth foam cushions which use polyurethane (PU) foam (Zhang *et al.* 2015). Cushions selected for the experimentation have been manufactured by a renowned manufacturer Sheela Foam Pvt Ltd, India under the brand name 'Sleepwell'. Feather Foam (FF) with 100% purity, commonly known as pure PU foam was selected for the experimentation purpose.

5.3 Evaluation of seat to head transmissibility without backrest

STHT is a complex ratio between the vertical acceleration at head (output) to the vertical acceleration at the seat (input) and is evaluated according to relation given in equation 4.3 using Lab VIEW Signal Express software and recorded in excel spread sheets for further processing. The analysis of the recorded data in terms of effects of various parameters on STHT is discussed in following sections.

5.3.1 Effect of vibration magnitude

Mean STHT for the 12 subjects exposed to vertical sinusoidal vibration at different excitation amplitudes for a sitting posture without backrest are shown in Figure 5.3 (a). It is seen that STHT increases with increasing vibration magnitude at all excitation frequencies. For vibration magnitude of 1.5 m/s^2 , it is seen that STHT shows a first peak value of 2.20, which gradually decreases up to 0.82 and again starts increasing and finally a second peak of 0.97 is observed.

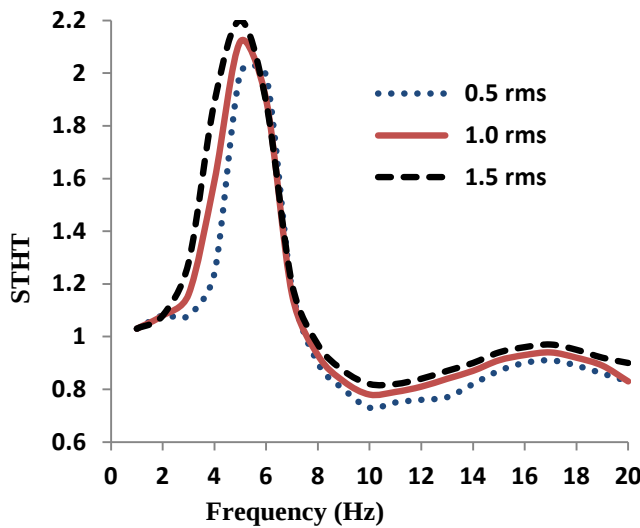
For vibration magnitude of 1.0 m/s^2 , first peak value of 2.12 is observed which gradually decrease to 0.78 and finally a second peak of 0.94 is observed. For vibration magnitude of 0.5 m/s^2 , first peak of 2.00 gradually decreases to 0.73 STHT and finally a second peak of 0.91 is observed.

An increase of 6 to 10% in STHT with increasing vibration magnitude is noticed. With increase in vibration amplitude, lowering of first peak frequency is clearly visible in all the cases and the STHT values and trend obtained for STHT are in validation with the previous study reported by Desta *et al.* (2011) shown in Figure 5.3 (b).

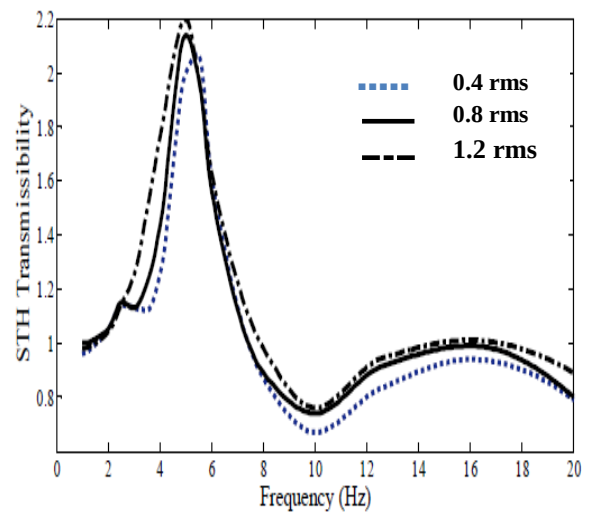
5.3.2 Effect of excitation frequency

Figure 5.3 (a) shows that in all the cases, first peak is observed between 4 to 6 Hz which is closer to the primary natural frequency (5 Hz) of the human body. It is seen that STHT increases with increasing frequency up to first peak followed by a dip in STHT around 10 Hz and a second peak is observed around 17 Hz in all the cases.

At low frequencies, STHT shows little change but in the range of 4 to 6 Hz, there is a noticeable increase in vertical vibration resulting in increase in STHT. At slightly higher frequencies, various body resonances tend to amplify the motion and overall discomfort is influenced by sensations in different parts of the body (abdomen, chest, shoulders, neck, head etc.) as the frequency is increased. It is seen that irrespective of the vibration magnitude, highest STHT occurs at around 5 Hz. Above 8 Hz, STHT is less than one indicating attenuation for all the magnitudes of excitation.



(a) Present Study



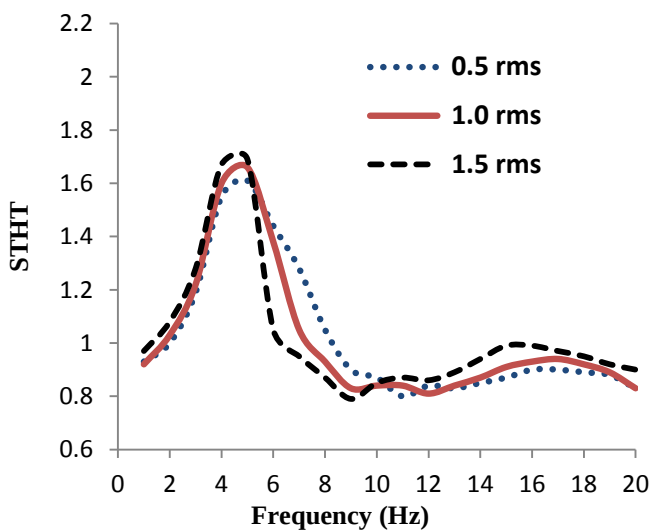
(b) Desta *et al.* (2011)

Figure 5.3 Comparison of mean STHT for 12 subjects exposed to vertical sinusoidal vibration at 0.5, 1.0 and 1.5 m/s^2 rms without backrest (erect posture)

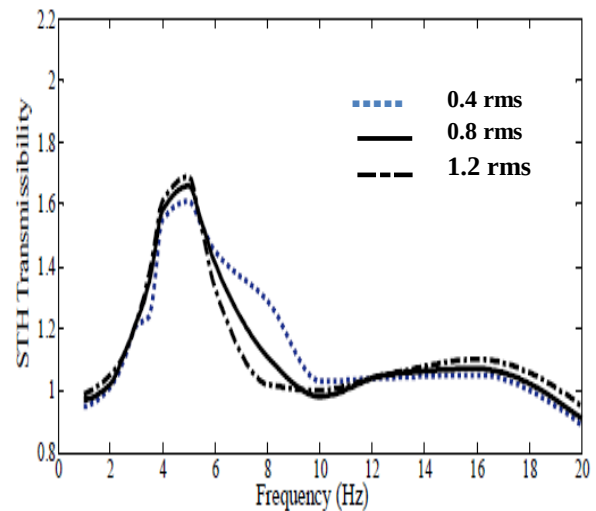
Comparison shown in Figure 5.3 shows that the trend of variation in STHT w.r.t. frequency matches with the results of Desta *et al.* (2011) and lowering of the first peak frequency is clearly visible for all the amplitudes. This may be due to the softening effect (lowering of the resonant frequency) shown by human body segments.

5.4 Evaluation of seat to head transmissibility with backrest

Comparison of mean STHT for the test subjects exposed to vertical sinusoidal vibrations, under given conditions of amplitudes and frequency range, for a rigid seat with backrest inclined at 0° with the vertical axis in the present study and previous studies is shown in Figure 5.4.



(a) Present Study



(b) Desta *et al.* (2011)

Figure 5.4 Comparison of mean STHT for test subjects exposed to vertical sinusoidal vibration at 0.5, 1.0 and 1.5 m/s^2 rms with backrest (0° inclination)

The comparison of STHT without and with backrest support indicates a considerable decrease in its value. From Figures 5.3 and 5.4, it is observed that STHT value decreases by an order of 19.5 % to 23.2 % for different vibration magnitudes, when backrest is used. This may be attributed to presence of higher ischium pressure in the former case. The reported responses (Dewangan *et al.* 2013) with the rigid seat also show similar trends. Earlier studies (Wu, Rakheja, and Boileau 1999; Wang, Rakheja, and Boileau 2004 and Desta *et al.* 2011) have also reported that change in the back support condition alters the proportion of body mass supported by the seat.

When a sitting subject is supported with a backrest, the lower body parts get support from the seat and upper body parts are supported by backrest. As a result due to backrest support, muscle tension decreases resulting in relatively relaxed sitting posture and attenuation in STHT around secondary peak. The results suggest that backrest support serves to constrain the motion and yields more damped response.

