EFFECT OF LOW FREQUENCY VIBRATIONS ON HUMAN COMFORT

A THESIS

Submitted in partial fulfilment of the requirements for the award of the degree
Of
DOCTOR OF PHILOSOPHY
In
MECHANICAL ENGINEERING

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **EFFECT OF LOW FREQUENCY VIBRATIONS ON HUMAN COMFORT,** in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy and submitted to the Department of Mechanical and Industrial Engineering of the Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from January 2010 to September 2013 under the supervision of Dr. V. H. Saran, Associate Professor and Dr. S. P. Harsha, Associate Professor, Mechanical and Industrial Engineering Department, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

(**PRASHANTH A S)**

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(V.H. Saran) Supervisor	(S.P. Harsha) Supervisor

Date:___________

The Ph.D. Viva-Voce Examination of **Mr. PRASHANTH A S**, Research Scholar, has been held on ………………………………………………..

Signature of Supervisors   Signature of External Examiner

ABSTRACT

Nowadays, the urban populace often spends a significant amount of their time for travelling and there is an increasing demand for comfort, both in private and public transportation. The quality of life in on-road vehicles is influenced by the level of ride comfort which is basically related to vibration levels. The ride comfort has developed facets that are as significant as safety and speed in assessing the physical characteristics of road transportation. The road roughness and vehicle vibration play a predominant role in the subjective evaluation of the ride comfort and activity comfort. A field study was therefore conducted by incorporating a questionnaire based study on public transport buses in India, in three different bus routes between Roorkee to Hardwar, Hardwar to Roorkee, and Saharanpur to Roorkee together with vibration measurements on the seat and floor. The subjective study involved reading of a national Hindi newspaper, to obtain a subjective opinion and to quantify the difficulty in reading and also from the vibration measurements the seat accelerations were measured for suggesting the proper design of seats in public transportation buses. The Preference technique method was adopted and the level of discomfort analyzed in 7- point semantic scale. The conclusions from the seat location, postures adapted for reading and the vibration measurements served as useful guidelines for conducting experimental work in the Laboratory.

There are many environments in which people stand upon vibration platforms. The commuters of metro trains and public transport buses often adopt standing postures, wherein they hold the handrail or the handle affixed to the handrail. In the present work, of floor to head transmissibility (FTHT) and floor to knee transmissibility (FTKT) of the standing subjects holding handrail and handle have been studied for sinusoidal vibration magnitude of 1m/s^2 rms in vertical as well as in lateral directions in the low frequency range 3-15 Hz.

The transmissibility results from the dynamic response of human body help in understanding the undesirable stimuli and the feelings of occupants on their activities caused by vibration. Both the vertical transmissibility values (FTHT and FTKT) were found to be higher with the handle as compared with the handrail. However the lateral vibration transmissibility is comparatively higher with the handrail posture. It was also observed that for normal standing posture of the subjects, the transmissibility is higher in lateral and vertical sinusoidal vibration in both handle and handrail postures.

The past decades have produced numerous studies on response of human body in vibrating environment which were supported by a number of experimental and analytical reports. Many of these focused on mathematical modeling for describing the biodynamic response of humans. Several biomechanical models have been proposed for responses to whole body vibrations (WBV), with different idealizations of the body structure and distribution of vibration, which are dependent on extrinsic and intrinsic variables, interfaces between the body and the vibration environment.

Even though a few previous studies reported the use of finite element method in whole body vibration on specific human body segments to analyze mode shapes, deflections and their dynamic responses to the force excitation on standing posture models using finite element method was deficient. Hence, in the present work a continuum – 3 dimensional biomechanical model of the human body in standing posture with truncated ellipsoidal shaped body segments was developed and analyzed its mode shape characteristics using finite element method (FEM) software ABAQUS 6.10. The main focus of the work was to find natural frequencies for whole body vibrations (WBV), mode shapes and its deflections from the starting mode to the final mode. The principal resonance frequency obtained computationally is found at 6.45 Hz. Mode shapes and deformations due to whole body vibration in all resonance frequency ranges are numerically obtained and found to be within the range of available literature. The model is also analyzed analytically using governing equations and found natural frequencies.

The dynamic responses of the standing human body subjected to vertical force were analyzed using finite element method. The objective of this study is to analyze the vibration signatures in time domain and frequency domain under low frequencies from 0 – 25 Hz under excitation conditions of 1m/s^2 acceleration and body mass of 75 kg. A vertical force was applied under the foot and the accelerations at the knee and head were computed. The acceleration levels were found to be lower at the head than the knee acceleration which could be attributed to damping in upper body parts. The frequency responses show that the resonances at head and knee occur around frequencies of 5 Hz and 12.5 Hz with the acceleration levels of 0.47 and 3.35 m/s^2, respectively. The low frequency vibration analysis of standing posture of human has been analyzed computationally and its results are verified with the experimental study performed on the vibration simulator at IIT Roorkee, India.

In seated human the experimental study has been conducted in the laboratory to provide supporting information concerning the effect of inter-subject variability, magnitudes, frequencies and postures. The experiments were performed to measure vertical vibration transmitted to the occupants head in two representative postures erect and inclined backrest under three magnitudes of vibration under the frequency range 3 – 12 Hz in vertical direction. The STH transmissibility and BTH transmissibilty were recorded for each frequency and magnitude undertaken in the experiment. The measured data of each subject were collected using sound and vibration analyzer (SVAN 958). The observed result revealed the shift in the frequency was more evident in the back supported postures than in erect posture. This suggests that the upper body supported against a back support exhibits more softening tendency under higher magnitudes of vertical vibration. The STHT also revealed that primary resonance frequency decrease by approximately1Hz (from 5Hz to 4 Hz) from the erect posture to inclined posture for 1.2m/s^2 r.m.s vibration magnitude.

Human beings are most sensitive to whole body vibration under low frequency in a seated posture, therefore, biodynamic responses of a seated human body have been the topic of interest over the years and a number of mathematical models have been established. Based on this a 15 degree of freedom (DOF) lumped parameter model for standing human body and 5 degree of freedom (DOF) lumped parameter model for sitting human body is developed and solved for natural frequency, eigen values and mode shapes using derivation of governing equations and free body diagrams. The modeling procedure presented in this paper involves several simplifying assumptions. The foremost being the approximation of the body segments to ellipsoidal bodies, truncation of the ellipsoids for evaluating segment stiffness, and the approximation of segment elastic modulus as a geometric mean of bone and tissue elastic moduli. Nevertheless, with the adopted approximations the proposed modeling procedure seems to give a fairly good estimate of the low order mode natural frequencies. The fundamental resonant frequency of the 15 DOF model was found at 13.85 Hz.

A 5 DOF lumped parameter model has been developed for a human in seated posture under sinusoidal excitation to determine the dynamic response characteristics such as driving point mechanical impedance (DPMI) and the seat to head transmissibility. As a part of this study analytical transmissibility data is validated with the experimental data. The resonant frequencies of the human subjects computed on the basis of transmissibility function are found to be close to that expected for the human body. It is concluded that the change in the

human body mass, pelvic stiffness and pelvic damping coefficient gives remarkable change in the biodynamic response behaviors of the seated human body.

ACKNOWLEDGEMENTS

Guru Stotram: "Guru Brahma Guru Vishnu, Guru Devo Maheshwara Guru Sakshat Param Brahma, Tasmai Shri Gurave Namah"
Guru is Brahma, Guru is Vishnu, and Guru is Lord Maheshwara. The guru is the ultimate supreme reality. Sublime prostrations to Him".
Upanishad: Matr daevo bhava , Pitr daevo bhava, "Let your mother be God to you, Let your father be God to you.
I humbly add: Bandu daevo bhava, "Let your friends be God to you".

I first truly express my heartfelt owe and gratefulness to my Supervisors (Guru) and Associate Professor's Dr. Suraj Prakash Harsha and Dr. V. Huzur Saran, for their constant guidance, inexhaustible liveliness and commitment throughout the accomplishment of the thesis work, and awaking me several times as my "state of mind fluctuates" as this thesis was being drafted. I am especially glad to my supervisors for the most vital, they provided me relentless inspiration and sustenance in countless manners which meaningfully enriched my knowledge with their unique insights into engineering research. The motivation, advice, applause, objections and comments that I have received from them, are particularly appreciated and I am very much indebted for their patience and perseverance with an average mind like mine.

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My special thanks to Dr. H.M Nanjundaswamy for his moral support as a teacher (Guru) and as a brother. Finally, I would like to thank my dear wife and daughter for her patience and love.

i dedicate this dissertation to my dearest mother, D. Jayalakshmi, and father, D. Srinivasa, where ‘i’ is only a creation of their dreams.

PRASHANTH A.S.

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Appendix A

Questionnaire survey of ride and activity comfort on Indian public transportation buses

Department of Mechanical and Industrial engineering
Indian Institute of Technology, Roorkee -247667.

Bus from ……………….. To ……………………………
Departure time……..........Date ………………………….
Type of Bus …………….

Namaskar!

We are a group of researchers and M.tech students working at IIT Roorkee. We are aware of the fact that some passengers are not completely satisfied with the comfort on road buses. Our aim is to increase knowledge on passenger needs to be able to suggest improvements on Bus comfort. The suggested improvements will support bus operators and bus manufacturers in their work.

It would be very helpful for us if you complete this questionnaire.
Thank you for your cooperation.

1. Occupation: ……………..
2. Gender ☐ Male ☐ Female
3. Year of birth? ………
4. How tall are you? About …………..meter. What’s your weight? About ……..Kilogram
5. Where did you start your trip today and where are you travelling to?

   Departed from: …..

   Destination: ……..
6. What is the purpose of your trip?
   - ☐ Going to/ from school?
   - ☐ Going to/ from work
   - ☐ Visiting with friends /relatives
   - ☐ Other leisure travel
   - ☐ Business travel

7. Where are you seated right now?
   - ☐ Back seat
   - ☐ Front seat
   - ☐ Middle seat

8. What have you been occupied with when you have been sitting in this seat on this bus?

Activity	Amount of minutes
Reading	
Drinking	
Sleeping	
No particular activity	

9. Answer this question if your answer on question 8 was that you have been reading. Please state how you were sitting when you READ.

Several alternatives may be marked	Often	Sometimes	Rare	Never
Leaning towards the front	☐	☐	☐	☐
Leaning towards an upright backrest	☐	☐		
Leaning towards aback leaning backrest				

Been sitting sunk in to the seat

Sitting with legs crossed

Sitting with both feets on the floor

Paper / book in my lap

None of the above alternatives

Other

10. Answer this question if your answer on question 8 was that you have been reading. Please state how you were sitting when you DRINKING.

Several alternatives may be marked	Often	Sometimes	Rare	Never
Leaning towards the front	☐	☐	☐	☐
Leaning towards an upright backrest	☐	☐		
Leaning towards aback leaning backrest				
Been sitting sunk in to the seat				
Sitting with legs crossed				
Sitting with both feets on the floor				
None of the above alternatives				
Other				

11. What mood are you in right now (mark one box)?

1	2	3	4	5	6	7

Very good either good/ bad Very bad

12. What kind of disturbances on this bus do you find most disturbing? (Mark with one or more crosses)

☐ No movements are disturbing

☐ While bus passes on road humps

☐ Acceleration

☐ Vibrations

☐ Strong shakings

☐ Annoying noise, for example rattling, horning

☐ Other

13. How do u perceive shaking and vibrations on this Bus generally?

1	2	3	4	5	6	7

Very good Either good/ bad Very bad

14. How could your activities on the bus be facilitated by changing the design of your seat?

…………………………………………………………………………………………………
…………………………………………………………………………………………………
…………………………………………………………………………………………………
………………………………………………………………….....

15. Other comments concerning the comfort of the bus and your different activities during travelling :

…………………………………………………………………………………………………
…………………………………………………………………………………………………
…………………………………………………………………………………………………
…………………………………………………………………

16. How did you perceive writing this text?

1	2	3	4	5	6	7

No difficulties at all Almost impossible

17. Shaking and vibrations made it difficult to write!

1	2	3	4	5	6	7

Not at all Very difficult

18. Other difficulties with Reading and drinking

…………………………………………………………………………………………………

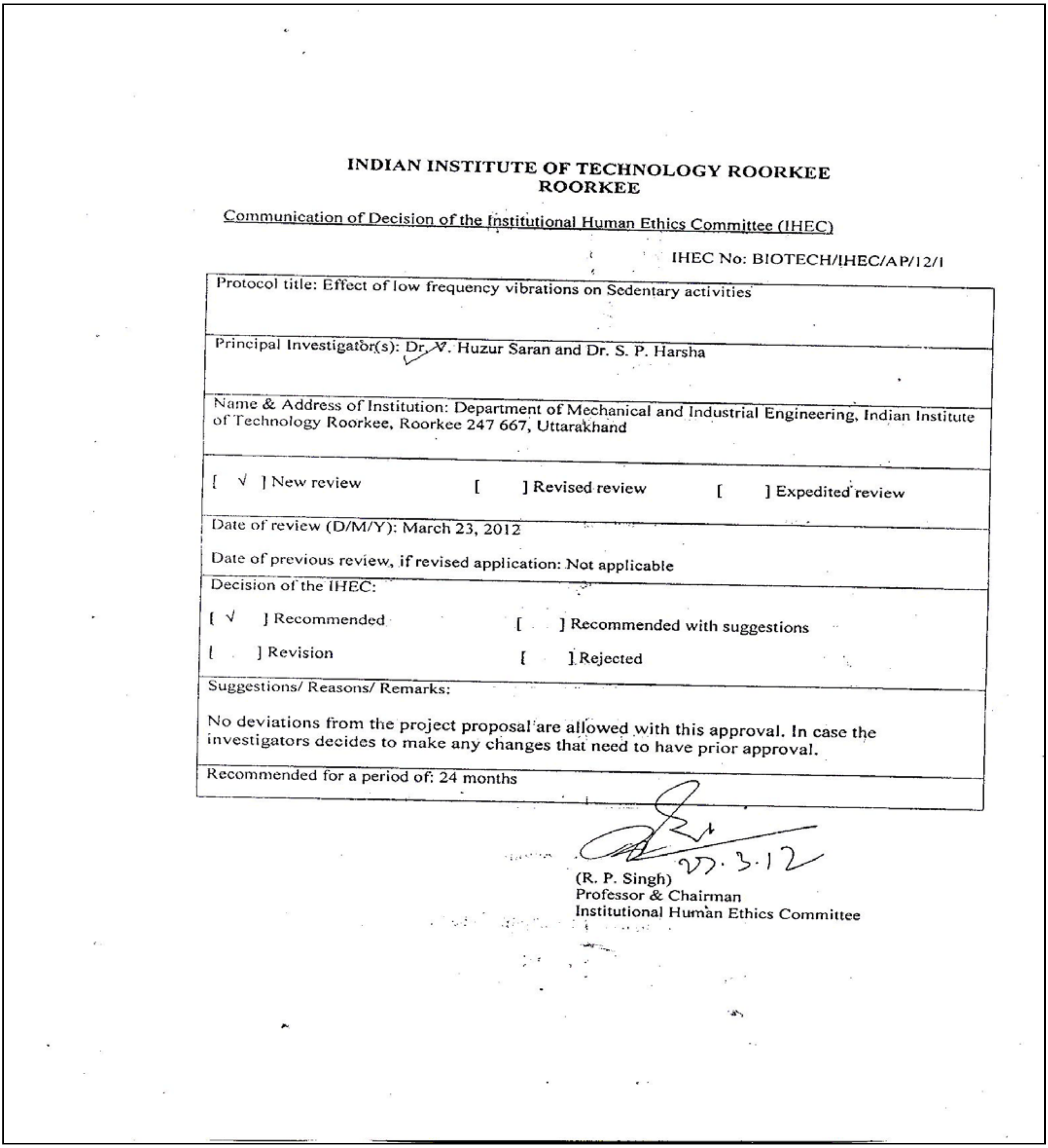
…………………………………………………………………………………………………

……………………………………………………………………………

19. How did you perceive the degree of difficulty of this questionnaire?
    - ☐ Hard
    - ☐ Average
    - ☐ Easy

20. How did you perceive this questionnaire as a whole?
    - ☐ Hard
    - ☐ Average
    - ☐ Easy

Appendix B



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Communication of Decision of the Institutional Human Ethics Committee (IHEC)

IHEC No: BIOTECH/IHEC/AP/12/1

Protocol title: Effect of low frequency vibrations on Sedentary activities

Principal Investigator(s): Dr. V. Huzur Saran and Dr. S. P. Harsha

Name & Address of Institution: Department of Mechanical and Industrial Engineering, Indian Institute of Technology Roorkee, Roorkee 247 667, Uttarakhand

[√] New review [ ] Revised review [ ] Expedited review

Date of review (D/M/Y): March 23, 2012

Date of previous review, if revised application: Not applicable

Decision of the IHEC:

[√] Recommended [ ] Recommended with suggestions

[ ] Revision [ ] Rejected

Suggestions/ Reasons/ Remarks:

No deviations from the project proposal are allowed with this approval. In case the investigators decides to make any changes that need to have prior approval.

Recommended for a period of: 24 months

27.3.12

(R. P. Singh)
Professor & Chairman
Institutional Human Ethics Committee

Appendix – C

Vibration Simulator

Specification of vibration platform

Size of platform 2m X 2m

Estimated weight of this platform was about 85 kg.

Stiffness of the platform is about 1000 Kn/m

Combined stiffness of the supporting springs 160 Kn/m

Specification of vibration exciter

The specification for the exciter was selected from the catalogue of M/s Saraswati Dynamics, Roorkee manufactures of exciters and shake table as given below;

Rated force (Peak sinusoidal)	1000 N
Frequency range	0.01 25 Hz
Max. baretable acceleration	50 g
Max. displacement	10 mm (peak to peak)
Max. Velocity	1 m/s
Type of motion	Sinusoidal
Type of shaker	Electro-dynamic
Max acceleration	2 m/s^2
Max pay load	350 kg

Appendix –D

PARTICIPATION INFORMATION SHEET

Human comfort studies on biodynamic response to the transmission of vibration to human segments.

The aim of this experiment is to investigate the transmission of vibration to different human body segments like head and knee in standing and sitting postures with different poses for totally four vibration magnitudes and in all using sinusoidal vibrations.

This experiment is investigating the transmission of vibration on your body to particular frequencies and excitation vibration magnitudes for the postures you will be asked to adopt. This is to measure the transmissibility from the excitation point to the measured point on your body using PCB accelerometers. The accelerometers will be mounted on your knee with Velcro straps and bite bar is placed in mouth between teeth's while standing and in sitting conditions head acceleration is measured using helmet in one experiment by replacing bite bar. While simulator is in excitation condition data is measured from your body using data acquisitions and measuring instruments from each subjects and recorded. The total duration of test each day is one hour and the duration of the each run is approximately 3 minutes. A 1-2 min break is given between each consecutive section as rest period. Once this is complete you are free to leave.

You are free to terminate the experiment at any time by pressing the alarm button

Thank you for taking part in the experiment.

List of publications

- **International journals**

1. Harsha, S. P., Desta, M., Prashanth, A. S., Saran, V. H., Measurement and bio-dynamic model development of seated human subjects exposed to low frequency vibration environment, International Journal of Vehicle Noise and Vibration, Vol 10, Numbers 1/2 publication, 2014.
2. Prashanth, A. S., Amar kishore, N.V., Saran,V.H., Harsha, S. P., Analysis of seated human body under low frequency vibrations using transmissibility and driving point mechanical impedance, International Journal of Engineering Research & Technology (IJERT), Published, ISSN: 2278-0181, Vol. 2 Issue 6, June, 2013.
3. Prashanth A.S., Saran V.H., Harsha S.P., Analysis of human comfort on normal standing posture human body using finite element method, International Journal of Acoustics and Vibration, (Comunicated).
4. Prashanth, A. S., Harsha, S. P., Saran, V. H., Vibration signature analysis of a standing human under low frequency vibration, International Journal af Acoustics and Vibration, (Comunicated).

- **International conferences**
    1. Prashanth, A. S., Saran, V. H., Harsha, S. P., Study of subjective responses on ride comfort in public transport Uttarakhand buses, Proceedings of the 1st International and 16th National Conference on Machines and Mechanisms (iNaCoMM2013), IIT Roorkee, India, Dec 18-20, 2013
    2. Prashanth, A. S., Harsha, S. P., Saran, V. H., Vibration signature analysis of a standing human under low frequency vibration, 5th International Conference on Whole Body Vibration Injuries, Accepted for publication, 2013.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Commuters of metro trains and public transport buses are subjected to whole body vibration from the supporting structures like seat and floor and passengers often prefer to adopt sitting and standing postures while on board. Additionally, a few other influences might consist of the vibration input from the track, location and mass of dissimilar body portions. Mainly analytical techniques and computational techniques have been used for studing the response of human body to vibration. Abundant number of biomechanical models have been proposed for responses to whole body vibrations (WBV), with different idealizations of the body structure and distribution of vibration, which are dependent on extrinsic and intrinsic variables, interfaces between the body and the vibration environment. Extrinsic variables are variables that express the state or environment of the dynamic system such as magnitude, frequency, direction etc., and intrinsic variables refer to the human subject's natural behavior, character and condition (age, posture, gender, weight, etc). The intrinsic variables can be further categorized as intra-subject variability and inter-subject variability. Inter-subject variability defines the variations among diverse subjects or persons and encompasses the populace sort (age, sex, size, fitness etc.), experience, expectation, motivation, and body dynamic response. Intra-subject variability is considered within a single person and contains adaptations of body posture, position and orientation of a person.

The past decades have produced numerous studies on response of human body in vibrating environment which were supported by a number of experimental and analytical reports. Many of these focused on mathematical modeling for describing the biodynamic response of humans.

The human body is far more sensitive to vibration than sound and even small doses can create discomfort (Griffin, 1998). Many factors such as vibration magnitude, frequency, direction and passenger attributes could contribute to the vibration annoyance (Maffei et al., 2009; Maffei et al., 2010, Accolti et al., 2010). The human model is intended to represent the responses in terms of forces and movements of specific people within a specific range of vibrating conditions. A biodynamic model defines relationships between one or more input as independent variables (input variable) and one or more output as dependent variables. A model cannot represent all the functions of the system but represent one or more aspect of the system. The first stage in the model formation is the identification of the relevant variables such as dependent and independent variables. The information to be expected from the model and what data is required to make the calculation will decide the dependent and independent variables. These models could be achieved by different modeling techniques: such as lumped-parameter (LP) models, finite element (FE) models, and multi-body models. A system in a lumped parameter model is represented by using massless elements (say dampers & springs) which are connected to one or more rigid elements. Numerous models have been developed with this method since analyzing and validating with experiments is easy. Literature shows that most of the lumped parameter models are one dimensional as compared to three dimensional models. In a study of dynamic response of standing and seated persons subjected to vertical sinusoidal vibrations from 1 to 20 Hz it was reported that the first resonance frequency was observed at 5.9 Hz for human subject with 'standing erect with stiff knees' posture, Matsumoto, (1999). The frequencies of standing subjects have been found to vary over a wide range from 4 to 16 Hz, which has been attributed to changing the stiffness by subjects by tensing their leg muscles or bending their knees. The resonant frequencies of standing man in the range of 8 to 10 Hz have been also reported elsewhere. Edwards and Lange, (1964), evaluated the mechanical impedance of two standing male subjects with three different magnitudes of vertical sinusoidal vibration, viz., 0.2, 0.35 and 0.5 g, in the frequency range from 1 to 20 Hz. The principal resonance was found to occur at a frequency between 4 to 5 Hz and subsequent resonance was located in the range of 11 to 15 Hz for a 'normal standing posture' with all magnitudes of vibration. The mechanical impedence of twenty standing subjects in various postures were investigated by Miwa, (1975) where, subjects were exposed to vertical swept sinusoidal excitation in a broad selection of frequency with amplitude of 0.1g, sweeping the frequency from 3 to 300 Hz for 90 seconds duration, a main peak was observed at 7 Hz.

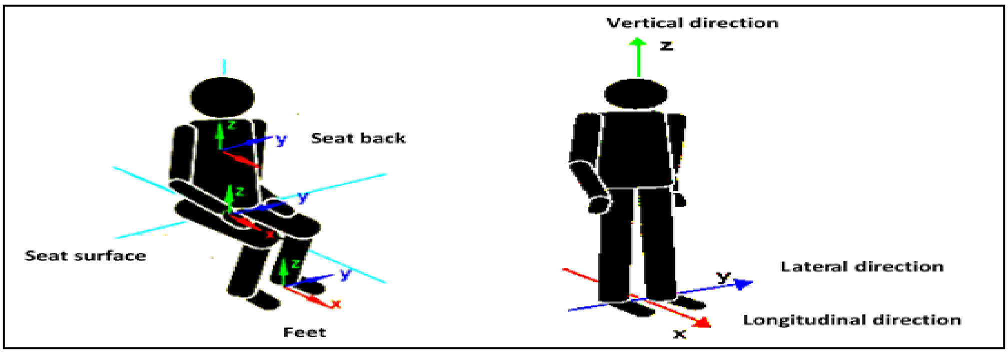


Fig. 1.1- Sitting and Standing postures (Coordinate system for the measurement of whole-body vibration (ISO 2631-1:1997).

In their investigations on human body during exposure to vertical floor vibration in standing posture with the legs straight, Miwa and Fairley, (1978) reported a resonance frequency of around 5 Hz. With the legs bent, the resonance frequency was found to decrease to the range from 2 to 3 Hz. Nigam and Malik, (1987), developed a 15 DOF model lumped parameter model of human in standing posture and computed the mass and stiffness values of elements and the natural frequencies.

Wei and Griffin, (1998), obtained simplified models of the vertical apparent mass of the seated human body for use in techniques for predicting seat transmissibility. Liang and Chiang, (2008), carried out a detailed review of literature on thirteen different lumped parameter models (which include one to eleven DOF) for persons who are seated and are subjected to vibration in vertical directions.

Numerous biodynamic models have been used to depict human motion varying from a single-DOF to multi-DOF models. They can be lumped parameter models, multi-body models or finite element models.

Multi-body human models can be further classified based on the type of joint used for connecting the rigid bodies, viz. pin joints or ball and socket joints. Pranesh et al., (2010), developed a 14 inertial segment and 14 DOF multi-body dynamic model of the seated human body to study the driving point, vibration transmissibility and energy absorption analysis for whole-body vertical vibration in the mid-sagittal plane. Tang et al., (2006), examined the forced vibration reactions of the human body in a crash event and assessed the injuries sustained to the occupant’s head, chest and pelvic regions.

Yoshimura et al., (2005), presented a detailed measurement of human response to vibration, and modeling of the seats human body for the assessment of the vibration risk. It was suggested that the multi-body dynamic model could be used to evaluate the vibration effect of the spinal column for seated subjects.

1.2 RIDE COMFORT

Today, ride comfort has developed facets that are as significant as safety and speed in assessing the physical characteristics of transportation. The road roughness and vehicle vibration play a predominant role in the subjective evaluation of the ride comfort and activity comfort. The quality of life on board road vehicles is influenced by the level of ride comfort which is basically related to vibration levels and the perception of fatigue. According to Suzuki, (1996), riding comfort generally means a “feeling or evaluation related to vibration and acceleration that occurs when a vehicle runs”. Different countries have different gauges, ratios of curves and speed restrictions, and as they have to deal with different weights and physical builds of passengers, it is extremely difficult to establish a universally applicable international standard for the riding comfort of railway vehicles and public transport buses. Hence, to make railways and public transport buses in India more comfortable and more competitive than any other transport mode, it is essential to develop an evaluation method compatible with the feeling of passengers.

Seated individuals are most sensitive to whole body vibration under low-frequency excitation. These responses are very useful to predict the comfort level of the passengers. For better understanding of how whole-body vibration influences the comfort, performance and health, better knowledge about the transmission of vibration through the body (transmissibility) is required. Furthermore, to minimize the transmission in the body it is necessary to have knowledge of the adverse effects of vibration. Ride comfort can be analyzed in three aspects i.e., dynamic factors, ambient factors and spatial factors (Corbridge, 1986).

Ride comfort performance of road and off-road vehicles is an important customer satisfaction issue, and is gradually being integrated within the total vehicle development process. Vehicle ride vibration coupled with constrained drivers' sitting postures and standing postures has been associated with a number of musculoskeletal disorders among vehicle drivers, in addition to the annoyance, discomfort and loss of productivity, particularly for commercial road and off-road vehicles.

The comfort performance of vehicles is related to a multitude of factors related to human driver attributes, vehicle design operating conditions and road/terrain conditions in a highly coupled and complex manner, while the present state of knowledge is insufficient for defining precise objective measures of ride performance for integration in the vehicle development process.

The subjective sensations of vehicle ride comfort show extreme variabilities and strongly rely on individual preferences, the supportive properties of seats, floor, holding structure, vehicle vibration and noise and work station design coupled with vehicle handling. The objective measures of vehicle ride comfort and annoyance, on the other hand, rely mostly on the nature of the vibration and noise of the vehicle.

Although recommendations in past studies on comfort have evolved into valuable guidelines and standards to assess and limit the driver's exposure to vehicle vibration and shock, the subject of assessment and control continues to pose an array of multi-disciplinary challenges. The chassis, suspension and tires are the key design factors affecting objective and subjective ride comfort performance, while the designs are heavily weighted for realizing greater handling performance opposed to ride comfort. High speed work vehicles such as articulated steer vehicles, particularly, encompass difficult challenges for suspension designs to achieve an acceptable compromise between ride and directional stability performance.

The road roughness plays a vital role in evaluating the ride comfort on the basis of subjective opinions and the level of ride comfort, which is essentially related to vibration levels and the perception of fatigue, influences the quality of life on board road vehicles, especially during long distance travels.

ISO 2631-1:1997 is an international standard that gives methods and procedures for the assessment of vibration comfort. This standard has a broad range of applications. Therefore, in order to provide a suitable environvent for satisfactory performance of ride comfort and sedentary activities, an assessment of ride comfort due to whole body vibrations needs pilot study. It provides basic and additional evaluation methods using the crest factor. Weighted r.m.s acceleration is the basic evaluation method if the crest factor is less than 9 and when the basic evaluation method is not sufficient, the running r.m.s method and fourth power vibration dose method were used to evaluate whole body vibration (Griffin, 1998). Guidance with respect to the use of evaluation methods and frequency weightings for health and comfort, and perception for motion sickness are provided. The basic evaluation method uses frequency weighted r.m.s accelerations and is defined by:

$$a_W = 1/T \left(\int_0^T (a_W)^2 \ (t)\, dt \right)^{½} \qquad (1.1)$$

a_w (t) is the weighted acceleration as a function of time in meters per second squared in (m/s^2) and T is the duration of the measurement, in seconds.

The standard defines using weighted r.m.s acceleration, the total vibration value for all directions as far as respective positions are concerned. At present, however, no weighting factors for using laptop or table are provided in the standard. Therefore, the weighting factor of the floor was used for both laptop and table in this study.

As per ISO-2631, Table 1.1 gives approximate indications of the likely reactions to various magnitudes of overall vibration values in public transport.

Table 1.1 - Perception of ride comfort according to (ISO 2631-1:1997).

r.m.s. Vibration levels	**Perception**
Less than 0.315 m/s^2	Comfortable
0.315 m/s^2 – 0.630 m/s^2	A little comfortable
0.50 m/s^2 – 1.00 m/s^2	Fairly comfortable
0.80 m/s^2 – 1.60 m/s^2	Uncomfortable
1.25 m/s^2 – 2.50 m/s^2	Awfully uncomfortable
Greater than 2.00 m/s^2	Exceptionally uncomfortable

Sperling Ride Index (Wz)

Sperling proposed a ride index and developed the so-called Wz method (Werzungzahl). For time intervals which span over defined track sections, Wz is an evaluated frequency weighted r.m.s value of accelerations (Gangadharan et al., 2007).

For any arbitrary acceleration signals which may or may not be harmonic, the value of W_z is given as

$$W_Z = 4.42\ (a^{wrms})^{0.3} \qquad (1.2)$$

where, a^{wrms} is the r.m.s. value of the frequency weighted acceleration in m/s^2. In order to calculate the total Wz in a continuous spectrum the following formula is used:

$$W_Z = \left(2\left(\int_{0.4}^{30} G(f) B^2 (f) df\right)^{0\cdot 14}\right) \qquad (1.3).$$

where *G(f)* is the power spectral density for the acceleration on the floor in m/s^2 (vertical, longitudinal and lateral), *B(f)* is an acceleration weighting function and *f* is the frequency of vibrations. The Sperling ride Index (W_z) is determined for each direction. The main disadvantage though with Wz is that accelerations in different directions are treated separately. The acceptable value of Wz for ride comfort on trains as far as vibrations due to motion is concerned is 2.5 and is comparable to 0.25 m/s^2, which is the standard acceleration value of ISO weighted r.m.s.

Table 1.2 - Ride evaluation scale as per Sperling ride index (Gangadharan et al., 2007).

Ride index Wz	Vibration sensitivity
1	Just noticeable
2	Clearly noticeable
2.5	More pronounced but not unpleasant
3	Strong, irregular, but still tolerable
3.25	Very irregular
3.5	Extremely irregular, unpleasant, annoying, prolonged exposure intolerable.
4	Extremely unpleasant ; prolonged exposure harmful

1.3 ACTIVITY COMFORT

There are several other factors influencing the performance of activities besides vibrations, namely, seat design, use of a backrest, postural conditions, etc. Passengers often use certain postures to attenuate the intensity of vibration and jerks in order to perform their activities satisfactorily. If a seated passenger uses armrest, backrest or places both feet on the floor, the transmission of vibrations to the body will be higher by Griffin, (2003) and Westberg, (2000).

Recent studies have shown that vibrations are a major source of disturbance for many passengers who wish to perform sedentary activities like reading, writing and drinking which makes it especially significant for research studies by Westberg, (2000); Sundstrom, (2004); Khan, (2008).

1.4 BIODYNAMIC MODELS

The comfort of passengers may be affected by several factors such as seat-interface pressure, posture of sitting, standing posture, noise and vibration, visualisation effects, temperature, etc. Based on the vehicle design and type for highway and off-highway operation, low frequency vibrations will be transmitted to the drivers from the floor, steering wheel, and the body surfaces which are in contact with vibrating structures. The suitable design and appropriate alteration of vehicle and suspension systems of seat are normally investigated by certain assumption of insignificant interactions due to vibration transmission on their sedentary activities of the human body Kim et al., (2005). During sinusoidal vertical oscillation at frequencies below about 2 Hz most parts of the body move up and down together. If the motion has a low frequency below 0.5 Hz it may ultimately cause symptoms of motion sickness such as sweating or vomiting. Vertical oscillation of seated person at some frequencies above 2 Hz causes amplification of the vibration within the body.