5.4.1 Effect of vibration magnitude

Mean STHT for all the subjects exposed to vertical sinusoidal vibration under given conditions have been shown in Figure 5.4. At resonant frequency of human body around 5 Hz, peak values of 1.69, 1.66 and 1.61 are observed for amplitudes of 1.5, 1.0 and 0.5 m/s² (rms), respectively. Second peak of 0.87, 0.84 and 0.80 and a third peak of 0.99, 0.97 and 0.90 are seen for amplitudes of 1.5, 1.0 and 0.5 m/s² rms, respectively.

For subjects sitting on a rigid seat with backrest inclined at 0° with the vertical, STHT increases with increasing vibration magnitude that means there is increase in discomfort with increase in vibration magnitude. Figure 5.4 reveals an increase of 3% to 5% in STHT with increasing vibration magnitude.

For all excitation magnitudes under consideration, first peak is observed around 5 Hz which is the primary natural frequency of the body. Results clearly reveal that resonance in STHT tends to shift toward left side, showing lowering of the peak frequency, with increasing vibration magnitude. This is due to the fact that upper parts of body exhibit softening effect when it is subjected to higher magnitudes of vibration. The trend matches well with that reported in earlier studies by Desta *et al.* (2011) and Harsha *et al.* (2014).

5.4.2 Effect of excitation frequency

A constant magnitude does not produce the same discomfort at all vibration frequencies. At low frequencies, the forces acting on the body are approximately proportional to the input acceleration and the same movement is transmitted throughout the entire body. At slightly higher frequencies various body resonances tend to amplify the motion and overall discomfort is influenced by sensations in different parts of the body.

Maximum value of STHT as seen from Figure 5.4 is 1.69 which corresponds to the maximum amplitude under given conditions of 1.5 m/s^2 . Similarly, maximum STHT values of 1.66 and 1.61 have been observed for amplitudes of 1.0 and 0.5 m/s^2 , respectively. In all the cases a peak is observed between 4 to 6 Hz which is closer to the primary natural frequency of the body. A small dip and a small peak are observed in between 9 to 12 Hz and a third peak is observed in frequency range of 15 to 17 Hz for all the vibration magnitudes.

Results clearly reveal that resonance in STHT tends to shift to a lower frequency with increasing vibration magnitude due to softening effect. The trend matches well with that reported in earlier studies (Desta *et al.* 2011 and Harsha *et al.* 2014).

5.4.3 Effect of backrest inclination

Change in backrest inclination angle can lead to change in transmission of vibrations through the body resulting in change in comfort level of human subjects.

Three backrest inclination angles of 0° , 15° and 30° with the vertical were considered in this study. Selection of the maximum inclination angle of 30° with respect to the vertical axis is based on physical restriction that occurs during travelling in vehicles (Shibata and Maeda 2010).

5.4.3.1 Effect of vibration magnitude

Figure 5.5 shows the variation of STHT with varying excitation amplitudes and frequencies. It is seen that STHT decreases with increase in inclination angle of the backrest.

For a rigid seat with backrest inclined at 0° shown in Figure 5.5 (a), first peak values of 1.69, 1.66 and 1.61 are observed for amplitudes of 1.5, 1.0 and $0.5 \text{ m/s}^2 \text{ rms}$, respectively. Second peak of 0.87, 0.84 and 0.80 and a third peak of 0.99, 0.97 and 0.90 are observed for amplitudes of 1.5, 1.0 and $0.5 \text{ m/s}^2 \text{ rms}$, respectively.

For a rigid seat with backrest inclined at 15° shown in Figure 5.5 (b), first peak values of 1.56, 1.48 and 1.45 are observed for amplitudes of 1.5, 1.0 and $0.5 \text{ m/s}^2 \text{ (rms)}$,

respectively. Second peak of 0.87, 0.90 and 0.84 and a third peak of 0.99, 0.98 and 0.90 are observed for amplitudes of 1.5, 1.0 and 0.5 m/s² rms, respectively.

For a rigid seat with backrest inclined at 30° shown in Figure 5.5 (c), first peak values of 1.52, 1.46 and 1.43 are observed for amplitudes of 1.5, 1.0 and 0.5 m/s² rms, respectively. Second peak of 0.85, 0.88 followed by a dip of 0.80 and a third peak of 0.99, 0.98 and 0.96 are observed for amplitudes of 1.5, 1.0 and 0.5 m/s² (rms), respectively.

It is observed from Figure 5.5 that when a rigid seat is used there is a decrease of 8 to 11 % in STHT when the seat inclination is increased from 0° to 15° and STHT decreases by 10 to 12 % with increase in seat inclination from 0° to 30°. STHT is more in case of 0° inclination in comparison to 15° and 30° inclination of backrest support irrespective of magnitudes of vibration. This clearly shows that comfort level is more in case of backrest inclined at 30° to the vertical.

5.4.3.2 Effect of excitation frequency

From Figure 5.5, it is clear that with increase in inclination of backrest, resonant frequency decreases. For all the backrest inclinations, first peak is observed between 4 to 6 Hz which is closer to the primary natural frequency of the body. Second peak is observed between 10 to 12 Hz and a third peak is observed in frequency range of 16 to 17 Hz for all vibration magnitudes.

Results clearly reveal that resonance in STHT tends to shift to a lower frequency with increasing vibration magnitude due to softening effect. Attenuation in the value of STHT is observed in and around second peak frequency. This trend matches with that reported in earlier studies (Desta *et al.* 2011 and Harsha *et al.* 2014).

As the frequency increases, presence of a dominant peak at first resonance and a smaller peak is clearly visible in all the cases. It may also be noted from Figures 5.3, 5.4 and 5.5 that STHT values are less than 1.0 (indicating attenuation in the flow of vibrations) in all the cases examined in the frequency range of 8 to 20 Hz. This highlights the importance of low frequency studies around the primary natural frequency of 5 Hz of the human body where STHT values are greater than 1.0.

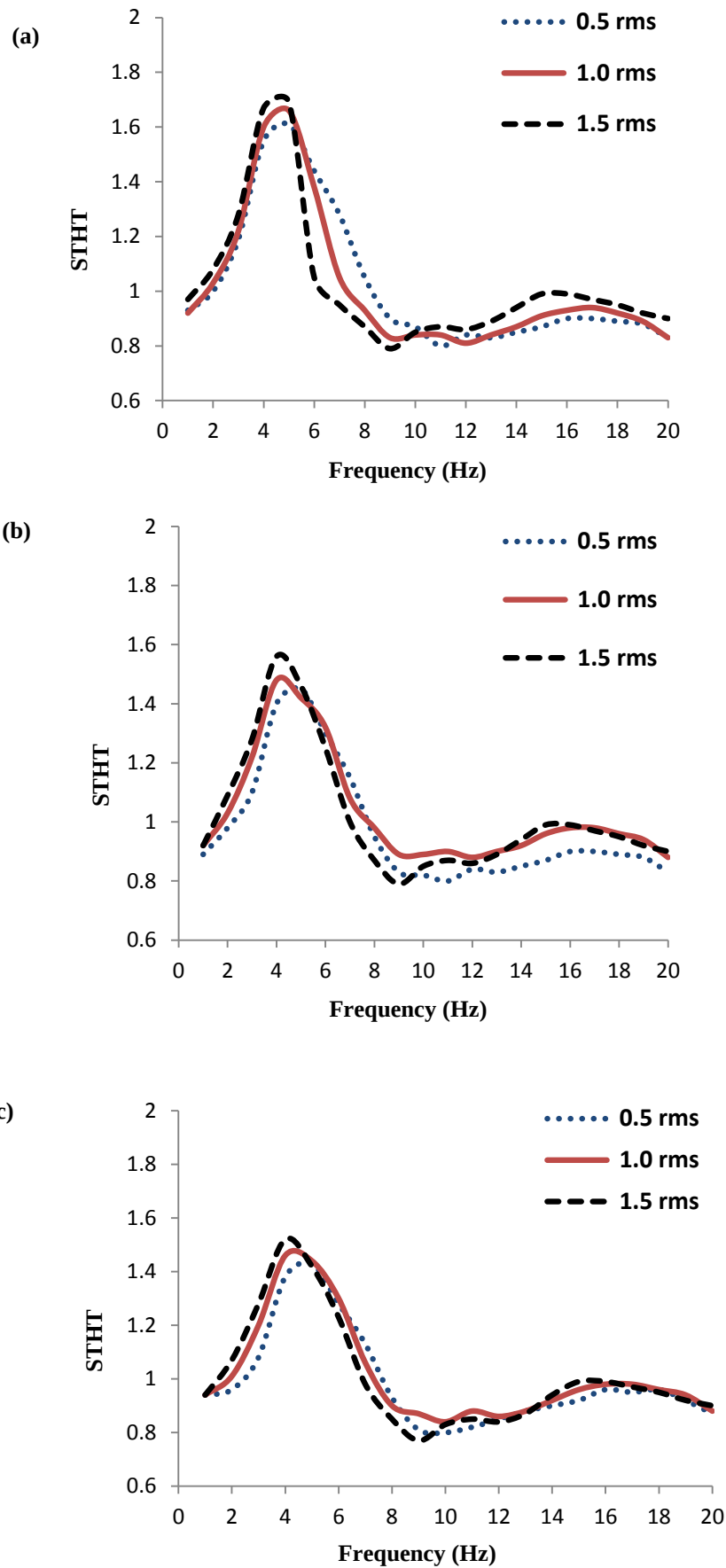


Figure 5.5 Mean STHT responses with varying amplitudes and frequencies for rigid seat with inclination angle (a) 0° (b) 15° (c) 30°

5.4.4 Effect of cushions

The comparison of mean responses of subjects seated on rigid and elastic seats (D_1) at excitation magnitude of 0.5 m/s^2 for without and with backrest posture is shown in Figure 5.6.

The results exhibit nearly identical mean response magnitudes obtained for the cushioned and rigid seats at low frequencies. The important effects of cushioned seat, however, are clearly evident in the frequency range of 3 to 12 Hz. The differences appear to be greater in the vicinity of the primary and secondary resonance frequencies.

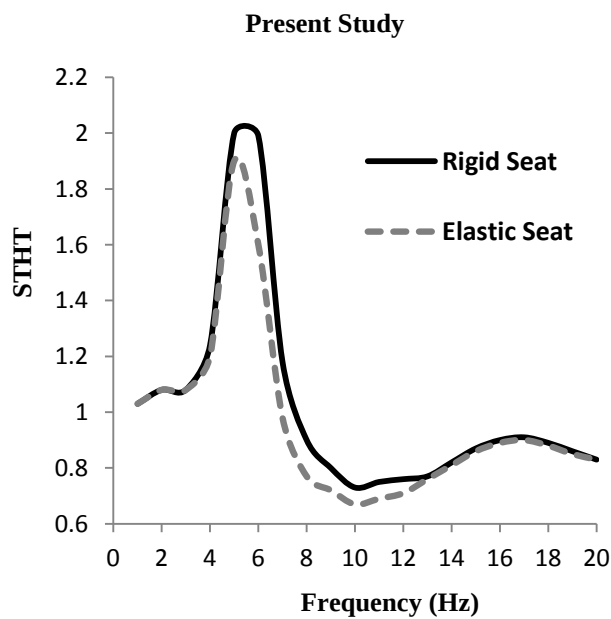
In the present study, Figure 5.6 (a) clearly depicts the occurrence of first, second and third peak values of 2, 0.73 and 0.90 corresponding to frequency of 5, 10 and 17 Hz, respectively. With the use of cushions the decrease in STHT of 11 to 15 % has been observed for an excitation magnitude of 0.5 m/s^2 .

The present study depicts that substantial decrease in transmissibility values with the cushioned seats vis-à-vis rigid seats and a little softening effect in terms of decrease in resonant frequency. A similar trend was observed in the work reported by Dewangan *et al.* (2013) in which human response to vibrations was measured in terms of normalized magnitude of apparent mass.

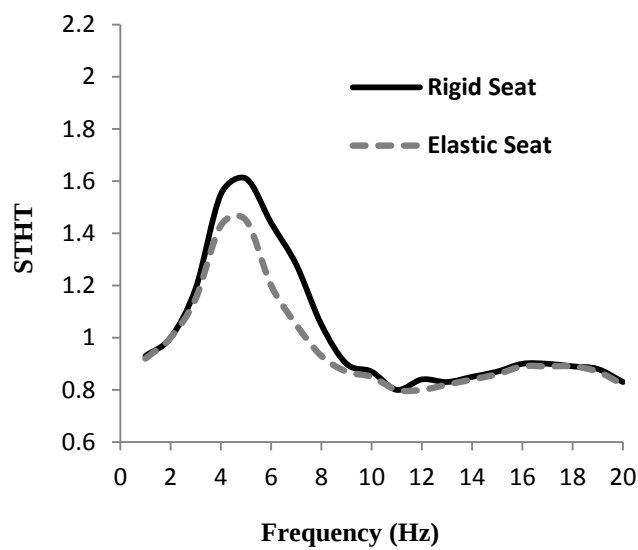
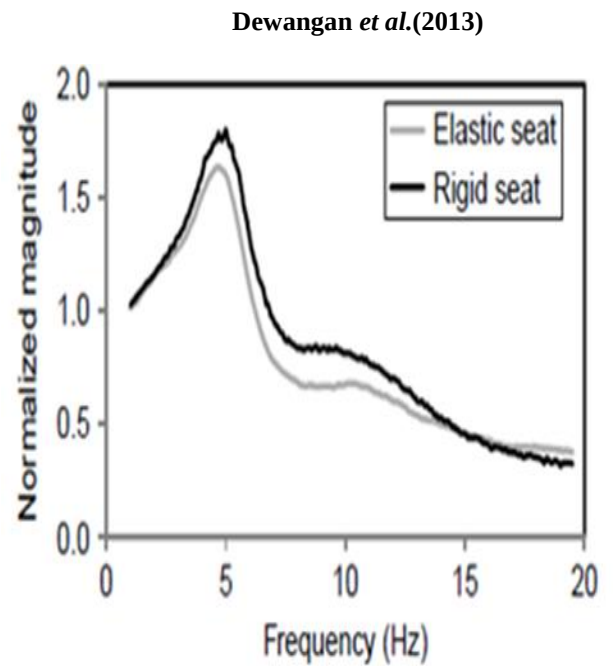
The results suggest considerably higher values of seat to head transmissibility magnitudes with the rigid seat compared to the cushioned seat, irrespective of the back support. For the case when no backrest is used, there is a decrease of 5% in STHT values when a cushion D_1 is used.

This could be due to coupling effect of sitting support and excitation on the occupant-cushion seat system. This may be attributed to higher seat interface pressure in the ischium region under high vibrations, when seated without a backrest support. The higher pressure in the ischium region, where the elastic seat experiences greatest deflection, can alter the effective stiffness and damping properties of the seat (Wu, Rakheja and Boileau 1999).

Softening tendency of the human body has been widely reported in studies on characterisation of biodynamic responses of human subjects seated on rigid seats (Fairley and Griffin 1989; Mansfield and Griffin 2002; Wang, Rakheja, and Boileau 2004; Patra *et al.* 2008; Toward and Griffin 2011; Dewangan *et al.* 2013 and Hinz *et al.* 2006).



(a) Without Backrest



(b) With Backrest (0° inclination)

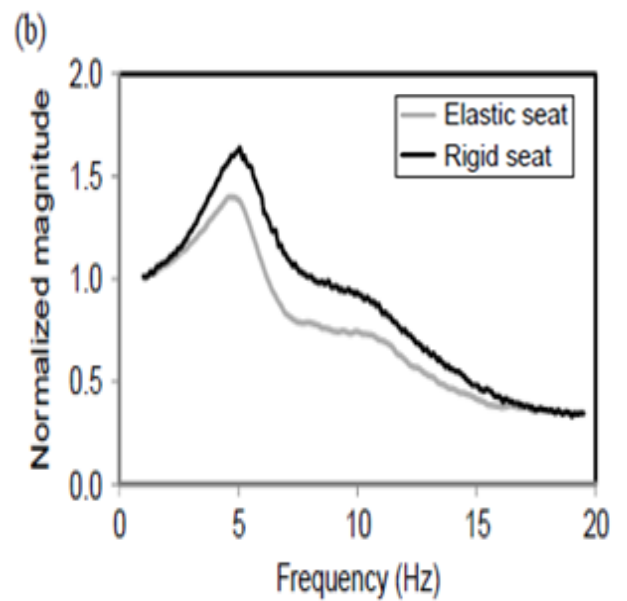


Figure 5.6 Comparison of mean responses of subjects seated on rigid and cushioned seat (D_1) at 0.5 m/s^2 for (a) without backrest (erect posture) (b) with backrest (0° inclination)

5.4.5 Effect of cushion density

The effect of cushion densities (32 kg/m^3 and 40 kg/m^3) on the mean STHT at different inclination angles and for varying vibration magnitudes and excitation frequencies was studied and is shown in Figure 5.7 and Figure 5.8. It is observed that the general trend of the variation in STHT with varying inclination angles, vibration magnitudes and excitation frequencies which was seen in the case of rigid seats and discussed in earlier sections, holds true for cushioned seats as well.

The primary peak amplitudes occur in between 4 to 5 Hz in all the cases and STHT values range from 1.50 to 1.39 for 0° inclination as the vibration magnitude decreases. For 15° inclination this range is from 1.39 to 1.26 and for 30° inclination the range is from 1.28 to 1.14. A short STHT peak ranging from 0.81 to 0.87 is also observed between frequencies of 15 to 17 Hz in all the cases. Further, a general attenuation in STHT values is observed beyond 6 Hz in all the cases.