The biodynamic models can be grouped into lumped parameter and distributed type models. In studies involving the lumped parameter modeling, the human body is considered to be consisting of several rigid bodies and spring-dampers. Whereas the distributed type modeling considers the spine in the form of layered structure of elements of rigid type that represents vertebral bodies, and the elements that are deformable represents inter vertebral discs by the FEM. A model developed by Kitazaki and Griffin, (1997), used FEM and the model analysis was executed to verify each segments's natural frequency. They reported the mode of the principal resonance at about 8 Hz. They also showed that a change of posture from erect to slouch caused the human body's natural frequency to decrease.

1.5 FINITE ELEMENT METHOD MODELS

In a finite element model the system to be modeled is discretized in a number of finite volumes, surfaces or lines. These elements are interconnected at a discrete number of points: the nodes to which degrees of freedom are associated. Griffin, (1998) suggested finite element method modeling beam, spring and mass elements can be used to model the spine, viscera, head, pelvis, and buttock tissue in the mid sagittal plane as shown in Fig 1.2.

Kitazaki and Griffin, (1997) used computational technique using a two dimensional model with beam, spring and mass to find human biomechanical responses to whole body. Elements were used to model the spine, viscera, head, pelvis, and buttock tissue in the midsagittal plane. The model was established by comparison of the vibration mode shapes with those measured in the laboratory. At frequencies below 10 Hz the model produced seven modes which coincided well with the measurements. The first and second principal resonances of the driving point response occurs at about 5 Hz and 8 Hz. A change in posture from erect to slouched raised the shear deformation of tissue beneath the pelvis in the entire human body mode, and the natural frequency was reduced as a result of the much lower shear stiffness of tissue compared to the axial stiffness.

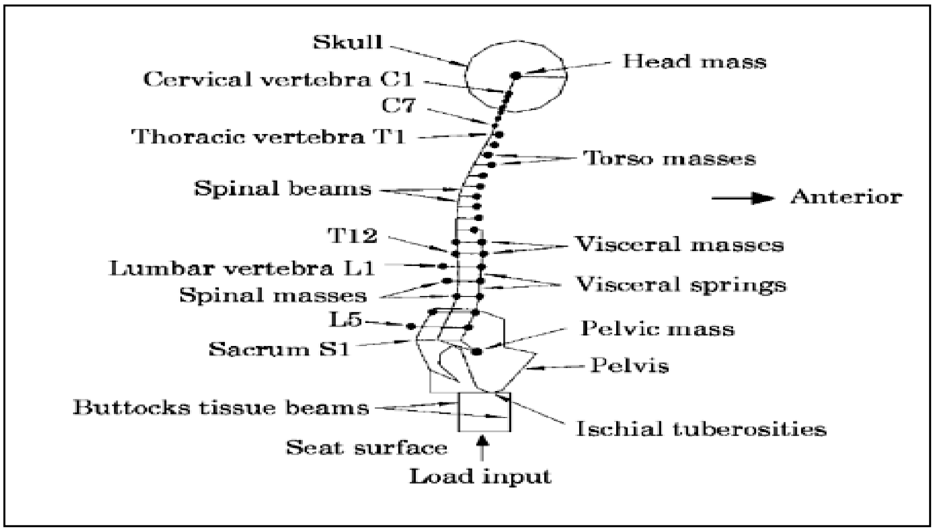


Fig. 1.2 The two dimensional finite element model in the normal posture (Griffin et al., 1998).

1.6 OBJECTIVES OF THE THESIS

The objective of this research work is to investigate the effect of whole-body vibrations on the human subjects in sitting and standing postures. To accomplish the objective, the study has been broadly classified into three major parts namely, field study on public transport buses, laboratory study on comfort under controlled conditions, analytical modeling and the finite element modeling.

The main aim of the field study is to measure the vibration levels in vertical (z) and lateral (y) translational axes at the seat and floor of the bus, so as to select the range of frequencies and amplitudes for excitation on the vibration simulator in the laboratory studies. Moreover, the knowledge of postures that standing passengers mostly adopt during travel onboard buses along with their sedentary activities is vital for carrying out the experimental study. The passenger’s opinion on vibration and noise during their journey while performing sedentary activities can be considered as a pilot study. Therefore, a questionnaire based study was conducted on public transport buses plying on different routes from Roorkee to Hardwar, from Hardwar to Roorkee and from Saharanpur to Roorkee to obtain a subjective opinion and to measure the difficulty in reading a Hindi newspaper.

The objective of the present experimental work using laboratory setup is to observe the effect of inter-subject variability, different posture, and various vibration magnitudes in sitting and standing postures.

Firstly the experimental studies in standing postures was considered because studies on standing subjects was minimum in previous studies and especially the study on bus passengers was very least. Hence, in the present work, a handrail is constructed to provide support for standing subjects as found in U.P transport buses. This study includes the transmissbility of the FTH and FTK under the sinusoidal vibration magnitude of 1m/s^2 r.m.s in vertical as well as in lateral direction between the frequency ranges from 3-15 Hz.

Secondly considering the sitting posture the seat to head transmission was measured for occupants who were seated and their whole body was exposed to vibration. The investigation was carried out on six subjects, all male adults with sitting conditions of variable nature. Characterization of transmissibility response measured vertically from seat to head were carried out to examine the influence of the two postures one erect posture and other inclined 30^0 back rest posture with excitation magnitudes of (0.4, 0.8, 1.2) m/sec^2 in the frequency range from 3-12 Hz. The next objective of the laboratory study was considered with standing postures.

In finite element model study the free and forced vibration of standing human is investigated. The present work aims to develop a continuum – 3 dimensional biomechanical model of human body in standing posture with truncated ellipsoidal shaped body segments and analyse its characteristics modal shapes using finite element method (FEM). The principal resonance frequency obtained computationally is compared with experimental and other FEA results from past literatures. In forced vibration of the present study, the objective is to study and analyze the vibration signatures in time domain and frequency domain under low frequencies from 0 – 25 Hz under excitation conditions of 1 m/s^2 acceleration and body weight of 75 kg. The model is being developed using finite element method and the dynamic response analysis of a human body in two postures, ie, normal standing posture, holding rod posture is being studied to measure transmissibility of accelerations from FTH and FTK. The Fast Fourier Transform technique is performed to analyze the responses in time domain and frequency domain.

In biodynamic response study, the objective of the present work involves the investigation with 5 DOF and 15 DOF lumped parameter models. The 5 DOF biodynamic model for sitting posture having no backrest under sinusoidal excitation is used to determine the dynamic response characteristics such as driving point mechanical impedance (DPMI). Thus, it describes the “to-the–body” force-motion relationship of the seat to human interference and while the transmissibility function shows the properties related to transmission of vibration "through–the-body". The 15 DOF lumped parameter model is developed and formulated with governing equations and solved for eigen values and natural frequencies.

1.6 ORGANIZATION OF THE THESIS

Chapter 1 gives an introduction of human response to vibration, ride comfort, activity comfort, vibration in moving buses, transmission of vibration through the human body, whole body vibration standards, how to reduce the effects of whole body vibration, ISO standards, variables influence human response to vibration and anthropometry of the human body. The objective of research study has been stated along with the organization of the work.

Chapter 2 deals with a critical review of the published literature on comfort studies on trains, buses, models having parameters that are lumped, finite element models, discrete models, modal analysis, transmission of vibration through the human body to the head, knee, backrest, dynamic responses of the human body subject to vertical force and studies of biodynamic models which respond to vibration.

Chapter 3 focuses on the field study on various public transport buses and the experimental setup for various experimental conditions. In the field study, subjective evaluation of ride comfort and activity comfort based on questionnaire survey has been discussed along with on board vibration measurement.

Chapter 4 covers the detailed experimental study, which was conducted on the vibration simulator located in the Vehicle Dynamics Laboratory of the Department. The laboratory study covers all experimental work carried out in laboratory using the vibration simulator. Experimental setup for the laboratory study includes;

- Standing human exposed to sinusoidal vertical and lateral floor vibration for the experimental subjects holding handle and subjects holding handrail postures.
- Sitting posture for a human subject sitting without backrest support exposed to vertical vibrations through the surface of seat, in two sitting postures for the experiment- erect posture and 30° inclined backrest postures. .
- Design of setup, equipment used for experimental study, vibration stimuli, postures, data acquisition using 4 Channel SVANTEK (Sound and vibration analyzer), etc.
- The biodynamic responses of floor to head (FTH) tramsmissibility and floor to knee (FTK) transmissibility of standing human with whole body exposed to vibration were investigated through measurements that were performed on 6 adult male as subjects,

and in varying standing posture situations. Measured vertical as well as lateral floor to head and floor to knee transmissibility biodynamic response were characterized to identify the influence of the two postures while holding the handle and while holding the handrail as found in Indian public transport buses.

The biodynamic responses of seat to head (STH) transmissibility of seated occupants exposed with whole body exposed to vibration were investigated through measurements performed with 6 adult male as subjects, and different sitting postures. The biodynamic responses of seat to head transmissibility that were measured vertically were characterized to examine the effects of the two postures: (erect posture and inclined back rest posture) with excitation magnitudes (0.40, 0.80, 1.2 m/sec^2 rms) in the frequency range from 3-12 Hz and both hands placed on lap.

Chapter 5, the finite element modeling and analysis has been done. The key points included in the computational study are:

- Free vibration analysis of standing human body in normal posture, mode shapes, displacements of different human body parts.
- Forced vibration analysis i.e, dynamic response of a standing human body in two postures holding rod and normal postures exposed to vertical vibration with 1 m/s^2 rms magnitude, time domain and frequency domain analysis on forced excitation.
- Modal analysis conducted for the computational model using the finite element method for seated human body.

Chapter 6 covers biodynamic modeling and simulation, and includes:

- 15 degree of freedom (DOF) lumped parameter for standing human body model is developed and solved for natural frequency, eigen values and mode shapes. Derivation of governing equations along with free body diagrams.
- 5 degree of freedom (DOF) seated human body is developed and solved the governing equations for natural frequency, seat to head transmissibility is determined, inter subject variability is calculated with the effect of stiffness mass and damping coefficient.

Chapter 7 summarises the conclusions along with the future scope of work.

CHAPTER 2

REVIEW OF LITERATURE

Research studies concerning the ride comfort, transmissibility, driving point mechanical impedance (DPMI), biomechanical, finite element method, the subjective effects of whole body vibration (WBV) on activity interference, and the review of the literature are discussed in this chapter. The chapter is structured into six main sections:

- Comfort studies on buses and trains
- Vibration and activity interference
- Transmissibility of vibration from the surface of floor to the head and knee i.e, (FTH and FTK) of human body parts
- Transmission of vibration through the body
- Response of biodynamic models to vibration and
- Finite element models on free vibration and modal dynamics which respond to vibration

2.1 COMFORT STUDIES

The emphasis of the study will be on vibration comfort, which is predicted to be of major importance for travelers’ comfort. Vibration comfort is divided into two categories i.e., ride comfort and activity comfort. Vibration measurement on railway trains is a function of many factors such as the train speed, variations in track quality and passing over turnouts and is therefore not statistically stationary. Vibration measurements in buses were performed lesser than the measurements performed on trains, due to lack of proper evaluation techniques on different road conditions and buses. But, few studies have been mainly focused on road irregularities and design aspects of buses.

The assessment of comfort is very tedious because of many factors like noise, vibration, temperature, humidity, odor, etc. (Maffei, 2009; Maffei et al., 2010; Ruotola et al., 2010; Sanders and McCormick, 1993). The comfort evaluation methods were effectively discussed with the available standards ISO 2631 -1985, BS 6841 -1987, CEN prENV -1996 and ISO 2631 -1997 by Heinz, (1999). The conclusion of the literature review is that there is no evaluating method specifically developed for comfort criteria in buses and coaches. ISO and

BS describe general methods for safety and comfort evaluation and several of the pre-studies of these methods were developed for industrial equipment and the result of such studies is not always entirely applicable to passenger transportation. CEN is a pre-standard, which means that it is not yet approved by the CEN board. Its application is restricted to comfort evaluation on trains, and it is not entirely applicable to other transportation situations. The conclusion of the study is that a good approximation could be reached by combining the different evaluation methods in an appropriate way, depending on kind of vehicle and transport situation.

Narayanamoorthy et al., (2008) conducted vibration measurements and questionnaire survey simultaneously on few long distance trains in Sweden in order to understand the effect of vibration on performing sedentary activities particularly typing on the laptop while the train is running. ISO 2631-1 :1985 and Sperling Ride Index were used to evaluate the ride comfort. The Sperling's ride index (Wz) is the ride index used by Indian Railways to evaluate ride quality and ride comfort. Ride comfort implies that the vehicle is being assessed according to the effect of the mechanical vibrations on the human body, whereas ride quality implies that the vehicle itself is being judged. According to International Standards Organisation (ISO), the influence of vibration on the human body is expressed by the fatigue time T. ISO 2631 (1985).The activity comfort of passengers was evaluated by the two standards and questionnaire survey on a Swedish trains results shown riding comfort in all the trains considered in the study. However, the questionnaire survey analysis clearly indicated that a significant number of passengers felt difficulties in performing sedentary activities which revealed the persistence of discomfort to perform these activities. This further reveals that these standards do not assess the effect of vibration on sedentary activities that are sedentary in satisfactory manner, which means that the levels of vibrations that are somewhat low can disturb the concert of such activities.

In the previous research works most of the experiments have been performed in vertical direction of excitation and few studies in lateral and fore and aft vibrations by Jacklin and Liddel, (1933); Suzuki, (1998); Nihat et al., (1994). The multiaxis vibration was studied due to the thoughtfulness depicted from commercial transport aircraft and since the size of these aircraft have increased in size, the amplitudes of vibrations in both vertical and lateral have intensified, while frequencies have decreased for those of the predominant body resonances as been observed. These tests showed that whereas vertical vibrations alone have little effect upon subjects, lateral alone has a marked detrimental effect and vertical combined with lateral produces an even greater degradation in comfort and performance.

A comprehensive field study by Nihat et al., (1994) investigated WBV exposure levels experienced by the train operators. The study measured mechanical vibrations spread to the seated train operators, to analyze daily WBV exposure levels and to compare these levels with maximum acceptable exposure level recommended by ISO 2631-1. It was exposed that train speed was the most momentous factor persuading vibration exposure levels. Parsons and Griffin, (1993) and Suzuki, (1998) studied the ride quality in terms of thermal comfort. Overall the travelers predilections and feelings on the comfort of inner and train travelling were also studied by Kottenhof, (1999).

The pilot study for evaluation tests on seats and the huge quantity of laboratory research work was carried on road vehicles, agricultural or forestry machines from Wollstrom, (2000). In the early years studies on vibration were conducted Japan as well as Great Britain and argued the passenger uneasiness by assessing vibration of rail vehicles by Corbridge et al., (1989); Suzuki et al., (2000); Howarth, (2004). Using a traveler appraisal on Swedish trains, Westberg, (2000), found that reading was one of the most common activities.

Johanning, (2002) assessed WBV exposure of 22 U.S. Locomotives under normal operating conditions and associated different locomotives, seats, and operating conditions. The mean basic vibration level (weighted r.m.s) conveyed for the fore-and-aft axis was 0.18 m/s^2, the lateral axis 0.28 m/s^2, and the vertical axis 0.32 m/s^2. The mean vector sum results was 0.59 m/s^2 (range 0.27 to 1.44). The study also gives the results that the mean seat transmissibility factor (SEAT) was 1.4 (X-axis), 1.2 (Y-axis) and 1.0 (Z-axis), demonstrating a general ineffectiveness of any of the seat suspension systems. The study revealed that the locomotive vertical and lateral vibrations were almost similar.

Ongoing researchers such as (Paddan and Griffin ,2002) and Hinz et al., (2002), have focused on multi-axis vibrations. (Huston and Zhao, 2000), inspected the influence of shape, frequency, and amplitude of mechanical shocks on the comfort reactions of the seated human. It has been observed that vibrations up to 12 Hz affect all of the human tissues, whereas, those above 12 Hz have local effects by (Hostens et al., 2003 and Von-Gierke et al., 1991). Overall concluded WBV in the range from 2 – 12 Hz can have an effect on human performance

The chief source of vibration in trains is due to an irregularity in track geometry (Harsha and Prakash, 2001); (Ganesh Babu, 2008, 2010); (Shukla et al., 2009);. Many frequency peaks occur in the range of 0.5 – 20 Hz as a result of the structural dynamics of the passenger rail car. Further, study of directions and motions on these vibrations results in a compound dependence of the altered motions in the train was reported by Harsha et al., (2003).

Sundstrom, (2006) piloted a field study on Swedish intercity trains established that about 80% of the passengers were involved in reading at some time during the journey, 25% were written by hand, and 14% worked with laptops. The passengers pragmatist a wide range of seats postures for executing their activities, while the trains were running on poor tracks during the survey, the vibration levels showed to be acceptable according to the available standards. Conversely, when the passengers were asked to perform a short written test without interruption, over 60 % of the passengers conveyed being ascetically disturbed by vibrations in the train.

Nahvi et al., (2009) accurately assessed vehicle comfort physiognomies by soundtracking compartment signals to evaluate vibrations transmitted to the passengers, vibration dose values, Skewness and kurtosis, frequency response functions and power spectral densities. The results indicate that energy concentration is at frequencies lower than 30 Hz. It was pragmatism that such low frequency excitations were well mitigated by seat suspension in the vertical axis, but were augmented up to 5 more times in very difficult conditions by a backrest in the fore-aft leaning.

2.2 VIBRATION AND ACTIVITY INTERFERENCE

To assist in elucidating various sedentary activities such as reading, writing, sketching and working with laptop computer etc., this section of literature review has been further divided into the following subsections: series of aforementioned sedentary activities with its disturbance due to vibration, the influence of vibration magnitudes, directions and postures on these activities.

Since the military personnel experience high levels of WBV in armored vehicles, Foremost learnings of the vibration outcomes of actions have frequently focused on military workforces, with explorations of its effects on the physical control of pilots and tank crew. The effects of vibration on tracking performance were studied by many investigators in the 1960s. A number of different approaches were used. (Shoenberger, 1972) noted that tracking error generally increased as the magnitude of vibration increased and that performance was most sensitive to 5 Hz vertical vibrations.

(Collins,1973) expanded by plotting the results of previous studies, as percentage of errors on a vibration magnitude vs. frequency graph (for Z-axis vibration). No significant differences were found between sinusoidal vibration and random vibration containing a sinusoid of the same frequency and comparable amplitude (Collins, 1973). The effects were best summarized by (McLeod and Griffin,1986), who formed a proposal guide for manual tasks in vibration environments which summarizes that vibration frequencies in the region of whole-body resonance (2 to 10 Hz for vertical vibration and below 3 Hz for horizontal vibration) may have adverse effects on manual task performance. Moreover, precise manual tasks such as writing was affected the most by the vibration of 4 to 6 Hz and errors increase approximately linearly with vibration magnitude. Subjects described writing as being “very difficult” when the vertical vibration magnitude was 1.0 m/s^2 or higher.

Numerous research has been performed on the effects of vibration on physical trailing errands and less focus is given to the actions performed by the general public as vehicle passengers. Exposure to train vibrations not only results in reduced ride comfort, but also affects the activity performance. This is of prime concern for travelers who mostly engage in sedentary activities while travelling, thus demanding higher comfort level in order to effectively perform such activities. A number of recent studies have shown that vibration is suggestively affecting many types of sedentary activities like reading, writing, etc. (Sundstrom, 2006; Nakagawa and Suzuki, 2005; Westberg, 2000; Wollstrom, 2000).

Many research studies on the comfort of ride as discussed passengers sedentary activities effected due to ride (Rebiffe, 1980; Richards, 1980). Vertical and lateral, sinusoidal and random (with third-octave center frequencies). (Corbridge and Griffin,1986) investigated low frequency range (0.5 – 5 Hz) vibrations for railway applications. It was concluded that there was little effect of vibration magnitude on the frequency dependence of vibration discomfort. Moreover, random vibration produced slightly greater discomfort than sinusoidal vibration but with the same frequency dependence.

In writing activity on railway trains, just two relevant studies were found (Corbridge and Griffin, 1991 and Griffin and Hayward, 1994). It was concluded that the frequency weighting stated in the international standard for assessment of WBV was somewhat different from when activities like reading and writing were performed under vibrations. This inconsistency in frequency requirement indicates that the frequencies that are most injurious for performing reading and writing activities are underestimated by the present standards. The same study also revealed that reading and writing are two of the most everyday activities among train travels for in-between to long distance travels. There are a number of studies on the responses of horizontal (X-, Y-axis) vibrations, but none of these studies have been executed in trains or use vibration conditions similar to trains. A literature study by Wollstrom (2000) determined that past studies on reading ability were not conducted under conditions that were appropriate for railway solicitations.

Mansfield, (2005) reported that the reading, writing, and eating can be affected by WBV. The extent of the disturbance depends on the nature of the vibration e.g., frequency, magnitude, direction, waveform and also human perception of vibration (including both magnitude perception and comfort). Recently, Baker and Mansfield (2010) investigated the effect of horizontal WBV and standing posture on task performance under the influence of random vibration up to 4 Hz. It was concluded that the impairment due to dual axis exposure were well predicted using the root sum of squares calculations based on single axis components.

2.3 TRANSMISSIBILITY

In order to investigate vibration transmission to the human body and to design seats or suspensions for vibration isolation in the vehicles, a driving point mechanical impedance was measured on many types of human physique postures (Miwa, 1975).

According to Boileau and Rakheja, (1998) an analysis of the experimental conditions used to derive a quantity of driving- point mechanical impedance under conditions of driving vehicles. In a previous study (Boileau, 1995) study the identification of 71 driving-point mechanical impedance data sets published in the literature, including that proposed in ISO CD 5982 (1993), only five were found to have been derived under conditions which could completely be associated with vehicle driving. These five data sets were selected based upon the requirements that (i) both magnitude and phase data be reported in the 0 -10 Hz frequency range; (ii) the posture be defined as erect seated with feet supported; (iii) the level of vibration excitation be less than or equal to 2 m/s^2 root-mean-square (rms) acceleration; (iv) the sample size include more than a single subject; and (v) the subject mass be within the 51 - 93.8 kg range. Eliminating the ISO CD 5982 (1993) data set which formed an outer and it was shown that by alignment and producing the remaining four published data sets by Suggs et al. (1969), Fairley and Griffin, (1986), Hinz and Seidel, (1987) and Sandover, (1982) mechanical impedance values related to conditions completely resembling those likely to apply while driving vehicles could be described. Since these Conditions did not meet exactly those formulated to characterize vehicle driving, driving-point mechanical impedance measurements were initiated using a whole-body vehicular vibration simulator (WBVVS) by applying rigid conditions with concerned to subject posture, hand position, excitation type and level.

The mechanical impedance of the human body in sitting posture and vertical direction was measured by Holmlund et al., (2000) during different experimental conditions, such as vibration level (0.5-1.4 m/s^2), frequency (2-100 Hz), body weight (57-92 kg), relaxed and erect upper body posture and results shown increase in impedance with frequency up to a peak at about 5 Hz after which it decreases in an intricate manner which includes two additional peaks. The frequency at which the first and second impedance peak occurs decreases with higher vibration level. Erect, compared with relaxed body posture resulted in higher impedance magnitudes and with peaks located at somewhat higher frequencies. Heavy persons show higher impedance magnitudes and peaks at lower frequencies.

The driving point mechanical impedance was studied for the various postures in the frequency range, 3-200 Hz, and obtained results were well established to design of an isolated system of vibration and also in analysis of transmission of vibration and shock in the human body.

2.4 TRANSMISSION OF VIBRATION THROUGH THE HUMAN BODY

Transmissibility can be defined as a tool that can be used to recognize the dynamic mechanisms of a multifaceted system. Vibration transmission consists of comparing the acceleration at one point of a human body (input) with the acceleration at another point of the human body (output). Vibration transmitted through the human body reflects the dynamic properties of the system. When, the transmissibility value exceeds the unity after measurement of the human body , then it's supposed to amplify the vibration is amplified through the body. If the transmissibility is less than unity the human body attenuates the vibration. The dynamic properties of a system can be described in terms of mass, stiffness and damping. A system can be composed of multiple independent systems, called degrees of freedom, each system having its own mass, stiffness and damping. At one degree of freedom system will resonate (amplify most the transmitted vibration) at the frequency defined by the square-root of the ratio stiffness over mass. The damping will affect the magnitude of the vibration transmitted at the resonance frequency**.**

2.5 DRIVING POINT MECHANICAL IMPEDANCE

Six persons instigated a four-limb coordination task on a shaker table assembled together an electronic mixture of 2.5 Hz and 5.0 Hz and single sinusoidal frequencies of 2.5 Hz and 5.0 Hz and vibration acceleration was held constant at 0.09 ms^{-2} (0,07 gas) rooms, i.e., a level below the international standard ‘ fatigue-decreased proficiency ’ boundary for 2½ h vertical vibration exposures. While, vibration transmission through the body was uniformly as strong for the mixture included of only a 50% 5.0 Hz component as for the pure 5.0 Hz sinusoid, performance data indicated extreme damage of response speed and greatest fatigue-decreased proficiency, under exposure to the vibrant mixture was experimented by (Cohen et al., 1977). The vibration ‘ crest factor ’ is presented as a possible description of the results which question a basic statement of ISO 2631–1974 that sinusoidal vibration data are clearly generalisable to more accurate environmental exposures.

Wei and Griffin, (1998) predicted seat transmissibility from mathematical models using curve fitting technique. The transmissibility was found in the frequency range of 1.25 Hz – 25 Hz on the foam ad sheet. The results were found on two models with one degree of freedom and two degrees of freedom model. From the two degrees of freedom model the results shown better with second principal resonance of 8 Hz and discussion of nonlinear models transmissibility on foam and the seat also discussed.

Desta et al., (2010) focused on three representative postures and under three magnitudes of vibration. This posture (backrest, erect and forward lean on the table) and magnitudes (0.4, 0.8, 1.2 m/s2 r.m.s.) under a frequency range of 1-20Hz are considered as representative of those likely overcome in a wide range of vehicles. Seat to head and back to head transmissibilities and phase difference and respective coherence were collected under the magnitudes and postures . Furthermore, to determine the effect of frequency, subjective readings were collected at the backrest Support with representative frequencies. With these response functions the effects of some representative variables were investigated.

2.6 STUDIES OF FEM MODEL

In public conveyance, industrial vehicles or buildings, persons are bare to vibration when standing. Such whole-body vibrations can have unpleasant effects on health, activities and feelings of occupants may be termed as discomfort. Predominantly in a standing posture, reductions in the nonlinearity of the dynamic response can be expected with increased muscle tension in both the upper body or the lower limb, assuming that increased muscle tension reduces spontaneous changes in muscle activity during vibration proposed by Subashi et al., (2005).

In the past decades the research studies on the standing posture humans exposed to vertical, fore and aft and lateral direction excitation of vibration has been studied to find the ride comfort guidelines, cause of vibration injuries, effect of mechanical impedance, the transmissibility of vibration to segments, effect of apparent mass and resonant frequencies of different segments by analyzing the results with validation and comparison to vivo, experimental models, biodynamic models and finite element models. The majority of the studies was carried with experimental models and analytical models compared to finite element models because of complexity in finding material properties and inertial properties of the tissue structure. In past years the initial studies made in the finite element tool are being used as the dominant tool to study mainly lumbar vertebral discs of complex human body made up of tissues and the outcomes of studies were combined and analyzed with in vitro and in vivo studies. The amount of vibration exposure depends on a number of factors, including the nature and design of the automobile, the speed at which the vehicle is travelling, the environmental conditions, and the body postures. Continuous and extended vibration to the passengers causes fatigue, pain and even injury over time (Lloyd et al., 1991). During exposure, vibration can also have negative effects on performance of the tasks at hand (Genaidy and Shell, 2008; Grandjean, 1988).

Harazin and Grzesik, (1998) suggested that the body posture has been found to be the major importance. Since, it impacts the surface of contact of man with the vibrating plane on the position of the spine and on the degree of tension in different muscle groups of the trunk and their boundaries. Differences in body postures modify the elastic and damping properties of the humans and determine the mutual location of masses within its area, not only does this lead to the change of resonance of body segments but it also results in an extensive change of vibration transmission in specific frequency bands.

A continuous human body model with standing posture is proposed by Tianjin, (1995) where the interpretations were crafted to look after the local vibrations of any part of the segment and the alterations between different segments in the upper and lower parts. Therefore this model was laid better validation for studying the global vibration of a standing person. The advantages of using this model in the study of the dynamic characteristics and the response of the human body to vibration helped to calculate responses as the summation of the responses of a few single degree-of-freedom systems according to their respective modes and model give the appreciation has less unknown parameters to be determined than a discrete model.

In biomechanics, finite element method modal analysis has become a frequently used method for studying the dynamic behavior of mechanical structures. Kitazaki and Griffin, (1997) used beam, spring and mass elements for analyzing the spine, viscera, head, pelvis and buttock tissue in mid-sagittal plane and found the resonance frequency at 5 Hz. Matsumoto and Griffin, (1998) compared the dynamic responses of the human body in standing position and sitting position and reported that the apparent mass occurs in the 5–6 Hz frequency range. Since then, there was a gap in research studies on human body segments and entire body to analyze as a continuous system in performing modal analysis using finite element method.

2.7 STUDIES OF BIODYNAMIC MODEL

The study of human response to vibration has been the topic of interest over the years and a number experimental and analytical studies were established in a different vibration environment. The objectives of this literature survey are to build a clear foundation for the research question of this work. So far, the study of biodynamic responses of humans can be conducted in two methods: Experimental and Analytical methods.

A typical representation of a single DOF human body model was developed by Coermann, (1962) has shown in Fig. 2.1. The mass of the subject, including the upper torso and head, supported by the seat is lumped and linked to the base through parallel spring and damping elements. Damping coefficient ‘c’ is due to the spine and the adjacent tissues. Stiffness coefficient ‘k’ represents the restoring properties of the spine. The model parameters were identified to match the driving point mechanical impedance (DPMI) responses measured with subjects sitting without their feet and back supported under sinusoidal excitation only.

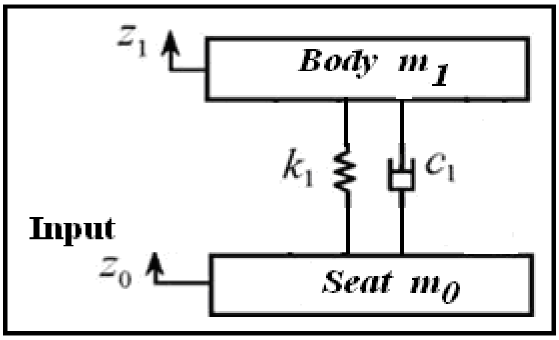


Fig 2.1 Schematic of single degree of freedom model. Coermann, (1962).

(Liang and Chiang, 2006), suggested that the human body is a very sophisticated dynamic system whose mechanical properties vary from moment to moment and from one individual to another. In the past few decades, plenty of mathematical models have been developed on the basis of diverse field measurements to describe the biodynamic responses of human beings. **(**Griffin, 2001), termed the study of human response to vibration is the definition of an engineering model of the response of the body and modeling should involve the identification, and inclusion of variables of greatest importance. A biodynamic model has defined relationships between one or more inputs as independent variables (input variable) and one or more outputs as dependent variables. A model is intended to represent the responses in terms of forces and movements of specific people within a specific range of vibrating conditions. A model cannot represent all the functions of the system but represent one or more aspect of the system. The first stage in the model formation is the identification of the relevant variables such as dependent and independent variables. The information to be predicted from the model and what data required to make the prediction will decide the dependent and independent variables. The model is a simple model or a complex model based on the propositions on which the model is developed. For a complete model to predict adverse effects of vibration or mechanical shock on human health the model should predict the forces and movements in the body and then it should relate them with injury or disease. To achieve this, model should be justified and validated on the basis of biomechanics as well as on the relevant injury mechanism. These models could be achieved by different modeling techniques: such as lumped-parameter (LP) models, finite element (FE) models, and multi-body models. In a Lumped parameter model a system is represented by one or more rigid elements often connected by mass-less elements like springs and dampers.Plenty of analytical work as been done with this method since it is simple to analyze and easy to validate with experiments.

Qassem et al. **(**1993**)** developed new bio-mechanical model modified from model proposed by Muksian and Nash (1974) by incorporating damping and elasticity constants of more body segments. The included mass segments were upper and lower arms, cervical, thoracic and spine. For investigation a 100kg human body has been taken with vertical and horizontal vibration sources comes from hand, seat, and the combination of the two. After the analysis of analogous electric simulation the result showed that the body segments (lower arm, head, torso, cervical spine and lumbar spine) are affected by horizontal vibrations when the input force comes from both hand and seat more than when comes from the seat alone. The head is affected by vertical vibrations when (Force comes from the seat more than when comes from both hand and seat. An experimental set-up has been designed and measurements of vibrational signals from the human lower arm, head and torso have been carried out. Similar trends were shown for both theoretical results and experimental findings.

Liang and Chiang (2006) carried out a thorough survey of literature on thirteen different DOF (include one to eleven) lumped parameter models for seated human subjects exposed to vertical vibration. The equations of motions were derived for each model and simulated in frequency and time domain. For validation, the data sets most closely satisfying the prescribed range of condition were selected from literature. Based on the analytical study and experimental validation, a four DOF model developed by Wan and Schimmels (1995) was found to be the best fitted to the existing test results, and recommended for the study of biodynamic responses of seated human subjects under vertical whole body vibration. In addition for pregnant female a six DOF model developed by Murksian and Nash (1974) was suggested.

Fairly and Griffin, (1989) proposed a 2-dof model, as shown in Fig. 2.10. This seated body model involved two masses: m_1 is the mass of the upper body moving relative to the platform, and m_2 is the mass of the lower body and the legs supported on the platform but not moving relative to the platform. The mass of the legs m_3 was included in the model only when the feet were supported on a stationary footrest. Nigam et al., (1987) proposed the model which involved several simplifying assumptions and the foremost being approximation of the body segments to ellipsoidal bodies, truncation of the ellipsoids for evaluating segment stiffness, and the approximation of segment elastic modulus as a geometric mean of bone and tissue elastic moduli. Jacobi method is employed to find the natural requencies for the 15 DOF model with 5 percent truncation. The antropometric data and stiffness values is evaluated from the reference of (Bartz and Gianotti, 1975);. Nevertheless, with the adopted approximations the proposed modeling procedure seems to give a fairly good estimate of the low order mode natural frequencies. Damping, though inherently present in a human body, has been ignored in the present study. Also, the vibrating body, has been assumed to be in the standing posture. The undamped resonant frequencies are important parameters of any vibratory system as they signify the location of the frequency response peaks of an externally excited system.

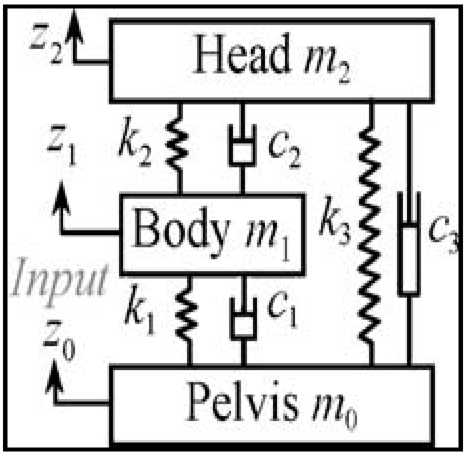


Fig 2.2 - Schematic of two degree of freedom model. Fairly and Griffin, (1989).

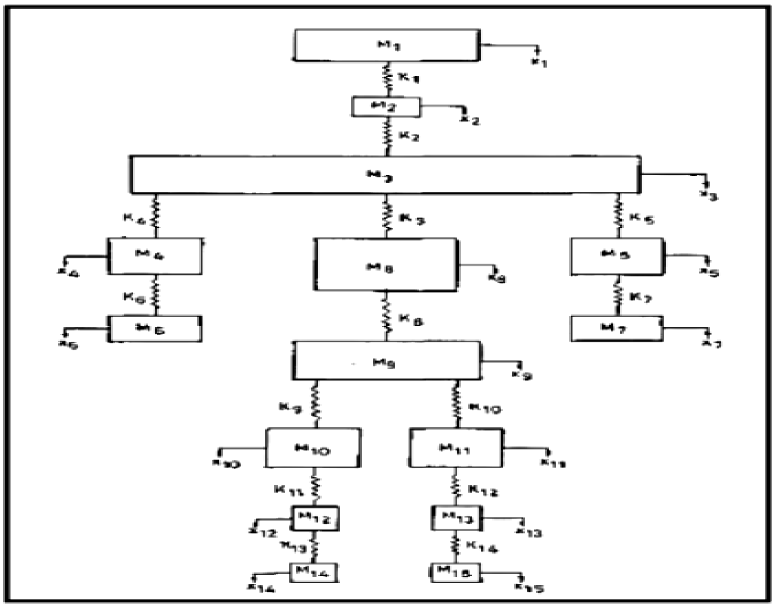


Fig 2.3 - 15 Degree of freedom (DOF) lumped parameter model from Nigam and Malik, (1987).

2.8 CONCLUSIONS

While numerous studies have been conducted to examine effects of railway vibrations on ride comfort of passenger and driver, vibration measurements on Indian trains in normal running conditions and studies on activity comfort onboard trains are seldom found in the available literature.

Numerous studies have investigated the effects of vibration on manual tracking tasks. There has been relatively less attention to the tasks performed by the general public as vehicle passengers. Exposure to train vibrations not only results in reduced ride comfort but also affects the activity performance. This is of prime concern for passengers, who mostly engage in sedentary activities while travelling, consequently demanding higher comfort level in order to efficiently perform such activities. Recent laboratory studies found that the difficulty in reading and writing is strongly influenced by vibration frequency, vibration magnitude, display vibration, observer vibration, character size, viewing distance, body posture etc. It is also observed that moderate levels of difficulty began at fairly low vibration levels. In general, laboratory studies showed that the difficulty in performing reading/writing task increased with the vibration magnitude and the maximum difficulty occurred between 2.5 Hz and 5.0 Hz for performing both reading and writing activities.

Regarding the influence of vibration axes, most studies indicate that vibrations in the vertical Z-axis are the most critical for reading ability. There are also studies indicating that vibrations in the X-axis can lead to transfer of vibrations to the head and thus decreasing the reading ability significantly. Vibrations in the Y-axis had little effect on the reading ability. It is important to note that the seat itself can greatly increase or decrease the motion depending on the frequency content of the vibration. The backrest can help to reduce the instability at low frequencies. On the contrary, the backrest can cause vibrations to transmit to the upper body at high frequencies.

Earlier studies have considered different vibration magnitudes, postures on both single axis and dual axes conditions for evaluating performance of various tasks. These studies have considered vibration in mono axis only; therefore it is difficult to arrive at any conclusion from the results about various axes for a particular task performed under a specific vibration condition. Also none of the earlier studies were found in dual and multi axis corresponding to those observed in a rail vehicle.

Generally it can be concluded from the reviewed biodynamic response studies that STH transmissibilty shows a first resonant frequency of around 4 Hz to 6 Hz for vertical vibration. In some of the studies, a second resonance was observed between 8 Hz and 12 Hz. In humans, the first resonance seems to correspond to the vertical motion of the entire body, accompanied by pelvic rotation and a bending motion of the lumbar spine in phase with the fore-and-aft and pitch motion of the head. The second resonant frequency corresponds to the rotation of the pelvis. Some of the investigations have shown the response of the head to be nonlinearly correlated with vibration magnitude, which indicates the softening effect on the human body is caused by changes in vibration excitation. The effect of posture is found to be one of the most important variables in the measurement of STH transmissibilty. There are two main extreme postures that have been investigated by many researchers: relaxed (slouched or slumped) and erect (tense or stiff). A common finding is that an erect posture increases the major resonant frequency of STH transmissibilty. This was associated with a combination of stiffening of the muscles and change posture, which increased the resonant frequency. This increase in frequency might indicate an increase in whole body stiffness. The studies on effect of a backrest on transmission of seat vibration to the head indicate that contact with a backrest will increase STHT in a seated person.

There are other studies concerned with the transmission of seat vibration to the heads of seats subjects, but the factors under investigation have been either irrelevant or the effect of a less reported variable has been determined. It can therefore be generally concluded that slouched or slumped postures usually yield higher STHT magnitude than relaxed and/or erect posture. Generally the available works discloses that when contact is made with a backrest, head motion will increase, compared with a situation in which no backrest is used. It has been shown that backrest support has the most dominant influence on STHT transmissibilty, with back support ensured an increased transmissibility at frequencies above 5 Hz.. Whereas, straight unsupported back produced lower transmissibility at low frequencies with more head motion at high frequencies.

From reviewing biodynamic response studies, lumped parameter models were usually derived from either measured mechanical impedance or vibration transmissibility response characteristics of the human subjects. The effects of different variables such as posture, effect of the backrest and vibration magnitude were not distinguishable. Most of the available biodynamic models were obtained by curve fitting method.

The transmissibility or apparent mass of the human body, was developed by Suggs et al., (1969) this was the simple model not sufficient to study the potential injury. Pankoke et al., (1998) developed an advanced model of a sitting man using Finite Element Modelling (FEM) techniques. The model focuses its detail on the lumbar spine region modelling the individual vertebrae and including the muscles of the lower back region as multiple springs. In order to reduce computational time the rest of the model is represented by rigid bodies with mass. The model was developed with three different postures, upright, relaxed (lorry driver) and slumped forward (crane operator). The model is also easily adjusted in both weight and height. The overall motion of the body model has been validated against experimental data and shows very good agreement with test data at frequencies up to about 7 Hz. Pankoke et al., use the model to predict forces in the lumbar region of the spine. Seidel et al., (2001) used the finite element model developed by Pankoke et al., (1998) to predict the loads in the spine during whole body vibration. They carried out further validation of the model against experimental data and a different model. The comparison shows that the model and the assumptions it is based on being valid. As with other work on this type of model it is impossible to validate the internal forces within the spine.

The dynamic responses of the human body exposed to vertical whole-body vibration have been explored from certain years. Many experimental studies concerning to living humans have been conducted so as to obtain data representing the dynamic characteristics of the living human body during exposure to vibration or shock. The complexity of the human body structure has made difficulty in developing assumptions to develop the model more effectively and the studies of past stated the requirement of some simplifications, or assumptions, in the models. The extent of simplification in the models has been dependent on various matters, such as the aims of the modelling, the availability of reliable data on the properties of the living human body, and the capability of computing. The majority of previous studies of the biodynamic responses to vertical whole-body vibration have focused on the seated body, although some have investigated the dynamic responses of the standing body they have been done using experimental conditions. The dynamic response is studied particularly on specific body segments or on the whole body, but no studies in the past have been conducted using finite element (FE) model method to study the whole body in a different standing posture made up of tissues and used appropriate material properties to construct and analyze for the dynamic response characteristics of the whole body as well as specific body segments. In the present work the effort is being made to study the lack of work using finite element (FE) model.

CHAPTER 3

FIELD STUDY ON HUMAN COMFORT

3.1 INTRODUCTION

In this section, the analysis of two major research areas i.e. the field study of various Indian buses and laboratory study for transmissibility of accelerations of human segments head and knee from the excitation of floor in vertical and lateral direction in standing posture and the effect of inter subject variability, effect of vibration magnitude, effect of phase angle, effect of posture and coherence in sitting postures with two experiments has been discussed. In the field study section, subjective difficulty based on questionnaire survey on ride comfort and activity comfort due to vibration, has been discussed along with the on-board vibration measurement. In the laboratory study section, subject's anthropometric data, postures, experimental setup, vibration parameters used for the experiment, experimental tasks, its performance evaluation and test procedures have been extensively discussed.

3.2 FIELD STUDY ON INDIAN BUSES

Public transport buses in India have a large transportation of passengers for their daily needs. Hence, people are using buses more frequently for travelling to other places. None of the available standards of vehicles which evaluate ride comforts consider the effects of vibrations on particular passengers' activities by Krishnakant, (2007). There are many factors in this environment that disturb passenger's activities. Some of the main sources of disturbance are noise and vibrations generated from the bus itself. The pilot study on the passenger's comfort produces good analytical responses to the questionnaire survey and helps to evaluate the ride comfort on their activities by Narayanamoorthy et al., (2008). Rudnicky and Kolers, (2009) conducted experiments on reading ability with the size and cause of type using stimuli and found reading goes forward in many ways at once rather than through an orderly sequence of operations, consistent with the reader's skills and the requirements of the task. Principal theories of performance appear impulsive in the absence of detailed analysis of task components.

Experimental evaluations of ride comfort using multiple regression analysis were performed and found good predictability on human dynamics reported by Koizumi et al., (2002). The effective amplitude, transmissibility, ride value, ride indices for different four vehicles using frequency weighting was studied by Park et al., (1998a) considering to-the-seat dynamic characteristics with subjects. According to Sundstrom (2006), field study conducted which comprised of questionarrie as well as vibration measurements on three types of Inter-

Regional trains during normal service showed that at some point of time in the journey around 80% of the passengers were reading, 25% were writing by hand, and 14% handled devices like portable computers and most of the activities were performed by seated humans in train. Many laboratory studies had been performed to study the effect of whole body vibrations in the three dimensional space representing translational directions. These directions were independent and similar to the one that can be experienced while travelling in train. Bhiwapurkar et al., (2011) reported the reading and sketching ability of low-frequency random vibration with the frequency range (1–10 Hz) and at accelerations of 0.5, 1.0 and 1.5 m/s^2. The level of comfort and discomfort was measured and the perceived difficulty to read and sketching was judged using 7-point scale.

In the present study, a questionnaire based study was conducted on three buses in the different routes between Roorkee to Hardwar, Hardwar to Roorkee and Saharanpur to Roorkee in public transport buses in India to obtain subjective opinion on comfort and discomfort while journey. The objective of the present work is to increase knowledge on passenger needs to be able to suggest improvements in bus comfort and the suggested improvements will support bus operators and bus manufacturers in their work.

3.2.1 Vibration measurements

The vibration measurements were made in all three above mentioned routes and the vibration samples was acquired with integration period of 1 sec and each individual measurements with 40 sec duration using 4 Channel sound and vibration meter (SVAN 958) and the mean noise level in three different route buses using Bruel and Kjaer sound meter. Fig. 3.1 and 3.2 shows sound and vibration meter in use for measuring floor acceleration. PCB tri-axial ICP seat pad accelerometers, model 356B41 were used to measure the accelerations on floor and on the passenger seat. Unweighted accelerations was also measured. Fig 3.3 shows the setup for measuring floor and seat acceleration using tri-axial accelerometer shown in Fig. 3.4.

Fig. 3.1 Measurement of floor acceleration

Fig. 3.2 Sound and vibration meter (SVAN 958)

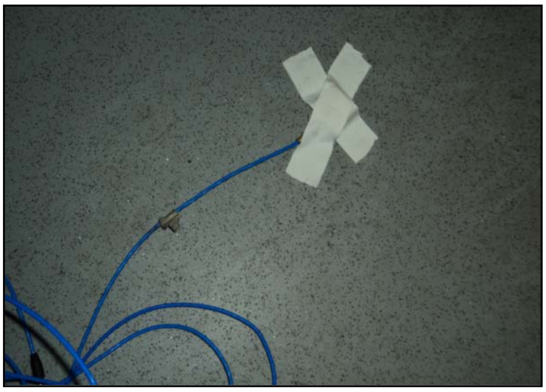


Fig. 3.3 Measurement of floor and seat accelerations

Fig. 3.4 PCB Triaxial accelerometer mounted on floor

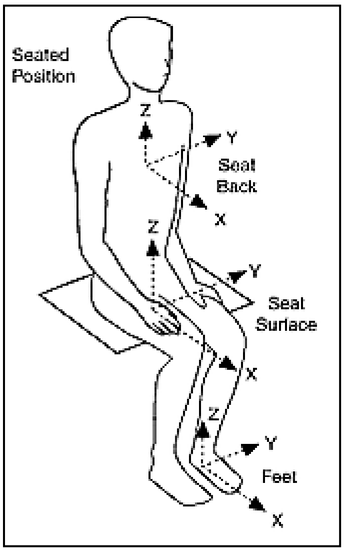


Fig. 3.5 Coordinate system for human body (ISO 2631-1:1997)

Table 3.1 Record of acceleration (m/s^2) amplitude in all vertical (Z) and lateral (Y) translational axes of motion.

Bus route	Seat			Floor		
	Z	Y	RSS	Z	Y	RSS
Roorkee to Haridwar	0.82	0.10	0.83	2.22	0.16	2.22
Haridwar to Roorkee	2.85	1.22	3.10	2.64	0.63	2.71
Saharanpur to Roorkee	2.18	1.15	2.46	2.55	0.94	2.71
Mean	1.95	0.82	2.13	2.47	0.57	2.54
Minimum	0.82	0.1	0.83	2.22	0.16	2.22
Maximum	2.85	1.22	3.1	2.64	0.94	2.71
SD	1.45	0.85	1.63	0.3	0.49	0.38

Table 3.2 Mean noise level in three route buses.

Bus route	Noise Level
	db
Roorkee to Haridwar	76
Haridwar to Roorkee	70
Saharanpur to Roorkee	72

The vibration amplitudes recorded from floor and seat during journey are investigated for possible artifacts and unwanted signals detected are filtered. The mean vibration levels (m/s^2, rms, unweighted) measured along vertical axis and lateral axis at floor, seat the vector sum (rss) are shown in Table 3.1. The noise level obtained inside buses for all the routes are mentioned in (Table 3.2). The vibration measurements were acquired using sound and vibration meter (SVAN 958) and were truncated to show the frequency range of interest up to 30 Hz as shown in Fig. 3.6 and 3.7. These figures represents translational vertical (Z) and translational (Y) FFT rms accelerations. Similarly vibration measurements were made in lateral (Y) directions.

From Fig 3.6, it is seen that FFT rms acceleration has magnitude of 0.82 m/s^2 at a resonance frequency of 4.76 Hz on seat and Fig. 3.7 shows magnitude of 2.22 m/s^2 for floor FFT rms acceleration at 4.94 Hz on floor. In the present study the resonance frequency at seats is amplifying rather than attenuating due to poor design and improper maintainence of seats. Therefore, it could be possible that the main source of discomfort for performing sedentary activities was due to augmentation of the vibration from the seat. To determine a relationship between bus vibration and passenger discomfort in performing sedentary activities, the results of questionnaire survey have been compared with vibration and noise level for all above mentioned route buses.

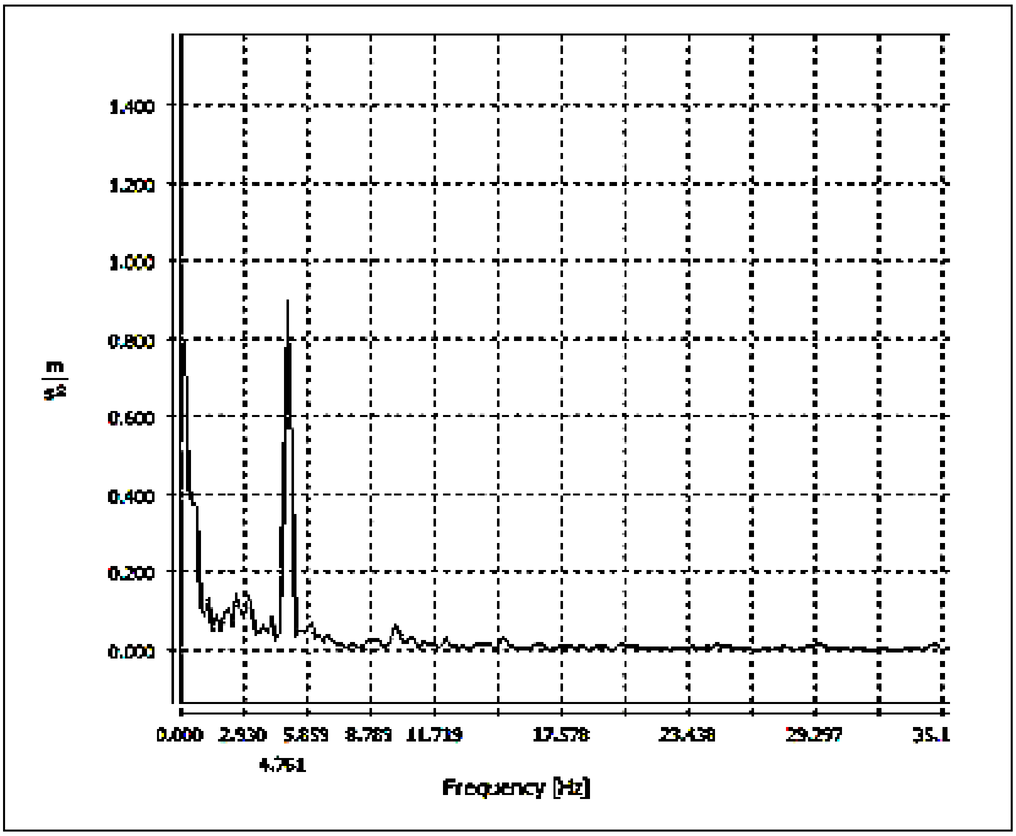


Fig. 3.6 FFT rms acceleration at bus seat in vertical direction for Haridwar-Roorkee route.

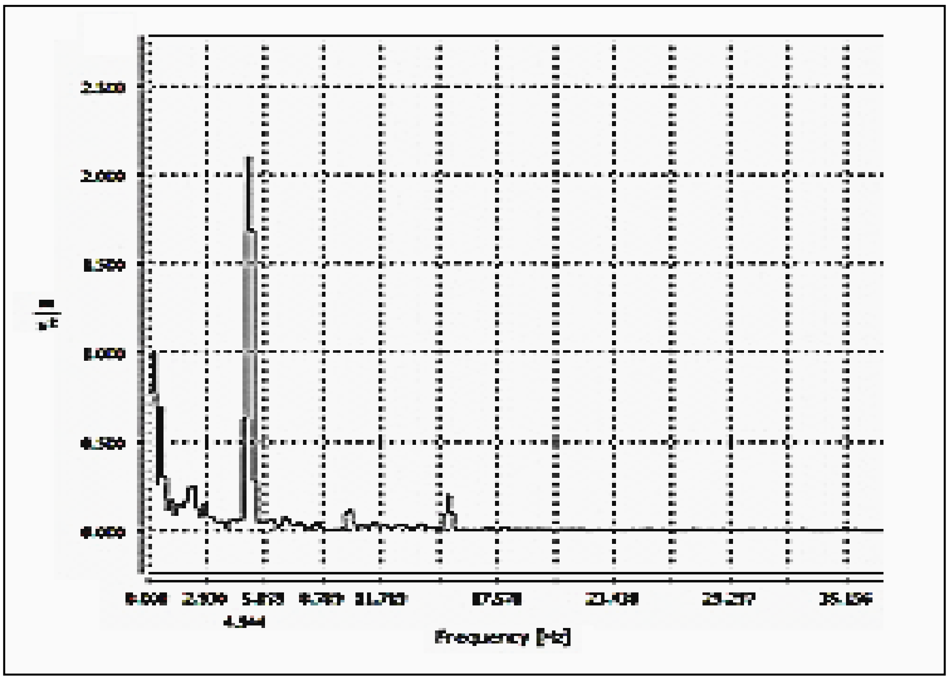


Fig. 3.7 FFT rms acceleration at bus floor in vertical direction for Haridwar-Roorkee route.

The effects of vibration frequency, distance of viewing and multiple frequency motions on the reading of numeric characters in vertical (Z) direction was measured and found degradation of the reading task from the frequency range 2.8 Hz to 63 Hz, where the effect of 3.15 Hz vibration was found to increase more faster with reductions in viewing distance than that of higher frequency of 16 Hz vibration as reported by Lewis and Griffin, (1980). The vibration measurements of FFT rms acceleration difference with minimum and maximum accelerations from all the buses on seats in the direction of vertical (Z) axes of motion ranges between (0.82 – 2.85 m/s^2), and vibration measurements of FFT rms acceleration difference with minimum and maximum accelerations from all the buses in the direction of vertical (Z) axes of motion on floor ranges between (2.22 – 2.64 m/s^2). Mean and standard deviation of floor acceleration in the direction of vertical (Z) axis of motion in all buses are 2.47 m/s^2 and 0.30 m/s^2 and on seat the mean and standard deviation is found to be 1.95 m/s^2 and 1.45 m/s^2.

Similarly, the vibration measurements of FFT rms acceleration difference with minimum and maximum accelerations from all the buses on seats in the direction of lateral (Y) axes of motion ranges between (0.10 – 1.22 m/s^2), and vibration measurements of FFT rms acceleration difference with minimum and maximum accelerations from all the buses in the direction of lateral (Y) axes of motion on floor ranges between (0.16 – 0.94 m/s^2). Mean and standard deviation of seat acceleration in the direction of lateral (Y) axes of motion in all buses 0.17 m/s^2 and 0.85 m/s^2 and on floor, the mean and standard deviation are found to be 0.57 m/s^2 and 0.48 m/s^2 .

3.2.2 Questionnaire survey

The passengers' subjective opinion was obtained to quantify the difficulty in reading a national news paper. A copy each of a national Hindi news paper was distributed to the passengers and they were instructed to read for 40 sec during their journey, while simultaneously accelerations from the vibration was measured on floor and seat. The questionnaire consisted of ride comfort and activity comfort related questions based on seven point semantic scale from excellent to extremely poor (Table 3.3).

Table 3.3. Seven point semantic scale

1	2	3	4	5	6	7

Excellent Extremely poor

The questionnaire consisted of 26 questions related to general background of the participants, information about present journey, types of sedentary activities and time spent on each activity, position of seating, drinking water and sleeping activity, postural positions related to the reported activities, a reading national hindi news paper for quantifying the difficulties of reading while the bus is running and a self rating of the performance and feeling from disturbances from noise, vibration, jerks, etc. in the buses. Finally, the questionnaire ended with an open question "How did you perceive this questionnaire as a whole" and a thanks note for their participations in the survey.

The questions were formulated using both preference and magnitude scaling techniques in order to obtain qualitative and quantitative information related to the effects of vibrations on the performance of sedentary activities and postural positions. Questions related to the postural positions were formulated using preference technique. On the other hand, questions related to vibrations and jerks were formulated using magnitude scaling technique. Here the subjects were asked to rate their feelings on a 7-points linear scale. The two extreme points were marked as "Excellent" and "Extremely poor". The rate of difficulty in reading the news paper is quantified with percentage of passengers feeling comfort and discomfort due to several factors like road bumps, vibration, noise, sudden shocks, and others.

3.2.3. Results and discussion

Fig 3.8 and Fig 3.9 show the percentage of passengers performing the reading activity in the various postures in three routes and number of passengers performing reading activity in different postures on three route. Arranging in descending order the preference of passengers for performing reading activity in all three routes are as follows, Roorkee – Haridwar route, it can be observed that passengers adopting ‘bending forward’ posture- 62%, ‘paper on lap’- 42%, ‘foot resting on floor’- 38%, ‘sitting with legs crossed’- 32%, ‘sitting with backrest’ posture - 22%, Haridwar – Roorkee route, it can be observed that passengers adopting ‘bending forward’ posture- 28%, ‘paper on lap’- 20%, ‘foot resting on floor’- 38%, ‘sitting with legs crossed’- 30%, ‘sitting with backrest’ posture - 36%, Saharanpur – Roorkee route, it can be observed that passengers adopting ‘bending forward’ posture- 12%, ‘paper on lap’-

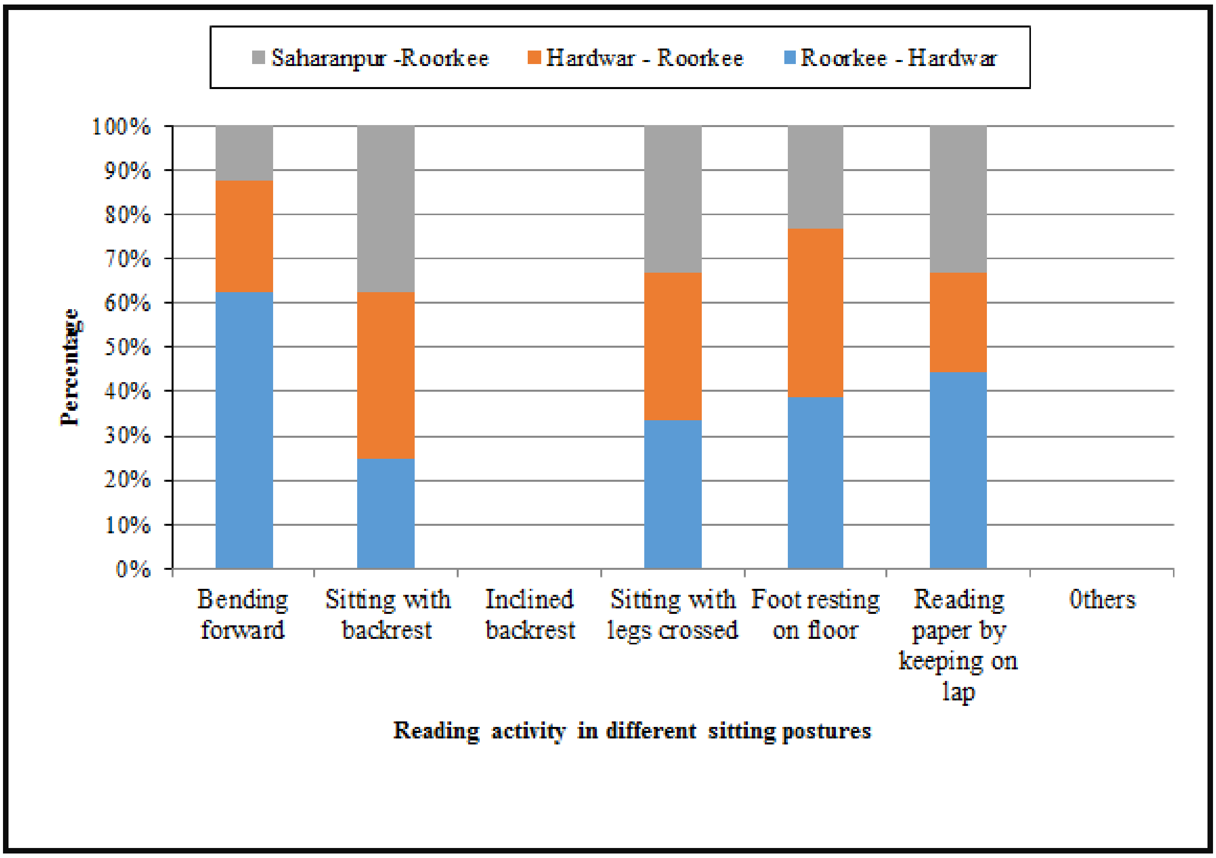
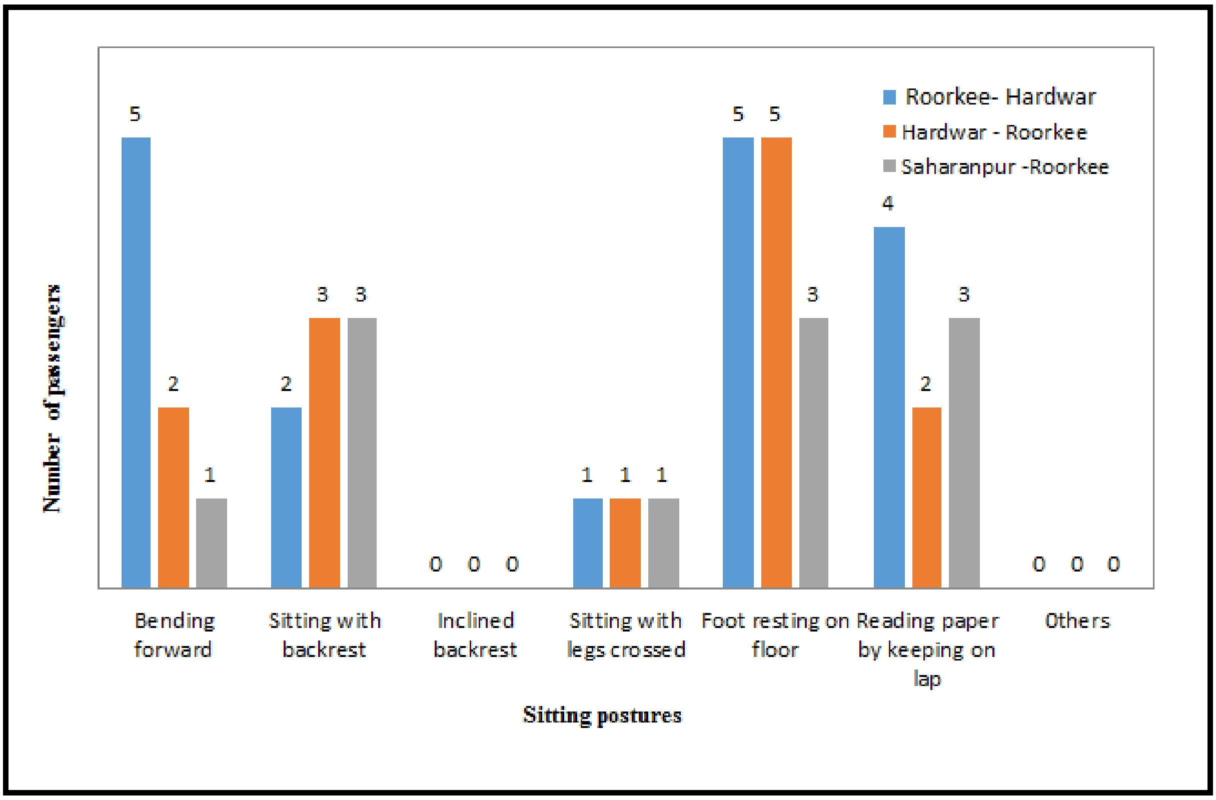


Fig. 3.8 - Percentage of reading difficulties in different postures on three routes



33%, ‘foot resting on floor’- 22%, ‘sitting with legs crossed’- 32%, ‘sitting with backrest’ posture - 38%. From the above results it has been found that in sitting with backrest and foot resting on floor, their is maximum transmissibility of accelerations causing discomfort for sedentary activities.

Fig 3.9 – Number of passengers performing reading activity in different postures on three route

Arranging in descending order the preference of passengers for sedentary activities in all three routes are as follows, Roorkee – Haridwar route, it can be observed that passengers adopting ‘drinking’ activity- 38%, ‘reading’- 68%, ‘sleeping’- 42%, ‘others- 0%, Haridwar – Roorkee route, it can be observed that passengers adopting ‘drinking’ activity- 30%, ‘reading’- 32%, ‘sleeping’- 30%, ‘others- 0%, Saharanpur – Roorkee route, it can be observed that passengers adopting ‘drinking’ activity- 30%, ‘reading’- 0%, ‘sleeping’- 20%, ‘others- 50%. In Saharanpur to Roorkee route passenger’s does not show interest in reading because of fatigue. From these above results it has been found the passengers perform reading and sleeping activity more in their journey and they perform other activities like chatting and they also relax when they are tired.

Fig. 3.10 shows the percentage of different sedentary activities performed by the commuter’s during their journey in the above mentioned three routes. In the Haridwar to

Roorkee route bus, the sedentary activities observed from the response of passengers to the questionnaire are drinking water 30%, reading 32 % and sleeping 38%. Also in the Roorkee to Haridwar route bus the following activities were observed, drinking 38%, reading 65%, sleeping 41% and other activities (like chatting, sightseeing) 50%. Furthermore in the Saharanpur - Roorkee route it is been observed that the activities included drinking 30%, sleeping 20% and other activies found 50% in (Fig 3.10).

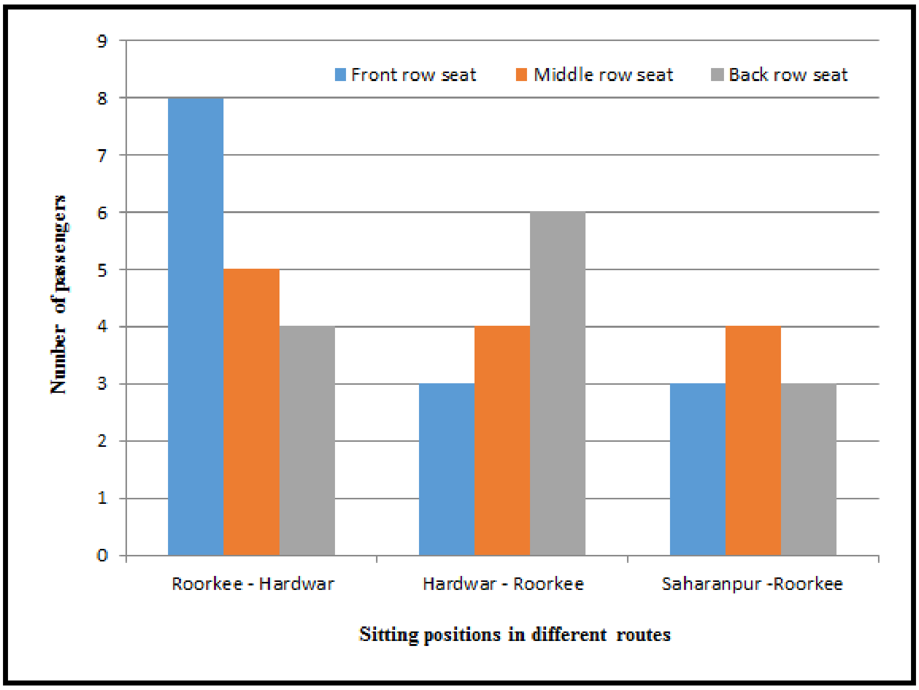


Fig. 3.10 Pecentage of different activities in three routes

Fig. 3.11 Number of passengers adopt sitting positions in three routes

Fig 3.11 shows the number of passengers sitting and their respective percentages in front row seat, middle row seat and back row seat from the three different route buses. The distribution is made with total of 40 passengers and found from the questionnaire the effect of discomfort on seating positions. Saharanpur to Roorkee passengers used 21% back row seat, Roorkee to Haridwar passengers used front row seat 57% and Haridwar to Roorkee passengers used middle row seats 22%.