It is noted that there is not much change in either the STHT values or in the peak resonant frequencies for the two cushion densities undertaken in this study for all the cases. It is probably due to the fact that there is not much difference in the cushion densities considered in this study.

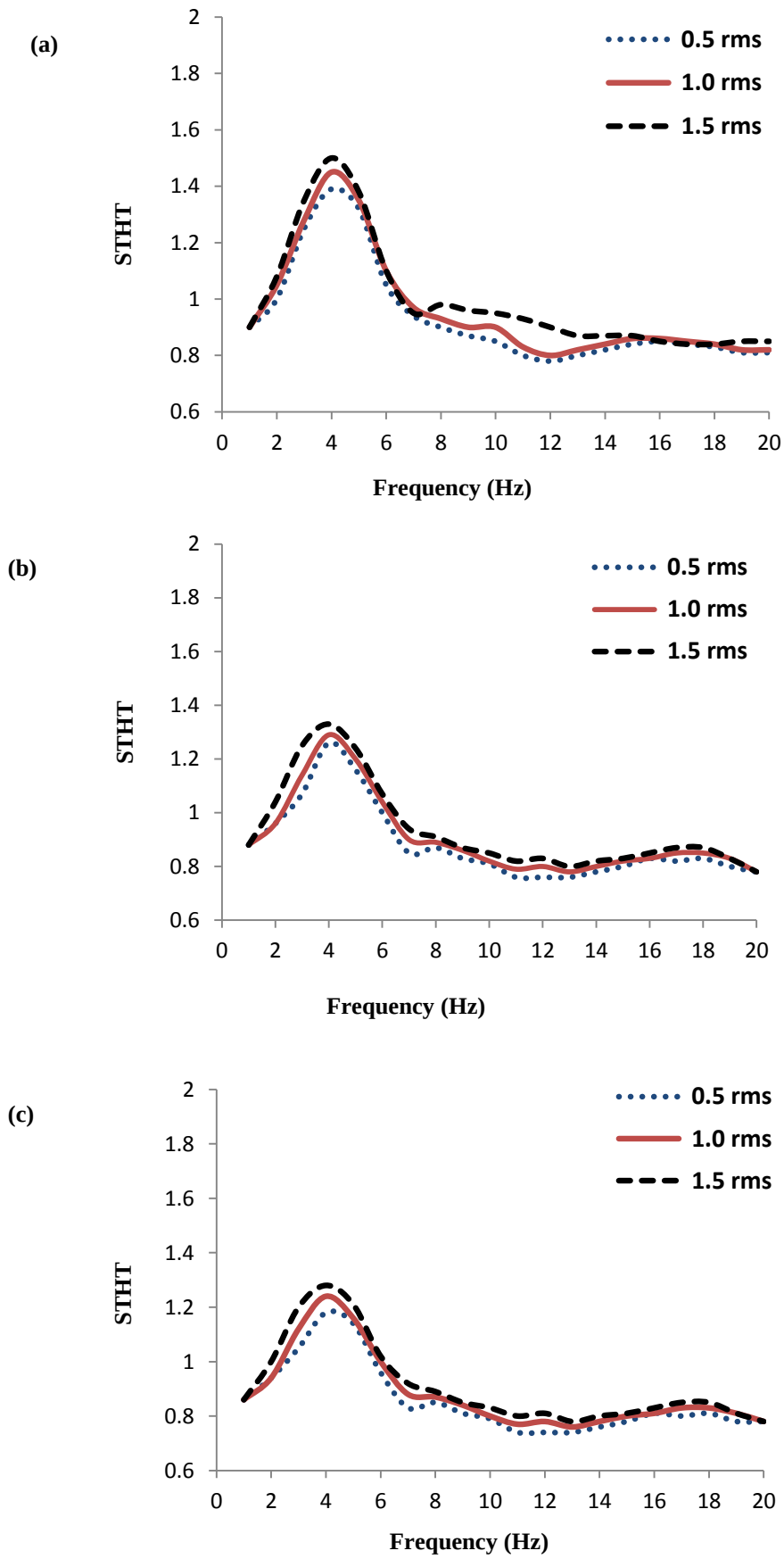


Figure 5.7 Mean STHT response with varying amplitudes and frequencies for subjects seated on cushioned seat (D_1) at inclination angle (a) 0° (b) 15° (c) 30°

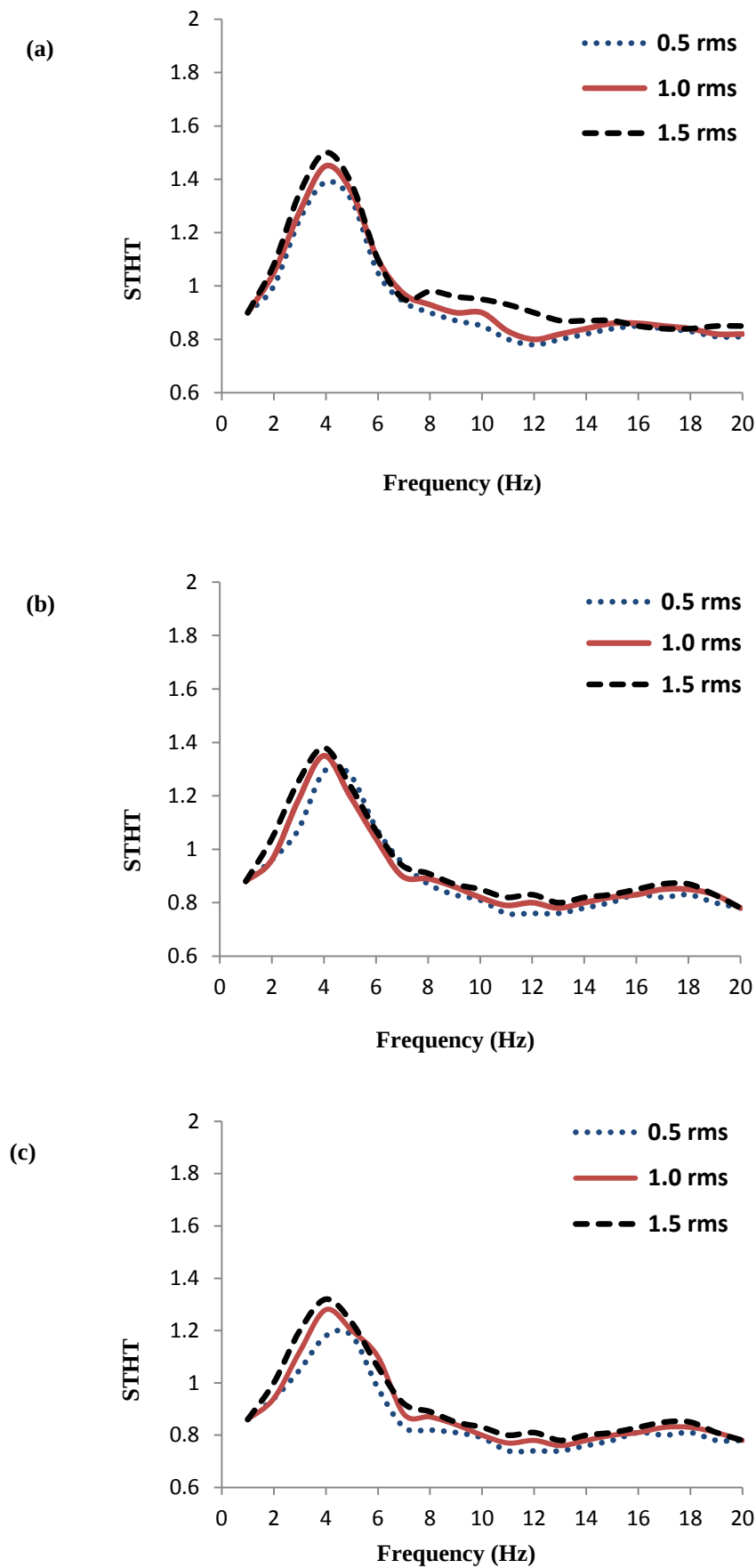


Figure 5.8 Mean STHT response with varying amplitudes and frequencies for subjects seated on cushioned seat (D_2) at inclination angle (a) 0° (b) 15° (c) 30°

5.5 Validation of developed mathematical model with the experimental investigations

Seat to head transmissibility determined from the developed mathematical models have been compared with the STHT evaluated through experimental investigations. Figure 5.9 shows the case of rigid seat without backrest. The peak frequencies lie between 4 to 6 Hz with small variation in peak STHT values. Beyond 12 Hz the attenuated values are found to be different in analytical study.