Fig 3.12 shows the location of number of passengers sitting and their numbers in window seat, middle seat and aisle seat from the three different route buses. The distribution is made with total of 40 passengers and found from the questionnaire the effect of discomfort on seating positions.

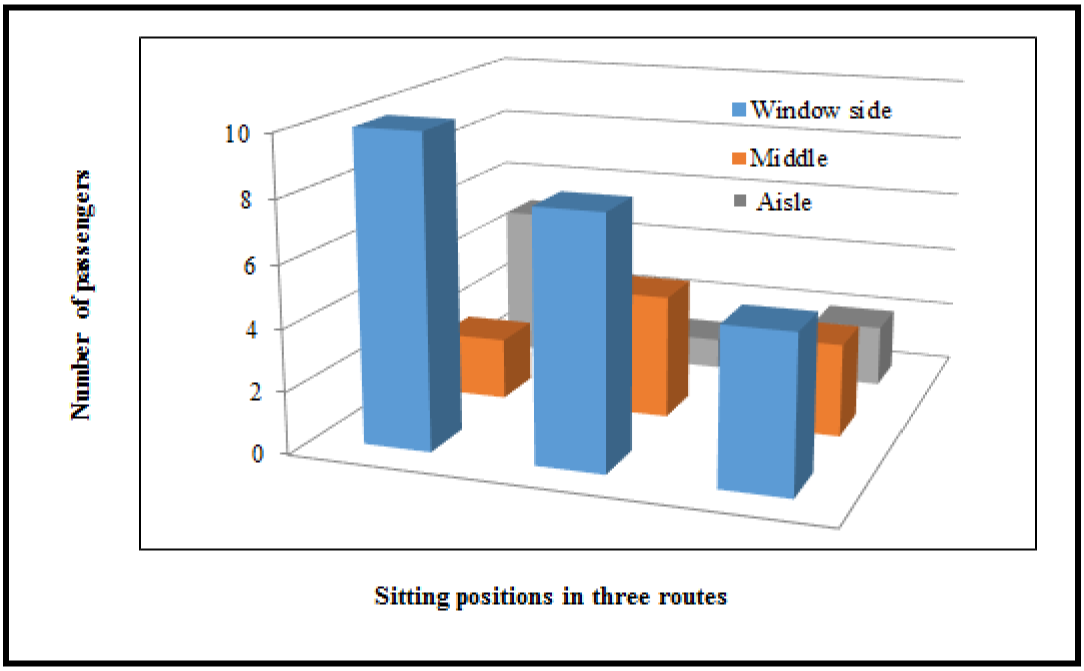


Fig. 3.12 Number of passengers sitting in different positions of seat in three routes

Most of the people prefer window side seat compared to middle and aisle side because of vibrations, disturbance and for sight seeing while in journey. The 23 passengers out of three routes prefer window side, 9 passengers preferred middle side, and 8 people sit in aisle side. From the Fig 3.13 factors causing discomfort in three routes while reading Hindi news paper on passenger’s using questionnaire based on seven point scale. From the study its been found passengers feel discomfort from vibration and noise mostly compared to other factors like road humps, oscillation, sudden shocks, and others. In all three routes 12 passengers reported difficulty in vibration and noise and 4 passengers found extreme difficulty from roadumps, 5 passengers faced discomfort from oscillation and 10 passengers from sudden shocks.

From Fig 3.14 it is seen that the effect on passengers posture and more discomfort due to transmissibility of accelerations from the vibration caused in three buses on different routes. In all the routes 8 bending forward posture passengers found more discomfort from the vibration transmissibility, while in their journey on reading activity, 8 passengers in sitting with backrest, 3 passengers in sitting with legs crossed, 13 passengers with foot resting on floor posture and 10 passengers with reading news paper keeping on lap. From the results the main outcome shows the human body which is in contact with the floor and supporting structures in buses have more transmission of vibration to the passengers causing extreme difficulty while travelling.

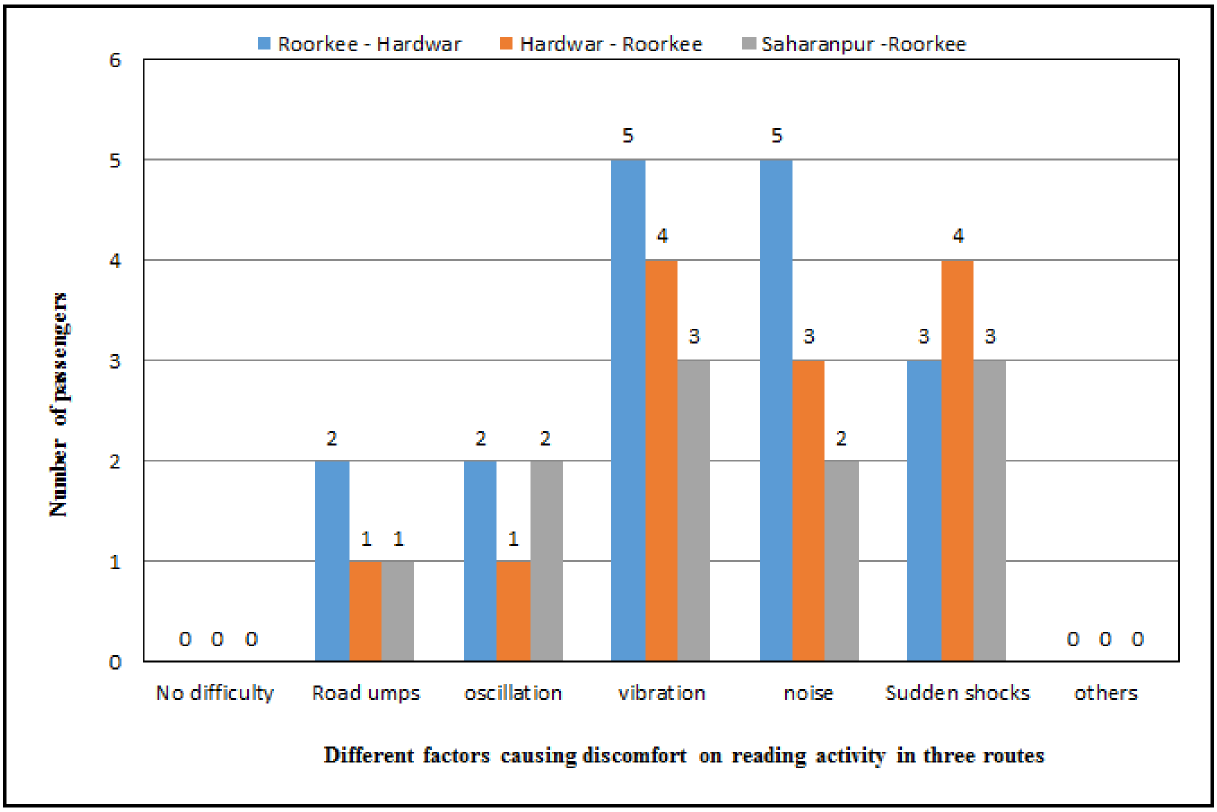


Fig. 3.13 Different factors causing discomfort in three routes while reading hindi news paper.

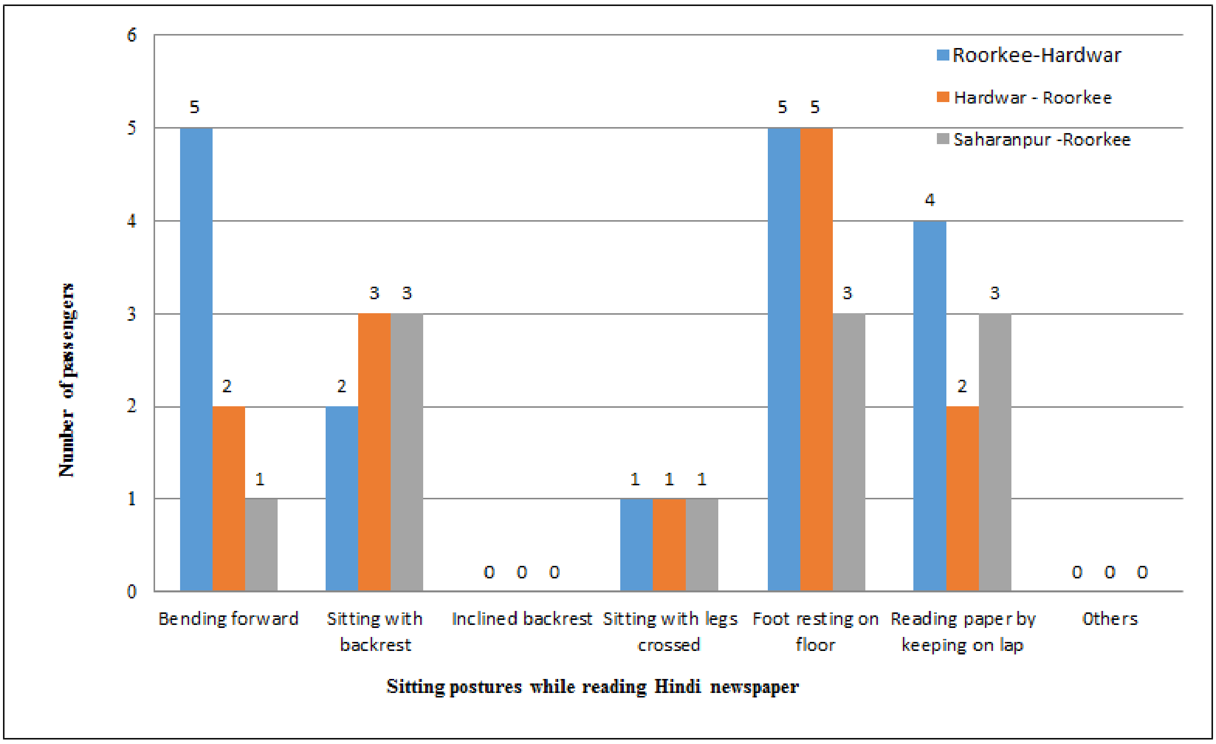


Fig. 3.14 Different sitting postures while reading hindi news paper in three routes

3.3 CONCLUSION

The present study quantified percentage of discomfort due to vibration and noise on sedentary activities. The vibration measurements is been made on floor and seat of the buses and unweighted FFT rms acceleration is acquired for analysis of discomfort. The ride comfort evaluation for buses with consideration of available ISO 2631-2:2003 standards are low. So, in advice of measuring the raw data of unweighted accelerations from public transportation buses has made a valid contribution for the assesments of ride comfort on subjects opinion using 7- point semantic scale. The measured accelerations is correlated with questionnaire survey for passenger's subjective opinion. The questionnaire analysis in three route buses significantly found reading activity is disturbed due to vibration. The postural effects on reading activity reveal that 'sitting with backrest' causes more discomfort than 'foot rested on floor' due to the excitation of supporting structures on human body. The amplification of vibration takes place in the measurement of seated passengers as compared to the attenuation of measurement of vibration on floor. It is found from the results that the maximum acceleration of 2.85 m/s^2 in Haridwar to Roorkee route in seated passengers whereas 2.64

m/s^2 in floor vibration measurement. Mean values in vertical direction suggests the floor vibration is more due to unweighted acceleration raw data measurements. From the questionnaire response of number of passenger's reporting it is observed that passenger's seating positions found more discomfort on back row seats and middle seats compared with front row seated passengers due to vibration. Drinking activity is more disturbed due to jerks and suddnen shocks, where sleeping activity is more disturbed and causes discomfort due to noise generated from the engine, and from the shattering of windows due to breeze while on the move. The main aim of this field study is to increase knowledge on passenger needs to be able to suggest improvements on bus comfort. The suggested improvements will support bus operators and bus manufacturers in their work. In future using proper weighting filters vibration measurements can be made and good suspension seats would be designed for reducing vibrations in buses.

Chapter 4

EXPERIMENTAL STUDY OF HUMAN COMFORT

4.1 INTRODUCTION

The chapter deliberates on the transmissibility measurements in the laboratory which consists of two main studies on standing and sitting positions in low frequency whole body vibration environment. The first study pertains to the measurement of floor to head transmissibility (FTHT) and floor to knee transmissibility (FTKT) in standing postures while the second focuses on seat to head transmissibility (STHT) in different sitting postures. In the laboratory study section like subject's anthropometric data, postures, experimental setup, vibration parameters used for the experiment, experimental tasks, its performance evaluation and test procedures have been extensively discussed.

4.2 EXPERIMENTAL SET UP

All the experimental studies were conducted on the vibration simulator available in the Vehicle Dynamics Laboratory at IIT Roorkee, India (Narayanamoorthy et al., 2008). The platform of stainless steel sheets for simulator is 2 m × 2 m in size, on which two chairs and a table are securely fixed. Three Electro-Dynamic vibration exciters of capacity 1000 N with a stroke length of 25 mm (peak-to-peak) are used to give forced vibration inputs in the three orthogonal directions. The platform can be excited either uniaxially or multiaxially with sinusoidal or random vibration stimuli. The above mentioned setup does not have any resonance within the frequency range of up to 20 Hz in any of the three directions.

4.3 STUDY OF TRANSMISSIBILTY FROM FLOOR TO HEAD IN NORMAL STANDING POSTURE

The daily train and bus commuters occassionally have to remain standing throughout the travel period owing to rush hours and overcrowding in these vehicles. In order to utilize their travel time, the passengers occasionally prefer to perform some sedentary activity such as reading, writing and working on laptop, etc. With the objective of making the train/ bus environment more conducive for performing such activities, some experimental studies were conducted in the laboratory.

A few published studies discuss the vibration transmissibility in standing subjects. Most of the relevant investigations concern the transmission of vertical vibration. There are many un-investigated variables that could influence the transmission of vibration in each axis, such as the effect of holding the handle or handrail. Matsumoto and Griffin, (2000) compared the biodynamic response in sitting and standing postures and concluded that there is a greater transmission of vertical vibration to the pelvis, 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. Later, Matsumoto and Griffin, (2001) investigated the influence of the posture of the legs and the vibration magnitude of the dynamic response of the standing human body exposed to vertical whole-body vibration.

Harazin and Grzesik, (1998) computed the magnitude acceleration in the Z-axis direction of six body segments: the metatarsus, ankle, knee, hip, shoulder and head during exposure to random vibration. In an earlier study, Paddan and Griffin, (1992) measured the head motion of standing subjects while they were exposed to floor vibration occurring in each of the three axes: fore and aft, lateral and vertical and it was concluded that during fore and aft vibration the head motion occurred mostly in the mid sagittal plane and rigid grip to the handrail resulted in higher transmissibility than a light grip. In a study Bhiwapurkar et al., (2011) measured the head motion using a bite bar. In this study the bite bar is held in place by gripping the mouthpiece between teeth. The design of the bite bar used in the present study ensured no resonances of the various attachments up to 60 Hz, which is greater than the frequency of interest. In the present study, the same bite bar is used for measurement of head motion using bite bar technique in measuring transmissibility of accelerations to the head from the excitation floor in vertical (z) and lateral directions (y)

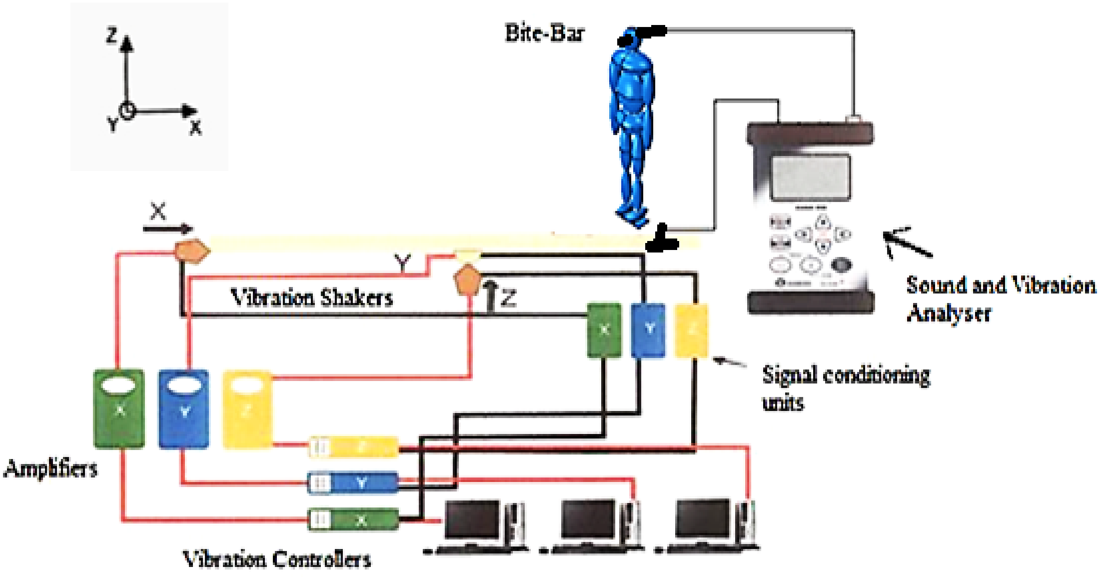


Fig. 4.1 Schematic of experimental setup for study of FTHT in normal standing posture

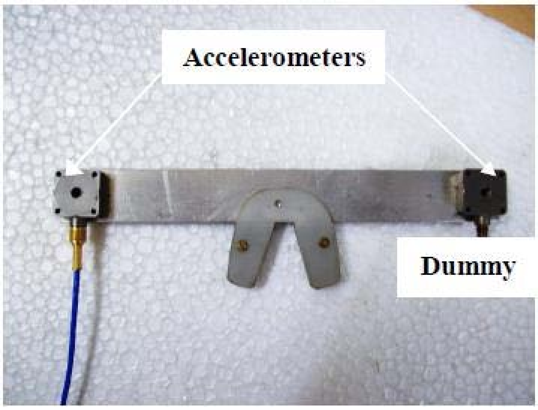


Fig. 4.2 Bite-bar used in the experiments (Bhiwapurkar et al., 2011)

4.3.1 Experimental conditions

The postures chosen for the experiment were selected from those generally adopted by the commuters while standing or sitting during travel in public transport buses. The experiments consisted of measuring the vertical vibration transmission to head under sinusoidal vibration magnitude of $1 m/s^2$ of floor (platform) in vertical direction with the sinusoidal frequencies 3, 5, 6, 8, 10, 12 and 15 (Hz). Six healthy subjects with an average age of 24 years and average height of 174.5 cm took part in the experiment. The physical characteristics of test subjects are summarized in Table 4.1.

For the standing posture, the subjects were instructed to stand erect without any support, with toes 30 cms apart and gripping the bite bar in the mouth to measure the acceleration at the head. The subject was further instructed to look straight ahead and maintain a steady posture throught the experiment, to minimize variability.

Table 4.1 Anthropometric data of standing test subjects

Subjects	Age (Years)	Weight (kg)	Height (cm)
Sub 1	24	68	168
Sub 2	24	60	167
Sub 3	24	76	178
Sub 4	24	66	175
Sub 5	23	72	177
Sub 6	23	78	183

Ethical experimental approval is taken (Appendix B).

4.3.2 Test procedure

Before beginning the experiment, each participant is required to fill out a general questionnaire about his personal information. He is also required to give his written consent (Appendix C) for participating in the experiment. Every subject is introduced about the experiment. The subject's anthropometric data were measured. The study of each subject involved about one hour of test each day to avoid the influence of fatigue. The 1-min break is introduced after exposure to each condition wherein the stimuli are stopped and the subjects are required to rate their perceived difficulty using Borg CR10 scale (Table 4.2). This procedure is repeated for all the vibration levels, directions and postures.

Table 4.2 Borg CR10 scale (2001).

0.0	Nothing at all
0.3	
0.5	Extremely weak (hardly noticeable)
0.7	
1.0	Very weak
1.5	
2.0	Weak (light)
2.5	
3.0	Moderate
4.0	
5.0	Strong (heavy)
6.0	
7.0	Very strong
8.0	
9.0	
10	Extremely strong (almost maximal)
*	Absolute maximum

4.3.3 Data analysis

In general "Transmissibility is defined as the ratio of output to input". If transmissibility is greater than one, it indicates amplification. The maximum amplification occurs when forcing frequency (f_f) and natural frequency (f_n) of the system coincide. No unit is used to designation transmissibility. The FTHT transmissibilty was measured for 6 subjects (S1 – S6). The minimum and maximum transmissibility from all the subjects varies between 0.33 – 2.45 m/s^2. Table 4.3 presents the measured values of FTHT transmissibility and mean FTHT transmisibilty in normal standing posture exposed to vertical sinusoidal excitation of 1 m/s^2 at floor while, Fig. 4.3 illustrates the effect of inter subject variability and mean transmissibility. A mean transmissibility of 1.98 can be observed at 5 Hz.

Table 4.3 – FTHT transmissibility in normal standing posture exposed to vertical excitation of 1 m/s^2 from floor.

Frequency (Hz)	S1	S2	S3	S4	S5	S6	Mean
3	0.80	0.72	0.90	0.35	0.62	0.56	0.66
4	1.32	1.26	1.19	2.09	1.72	1.97	1.59
5	2.45	2.12	1.95	1.75	2.01	1.64	1.98
8	0.56	0.78	0.66	0.82	0.67	0.81	0.72
10	0.54	0.73	0.53	0.63	0.82	0.69	0.65
12	2.12	0.95	1.27	1.76	1.58	1.39	1.51
15	0.33	0.56	0.67	0.87	0.75	0.85	0.67
18	1.5	1.2	0.50	0.80	1.10	1.50	1.11
20	0.98	0.82	1.09	1.01	0.93	1.01	0.97

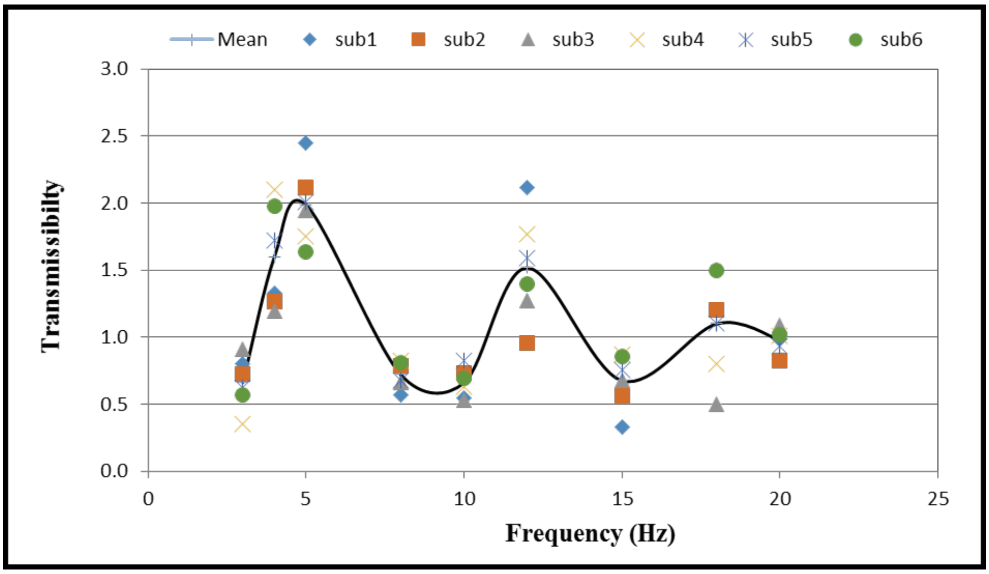


Fig. 4.3 – Effect of inter-subject variability on FTHT for subjects standing in normal posture exposed to vertical excitation of 1 m/s^2 .

4.4 STUDY OF TRANSMISSIBILTY IN STANDING POSTURES HOLDING HANDLE AND HANDRAIL

4.4.1 Subject and Subject postures

The experiments were conducted to measure the vertical vibration transmission to the knee and head under sinusoidal vibration magnitude of $1 m/s^2$ in vertical and lateral directions in two postures, one holding the handle and the other holding handrail. The physical characteristics of test subjects are summarized in Table 4.1.

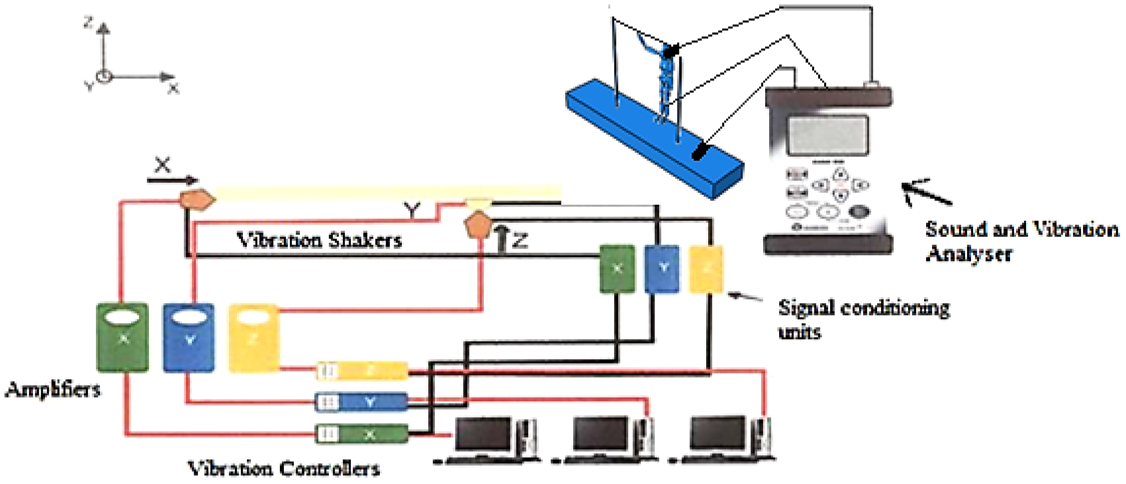


Fig. 4.4 - Schematic drawing of experimental setup of a subject holding handle.

Fig.4.5 - Two standing postures for the experiment - Holding the handle and Holding the handrail.

4.4.2 Experimental set up

The existing experimental setup (section 4.2) was suitably altered for conducting the experiment. Two vertical pipes of outer diameter 0.40 m and height 2.1 m are rigidly fixed on the platform at a distance of 1.50 m. Between these pipes a horizontal pipe (Handrail) of outer diameter 25 mm is tightened at a height of 1.9 m which serves as a support for standing passengers, as found in State Transport buses, (Fig. 4.6). A handle is also provided on the handrail which has a handgrip at 20 cm length below the handrail. The above mentioned setup does not have any resonance within the frequency range studied (up to 20 Hz) in any of the three directions.

Fig. 4.6 - Handle and handrail in the experimental setup

4.4.3 Experimental conditions

The standing test subjects are exposed to sinusoidal excitation aplitudes of 1 m/s^2 in vertical (z) and lateral (y) directions at various frequencies (values 3,5,6,8,10,12 and 15 Hz). A steady position was maintained by the subject during the experiment. The transmissibility of vibrations from floor to knee is measured by mounting tri-axial accelerometers (PCB 356A32 Piezoelectric) at the right knee with the help of Velcro and rubber strap, Fig.4.7. A one-min. break is introduced after exposure to each condition wherein the stimuli are stopped and the subjects are required to rate their perceived difficulty using Borg CR10 scale. This procedure is repeated for all the vibration levels, directions and postures. The floor-to-head transmissibility was measured for 6 subjects and mean value obtained.

Fig. 4.7 Accelerometer mounted on the knee for FTKT

4.4.4 Data analysis

Table 4.4 shows the respective inter subject FTHT transmissibility and mean FTHT transmisibilty in standing posture holding handle while exposed to vertical floor excitation of 1 m/s^2. Fig 4.8 exhibits the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handle standing posture exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility from all the subject varies between 0.25 – 2.96 m/s^2. From the mean transmissibility measured, the peak value (of 2.58 m/s^2) was observed at 5 Hz as shown in Fig. 4.8.

Table. 4.4 – FTHT transmissibilty in holding handle standing subjects exposed to vertical excitation with 1 m/s^2.

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	1.74	1.20	1.40	1.50	2.10	2.50	1.74
5	2.15	2.96	2.40	2.80	2.75	2.41	2.58
6	0.75	0.70	1.00	0.75	0.25	0.60	0.68
8	1.50	1.45	1.75	1.50	1.60	1.40	1.53
10	1.70	1.65	2.40	1.90	2.10	1.50	1.88
12	2.20	1.90	2.25	1.40	1.75	1.75	1.88
15	1.80	1.70	2.20	1.20	1.40	1.35	1.61

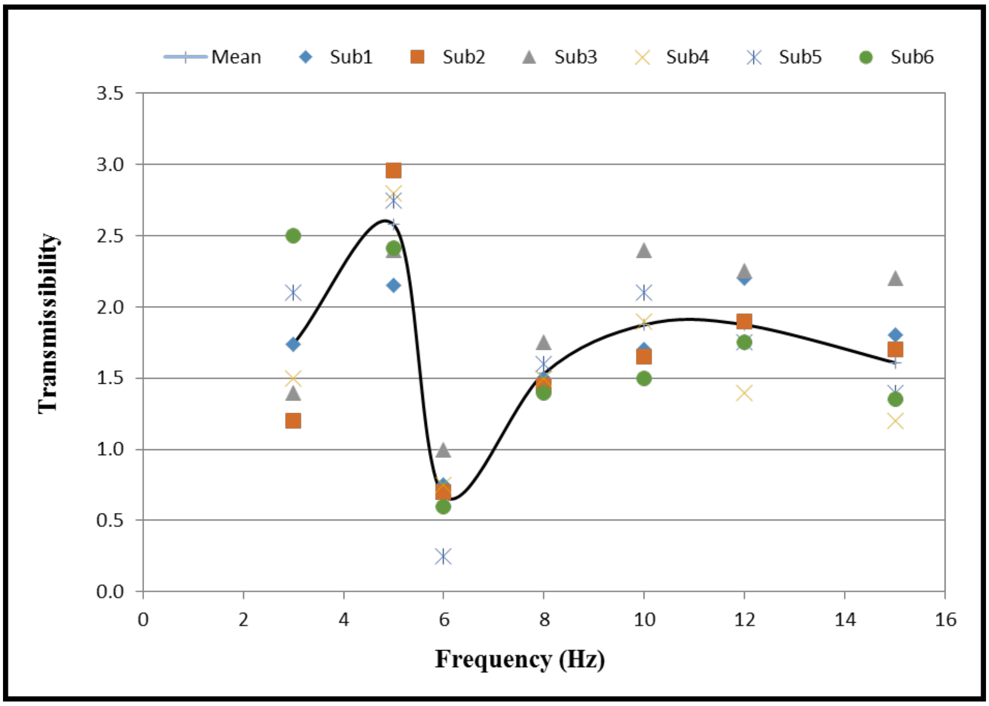


Fig. 4.8 - Effect of inter-subject variability on FTHT for standing subjects holding handle exposed to vertical excitation with 1 m/s^2.

Table 4.5 Shows the respective inter subject FTHT transmissibility and mean FTHT transmisibilty in standing posture holding handrail while exposed to vertical floor excitation of 1 m/s^2. Fig. 4.9 shows the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handrail standing posture exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility values from all the subjects are 0.54 and 2.90 m/s^2, respectively. From the mean transmissibility plot, the peak value of 2.59 was observed at 5Hz as shown in Fig. 4.9.

Table. 4.5 - FTHT transmissibilty in holding handrail standing subjects exposed to vertical excitatio n with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	1.20	1.04	1.20	1.32	2.30	2.39	1.58
5	2.67	2.81	2.23	2.70	2.90	2.20	2.59
6	0.54	1.60	0.72	1.13	0.99	0.73	0.95
8	1.77	1.70	1.64	1.68	1.62	1.21	1.60
10	1.38	1.93	1.58	1.46	1.68	1.00	1.51
12	1.80	1.90	1.84	1.88	1.33	1.31	1.68
15	1.28	1.85	1.49	1.63	1.09	1.10	1.41

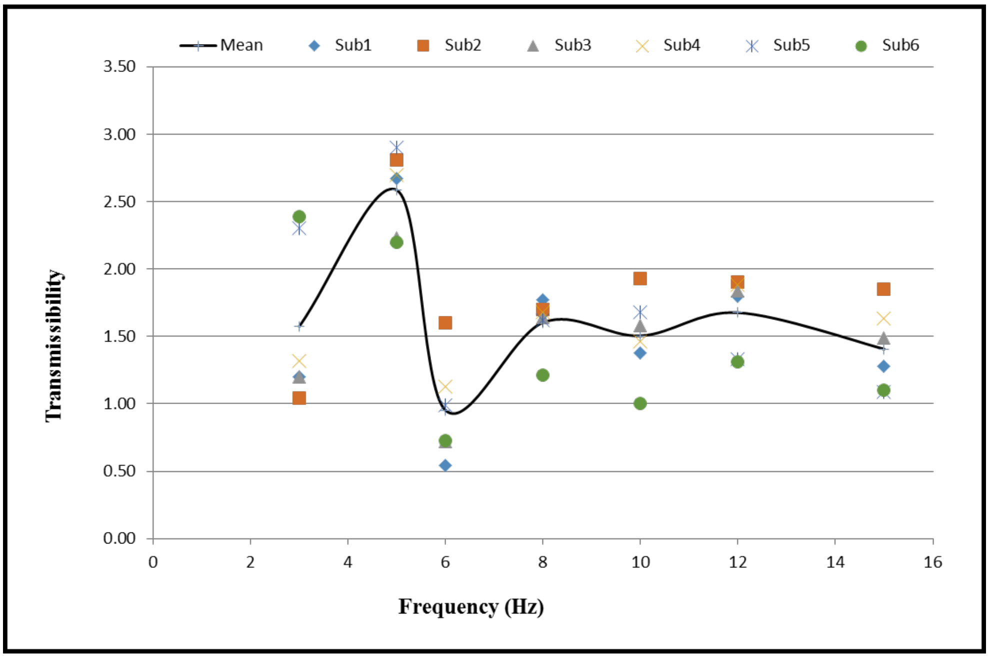


Fig. 4.9 - Effect of inter-subject variability on FTHT for standing subjects holding handrail exposed to vertical excitation with 1 m/s^2.

Table 4.6 shows the respective inter subject FTKT transmissibility and mean FTKT transmisibilty in standing posture holding handle while exposed to vertical excitation with 1 m/s^2 of floor. Fig.4.11 illustrates the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handle standing posture exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility from all the subject varies between 0.78 – 2.90 m/s^2. From the mean transmissibility plot, the peak value of 2.73 was observed at 5 Hz as shown in Fig. 4.10.

Table. 4.6 - FTKT transmissibilty in holding handle standing subjects exposed to vertical excitation with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	1.90	1.88	2.10	2.20	2.40	2.09	2.10
5	2.40	2.80	2.90	2.90	2.85	2.50	2.73
6	1.19	1.90	1.23	0.78	0.98	1.50	1.26
8	1.40	1.50	1.19	1.65	1.46	0.87	1.35
10	1.56	1.77	1.59	1.81	1.32	1.50	1.59
12	1.47	1.93	1.12	1.06	1.33	1.00	1.32
15	2.37	2.18	1.86	2.20	1.68	1.58	1.98

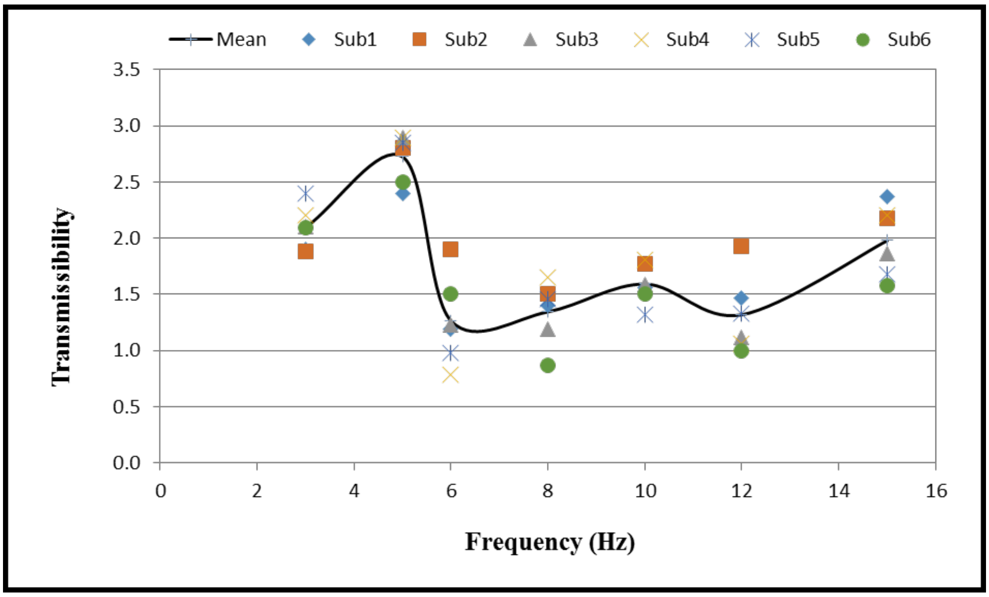


Fig. 4.10 Effect of inter-subject variability on FTKT for standing subjects holding handle exposed to vertical excitation with 1 m/s^2.

Table 4.7 shows the respective inter subject FTKT transmissibility and mean FTKT transmisibilty in standing posture holding handrail while exposed to vertical excitation with 1 m/s^{2}of floor. Fig. 4.11 illustrates the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handrail standing posture exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility from all the subject varies between 0.92 – 3.00 m/s^2. From the mean transmissibility plot, the peak value of 2.72 was observed at 5 Hz as shown in Fig. 4.10.

Table. 4.7 - FTKT transmissibilty in holding handrail standing subjects exposed to vertical excitation with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	1.86	1.81	2.05	2.16	2.27	2.18	2.06
5	3.00	2.90	2.70	2.80	2.50	2.40	2.72
6	1.08	2.00	1.50	1.38	0.92	1.70	1.43
8	1.49	1.53	1.32	1.78	1.57	1.07	1.46
10	1.56	1.70	1.59	1.72	1.28	1.58	1.57
12	1.46	1.93	1.16	0.96	1.36	1.03	1.32
15	2.24	2.17	1.90	2.07	1.70	1.46	1.92

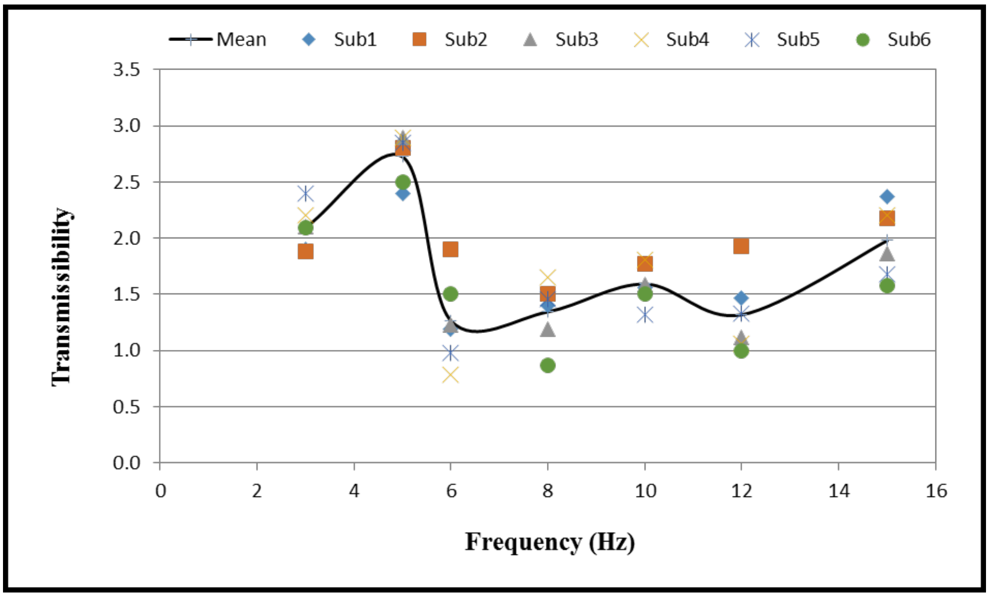


Fig 4.11 - Effect of inter-subject variability on FTKT for standing subjects holding handrail exposed to vertical excitation of 1 m/s^2.

Table 4.8 shows the respective inter subject FTHT transmissibility and mean FTHT transmisibilty in holding handle standing posture exposed to lateral excitation of floor with 1 m/s^2. From the Fig. 4.12 it was observed that the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handle standing posture exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s. The floor-to-head transmissibility was measured for 6 subjects. The minimum and maximum transmissibility from all the subject varies between 0.01 – 0.46 m/s^2. From the mean transmissibility plot, the peak value of 0.37 was observed at 5Hz as shown in Fig. 4.12.

Table. 4.8 FTHT transmissibilty in holding handle standing subjects exposed to lateral excitation with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	0.14	0.14	0.22	0.21	0.16	0.34	0.20
5	0.46	0.42	0.33	0.33	0.32	0.36	0.37
6	0.37	0.25	0.16	0.38	0.41	0.44	0.34
8	0.07	0.07	0.12	0.17	0.05	0.02	0.08
10	0.05	0.05	0.05	0.02	0.02	0.02	0.03
12	0.02	0.01	0.04	0.01	0.01	0.01	0.02
15	0.00	0.00	0.01	0.00	0.00	0.01	0.00

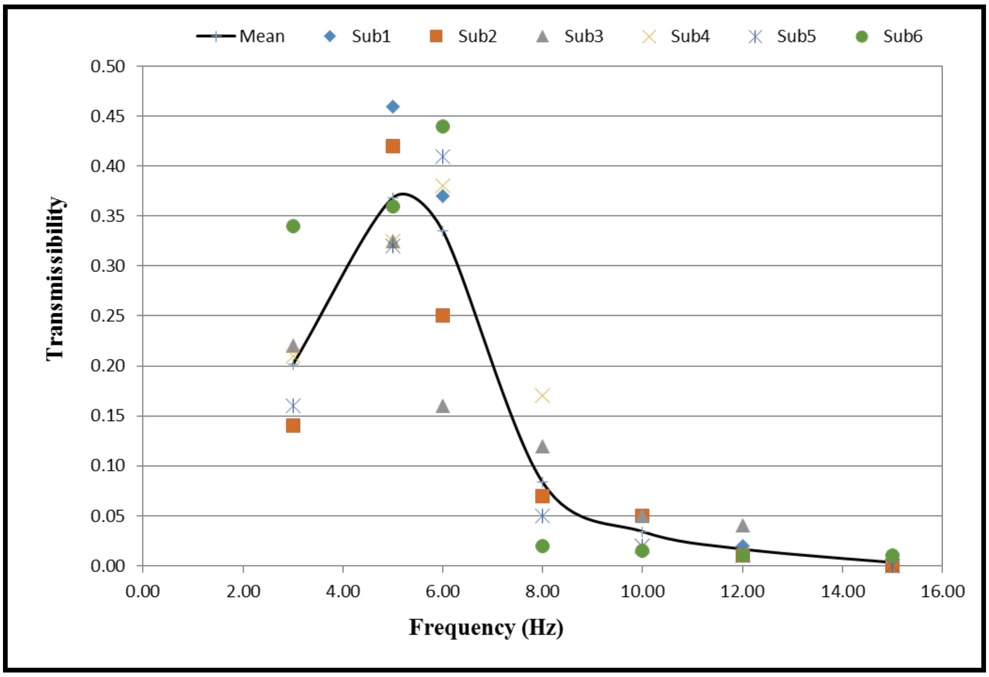


Fig. 4.12 - Effect of inter-subject variability on FTHT for standing subjects holding handle exposed to lateral excitation of 1 m/s^2.

Table 4.9 shows the inter subject FTHT transmissibility and mean FTHT transmisibilty in holding handrail standing posture exposed to lateral excitation of floor with 1 m/s^2. Fig. 4.13 exhibits the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handrail standing posture exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility values from all the subjects are 0.01 and 0.49 m/s^2, respectively. From the mean transmissibility plot, the peak value of 0.44 is observed at 5Hz as shown in Fig. 4.13.

Table. 4.9 - FTHT transmissibilty in holding handrail standing subjects exposed to lateral excitation with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	0.42	0.44	0.41	0.40	0.40	0.31	0.40
5	0.32	0.49	0.45	0.45	0.55	0.38	0.44
6	0.30	0.47	0.42	0.46	0.47	0.46	0.43
8	0.05	0.07	0.10	0.08	0.08	0.12	0.08
10	0.02	0.02	0.02	0.05	0.05	0.03	0.03
12	0.01	0.01	0.03	0.03	0.04	0.01	0.02
15	0.01	0.01	0.01	0.01	0.01	0.05	0.02

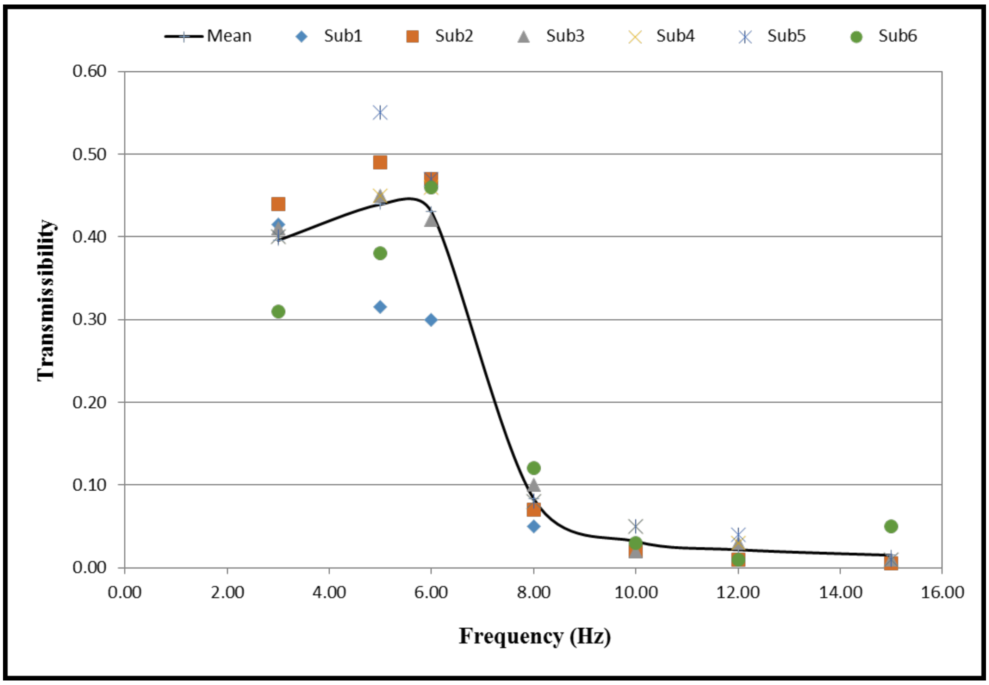


Fig. 4.13 - Effect of inter-subject variability on FTHT for standing subjects holding handrail exposed to lateral excitation of 1 m/s^2.

Table 4.10 shows the inter subject FTKT transmissibility and mean FTKT transmisibilty in holding handle standing posture exposed to lateral excitation of floor with 1 m/s^2. Fig 4.14 exhibits the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handle standing posture exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility values from all the subjects are 0.01 and 1.89 m/s^2, respectively. From the mean transmissibility plot, the peak value of 1.46 is observed at 8Hz as shown in Fig. 4.13.

Table. 4.10 - FTKT transmissibilty in holding handle standing subjects exposed to lateral excitation with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	0.42	0.18	0.30	0.30	0.30	0.30	0.30
5	0.18	0.01	0.20	0.20	0.01	0.21	0.15
6	1.40	0.80	1.40	1.20	1.30	1.20	1.22
8	1.89	1.00	1.50	1.50	1.48	1.41	1.46
10	1.40	0.80	1.30	1.20	0.90	0.90	1.08
12	0.40	0.58	0.60	0.60	0.50	0.40	0.51
15	0.37	0.43	0.30	0.30	0.30	0.30	0.33

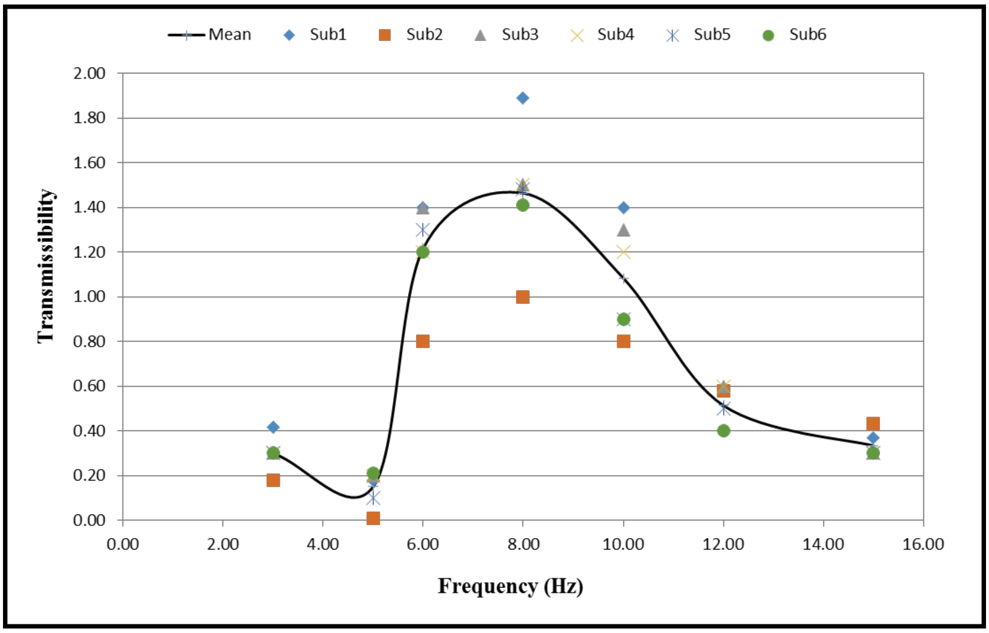


Fig. 4.14 - Effect of inter-subject variability on FTKT of standing subjects holding handle exposed to lateral excitation of 1 m/s^2.

Table 4.11 shows the inter subject FTKT transmissibility and mean FTKT transmisibilty in holding handrail standing posture exposed to lateral excitation of floor with 1 m/s^2. Fig 4.15 exhibits the effect of inter subject variability and mean transmissibility on measuring the transmissibility of subjects in holding handrail standing posture exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s. The minimum and maximum transmissibility values from all the subjects are 0.10 and 1.78 m/s^2, respectively. From the mean transmissibility plot, the peak value of 1.48 is observed at 8Hz as shown in Fig. 4.15.

Table. 4.11 - FTKT transmissibilty in holding handrail standing subjects exposed to lateral excitation with 1 m/s^2

Frequency (Hz)	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	Mean
3	0.19	0.10	0.22	0.19	0.41	0.30	0.24
5	0.10	0.21	0.10	0.10	0.13	0.10	0.12
6	1.20	0.80	1.50	1.20	1.18	1.50	1.23
8	1.50	1.00	1.78	1.50	1.38	1.70	1.48
10	1.00	0.80	1.42	1.00	1.00	1.00	1.04
12	0.40	0.50	0.58	0.40	0.58	0.38	0.47
15	0.35	0.41	0.38	0.35	0.30	0.37	0.36

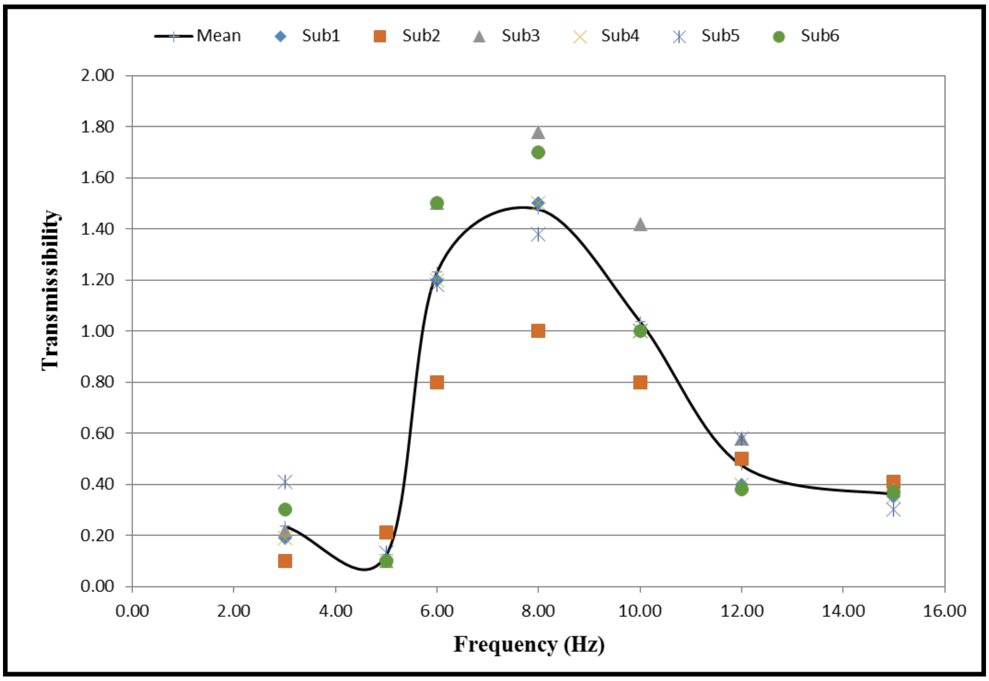


Fig. 4.15 - Effect of inter-subject variability on FTKT of standing subjects holding handrail exposed to lateral excitation of 1 m/s^2.

Fig. 4.16 shows that the mean Floor-to-Head of transmissibility of different subjects in vertical direction is increased while holding the Handle as compared to while holding the Handrail at 5 Hz and at 10 Hz. This is because when the floor is vibrating in vertical direction, there is movement of hand while holding the handle due to which magnitude of vibration increases which is coming from the hand. This also adds to the vibrations which are coming from the feet and hence increases the transmissibility.

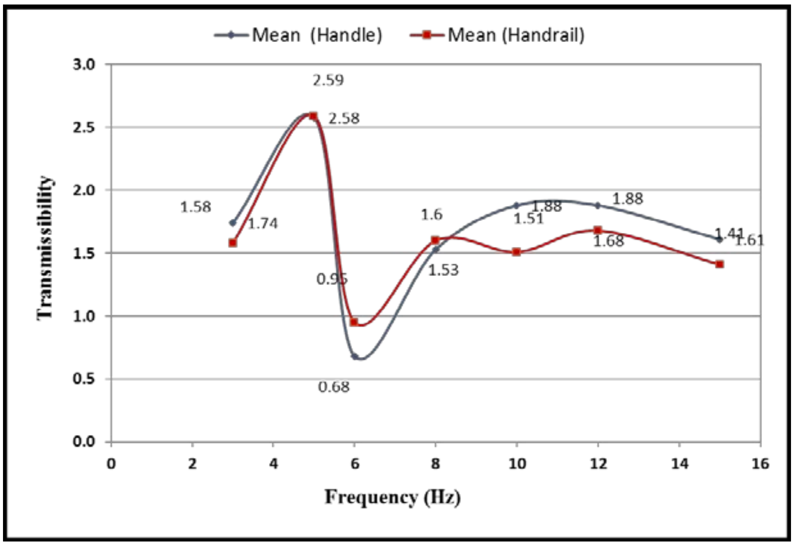


Fig. 4.16 - Comparison of Mean FTHT vertical transmissibility for 6 subjects while holding the Handle and Handrail postures.

From Fig.4.17 it is concluded that at 5 Hz the transmissibility at the head in the lateral direction is slightly larger while holding the handrail posture than compared with while holding the handle posture but the difference is very small.

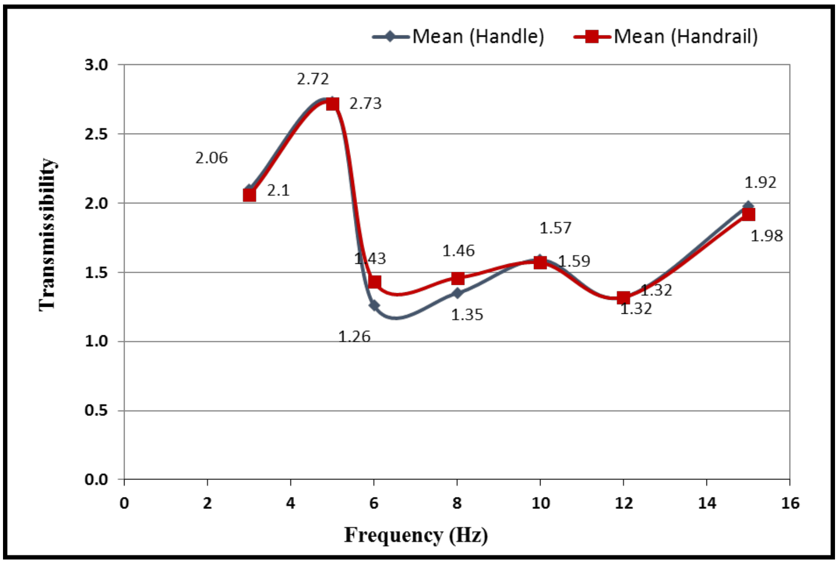


Fig. 4.17 - Comparison of Mean FTHT lateral transmissibility for 6 subjects while holding the Handle and Handrail postures

Fig 4.18 and Fig 4.19 shows the comparison of mean values of floor to knee transmissibility in vertical and lateral sinusoidal vibration with 1m/s^2 magnitude and it has been concluded that there is not much change in the transmissibility values while gripping handle and handrail in both the direction.

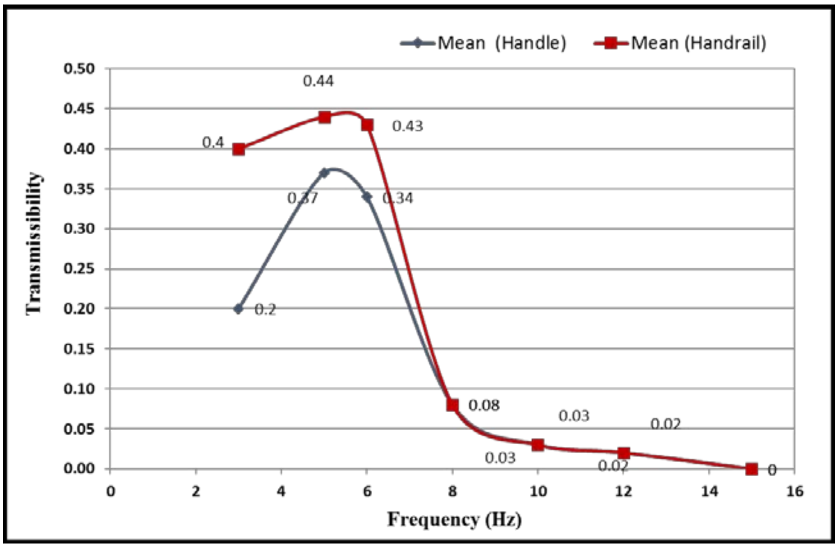


Fig. 4.18 - Comparison of Mean FTKT vertical transmissibility for 6 subjects while holding the Handle and Handrail postures

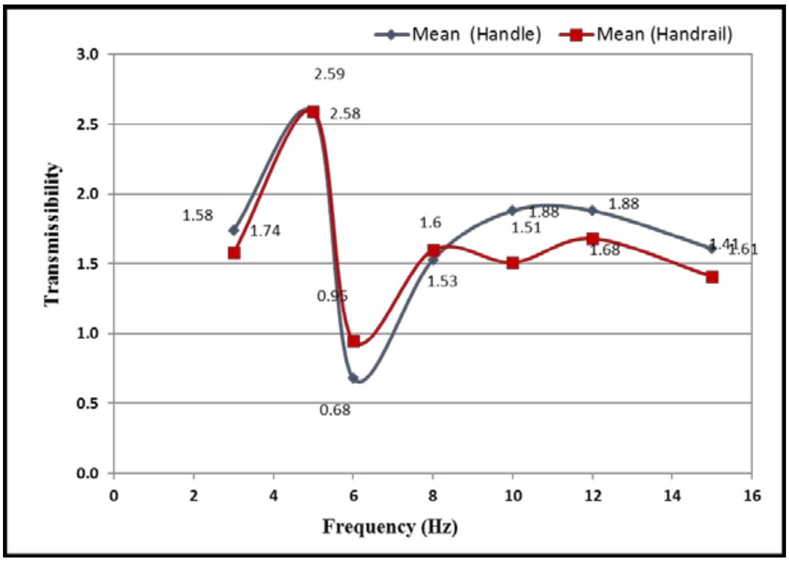


Fig. 4.19 - Comparison of Mean FTKT lateral transmissibility for 6 subjects while holding the Handle and Handrail postures.

4.5 STUDY OF TRANSMISSIBILTY IN SITTING POSTURES

Whole body vibration under low frequency to human is observed in most of the occasion in public transportation buses, metro trains and in escavators. Where, human beings feel a sensitive excitation in a seated posture, therefore, biodynamic responses of a seated human body have been the topic of interest over the years and a number of mathematical models have been established. Based on this an experimental study has been conducted to provide supporting information concerning the effect of inter-subject variabilities, magnitudes, frequencies and postures. In addition, it was conducted to provide experimental data sets to validate the models developed and presented in previous chapters.

4.5.1 Study on effect of Backrest inclination

The experiments were performed to measure vertical vibration transmitted to the occupants head in two representative postures under three magnitudes of vibration in vertical direction. Six healthy subjects with average age 24 years, average weight 69 kg and average height 174 (cm) took part in the experiment. The physical characteristics of test subjects are summarized in Table. 4.16. Prior to the tests, each subject was asked to hold the bite bar in the mouth so that the acceleration at the head can be measured. Each subject was asked to sit in position in accordance to the test procedure which requires average thigh contact so that upper legs are comfortably supported on the seat pan and the lower legs are oriented vertically with the feet on the vibrating platform. Each subject was further asked to maintain a steady head position while data is acquired. Meanwhile the subject's posture during each trial and each posture was visually checked by the experimenter to ensure consistency. Each subject was exposed to three sinusoidal vibration magnitudes over the frequency range of 3 to 12 Hz for 7 representative frequencies 3,4,5,6,8,10 and 12 (Hz) in two different postures. The two postures which are used in the experiment are the postures of the seated human body performing sedentary activities while travelling. Studies of the effect of backrest angle on disc pressure have been conducted within a narrow range of angles ranging from 80° to 130°.

Magnusson and Hansson, (1994) and Magnusson and Pope, (1998) considered backrest angles from 80° to 130° and suggested using a backrest angle of 110° or more with a lumbar support to reduce disc pressure. Goel et.al., (1999) suggested an optimal backrest angle of 120° and emphasized the importance of a lumbar support.

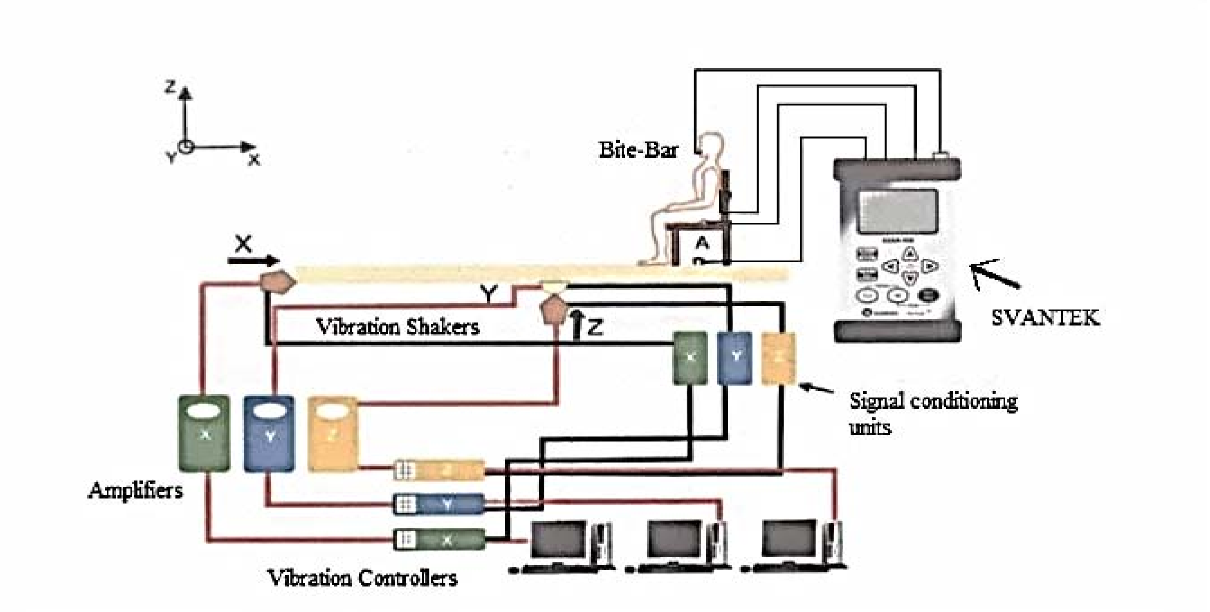


Fig. 4.20 - Schematic drawing of experimental setup of a subject in sitting posture

Table. 4.12 - Anthropometric data of sitting test subjects

Test subjects	Total weight (kg)	Total height (cm)	Age
Sub 1	58	170	24
Sub 2	59	162	25
Sub 3	72	176	23

Sub 4	78	176	29
Sub 5	74	173	23
Sub 6	72	185	23
Average	69	174	24

4.5.2 Experiment: Effect of Backrest inclination

The vibration simulator in the laboratory (Vehicle dynamics lab, MIED, IITR) is used for performing experiment on which a table and two rigid chairs one with variable back support from 80^0 to 130^0 can be adjusted for inclination and the other chair with backrest is rigid, flat, and vertical with fixed back support have been securely mounted and fixed on the floor.

Neither the seat, nor the backrest, nor the table had any resonances within the frequency range studied (up to 20 Hz) in any of the three axes. The posture is shown in Fig. 4.21 (a) and Fig. 4.21 (b).

Fig. 4.21 - (a) Sitting erect posture with hands on the lap, (b) Sitting 130^o inclined posture on backrest support.

4.5.3 Experimental conditions: Test procedures

In this study the subjects were exposed to sinusoidal vertical whole-body vibration by vertical electro-dynamics exciter (Vehicle dynamics laboratory, MIED, IITR). The tri-axial accelerometers (KISTLER 8393B10) are placed on the seat, back and head positions through the attachment of the bite bar in order to measure the acceleration at the respective points. The vibration signals from the accelerometers were conveyed to the SVAN 958 Four channel sound & vibration level meter & analyser shown in the Fig. 4.20. The test subjects were seated on the chairs rigidly mounted on the platform of Vibration Simulator such that these are excited with the same frequency as the platform, up to 12 Hz.


[redacted]

Fig. 4.22 Instrumented bite bar gripped between teeth by subject

In the present study the task includes measurement of head acceleration as discussed in section 4.2.1. The test procedure involves data acquisition through gathering signals from measurement sources and digitizing the signal for storage, analysis, and presentation on a computer. For this study, tri-axial accelerometers (KISTLER 8393B10) has been mounted on floor, seat, backrest support and head in order to measure accelerations in the vertical (Z) direction.

The seat pad tri-axial accelerometers were securely attached to seat and back support at the proper place to measure the seat and back support acceleration respectively.

The accelerometer used to measure head acceleration was securely attached to the bite bar of 3 mm aluminum bar is prepared. Signals from the accelerometers were amplified using three (for head, back support, head) three channel lightweight ICP®sensor signal conditioner

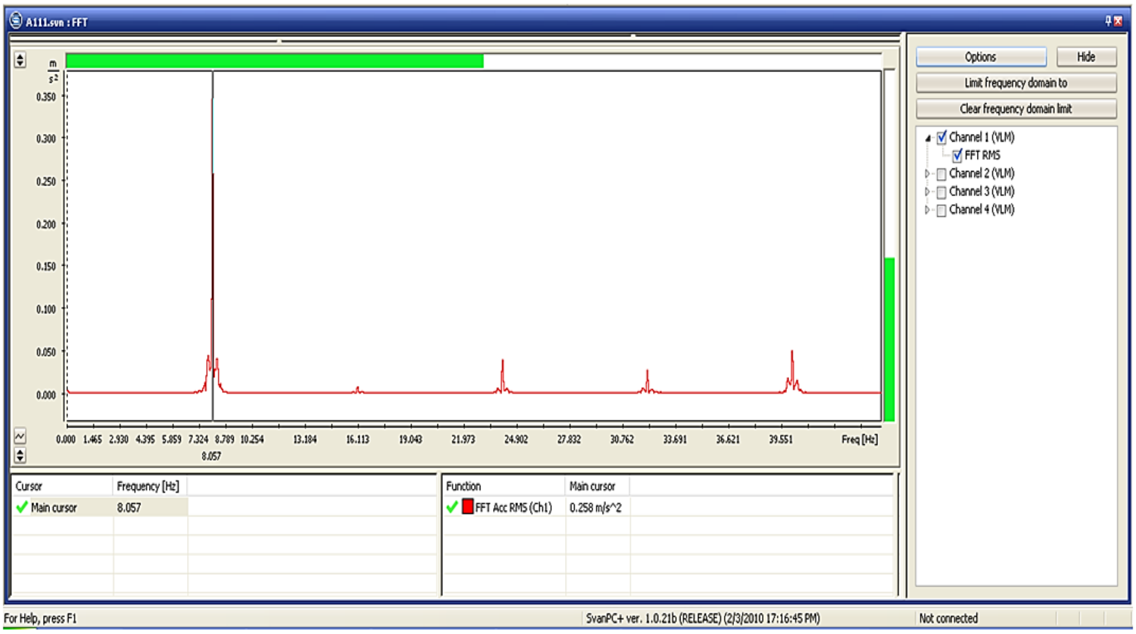
(480B21) with the gain of x100 for each channel. Then the data are collected by using SVAN 958 four channels sound & vibration level meter & analyzer. The required graphs were obtained from the SVAN through a data cable connected to the computer. Fig.4.20 shows the graphical view of the data obtained from the SVAN 958. The cursor shows the value of the frequency on the X-axis and the value of the rms in the Y-axis. The r.m.s. value at a particular frequency is obtained by positioning the cursor at the required frequency on the X-axis. By clicking on the required channel the r.m.s. value at that channel is extracted. Similarly the area under the graph indicates the r.m.s.value of each channel.