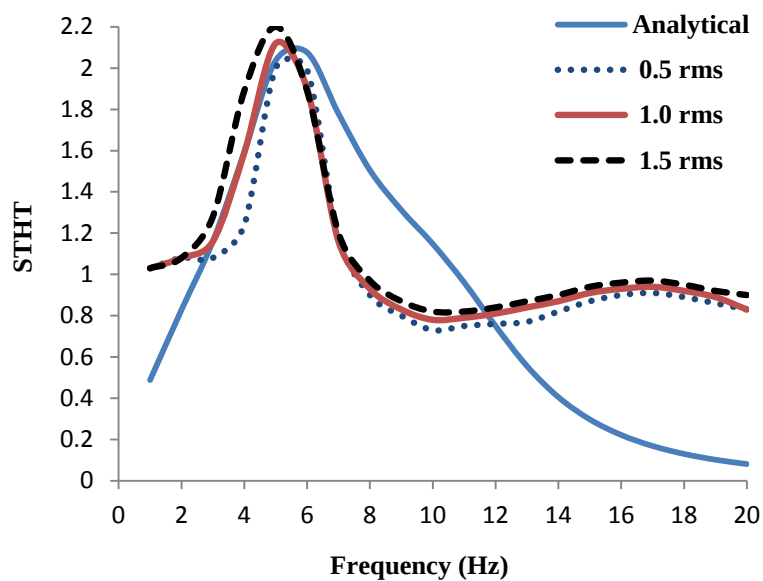


Figure 5.9 Comparison of STHT obtained analytically and experimentally for a rigid seat without backrest

Effect of backrest and its inclinations is shown in Figure 5.10. Peak STHT values match in the analytical and experimental cases with frequency ranging in between 4 to 6 Hz. Due to non-linearities and uncertainty in damping values the analytical peak frequency are slightly higher. Also the attenuated STHT values beyond 10 Hz are different.

Effect of cushion D_1 on STHT values is shown in Figure 5.11. The peak STHT values are slightly lower in analytical studies with peak frequencies on higher side in the range of 4 to 6 Hz. More attenuation is observed beyond 10 Hz in analytical studies.

Similar observations were made in the case of cushion D_2 are shown in Figure 5.12.

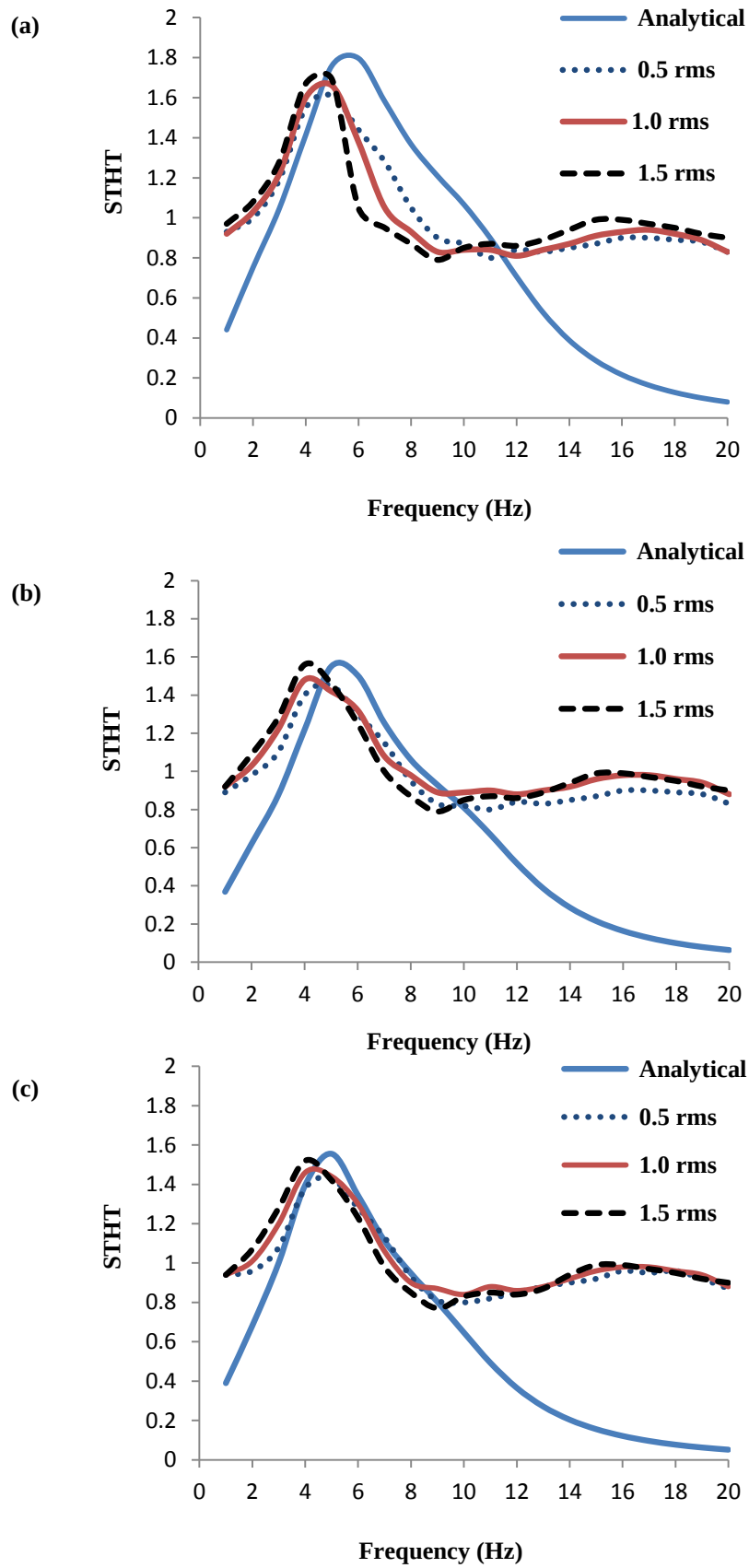


Figure 5.10 Comparison of STHT obtained analytically and experimentally for rigid seat with inclination angle (a) 0° (b) 15° (c) 30°

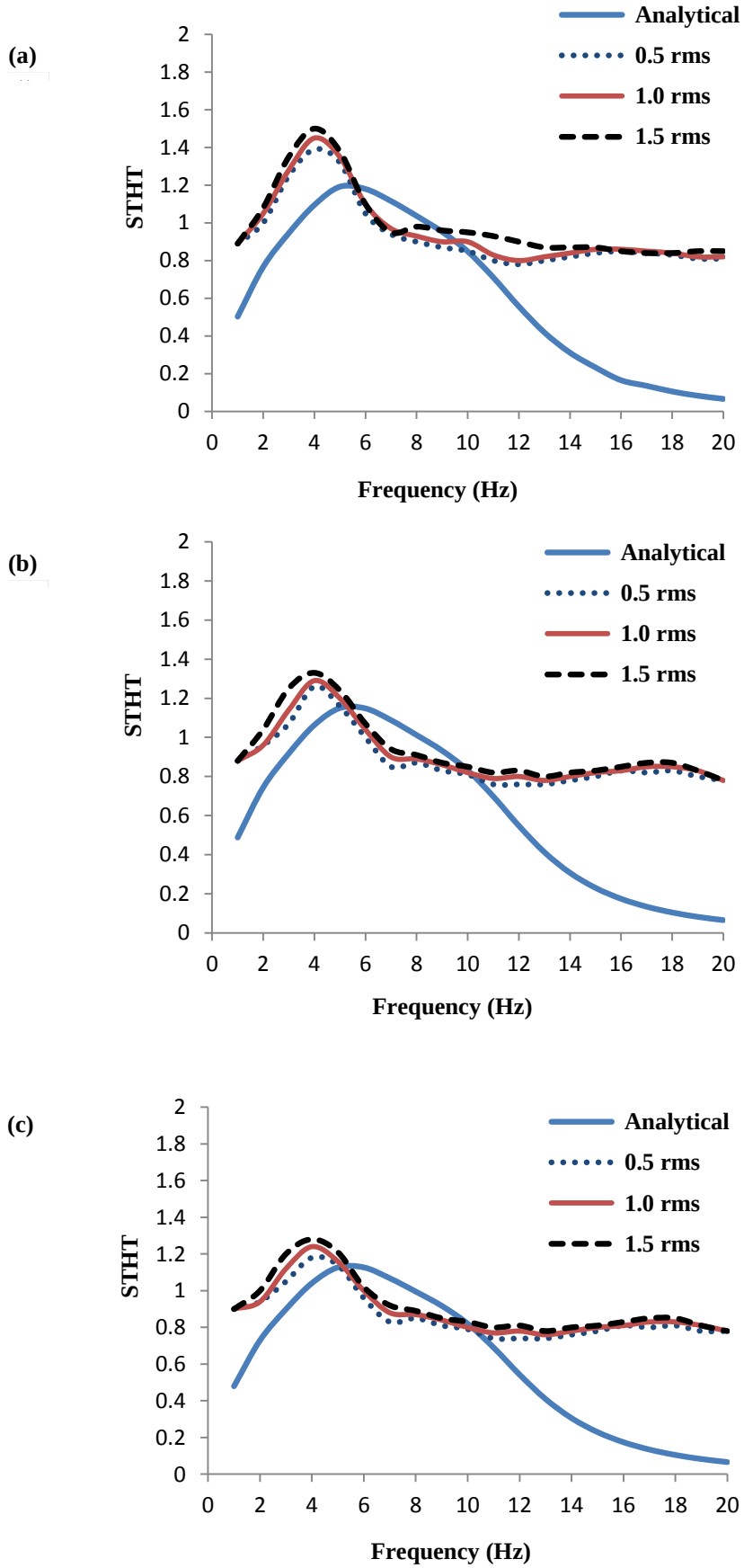


Figure 5.11 Comparison of STHT obtained analytically and experimentally for cushioned seat (D_1) at inclination angle (a) 0° (b) 15° (c) 30°