The data obtained for each channel for each subject at the particular frequency and particular vibration magnitude was entered in the excel sheet for the prior calculation of transmissibility for the two postures. The seat-to-head transmissibility in vertical direction is evaluated by calculating the ratio between the seat acceleration and the head acceleration. Such that

$$\mathrm{T_{STH}}\ (f) = \frac{a_{head}}{a_{seat}} \tag{4.1}$$

$$\mathrm{T_{BTH}}\ (f) = \frac{a_{head}}{a_{seat}} \tag{4.2}$$

where $\mathrm{a_{head}}$ is the head acceleration, $\mathrm{a_{seat}}$ is the seat acceleration, $\mathrm{a_{back}}$ is the back support acceleration, $\mathrm{T_{STH}}$ (*f*) is the seat to head transmissibility and $\mathrm{T_{BTH}}$ (*f*) is the back to head transmissibility for frequency (f).



Cursor	Frequency [Hz]
✓ Main cursor	8.057

Function	Main cursor
✓ 🟥 FFT Acc RMS (Ch1)	0.258 m/s^2

Fig. 4.23 - Measurement of floor acceleration using SVAN 958

The STHT, BTHT, phase angles and respective coherence were recorded for each forced frequency and magnitude undertaken in the experiment. The measured data of each subject were collected in Microsoft Excel to calculate the lower limit, mean (target values), and upper limit of transmissibilities, phases and coherences. The analyzed data were summarized in next section on data analysis using tables.

4.5.4 Data analysis

The present experimental studies have been conducted on sitting postures for the measurement and analysis of transmissibility, inter subject variability, effect of vibration magnitude within the range of sinusoidal excitation frequencies and magnitudes in two different postures in vertical direction and their data were collected and analyzed using vibration measuring instrument SVAN for data analysis and also Microsoft Excel is used to plot and study the responses of acceleration and frequency effects on postures.

The main factors which affect the humans under low frequency vibrations are magnitude, direction, intra-subject variability (changes in a person over time), inter-subject variability (differences between people) and postures.

From the Fig. (4.24 - 4.25) mean STHT transmissibility in erect and inclined backrest posture has been observed. Resonance frequency value decreases as vibration amplitude increases. For 1.2 m/s^2 r.m.s value, resonance value is 4 Hz and for 0.4 m/s^2 the resonance frequency is between 5.5 to 5.8 Hz. Back supported postures revealed the frequency shift. For vertical vibrations of higher magnitude, the upper body which was having back support experienced more comfort. A decrease in primary resonance frequency by an amount of 1 Hz was revealed by seat to head transmissibility due to the erect posture and inclination of back support.

Table 4.13 - STHT transmissibilty of seated human exposed to vertical sinusoidal vibration of magnitude 0.4 m/s^2 r.m.s in both erect and 30^0 inclined backrest posture.

Erect posture				**30^0 inclined backrest posture**			
Frequency (Hz)	**Lower value**	**Mean value**	**Higher value**	**Frequency (Hz)**	**Lower value**	**Mean value**	**Higher value**
3	0.56	0.745	0.9	3	0.683	0.75	0.832
4	0.998	1.321	1.624	4	1.063	1.362	1.689
5	1.222	1.556	2.029	5	1.303	1.564	1.814
6	0.634	1.039	1.257	6	1.441	1.691	2.02

8	0.605	0.903	1.02	8	0.776	0.882	0.918
10	0.483	0.789	0.895	10	0.629	0.753	0.895
12	0.461	0.649	0.79	12	0.4	0.597	0.788

Table 4.14 - STHT transmissibilty of seated human exposed to vertical sinusoidal vibration of magnitude 0.8 m/s^2 r.m.s in both erect and 30^0 inclined backrest posture.

Erect posture				**30^0 inclined backrest posture**			
Frequency (Hz)	**Lower value**	**Mean value**	**Higher value**	**Frequency (Hz)**	**Lower value**	**Mean value**	**Higher value**
3	0.69	0.912	1.03	3	0.723	0.878	1.043
4	1.073	1.448	1.843	4	1.217	1.350	1.449
5	1.295	1.695	2.31	5	1.59	1.981	2.432
6	0.901	1.186	1.409	6	1.242	1.463	1.829
8	0.459	0.808	0.991	8	0.902	1.028	1.286
10	0.431	0.706	0.786	10	0.702	0.835	1.111
12	0.405	0.632	0.752	12	0.405	0.647	0.909

Table. 4.15 - STHT transmissibilty of seated human body exposed to vertical sinusoidal vibration of magnitude 1.2 m/s^2 r.m.s in both erect and 30^0 inclined backrest posture.

Erect posture				**30^0 inclined backrest posture**			
Frequency (Hz)	**Lower value**	**Mean value**	**Higher value**	**Frequency (Hz)**	**Lower value**	**Mean value**	**Higher value**
3	0.69	0.912	1.03	3	0.723	0.878	1.043
4	1.073	1.448	1.843	4	1.217	1.350	1.449
5	1.295	1.695	2.31	5	1.59	1.981	2.432
6	0.901	1.186	1.409	6	1.242	1.463	1.829
8	0.459	0.808	0.991	8	0.902	1.028	1.286
10	0.431	0.706	0.786	10	0.702	0.835	1.111
12	0.405	0.632	0.752	12	0.405	0.647	0.909

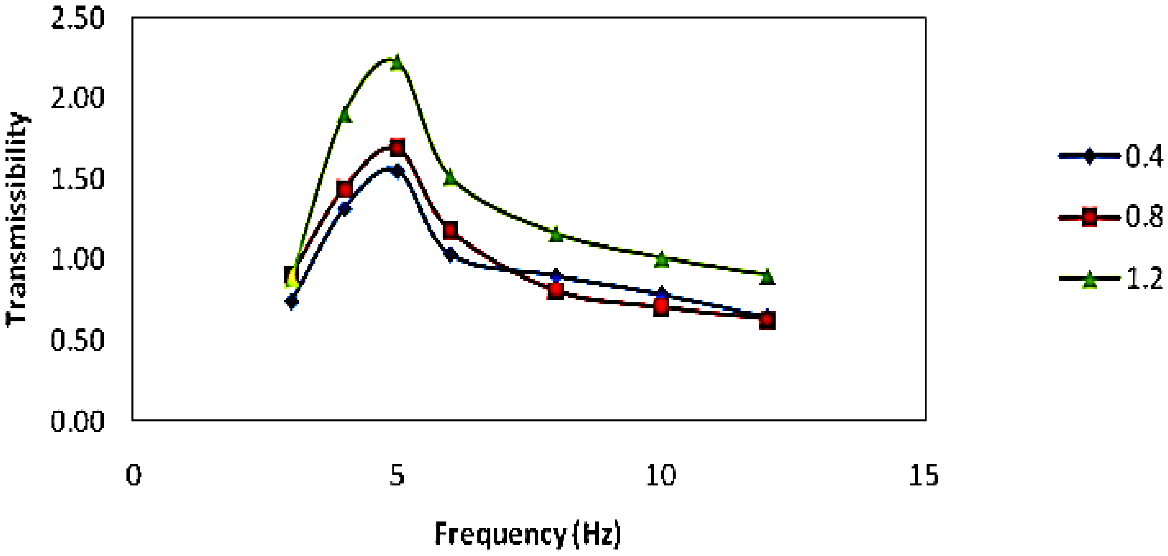


Fig. 4.24 - Mean STHT transmissibility for 6 subjects exposed to vertical sinusoidal vibration at 0.4, 0.8, 1.2 m/sec^2 in erect posture.

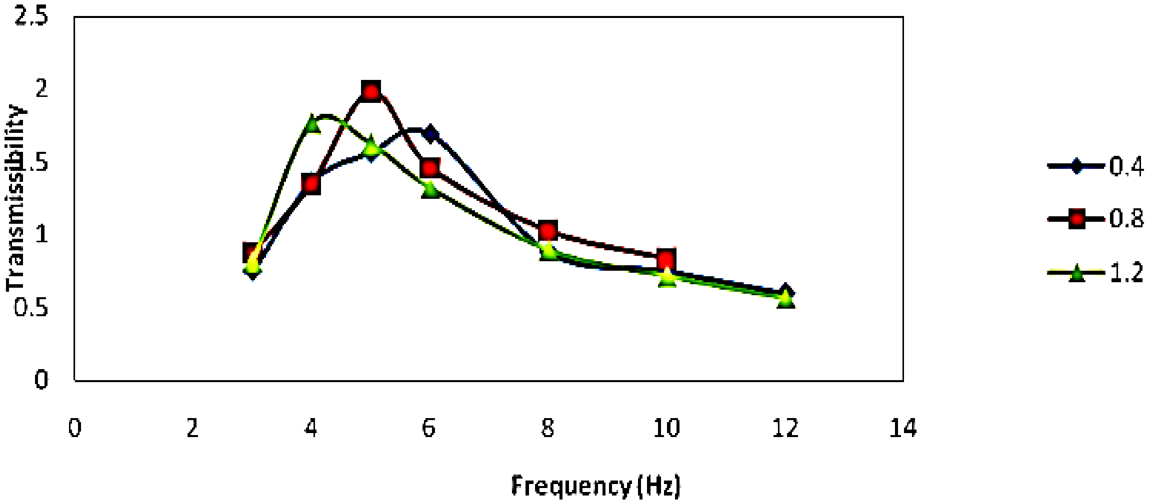


Fig. 4.25 - Mean STHT transmissibility for 6 subjects exposed to vertical sinusoidal vibration at 0.4, 0.8, 1.2 m/sec^2 in 30^0 inclined backrest posture.

From Fig (4.26 – 4.28) it has been observed that, transmissibility is higher for SUB 6 at a frequency of 5 Hz. This has been attributed to higher heights of the subject (Table 4.12). For SUB 4 whose weight is 78 kgs (maximum among all subjects), the resonance frequency is observed at 4.5 Hz. For SUB 1 with weight 58 kgs (minimum among all subjects), the resonance frequency is observed at 4.5 Hz.

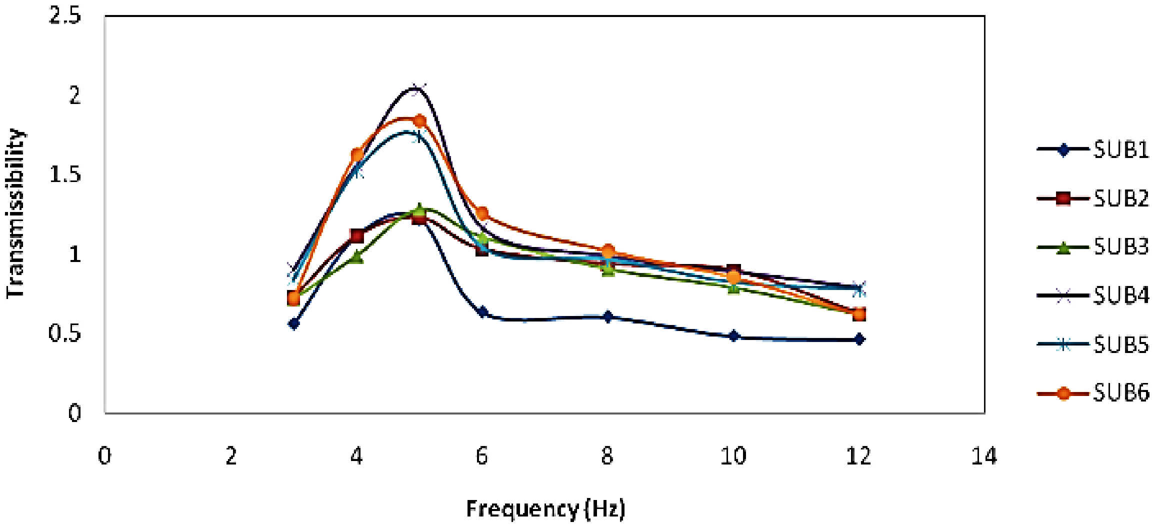


Fig. 4.26 - Effect of inter subject STHT Transmissibilty of for 6 subjects exposed to vertical vibration at 0.4 m/s^2 r.m.s. in erect posture.

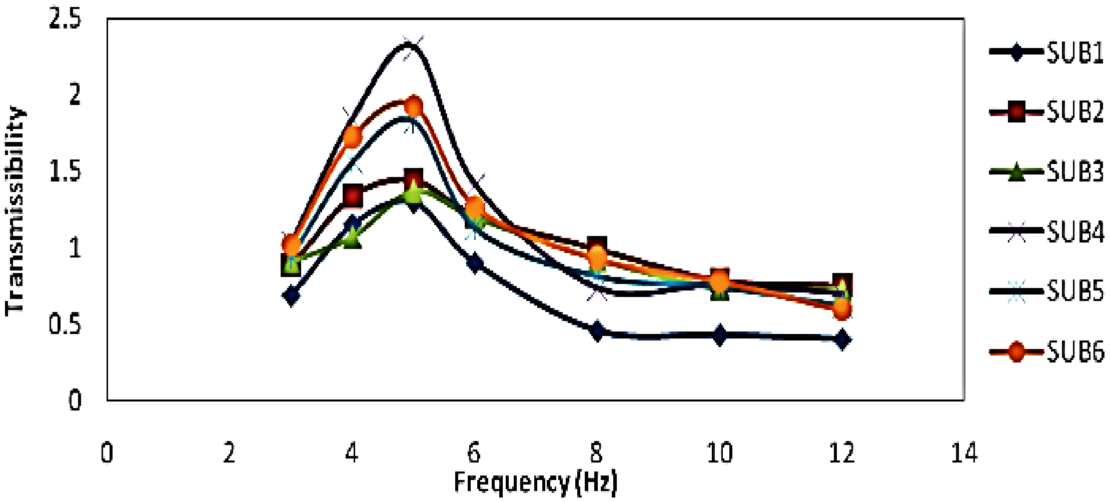


Fig. 4.27 - Effect of inter subject STHT transmissibility for 6 subjects exposed to vertical vibration at 0.8 m/s^2 r.m.s. in erect posture.

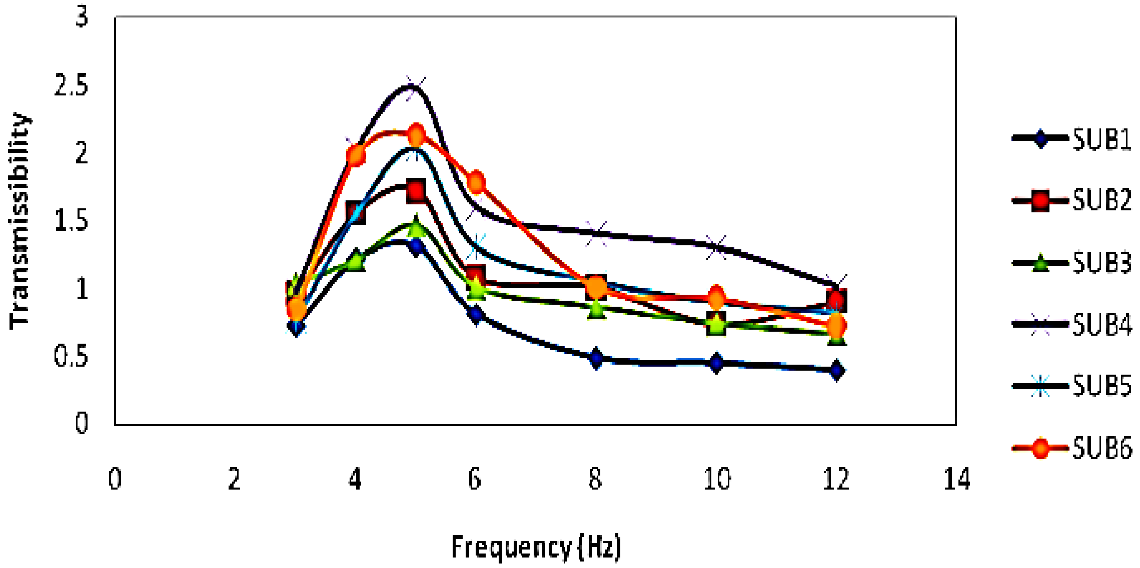


Fig. 4.28 - Effect of inter subject STHT transmissibility for 6 subjects exposed to vertical vibration at 1.2 m/s^2 r.m.s in erect posture.

Fig. (4.29 – 4.31) describes the STHT of seated human at 30° inclined backrest posture under (0.4 m/s^2, 0.8 m/s^2, 1.2 m/s^2). It has been observed that, transmissibility is highest for SUB 6 whose height is 185 cms (Table 4.12). The resonance frequency is at 5 Hz for Sub 6.

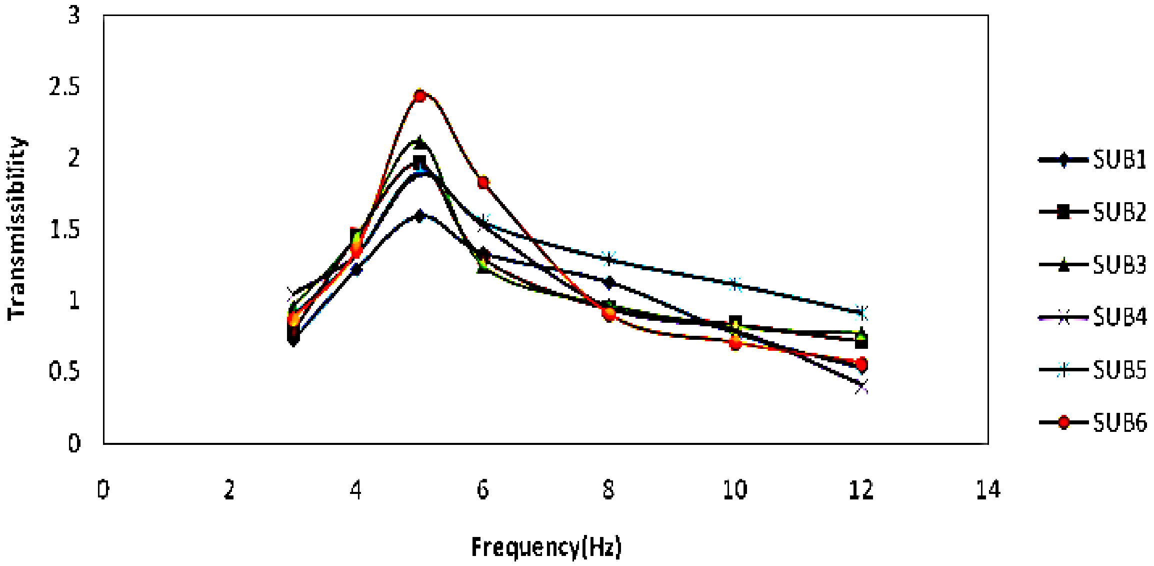


Fig. 4.29 - Effect of inter subject STHT transmissibility for 6 subjects exposed to vertical vibration at 0.4m/s^2 r.m.s at 30^0 inclined backrest posture.

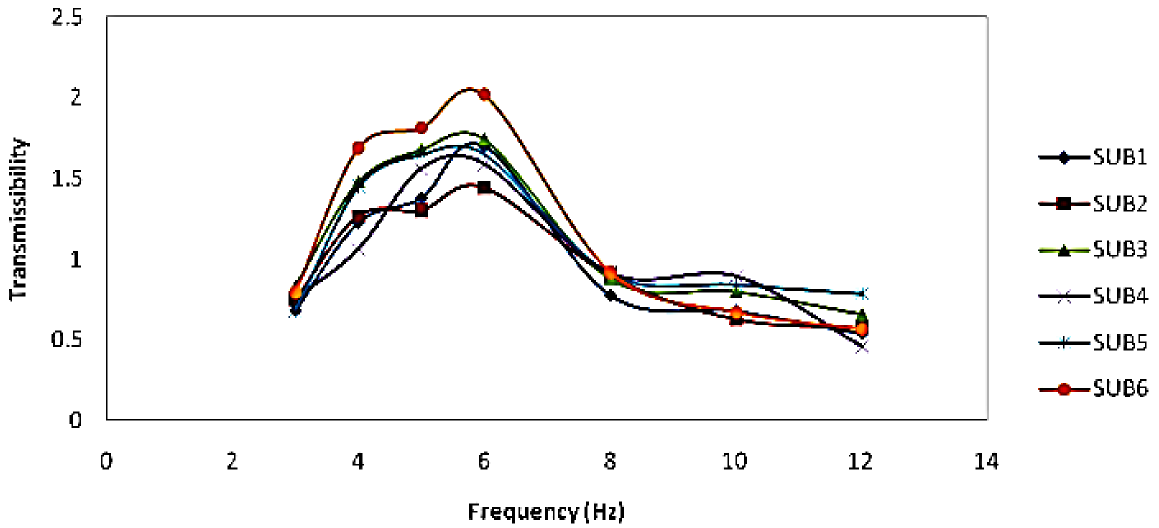


Fig. 4.30 - Effect of inter subject STHT transmissibility for 6 subjects exposed to vertical vibration at 0.8 m/s^2 r.m.s 30^0 inclined backrest posture.

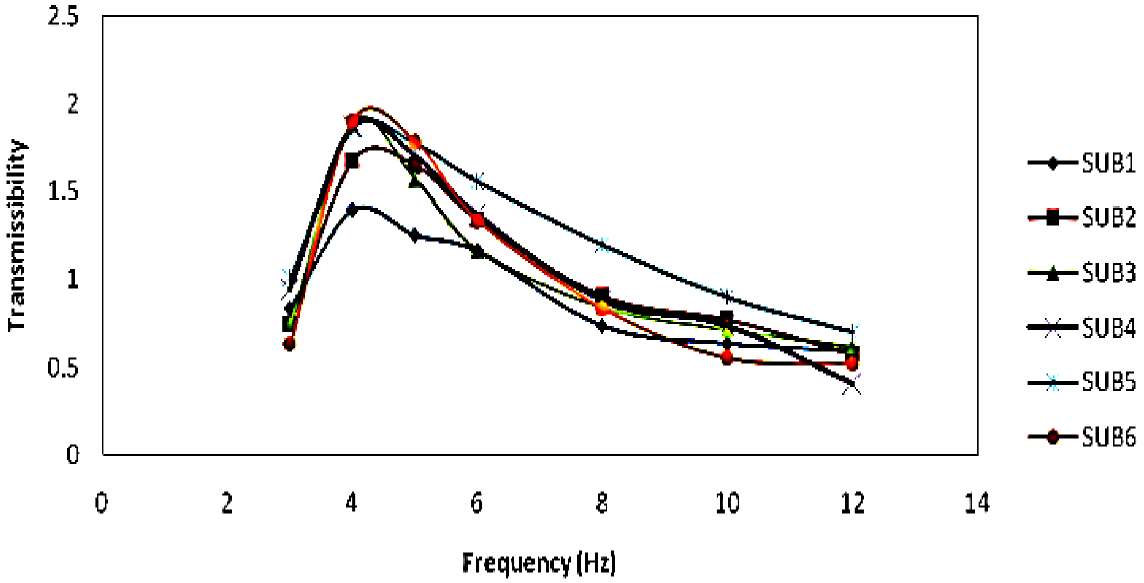


Fig. 4.31 - Effect of inter subject STHT transmissibility for 6 subjects exposed to vertical vibration at 1.2 m/s^2 r.m.s 30^0 inclined backrest posture.

4.6 Conclusion

4.6.1 Standing postures

The mean floor to head transmissibilty (FTHT) in normal standing posture exposed to vertical sinusoidal excitation of 1 m/s^2 is observed to be 1.98 at 5 Hz. Investigation for FTHT and floor to knee transmissibilty (FTKT) measures of biodynamic responses were made through measurements for standing humans with exposure to whole body vibration. Six subjects who were adult male, and were in varying standing posture conditions were considered. Measured vertical as well as lateral floor to head and floor to knee transmissibility biodynamic response were characterized to examine the effects of the two postures while holding the handle and while holding the handrail as found in Indian buses. Excitation magnitude is 1 m/s^2 r.m.s in the frequency range of 3-15 Hz.

In vertical direction, the resonance peak is found at 5 Hz at the head and at the knee in both the postures, and in lateral direction the resonance peak is observed at near 6 Hz of head in both the postures. But the resonance peak of knee in lateral direction is observed at 8 Hz in both the postures. For the subject holding handle there is a significant decrease in the FTHT value and the minimum is 0.01m/s^2 which is observed in the lateral direction. This value when compared to the FTHT in vertical direction is very low. The floor-to-head transmissibility of different subjects in vertical direction is slightly increased while holding the handle as compared to while holding the handrail. It is also observed that the transmissibility is increased in lateral as well as in vertical direction in both the postures while compared to the normal standing posture.

4.6.2 Sitting postures

Measurement were performed on six adult male subjects so that the STHT measures of biodynamic responses of seat inhabitants exposed to whole body vibration could be examined for different sitting postures.

The two postures (erect posture and inclined back rest posture) were examined through measured vertical STHT biodynamic response in order to characterize their effects with excitation magnitudes (0.40, 0.80, 1.20 m/sec^2 r.m.s with 3-12 Hz as the range of frequency) and two hands on the lap. STHT transmissibilty of erect posture human for three vibration magnitudes were measured and resonance frequency was observed to be 5 Hz. STHT transmissibilty of inclined seated posture under three vibration magnitudes were measured. It is seen that the resonance frequency value decreases with increase in vibration magnitude. Hence, the frequency shift is quite obvious in the postures that are back held. Thus the upper part of the body under high magnitudes of vertical vibrations presents more relaxing tendency when held against a back support. The STHT transmissibilty also revealed that the resonance frequency (primary) decreases by nearly 1 Hz from the erect posture to inclined posture for 1.2 m/sec^2 r.m.s vibration magnitude.

CHAPTER 5

ANALYSIS OF HUMAN COMFORT USING FINITE ELEMENT METHOD

5.1 INTRODUCTION

Finite element method (FEM) is the discretization technique and will be capable of implementing it to engineering models, biomechanical models and also any practical problem with complex geometry and loading. In the past, Nigam and Malik, (1987) computed the mass and stiffness values for elements of a 15 DOF lumped parameter model and analytically computed the natural frequencies. From the time, there was a large gap in the area of the whole body human vibration biomechanical study models being designed as continuous models and analyzed the whole human body as a continuous system using finite element computational approach. Hence, the present work of the chapter from 5.1-5.2.5 aims to develop a continuum – 3 Dimensional biomechanical model of the human body in standing posture with truncated ellipsoidal shaped body segments and analyze its mode shape characteristics using finite element method (FEM). The principal resonance frequency obtained computationally is compared with experimental and other FEA results from past literatures. The 3–Dimensional FEM model is proved very effective to study continuous system represented by human body geometry with a discretization of elements and to make changes in parameters, conditions with lesser time and it also reduces the cost of experimentation with its simulation capabilities to analyze the model. The iterations and optimization can be made to make changes in the model.

5.2 MODAL ANALYSIS OF HUMAN BODY

The aspiration of performing modal analysis in whole body human vibrations is mainly to find out the natural mode shapes and frequencies of a human during free vibration. In general the use of finite element method (FEM) for modal analysis gives better arbitrary shape and the results are conventional in nature. The forms of equations which result from modal analysis are those seen in Eigen systems. In many studies from the past using modal analysis it has been proved that the better result modes are the first few frequencies because they can be the most prominent modes at which the object will vibrate, governing all the high frequency modes.

In general conception a 3-Dimensional continuous finite element structure can give limitless vibration modes. But, the main interest deals with the low order vibration modes which gives better and nearby results to the vibration injury frequencies found under the range of whole body human vibration in (0-80 Hz). Li-Xin et al., (2011) employed finite element and developed 3D model of spine (T12-Pelvis) to obtain frequencies representing resonance and mode shapes of spines in human under the three low order vibration modes resonant frequencies. The excitation of T12-Pelvis in all the order of frequencies were found to be as follows. In the first mode the T12-Pelvis excited resonant frequencies found using finite element models in lateral view and back view, first order resonant frequencies found in the second mode excited in the flexion extension direction, Second order resonant frequencies found in third mode excited in the lateral bending direction. Third order resonant frequencies found in the fourth mode in the vertical excitation direction.

Since, the geometrical configuration, mass distribution, and material property are vitally important and plays a significant role in obtaining and understanding the structural or segment resonant frequencies, Li-Xin et al., (2011) also focused on the assignment of properties before performing the modal analysis using finite element method. For all these parts the adaptation of material properties like Young's modulus and Poisson's ratio had been made on the complexity of geometry, mass of different age, gender and tissue degeneration alongside in vivo.

Kumaresan et al., (1999) developed an FE model of human spine and defined the material properties for T12-S1 part of the spine. A similar work by the author carried definition of material properties of ligaments and annulus fibers. The human spine consist of the following parts: cortical bone, cancellous bone, posterior element, end plate, nucleus pulpous, annulus ground substance, annulus fibers. For all these parts the adaptation of material properties like Young's modulus and Poisson's ratio had been made on the complexity of geometry, mass of different age, gender and tissue degeneration alongside in vivo. Since the upper body mass is very significant in understanding the physiognomies of vibration frequency an additional lumped mass of 40 kg is laid above the T12 part. The results determined the vertical resonant frequencies to be 25.7 and 26.7 Hz in one motion segment due to resonance in finite element models (L2-L3 and T12-L1) with the addition of 40 kg. For two segments (L3-L5) the frequency was 19.6 Hz and at the same time the vertical frequencies of (L1-S1) and (L1-L5) with a lumped mass of 40 kg were identified as 9.12 Hz and 11.5 Hz. The material property of the finite element models of the human spine as defined by Kumaresan et al. (1999) and Li-Xin et. al. (2011) are arranged in Table 5.1 for complete understanding.

Table 5.1 - The material property of the finite element models of the human spine (Li-Xin et al., 2011).

Youngs modulus / Poisson's Ratio		
Spinal components	**Kumaresan et al., (1995)**	**Li-Xin et al., (2011)**
Cortical bone	10000/0.29	10000/0.3
Cancellous bone,	100/0.29	100/0.2
Posterior element,	3500/0.29	3500/0.25
End plate,	500/0.4	500/0.25
Nucleus pulpous,	3.4/0.49	1/0.499
Annulus ground substance	3.4/0.49	4.2/0.45
Annulus fibers.		500

The above results were found in confirmance to the literature. The frequency response analysis was also made on the T12, L2, and L4 parts of the vertebrae and the vibration amplitude was studied in vertical direction within the frequency range of 5 Hz to 9 Hz. Results indicate variation in amplitudes of vibration at various locations for given vertebra because of vertebrae rotation when the segment is excited in a vertical vibration. The third order resonant frequency obtained in the same vertical direction was found at 7.21 Hz. The entire study on the human spine by Li-Xin et al., (2011) made a huge contribution in developing the principal course of action for treatment in clinics and design of product and their development in the industry.

The lower vibration modes up to third order resonant frequencies and the amplitude of vibration in vertical direction for T12,L2 and L4 as shown in Figs. 5.1 -5.5

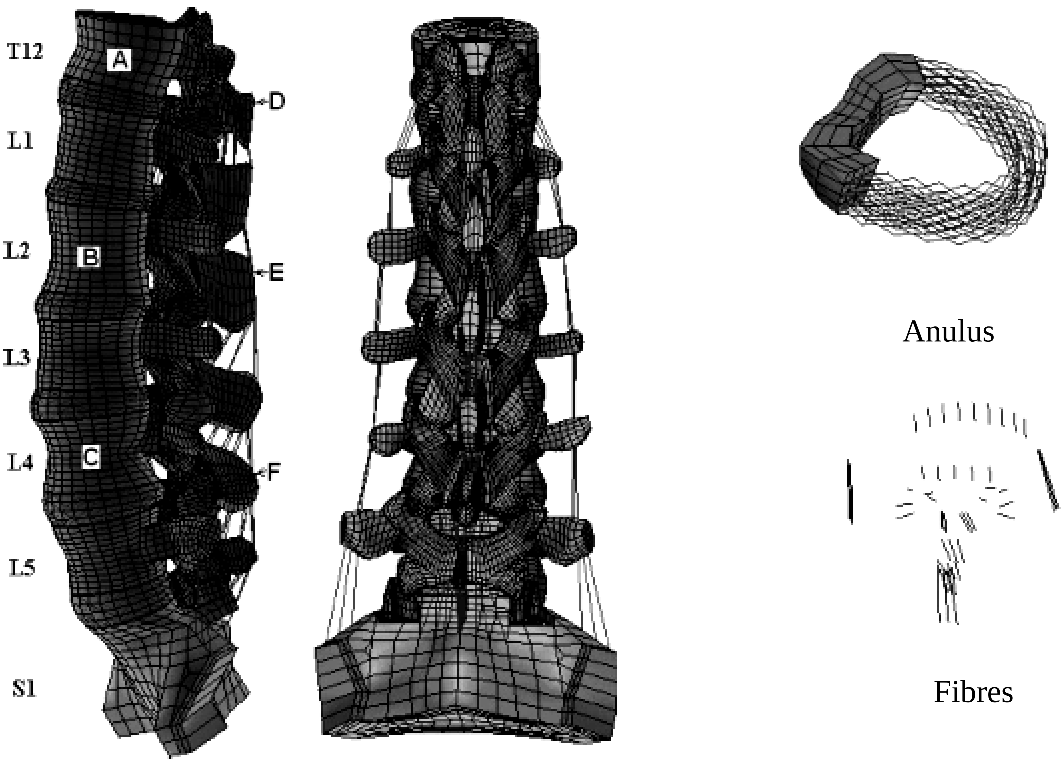


Fig. 5.1 – Lateral and back view of T-12 pelvis spine segment using finite element approach (Li-Xin et al., 2011)

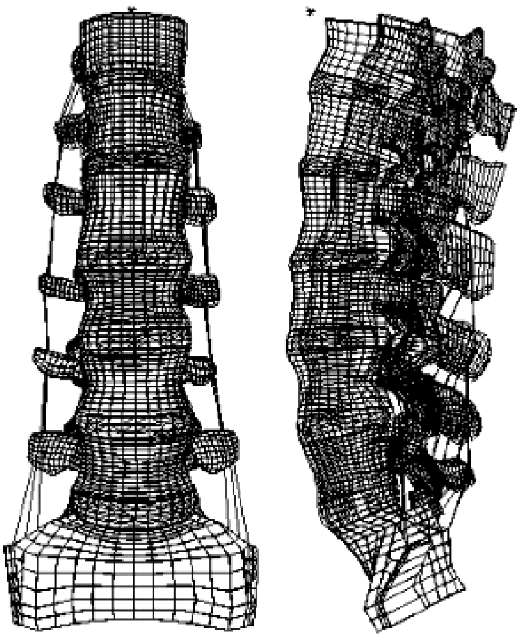


Fig. 5.2 – T12 –Pelvis (FEmodel) showing 1st order mode of vibration in the flexion extension direction. (Li-Xin et.al., 2011).

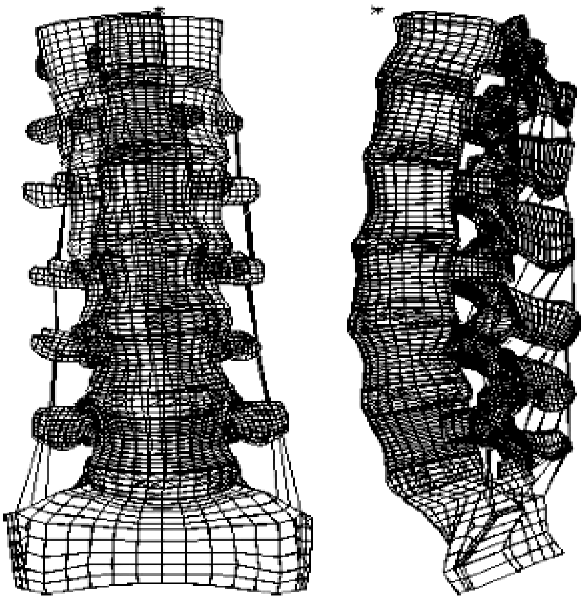


Fig. 5.3 – T12 –Pelvis (FE model) 2^{nd} order mode of vibration for lateral direction (Li- Xin et al., 2011).

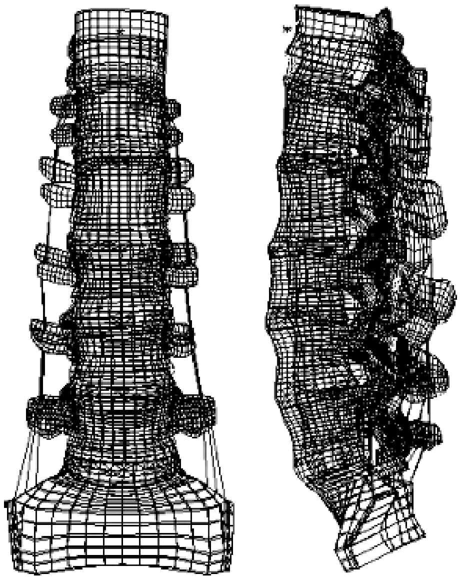


Fig. 5.4 –T12 Pelvis (FE model) showing 3^{rd} order mode of vibration for vertical direction (Li-Xin et al., 2011)

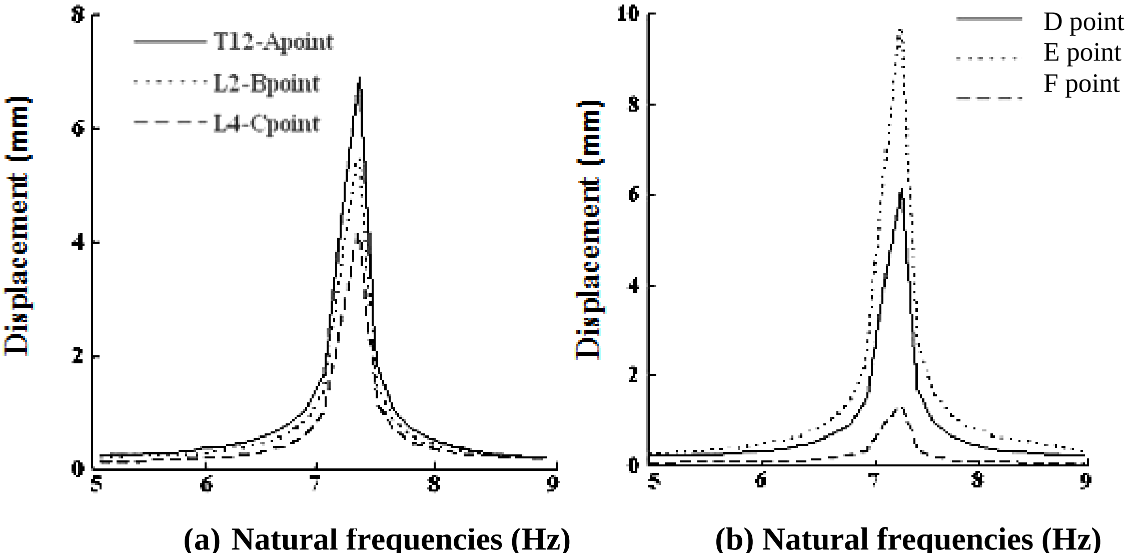


Fig. 5.5 - Frequency response results of T12-Pelvis FE model in the vertical direction.
(a) For A–C points. (b) For D–F points from Fig. 5.1
(Li-Xin et al., 2011).

5.2.1 Construction of 3-dimensional geometry using ellipsoids

From the research studies on the effect of shock and vibration Henning et al., (1971) as reported “The shape of a solid body having an effect on the surface of the human is as significant as the position or shape of the human body itself in establishing the causes for discomfort created by vibration. “The geometric models of the human body take part an important role in analyzing the human response to the vibration platform in industries, vehicles and also in product design, allowing industrial products such as cars, furniture and clothing to be custom-designed for an individual’s body shape” reported by Bischoff and Kobbelt, (2002).

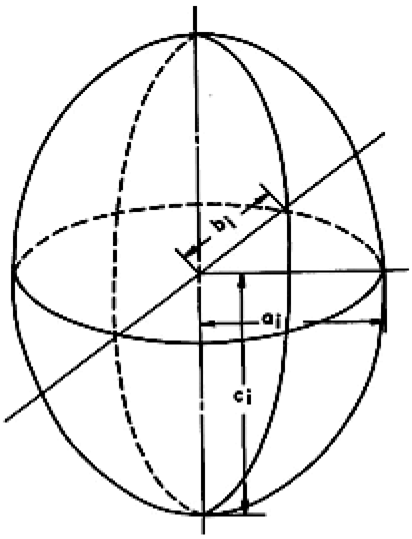


Fig 5.6 - 3 Dimensional Ellipsoidal body segment.

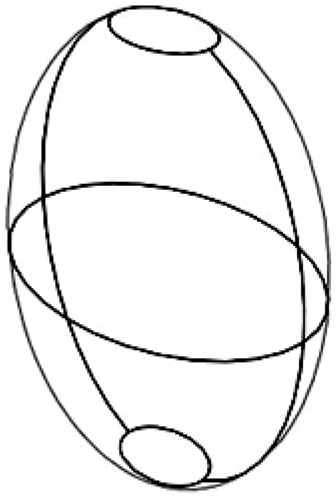


Fig 5.7 5% 3-Dimensional truncated ellipsoidal bodysegment.

The present model is constructed in 3D geometry based on Nigam and Malik, (1987). These solid ellipsoidal models define the volume of the object they represent, and hence density of each part is being calculated. Bartz and Gianotti, (1975) suggested that the human body in reality is not a homogeneous mass, the bulk (average) densities of different body segments are nearly the same. Considering these observations the present standing posture model in 3-Dimension is developed with five percent truncated ellipsoidal segments using anthropometric data and mass, stiffness values of these segments are considered from Nigam and Malik, (1987). The Young's modulus (E) has been considered from Nigam and Malik, (1987) using elastic moduli of bones and tissues. The geometric truncated ellipsoidal body shapes are shown in Fig 5.7. In the early days a digital computer program has been established to calculate dimensional and inertial properties of the human body segments from Bartz and Gianotti, (1975). The computed body dimensions from the previous studies were utilized to construct 3 –dimensional geometry and analyzed using finite element method for modal responses like natural frequencies and deflections in different modes on each individual body segments.

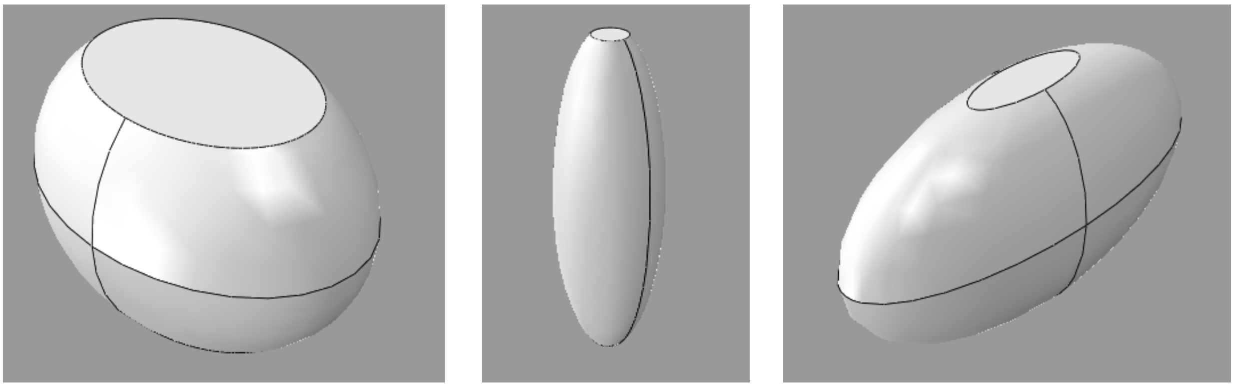
Table 5.2 - Dimensional values of each individual body segments (Nigam and Malik, 1987).

Part numbers	**Human body part names**	**a_i (cm)**	**b_i (cm)**	**c_i (cm)**
1	Head	7.785	7.785	9.931
2	Neck	6.02	6.02	1.13
3	Upper torso	16.45	11.66	9.385

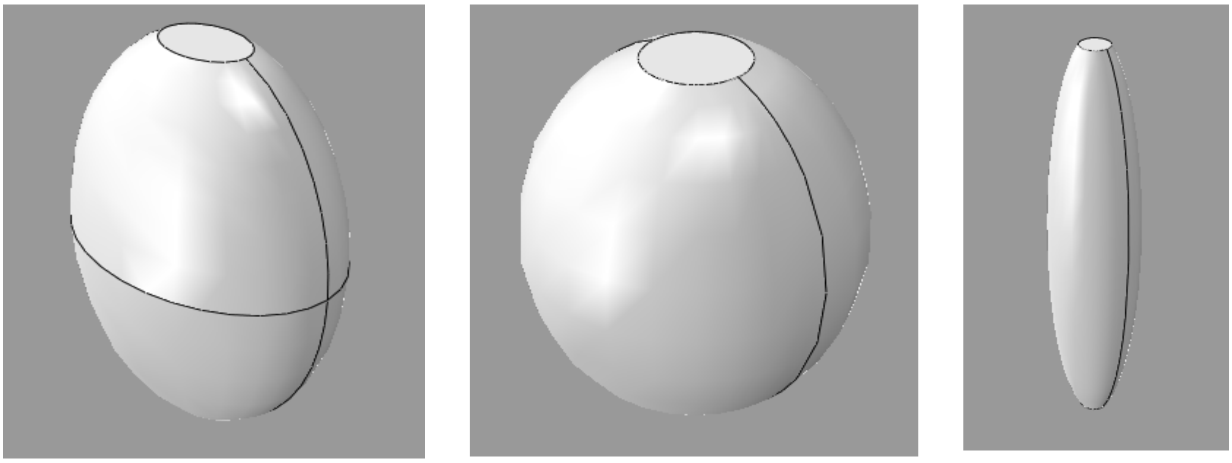
4	Right upper arm	5.239	5.239	18.77
5	Right lower arm	4.629	4.629	24.33
6	Central torso	14.11	10.76	21.55
7	Lower torso	17.72	11.6	12.11
8	Right upper leg	5.926	5.926	27.93
9	Right lower leg	5.304	5.304	23.11
10	Right foot	4.674	12.7	6.909

Table 5.3 - Mass and density values of 3-dimensional body segments (Present FE model).

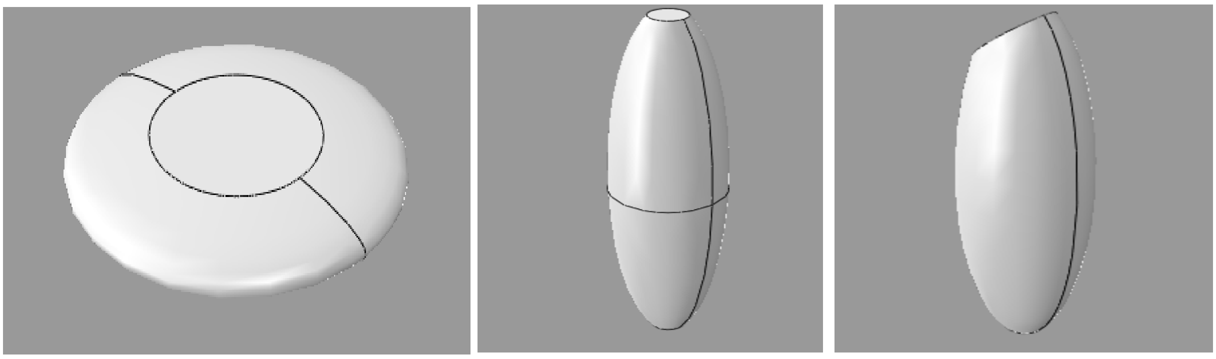
Part numbers	**Human body part names**	**Mass (kg)**	**Density (kg/m^3)**
1	Head	3.044	1271.576
2	Neck	0.207	1270.887
3	Upper torso	9.105	1271.713
4, 5	Right upper arm, Left upper arm	2.322	1133.207
6, 7	Right lower arm, Left lower arm	1.91	921.1384
8	Central torso	16.55	1271.802
9	Lower torso	12.59	1271.651
10, 11	Right upper leg, Left upper leg	7.827	2006.361
12, 13	Right lower leg, Left lower leg	3.445	1332.264
14, 15	Right foot, Left foot	1.198	734.4415



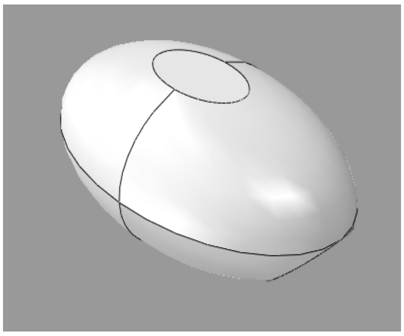
Lower torso Lower arm Foot



Central torso Head Lower leg



Neck Upper leg Upper arm



Upper torso

Fig 5.8 - 3 Dimensional human body segments with 5% truncated ellipsoid.

5.2.2 Normal standing posture human body free vibration analysis using finite element method

The previous studies using finite element method on standing postures to analyze mode shapes and deflections as being carried on some parts of specific body segments. Hence, in the present work a continuum – 3 dimensional biomechanical model of the human body in standing posture with truncated ellipsoidal shaped body segments was developed and analyzed its mode shape characteristics using finite element method (FEM) using its applications with the finite element analysis software (ABAQUS 6.10) . The main focus of the work was to find natural frequencies for WBV, mode shapes and its deflections from the starting mode to the final mode.

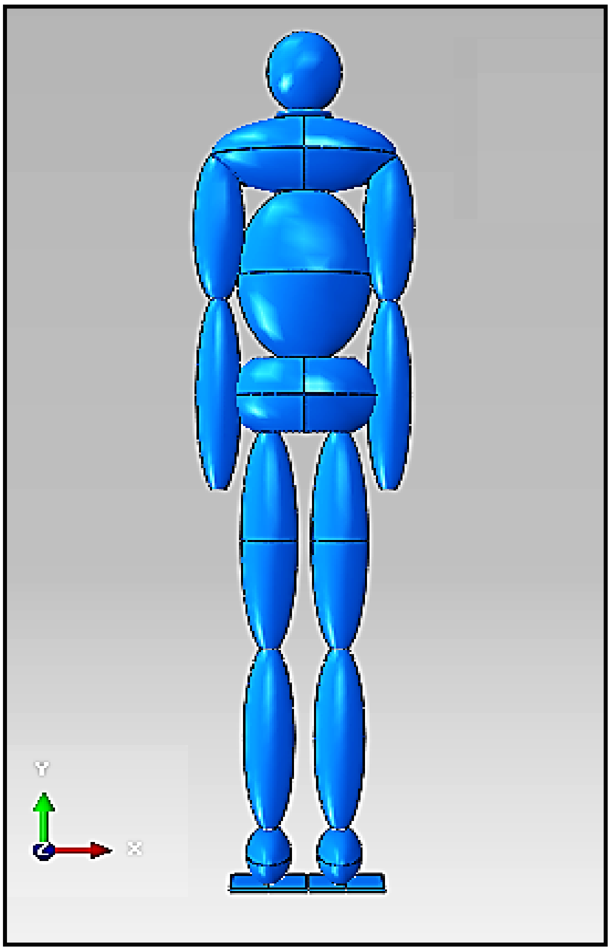


Fig. 5.9 - Normal standing posture human body (Present FE model)

5.2.3 Element type and meshing

Fig 5.10 shows the quadratic tetrahedron element and Fig. 5.11(a) show that the quadratic tetrahedral elements are not as sensitive to mesh density as C3D20R element (Fig. 5.11(b)). Hence, require far fewer elements to converge to a solution. Quadratic tetrahedral of 0.25 edge length from both systems predicted results extremely close to that of the C3D20R element.

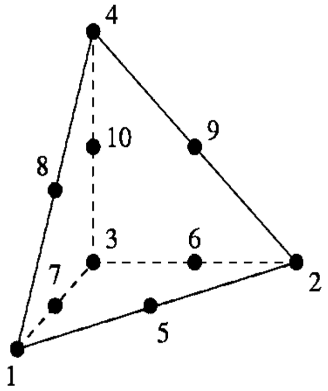


Fig 5.10 - C3D10 quadratic tetrahedron element

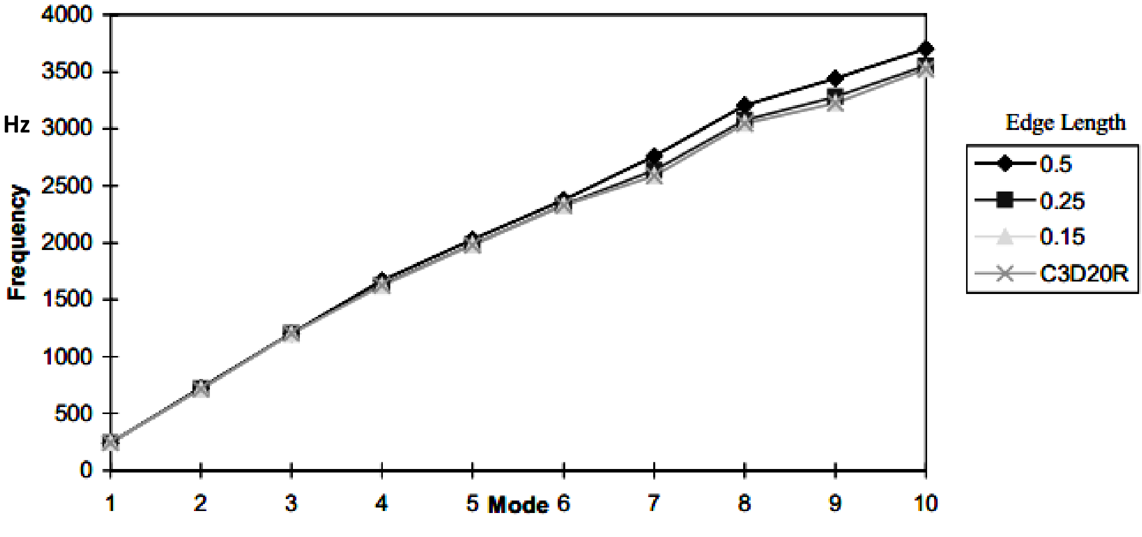


Fig 5.11 - (a) Effect of mesh density C3D10 quadratic tetrahedron element

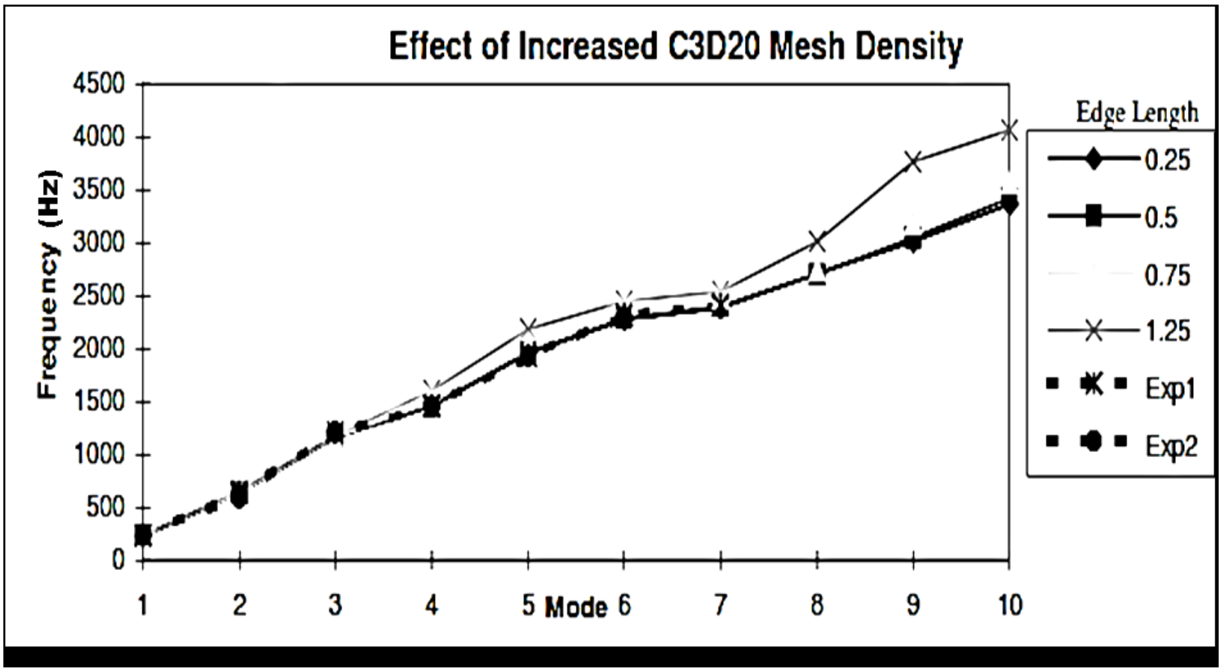


Fig 5.11(b) Effect of mesh density C3D20 quadratic hexahedron element

The C3D10 element is a general purpose tetrahedral element. The element performs very well and is a good all purpose element, although the C3D20R element yields still better results for the same number of degrees of freedom. The C3D10 element is mainly attractive because of the existence of fully automatic tetrahedral meshes. The quadratic C3D10 tetrahedron element used with free meshing and is specifically used. The geometry with ellipsoidal shape is used to construct the human body. Fine meshing is carried with an aspect ratio of 0.05. The total number of elements and total number of nodes in the assembly of the normal standing human body using finite element analysis (ABAQUS 6.10) are 84,074 and 1,33,908 respectively.

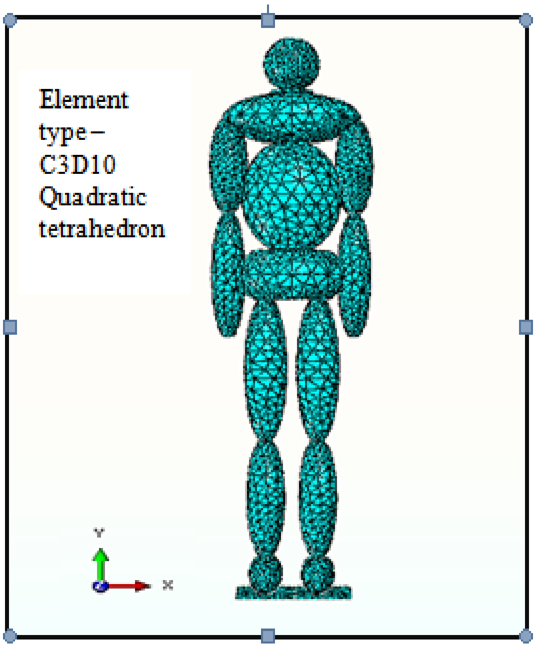
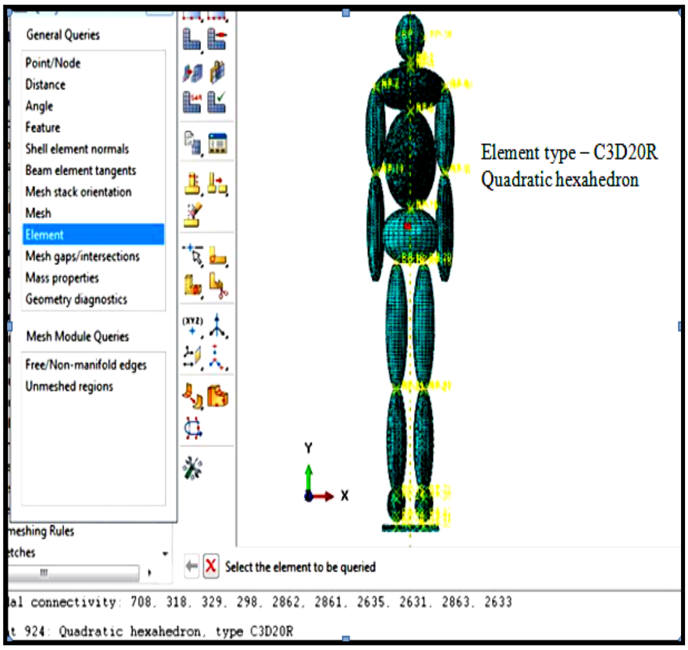


Fig 5.12 Quadratic C3D10 tetrahedron mesh.