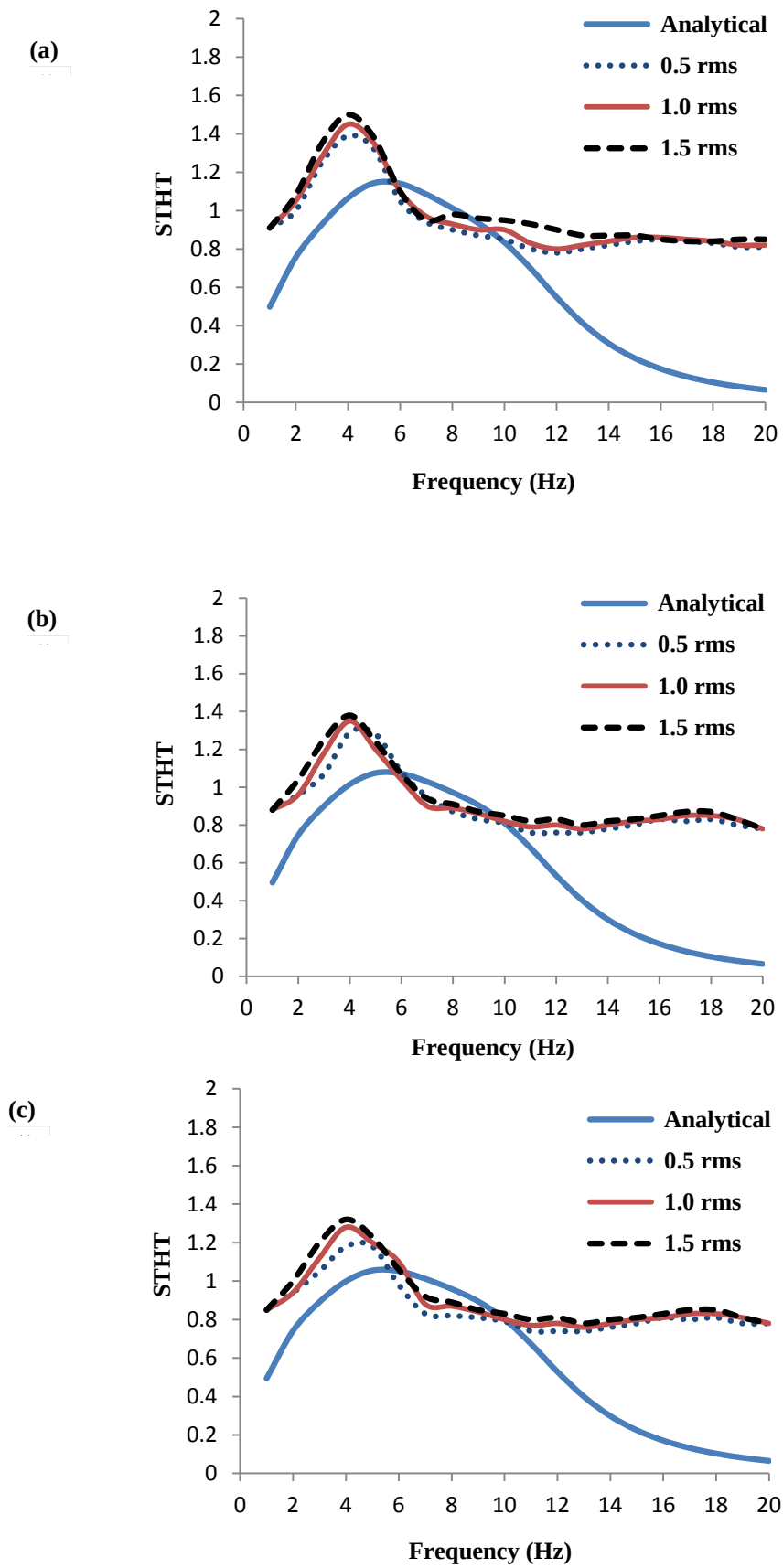


Figure 5.12 Comparison of STHT obtained analytically and experimentally for a cushioned seat (D_2) at inclination angle (a) 0° (b) 15° (c) 30°

Summarizing, it is seen that the first peak is observed around 4 to 6 Hz, which corresponds to the natural frequency of human body, in both analytical and experimental analysis.

Second peak which is rather a flat one is observed around 17 Hz in the experimental results whereas same is not observed in the analytical investigations. Existing literature clearly indicates that when a system is excited with single axis vibration, cross coupling effect is observed and a secondary peak is present. In the present experiment the second peak around 17 Hz indicates the excitation along the fore and aft direction.

Reason for non-occurrence of the second peak in the analytical work could be the difference in the damping values which have been taken for evaluation for the STHT in the numerical computation and the actual non-linear damping of the body segments which affect the responses in the experimental measurements. Damping values used in the present model have been taken from the existing literature (Gupta, 2007) and have been iterated to obtain a best fit response.

Another plausible reason could be that in the analytical investigations system parameters like stiffness and damping are considered as linear, which inherently are non-linear in actual situations, though this difference may be small for low excitation frequencies. A review of literature indicates that many a time's second peak is not visible in the numerical computations (Desta *et al.* 2011).

The frequency of the peak is a function of the vibration magnitude; this non-linearity is characterized by the resonance frequency decreasing as the vibration magnitude increases (Mansfield and Griffin 2000 and Mansfield and Maeda 2005).)

Results obtained in this research work match with the trend seen in the existing studies (Cho Y and Yoon YS, 2001) and (Liang, C.C. and Chiang, C.F 2008).

It is seen that by and large, the analytical modelling results match well with the experimental results, given the uncertainties and limitation of the accuracy of the experimental investigations.

CHAPTER 6

ASSESSMENT OF SUBJECTIVE RESPONSE

6.1 Introduction

The objective of this study was to assess the subjective response of seated human beings subjected to vertical harmonic vibrations. In order to achieve this goal, twelve human males were subjected to different levels of excitation amplitudes and frequencies to assess the response. Their common subjective response in the form of vibrations being felt by them at different body segments, their severity, significance and comfort level were recorded. The results of the typical responses in all the cases have been presented in this chapter.

Non-invasive experimental investigations were conducted for three different sitting postures at three different backrest inclination angles (0° , 15° and 30°) with the vertical and with or without cushions. The postures and parameters considered in this study intended to represent the seated human body while travelling.

6.2 Resonant frequency and symptoms of human body segments

It is well known that different body segments have different natural frequency and are expected to respond to stimulus differently. Natural frequency of some human body segments along with the reported symptoms related to discomfort and pains which will help in understanding the response behaviour are given in Table 6.1.

Table 6.1 Symptoms due to WBV and resonant frequency of human body segments (Bruel and Kjaer 1982)

S. No.	Symptoms	Frequency (Hz)
1.	General feeling of discomfort	4-9
2.	Head	13-20
3.	Lower Jaw	6-8
4.	Shoulders	4-5
5.	Arms	5-10
6.	Chest	5-7
7.	Abdomen	4-10
8.	Back	10-12
9.	Legs	2-20

6.3 Subjective response of seated human subjects

For understanding this study, the details of experimental set-up, experimental conditions, physical data of test subjects, range of stimuli etc. have been already presented in section 5.2.

Subjective responses when subjects were subjected to different vibration magnitudes (0.5, 1.0 and 1.5 m/s^2 rms) and excitation frequencies (1 to 20 Hz) were recorded. Each human subject was exposed to vertical WBV for 60 seconds and after each sitting every subject was asked to share his feelings regarding exposure to vibrations in terms of comfort level, severity of vibrations felt at various body segments and flow of vibrations from one body segment to other(s). Subjective response was recorded separately for each subject. Common response of all the subjects has been presented in all the cases studied in a tabular form.

6.4 Effect of backrest inclination on sitting subjects exposed to vertical harmonic vibrations

Sitting human subjects seated with a rigid support during experimentation and backrest inclination angle of 0° , 15° and 30° with the vertical have been shown in Figure 6.1.



Figure 6.1 Seated human subjects with rigid support and backrest inclination angle (a) 0° (b) 15° (c) 30°

Nomenclature shown in table 6.1 (a) has been used to assist the interpretation of the subjective response of the subjects in different cases, given in tables 6.2 to 6.6.

Table 6.1 (a) Nomenclature

A	arms	LL	lower legs
Ab	abdomen	LB	lower back
B	back	N	neck
C	chest	S	shoulders
F	feet	UL	upper legs
H	head	UB	upper back
Hp	hips	WBV	whole body vibration
Hs	hands	*	Moderate to severe vibrations experienced

6.4.1 Backrest inclination angle 0°

The table summarizes the common vibratory response felt by the 12 subjects under different combinations of frequency and excitation amplitudes. Each block contains within it the body segments at which the subjects responded feeling of vibrations accompanied with discomfort of different levels. Comfort level of the subjects has been hypothesized on the basis of vibrations felt, irritation and number of body segments at which these were observed.

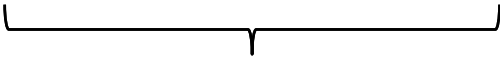
Table 6.2 gives common subjective response of different body segments when subjected to different amplitudes and frequencies for 0° backrest inclination.

It is seen that most of the human subjects felt vibrations in the whole body at 5 Hz for all the excitation amplitudes resulting into a general feeling of discomfort. The responses corresponding to 8, 12, 16 and 20 Hz were limited to body segments as indicated in each block.

It is clearly observed that results shown in Table 6.2 match with the resonant frequency of the individual body segments (as shown in Table 6.1). At a combination of 0.5 m/s² rms and 12 Hz, transfer of vibrations from abdomen to chest was significantly felt by the subjects.

Table 6.2 Common subjective responses at different body segments when subjected to different amplitudes and frequencies at 0° backrest inclination

Amplitude (m/s ²)	Frequency (Hz)				
	5	8	12	16	20
1.5	WBV (C, Ab)*, B to S, Pressure below C	C, B, UL	Back side of N & C, Ab, L	WBV (below N)	LB, UL, F
1.0	WBV (upper body)*	S, B, F	N, B, Ab, UL, LL	H, B, Ab, LL	F to LL
0.5	WBV (upper body)*	H, C*, S, B, UL	WBV	H, B, UL, LL	B, LL



Upper Body Segments



Lower Body Segments

* Severe vibrations were felt at particular body segment

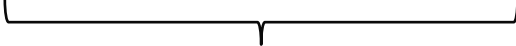
6.4.2 Backrest inclination angle 15°

Some of the major observations made during experimentation in this case are given below:

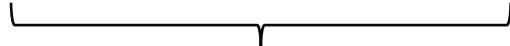
- i. The subjects responded in terms of vibrations being felt at different body segments while subjected to vertical harmonic vibrations. It was observed that at a frequency of 5 Hz, whole body vibrations (WBV) were felt which particularly were significant at chest, shoulder and abdomen at an amplitude of 1.5 m/s² indicating the upper body segments are affected more at higher value of excitation.
- ii. It was further seen that at higher excitation frequencies the lower body segments are predominantly affected as most of the subjects reported vibrations sensations in the lower part of the body which is close to the source of excitation. This may be due to resonant frequencies of the lower body segments nearing these excitation frequencies.
- iii. No specific trend was observed vis-à-vis the excitation amplitude at different frequencies barring the fact that some of the subjects responded slightly uncomfortable feeling in the mid portion of the body at higher amplitudes.

Table 6.3 Common subjective responses at different body segments when subjected to different amplitudes and frequencies at 15° backrest inclination

Amplitude (m/s ²)	Frequency (Hz)				
	5	8	12	16	20
1.5	WBV (C, S, Ab)*	H, C, B, Ab, LL	WBV (till Neck)	B, Ab Hp, LL	B, Ab, F
1.0	WBV	H, A, C, LL	B, Ab, UL, LL, F	C, B, F	H, Ab, B, LL, F
0.5	WBV	H, C, Ab, B, LL	F	LB, Hp	N, B LL, F



Upper Body Segments



Lower Body Segments

6.4.3 Backrest inclination angle 30°

In order to study the effect of increasing backrest inclination, experiments were performed at an inclination angle of 30° and following observations were made:

- i. The general trend of WBV being predominant at low frequency excitation continued. The vibrations being felt at the lower part of the body for high frequency excitation was again reported. However, the amount of vibrations at inclination of 30° was significantly lower than those at 15° and 0°.
- ii. It is also seen that change of inclination causes the response to be felt by the subjects at upper portion for some combinations of frequency and excitation amplitude and in the middle portion in some other combinations. No particular trend was observed in this regard.
- iii. In general the comfort level reported by most of the subjects was more when the inclination angle of backrest was increased.

Table 6.4 Common subjective responses at different body segments when subjected to different amplitudes and frequencies at 30° backrest inclination

Amplitude (m/s ²)	Frequency (Hz)				
	5	8	12	16	20
1.5	WBV (C, Ab)*, B to S, Pressure below C	C, B, F	Back side of N & C, Ab, L	WBV (below N)	LB, UL, F
1.0	WBV (upper body)*	S, B, F	N, B, Ab, UL, LL	H, B, Ab, LL	F to LL
0.5	WBV (upper body)*	H, C*, S, B, UL	WBV	H, B, L	B, LL

Upper Body Segments

Lower Body Segments

The results shown in tables 6.2, 6.3 and 6.4 clearly show that some subjects reported mild vibrations with tickling at feet at high frequencies (around 20 Hz), whereas in mid frequency range (8 to 16 Hz) transfer of vibrations through the body was clearly noticed.

At excitation amplitude of 1.5 m/s², comfort level increased with increase in frequency from 5 to 20 Hz. Most of subjects were uncomfortable at amplitude of 1.5 m/s² and frequency of 5 Hz and reported the response as irritating. At the same amplitude (1.5 m/s²) within frequency range of 8 to 16 Hz most of the subjects reported pressure on chest, weight on chest etc. But at same amplitude with frequency of 20 Hz most of subjects were comfortable.

Symptoms and values shown in tables 6.2, 6.3 and 6.4 by, and large, are well correlated with the values given in Table 6.1, indicating occurrence of resonance in body segments at different excitations frequencies.

It was observed that at excitation frequency of 5 Hz, which is matching with the primary natural frequency the response of all the subjects at all amplitudes, is in the form of WBV. Whereas, at 20 Hz excitation, the response is limited to lower part of the body like feet, lower legs and upper legs only which are closer to the source of excitation. In the mid-frequency range the response widely varied from a feeling of discomfort at different body segments to mild to moderate vibrations in certain situations being felt by the subjects.

It was also clearly seen that with increase in inclination of backrest, comfort level of human subjects also increases. The results obtained in this study have been clearly validated with the previous studies (Griffin 1990; Rasmussen 1983 and Whitham and Griffin 1978). Results obtained in this study are similar to those specified in ISO 2631-1(1997) that are based on subjective comfort and perception data.

Studies undertaken revealed the following:

- i. **Effect of frequency:** At low frequencies same vibrations as at feet/ seat are transmitted throughout the whole body. At slightly higher frequencies resonance in various body segments amplify the motion and overall discomfort is accompanied by sensations in different parts of the body (abdomen, chest, shoulders etc.). Further increase in frequency leads to increased vibrations in the body and localization of discomfort finally shifts to close proximity of the source of vibrations (feet).
- ii. **Effect of amplitude:** With increase in amplitude, comfort level decreased as moderate to severe vibrations were experienced by the subjects. There was increase in vibration sensation with increase in magnitude. This can be attributed to Steven's power law which suggests that the psycho-physical magnitude of the stimulus is related to its physical magnitude.
- iii. **Effect of backrest inclination:** With increase in backrest inclination angle from 0° to 15° to 30°, comfort level of human subjects also increases. The common response from the subjects clearly indicated that number of the body segments which showed vibratory effects was less when the inclination angle increases. This was particularly true for high frequency excitations (which correspond to lower body segments) and low excitation amplitudes. It was also observed that corresponding to the fundamental body resonance of 5 Hz the effect of backrest inclination was not considerable as in all the cases vibrations in the whole body were predominant. This may be due to the fact that with increase in angle, pressure on the intervertebral discs is minimal and stress on the back (disc pressure) decreases.

The summarized responses have been concluded and these could be applied judiciously in the design of driving seat and backrest inclination such that comfort level of drivers and passengers is enhanced.

6.5 Effect of cushions on sitting subjects exposed to vertical harmonic vibrations

The effect of cushions (density 32 and 40 kg/m³) at seat and backrest was studied. It has been observed that at low frequency excitations whole body vibrations (WBV) and upper portion of the body respond with mild to moderate vibrations and at high frequency excitations the lower portion of the body which is close to the point of excitation responds significantly. Use of cushion at seat and backrest increases the human comfort level with shifting of responding segments in some cases.

Table 6.5 Common subjective responses at different body segments when subjected to different amplitudes and frequencies without cushion

Amplitude (m/s ²)	Frequency (Hz)				
	5	8	12	16	20
1.5	WBV	F to UL, S to H	F to UL, A to H	WBV (below N)	LB, UL, F
1.0	WBV	LL, UL, C	UL, LL, B, AB	H, B, Ab, LL	F to LL
0.5	WBV	UL, B, C, S	F to B	H, B, L	B, LL

Upper Body Segments
Lower Body Segments

Experiments were performed under three different conditions: without cushions and with two different cushions D₁ and D₂.

Table 6.6 Common subjective responses at different body segments when subjected to different amplitudes and frequencies with cushion

Amplitude (m/s ²)	Frequency (Hz)				
	5	8	12	16	20
1.5	WBV	WBV; Hp, B	LB, UL, A	LL, LB, UB, H	F, LL
1.0	WBV	L, B, A, Ab	C, Ab, LL, LB	F, H, B	F, LL, LB
0.5	WBV	H, A, S, C, Ab	WBV, H, N, C; Ab to C	H, C, Ab, H	LL, LB, H

Upper Body Segments
Lower Body Segments

At high amplitudes, subjects responded with more discomfort accompanied with more vibrations in different body segments. By and large effect of cushions in improving the comfort level is more visible in the higher frequency range with shifting of responses at different body segments in certain cases. It can be concluded that cushions affect the comfort level more under high frequency excitations. However, at low frequency excitations coupled with higher excitation amplitudes, subjects responded with more discomfort in certain body portions.

It was seen that variation in cushion density from 32 to 40 kg/m³ does not show any visible change in human comfort level.

CHAPTER 7

CONCLUSIONS AND SCOPE OF FUTURE WORK

7.1 Conclusions

In the present research work, modelling, experimental investigations and its validation have been done for studying the effect of the excitation frequency, vibration magnitude, backrest and its inclination angles and cushion on seat to head transmissibility of seated Indian male subjects under sinusoidal vertical whole body vibrations.

Following conclusions have been drawn from the present research work:

- i. Mathematical models and the model parameters in the existing literature are usually derived from the experimental investigations using error minimization technique. In the present research work, an alternate methodology for determining the model parameters like stiffness and mass of the model based only on anthropometric data has been successfully applied for obtaining the model which obviates the need of experimentation.
- ii. Earlier models considered connecting springs as mass-less. In the present model spring mass has also been taken into consideration to make the model more realistic which led to better results.
- iii. Equations of motion have been developed by using a new concept of slippage force term which is an off-shoot of free body diagram/Newton's Law and is much simpler to apply to multi degree freedom systems.
- iv. Eigen values and vectors have been evaluated and the results have been compared with the values available in the literature. It was found that the eigen values evaluated in the present work are comparable with the resonant frequency peaks obtained from the experimental data obtained in this work and available in the existing literature. Eigen values obtained clearly establish decoupling of vertical and fore and aft oscillations. In comparison to the experimental values, frequencies calculated in the analytical study seem to be slightly on higher side, as damping has not been included in the present free vibration analysis.

- v. Seat to head transmissibility was obtained analytically and experimentally for all the cases. It was seen that seat to head transmissibility increases with increase in vibration magnitude in each case.
- vi. The effect of increase in frequency on seat to head transmissibility is visible in terms of a dominant peak near first resonance. Attenuation in STHT is observed as frequency increases.
- vii. It was observed that when backrest is used, STHT value decreases by an order of 19.5 % to 23.2 % for different vibration magnitudes in comparison to without backrest posture. For subjects sitting on a rigid seat with backrest STHT increased with increasing vibration magnitude, resulting in increase in discomfort with increase in vibration magnitude and resonance in STHT tends to shift to a lower frequency with increasing vibration magnitude due to softening effect.
- viii. Change in backrest inclination angle led to change in transmission of vibrations through the body resulting in change in comfort level of human subjects. STHT was more in case of 0° inclination in comparison to 15° and 30° inclination of backrest support irrespective of magnitudes of vibration indicating more comfort level in case of backrest inclined at 30° to the vertical. As the frequency increased, presence of a dominant peak was observed around 5 Hz which is the primary natural frequency of the human body and in the frequency range of 8 to 20 Hz STHT values were less than 1.0 (indicating attenuation in the flow of vibrations) in all the cases examined.
- ix. The present study depicts a substantial decrease in transmissibility values with the cushioned seats vis-à-vis rigid seats and a little softening effect in terms of decrease in resonant frequency. The results suggest considerably higher values of seat to head transmissibility magnitudes with the rigid seat compared to the cushioned seat, irrespective of the back support. For the case when no backrest is used, there is a decrease of 5% in STHT values when a cushion D1 is used. Comparison of two cushion densities (D_1 and D_2) undertaken in this study do not show much variation in STHT values as well as resonant frequencies.
- x. During validation of analytically developed models and experimental investigations conducted it was found that the first peak is observed around 5 Hz, which is the natural frequency of human body, in both analytical and experimental analysis, whereas, second

peak is observed around 17 Hz in the experimental results only and the same is not observed in the analytical investigations. In all major studies, the analysis near the fundamental natural frequency is of utmost importance.

- xi. Existing literature clearly indicates that when a system is excited with single axis vibration, cross coupling effect is observed giving rise to a secondary peak. In the present experimentation a second peak around 17 Hz indicates the excitation along the fore and aft direction.
- xii. In the analytical investigations system parameters are considered as linear, which inherently are non-linear in actual situations, though this difference may be small for low excitation frequencies. A review of literature indicates that many a time's second peak is not visible in the numerical computations (Desta *et al.* 2011, Liang and Chiang 2010).
- xiii. Another plausible reason for non-occurrence of the second peak in the analytical work could be the difference in the damping values which have been taken for evaluation for the STHT in the numerical computation and the actual non-linear damping of the body segments which affect the actual responses in the experimental measurements.
- xiv. Results obtained in this research work match with the trend seen in the existing studies (Cho and Yoon 2001 and Liang and Chiang 2008).
- xv. In the present research work, subjective response has also been conducted to study the severity of response felt by human subjects at various body segments for different values of vibration magnitudes and excitation frequencies. It was seen that most of the human subjects felt vibrations in the whole body at 5 Hz for all the excitation amplitudes resulting into a general feeling of discomfort. The responses corresponding to 8, 12, 16 and 20 Hz were limited to individual body segments. It has been observed that at low frequency excitations whole body vibrations (WBV) and upper portion of the body respond with mild to moderate vibrations and at high frequency excitations the lower portion of the body which is close to the point of excitation responds significantly.

The above results give an insight to the flow of vibrations through a sitting human body when subjected to vertical vibrations under the given conditions. The information can be judiciously employed in the design of seat of a vehicle to reduce the transmissibility and improve the human comfort.

7.2 Scope of future work

It is believed that this research work has provided more comprehensive understanding of the aforementioned biodynamic responses for a seated human subject. This research work can be further extended considering following aspects:

- i. Development of reliable mathematical models can save the time to conduct experiments, save energy, save setup cost and totally eliminate the ethical problem associated with subjects taking part in experiments. Advanced computation of complex human body can become possible with the help of powerful softwares so that more representative human body model can be developed using lumped parameter, multi-body and finite element methods in order to describe human body motion under whole body vibration better than before.
- ii. Mathematical models developed in this research work considered human body as a linear system. Non-linear models may be developed to get better results.
- iii. This study deals with analytical evaluation of masses and stiffness of springs connecting human body segments using anthropometric data. Similar approach may be developed for evaluating damping coefficients of dashpots connecting human body segment.
- iv. Present study can be extended for other biodynamic response functions such as driving point mechanical impedance and apparent mass.
- v. This study was conducted for the conditions to which a human subject is exposed to while travelling and the subjects were subjected to harmonic vibrations. But, in addition to vertical vibrations, human subjects while travelling are also exposed to random vibrations. Effect of random vibration may be considered for extending this study.
- vi. Present research work can be extended for recumbent posture to study the effect the vibration on human subject lying on the bed while travelling.

LIST OF PUBLICATIONS

INTERNATIONAL JOURNALS

1. **Singh Ishbir**, Nigam S.P. and Saran V. H., “Modal Analysis of Human Body Vibration Model for Indian Subjects Under Sitting Posture”, *Ergonomics*, Vol. 58, Issue 7, pp. 1117-1132 (2014). **DOI:** 10.1080/00140139.2014.961567.
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3. **Singh Ishbir**, Nigam S.P. and Saran V. H., “Effect of Cushions on Sitting Subjects Exposed to WBV”, *Materials Today: Proceedings*. Publisher: ELSEVIER. ISSN: 2213-0209.
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INTERNATIONAL CONFERENCE

1. **Singh Ishbir**, Nigam S.P. and Saran V. H., “An Analytical Study on Human Body Vibration for Indian Subjects Under Sitting Posture”, 5th International Conference on “Whole Body Vibration Injuries”, held from 5th to 7th June, 2013 at Academic Medical Center, University of Amsterdam, **Amsterdam, The Netherlands**.
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