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al connectivity: 708. 318. 329. 298. 2862. 2861. 2635. 2631. 2863. 2633
t 924: Quadratic hexahedron, type C3D20R
```

Fig 5.13 C3D20R Quadratic hexahedron mesh

Table 5.4 C3D10 Element type, number of nodes, meshing seed size, number of elements

Part Nos.	Human body part names	Number of elements	Number of nodes
1	Head	5287	8573
2	Neck	11653	18150
3	Upper torso	20869	31436
4, 5	Right upper arm, Left upper arm	7634	12331
6, 7	Right lower arm, Left lower arm	3681	6239
8	Central torso	1794	2872
9	Lower torso	10733	16409
10, 11	Right upper leg, Left upper leg	992	1755
12, 13	Right lower leg, Left lower leg	3801	6414
14, 15	Right foot, Left foot	675	1261
16	Floor	172	468

5.2.4 Mode shapes and displacements

Modal analysis is the most fundamental analysis of all other dynamic analysis and its obtained mode shapes from the finite element analysis participates its contribution in prescribed direction of excitation. The modal analysis is carried by ABAQUS 6.10 for the present finite element model, the modes were extracted with frontal solver using subspace method. This method uses large disk space and relatively less memory compared to the ‘Block Lanczos method’ in ABAQUS 6.10 with superseded size elements. For the ellipsoidal shaped human body assembly, considering the complexity of geometry in assigning regular pattern mesh size, this subspace method used effectively to obtain accurate results. Damping property is generally ignored in modal analysis. The procedure adopted is this analysis was firstly developed the finite element model with the accurate assignment of the density property of the body segments and material is assumed linear and non linearity was ignored by applications of boundary conditions, analysis type and finally the number of nodes required was extracted from mode extraction step and analyzed in time domain and frequency domains.

The human vibration effects are mainly considered from 0 – 80 Hz and there was a very little information on the effects of exposure to WBV above 80 Hz. Since the whole body vibrations (WBV) mainly concerns with low frequency in the range 0 – 80 Hz. But the model proposed by Rasmussen, (1983) showed that a general feeling of discomfort mainly lies in the range of 4 – 9 Hz. Hence, the frequencies above 10 Hz, are not considered by Rasmussen.

In the present research on normal posture standing man the natural frequencies were obtained using finite element (FE) models. The modes were extracted from the analysis and compared with the finite element models developed by Li-Xin et al., (2011), Kitazaki et al., (1997) and Alphin et al., (2011). The main importance has been given to principal resonance frequency, body segment displacements and natural frequencies of different modes and the principal resonant frequency was found to be 6.45 Hz in which all the body segments have axial deformation and relative displacement of body segments. When the foot was strapped to the ground it showed perfect resemblance with the Nigam and Malik, (1987) model for higher stiffness values. It is also observed that the stiffness of the foot to the ground should be very high for the resonance frequency to be in the range of 4 – 6.5 Hz. The second resonance mode is identified at a frequency of 13. 82 Hz as compared to a value of 23.97 Hz by Nigam and Malik, (1987).

In the present model, the maximum deformation of the body is in the lower leg with 2.71 mm displacement and minimum with 1.11 mm in the upper arm. For the frequency of 6.45 Hz the lower arm is having a displacement of 1.21 mm and the respective modes vary with the natural frequencies and relative displacements as shown in (Table 5.5). Even though the finite element (FE) model results slightly varies in comparison to analytic results, some resonances of (FE) model matches with the head resonance that lies in the range from 40 - 50 Hz. The spinal column frequencies lies in the range of 10 -12 Hz for a standing person as proposed by Griffin, (1990). The experimental results, analytic results and finite element results from the literature clearly shows the fundamental resonance frequencies lies from 4 – 6 Hz and the most significant range of frequencies to measure the response of vibrations in the human body lies from 4 -16 Hz as proposed by Herterich and Schnauber, (1992).

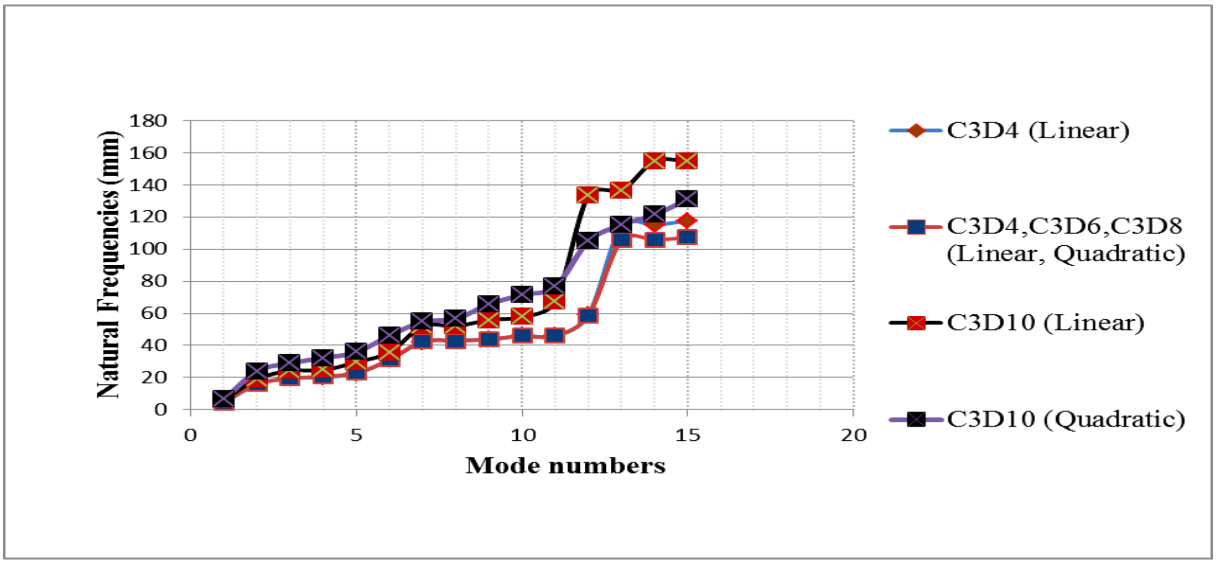
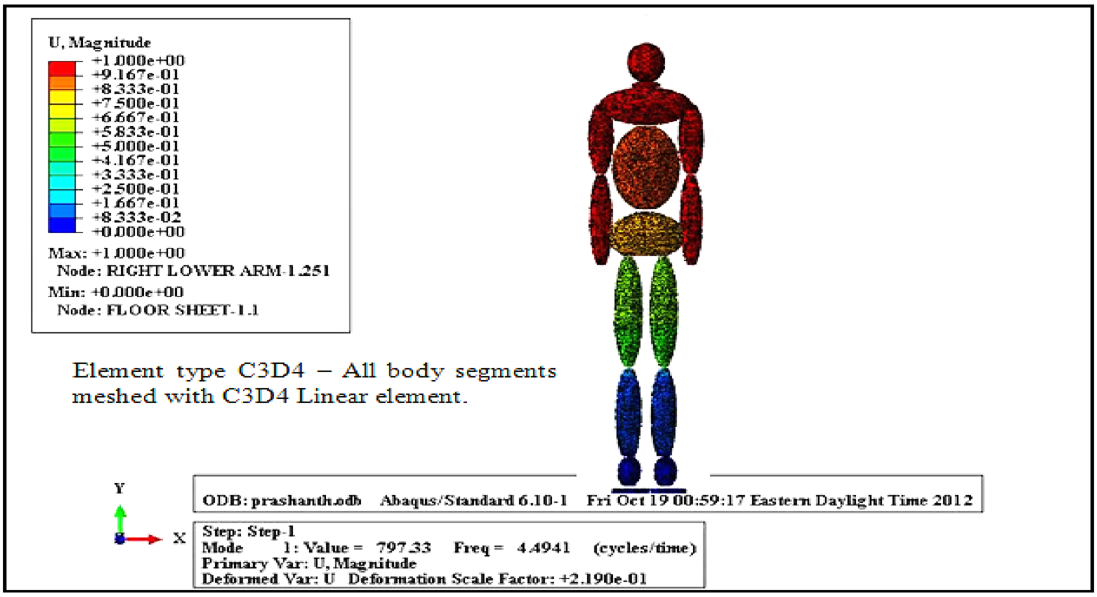


Fig 5.14 - Comparisons of natural frequencies for different element types.



Element type C3D4 – All body segments meshed with C3D4 Linear element.

Fig 5.15 (a) - C3D4 Linear element

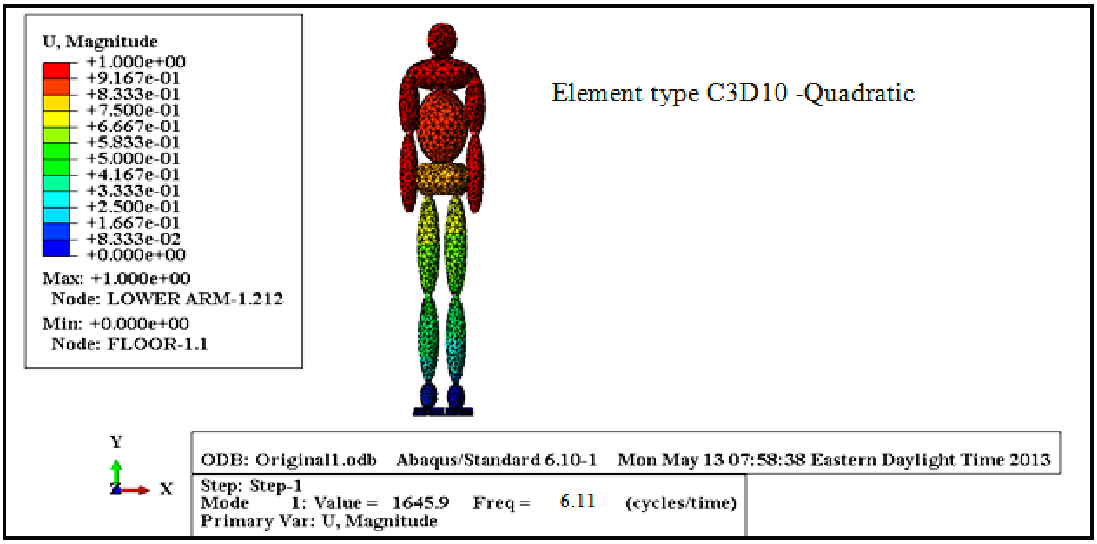


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Fig 5.15 (b) - C3D10 Quadratic element

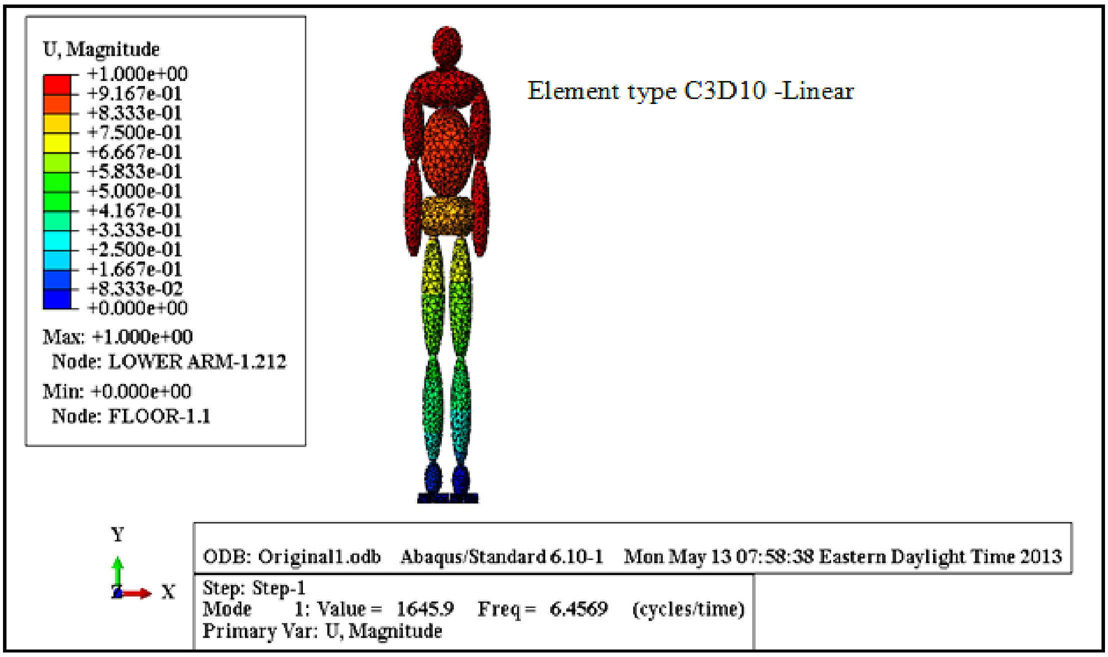

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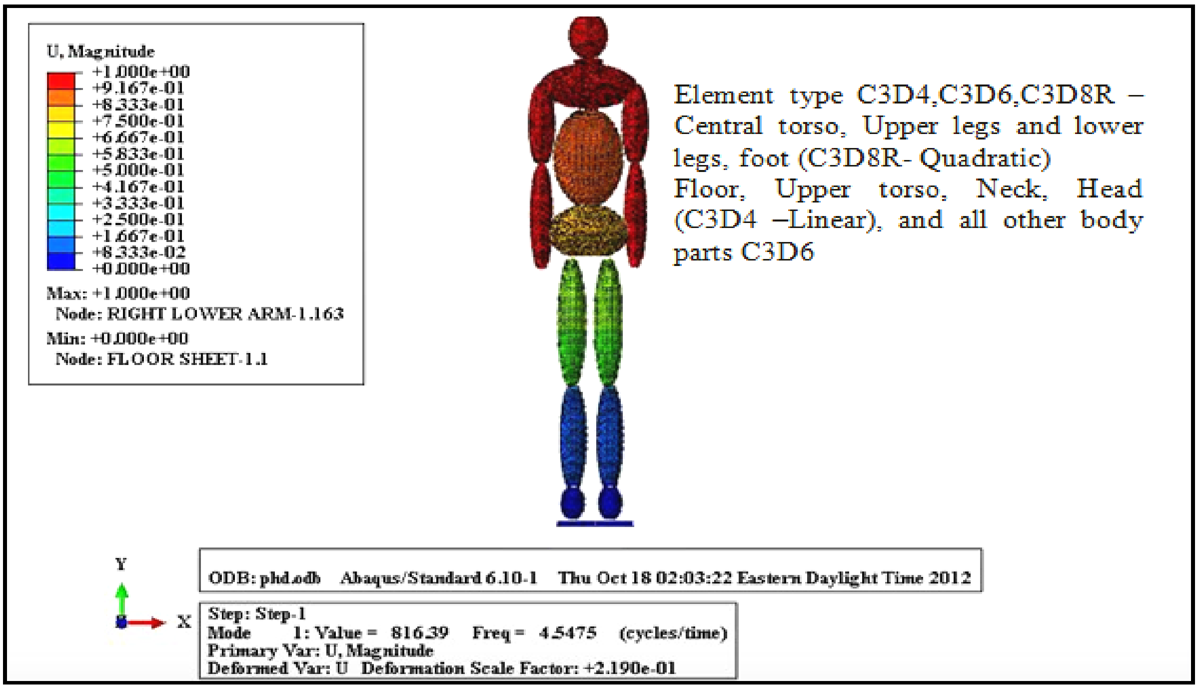
Fig 5.15 (c) - C3D10 Linear element



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 Node: FLOOR SHEET-1.1
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Element type C3D4,C3D6,C3D8R – Central torso, Upper legs and lower legs, foot (C3D8R- Quadratic) Floor, Upper torso, Neck, Head (C3D4 –Linear), and all other body parts C3D6

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Deformed Var: U   Deformation Scale Factor: +2.190e-01
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Fig 5.15 (d) - C3D4, C3D6,C3D8R elements

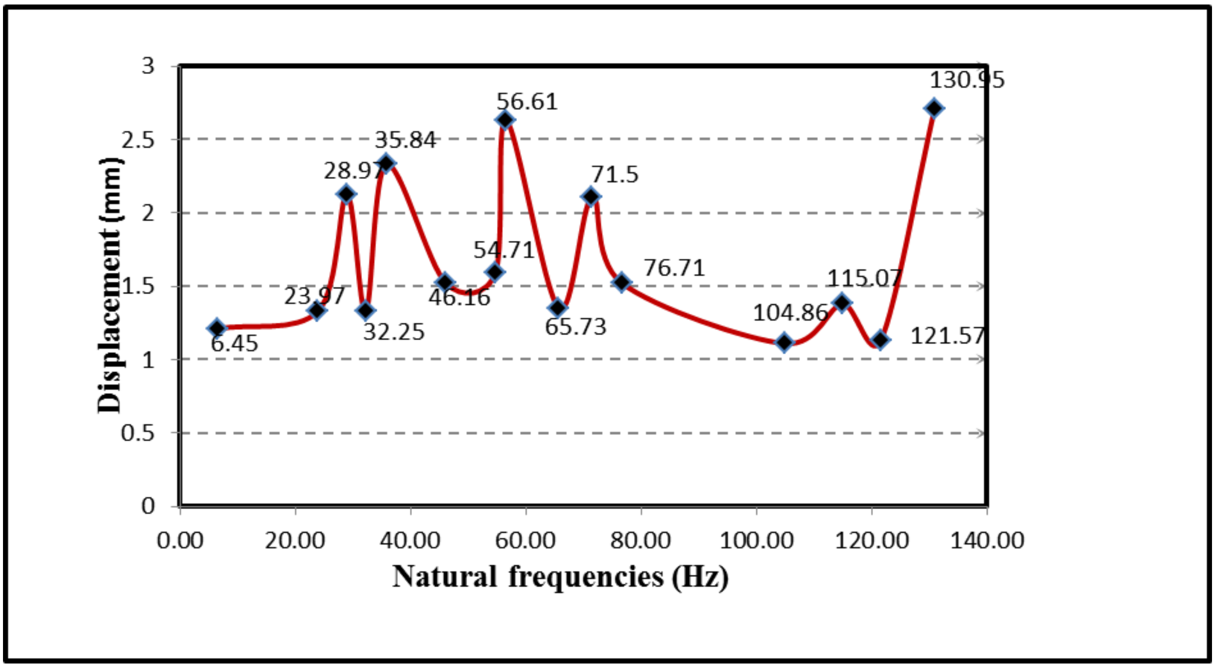


Fig 5.16 - Displacement values with respect to first 15 modes (Present FE model)

Table 5.5 - Natural frequencies and respective displacement values for body segments (Present FE model).

Mode numbers	Human body parts	Natural frequency (Hz)	Displacement (mm)
1	Lower arm	6.45	1.21
2	Lower arm	23.97	1.33
3	Upper leg	28.97	2.12
4	Lower arm	32.25	1.33
5	Lower arm	35.84	2.33
6	Head	46.16	1.52
7	Lower leg	54.71	1.59
8	Lower leg	56.61	2.63
9	Head	65.73	1.35
10	Upper arm	71.50	2.11
11	Upper arm	76.71	1.52
12	Upper arm	104.86	1.11
13	Foot	115.07	1.38
14	Lower torso	121.57	1.13
15	Upper leg	130.95	2.71

5.2.5 Results and discussion

The validity of the present aimed modeling may be satisfactorily evaluated on the basis of a comparison of the frequency values and displacement values for the modal response results obtained from Li-Xin et .al., (2011), Kitazaki and Griffin, (1997), Alphin and Sankaranarayanasamy, (2011).

Based on model of Kitazaki et al., (1997), the cross section of human vertebra and the human trunk –neck–head FE model above the pelvis was developed by Alphin and Sankaranarayanasamy, (2011) for the analysis of modal response and found ten modes with their respective natural frequencies and displacements on their specific segments.

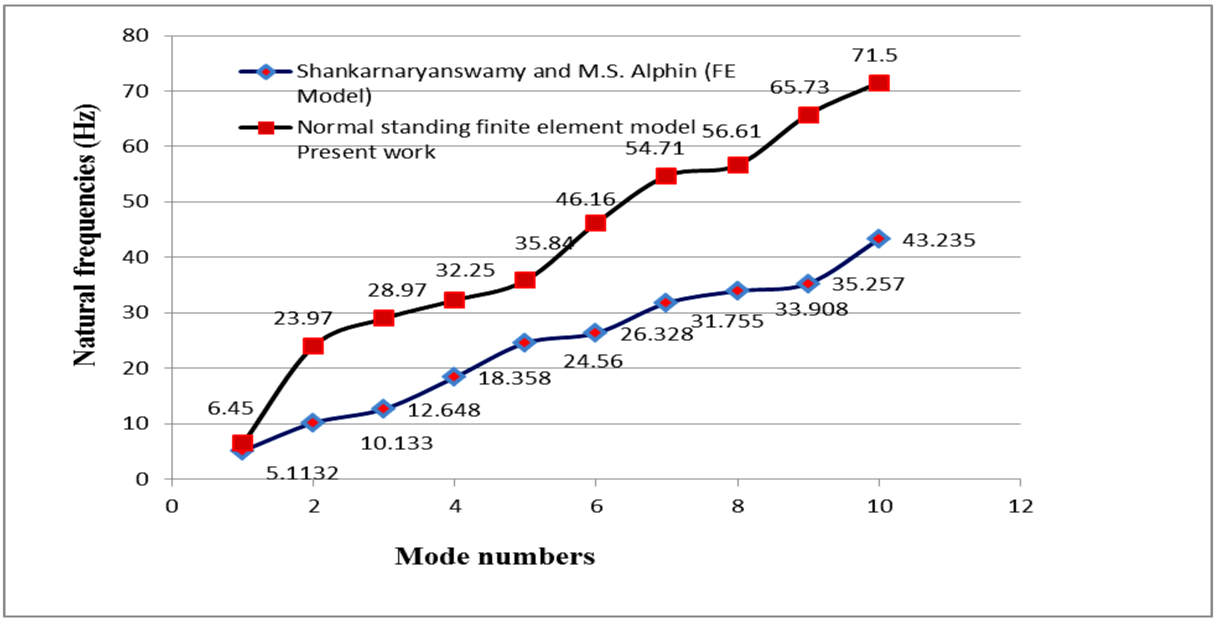


Fig 5.17 - Comparisons of natural frequencies of Alphin, et.al., (2011) with the present model.

Alphin et al., (2011) studied relative displacement of links with constraint of base point. The maximum deflection was observed in the head at 5.113 Hz and the first six modes obtained corresponds to low frequencies below 26.32 Hz. The remaining four modes correspond to deflection of lower body which includes lower lumbar, upper lumbar, lower torso and upper torso. Alphin et al., (2011) studied displacement of the body with respect to the frequency from the analysis on head, upper and lower body and finally results shown that the further increase in frequency increase slight bending whereas, the upper body shows increase in displacement when frequency is low and lower body indicates larger displacement at frequencies above 30 Hz and reported that the deflections witnessed are similar competed to earlier models established in literatures but bending postulated curious observation, when the model was loaded under frequency of 10 Hz by providing deflection of 0.47 mm. Kitazaki et al., (1997) proposed two dimensional distributed parameter model of biomechanical response to vertical whole body vibration and calculated a total of seven modes for a normal body posture below 10 Hz, and the mode shapes of the model coincided with the model results obtained from measurements. The outcome of results on modal analysis has proven and assisted as a good relative instructions for the finite element (FE) methodology in understanding frequencies of human vibration. In comparision to other finite element model studies, the proposed work from Kitazaki et al., (1997) reported shear deformation of tissues. Where as in Li-Xin et al., (2011) case they found the deflection from 5-9 Hz on different segments. The entire body mode was obtained at 5.06 Hz with vertical and fore and aft pelvic motion, second mode at 8.96 Hz and also three postures were studied for principal resonance frequencies in erect, normal and slouched postures and obtained the principal frequencies of 5.25 Hz, 5.06 Hz and 4.53 Hz respectively.

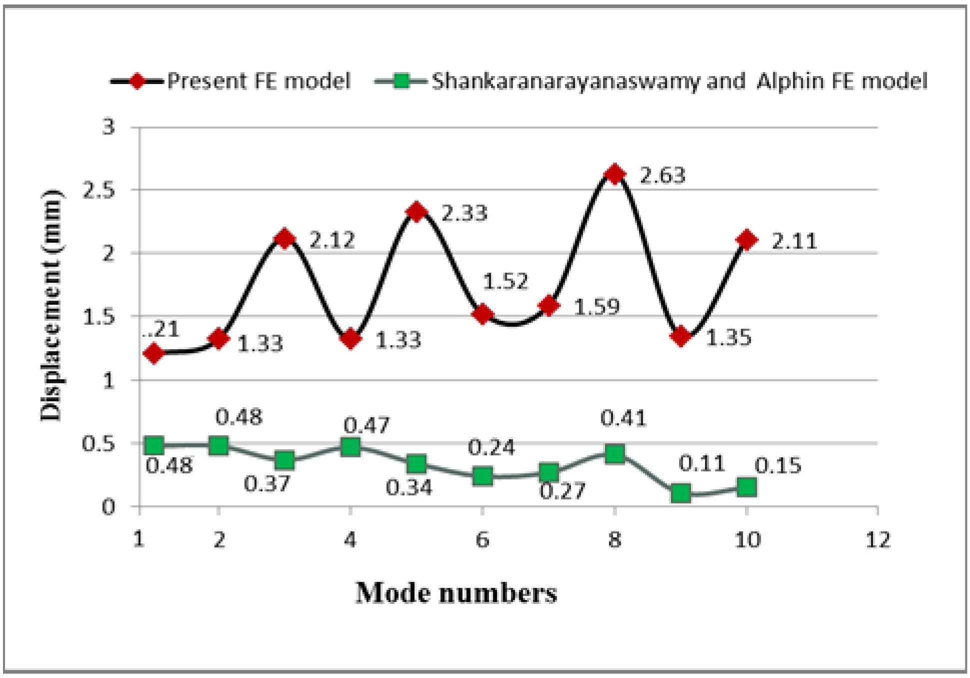


Fig. 5.18 - Displacements comparison of present FE model with other FE model (Shankaranarayanaswamy and M.S Alphin, (2011) FE model)

Fig 5.18 gives the clear comparison of first ten modes of present FE model with Shankaranarayanaswamy and Alphin et al., (2011) FE model. In the Fig. 5.18 first principal resonance of both the model causes a feeling of discomfort and lies in the range of 4 -9 Hz as reported by Rasmussen, (1983).

Nigam and Malik, (1987) found a peak resonance near 12 to 14 Hz for discrete mass segments with mass-spring combination for 15 DOF discrete models without feet strapped to the floor. The natural frequencies obtained with 15 DOF model is compared with FE model and is shown in Fig 5.20. According to the biodynamic response of different human parts resonance peaks, Nigam and Malik, (1987) evaluated the frequency range of 20 -30 Hz head resonance, 40 -50 Hz hand resonance, 60 - 90 Hz eye ball resonance resonance and compared with the experimental values of past literatures. But the main importance of the study is on principal resonance which makes entire body to resonate. In the present FEM models the displacement on increasing frequency increases on the lower parts of the body and above the lower torso the deflection is minimum compared to the deflection on upper leg. The maximum deflection occurs in upper leg with 2.71 mm in the 15th mode with a frequency of

130. 95 Hz. In the second resonance mode at 23.95 Hz the displacement is 1.33 mm. The head resonance occurs at 46.16 Hz with the displacement of 1.52 mm. The corresponding resonance modes occur with the displacement values as shown in Fig. 5.11. Alphin and Sankaranarayanasamy, (2011) observed that deformation decreases with an increasing value of frequency simultaneously with increased bending. The model indicates the minimum deflection for the maximum value of frequency (43.235 Hz). The harmonic analysis give deformed mode shapes which were analyzed for obtaining maximum and minimum displacements of nodes for each frequency.

According to the results obtained by Li-Xin et al., (2011) for the concerned model of the T12-Pelvis, the flexion–extension direction carries the resonant frequency of lowest value whereas the direction for lateral direction carries the resonant frequency of the second order and the vertical direction carries third-order resonant frequency which is 7.21 Hz. The natural frequencies of different spinal segments also analyzed and it is being shown in Fig 5.16. The vibration amplitudes of different points in the same vertebra are different as seen through harmonic response analysis results and the lumbar spinal vertebrae rotates WBV.

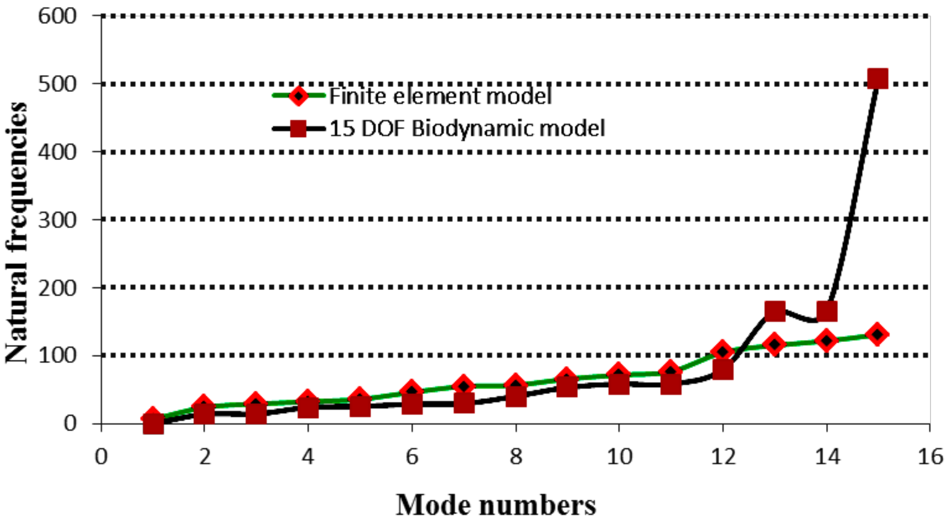
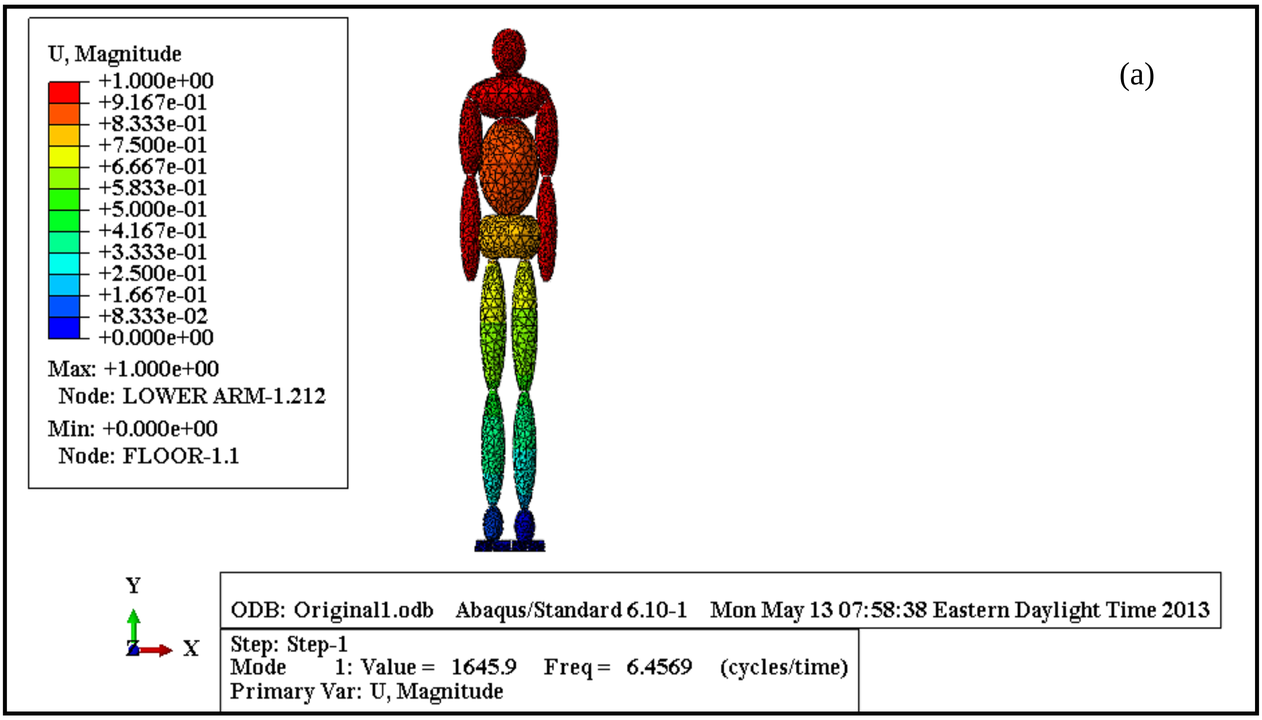


Fig 5.19 - comparisons of natural frequencies (Present FE model v/s Present Biodynamic 15 DOF model)

The mode shapes and deflections extracted from the finite element human body model is shown in below figures with all 15 modes with their resonant frequencies (Fig. 5.20).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+4.167e-01
+3.333e-01
+2.500e-01
+1.667e-01
+8.333e-02
+0.000e+00
Max: +1.000e+00
Node: LOWER ARM-1.212
Min: +0.000e+00
Node: FLOOR-1.1
Y
Z
X
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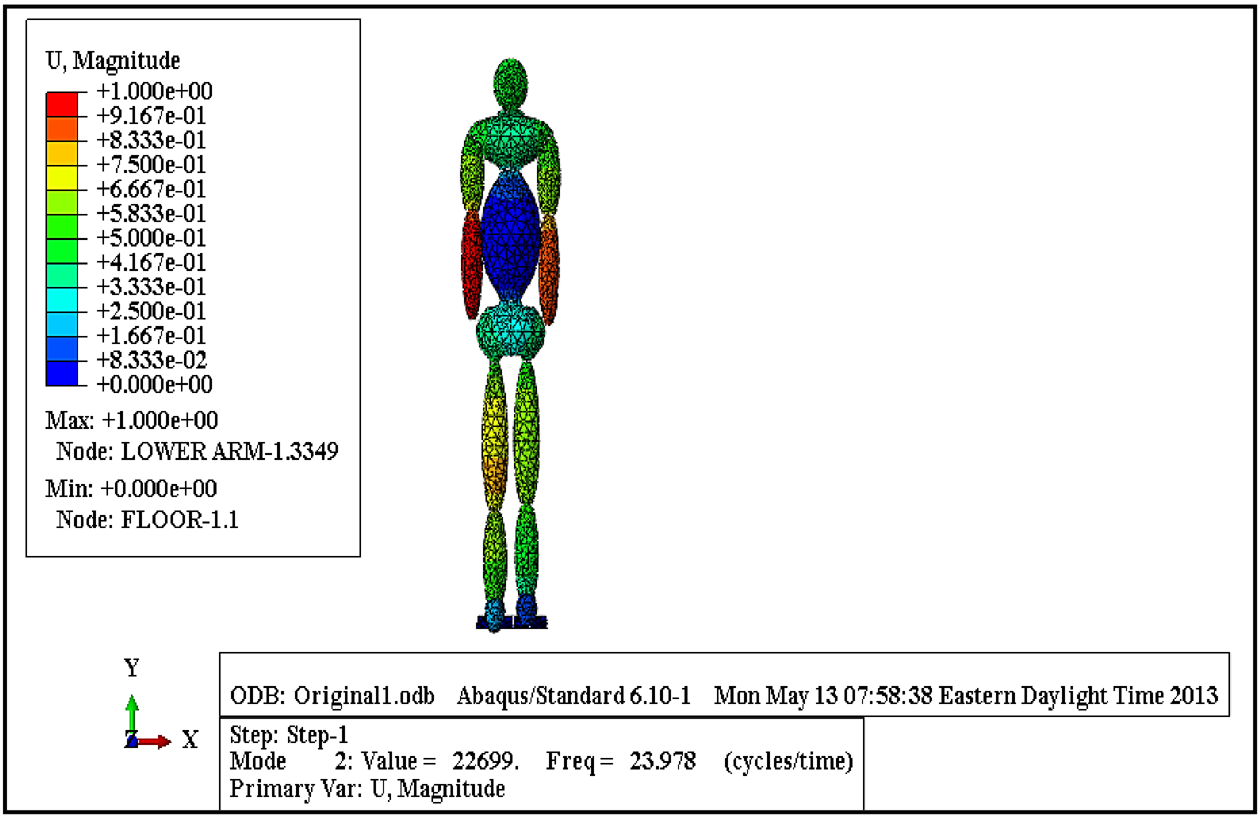
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+8.333e-01
+7.500e-01
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Y
Z
X
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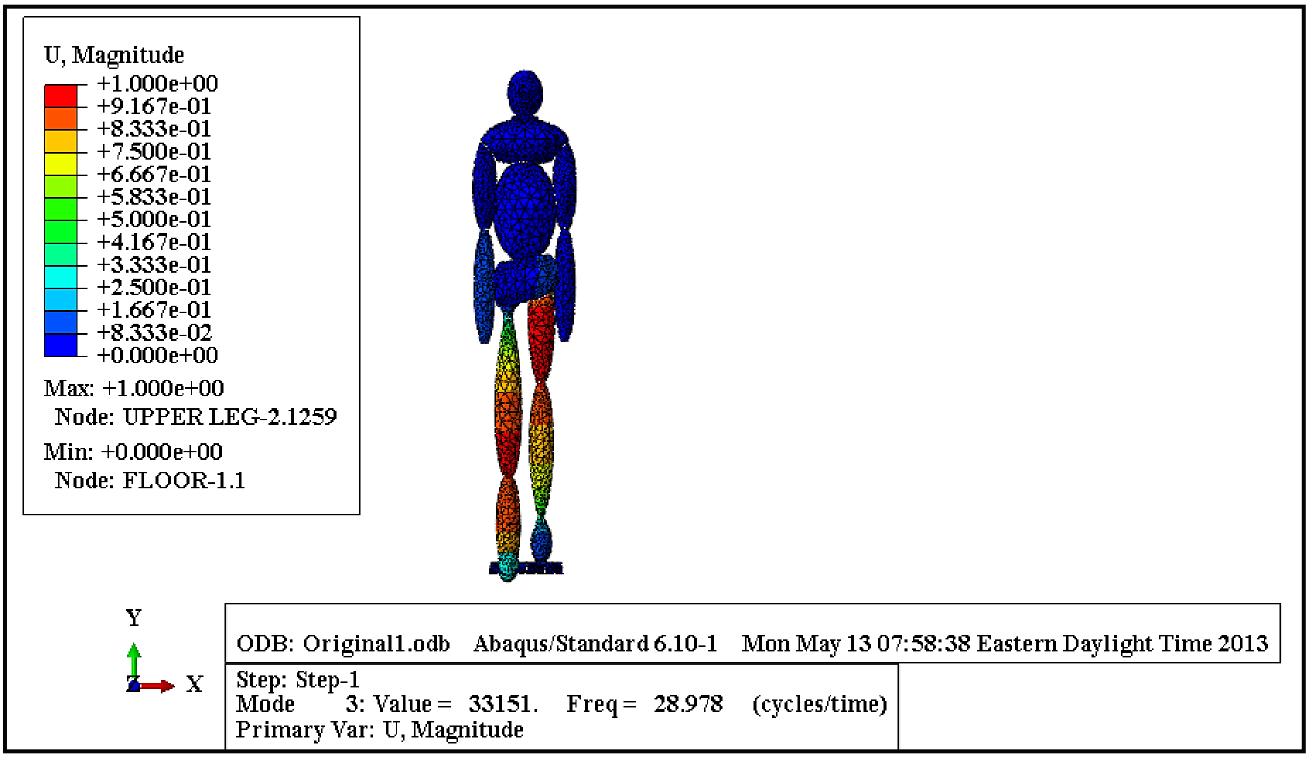

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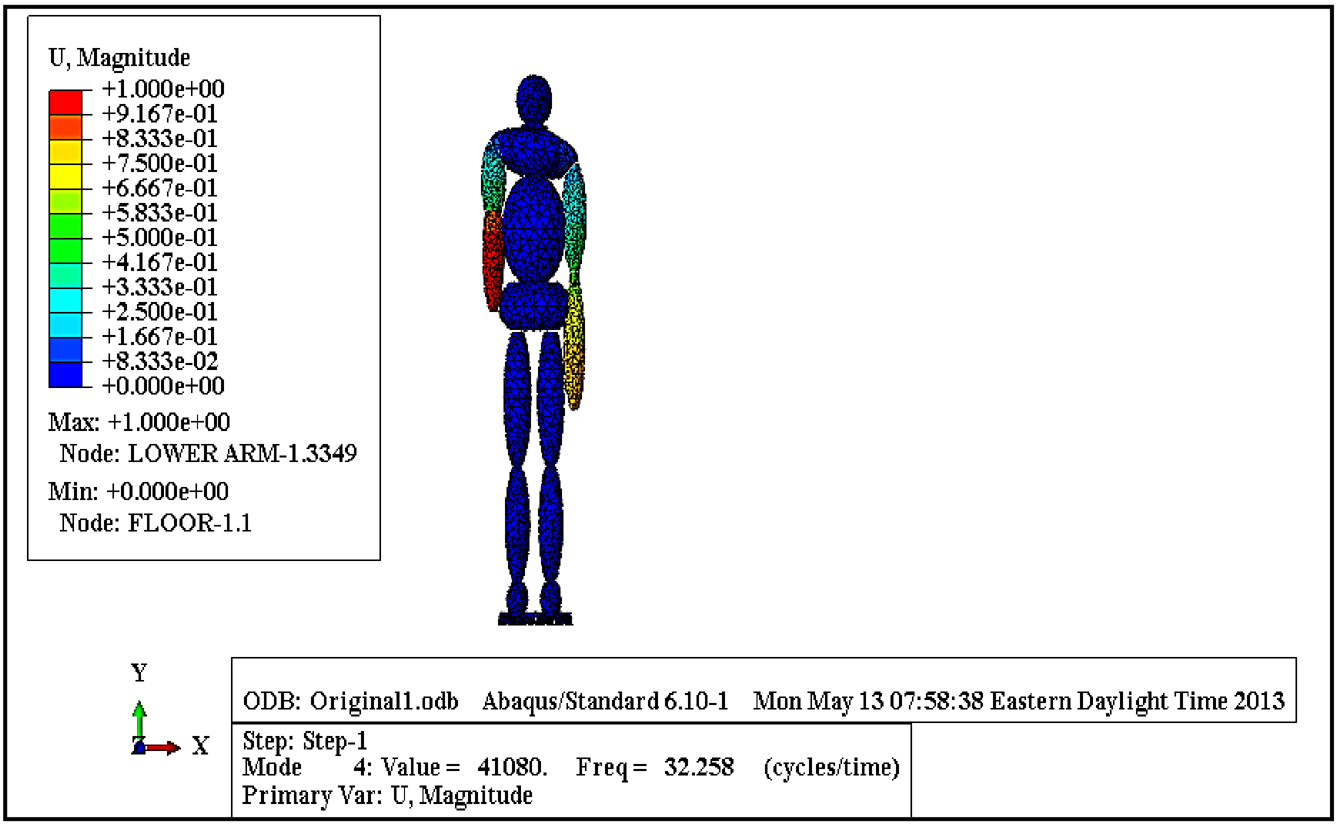

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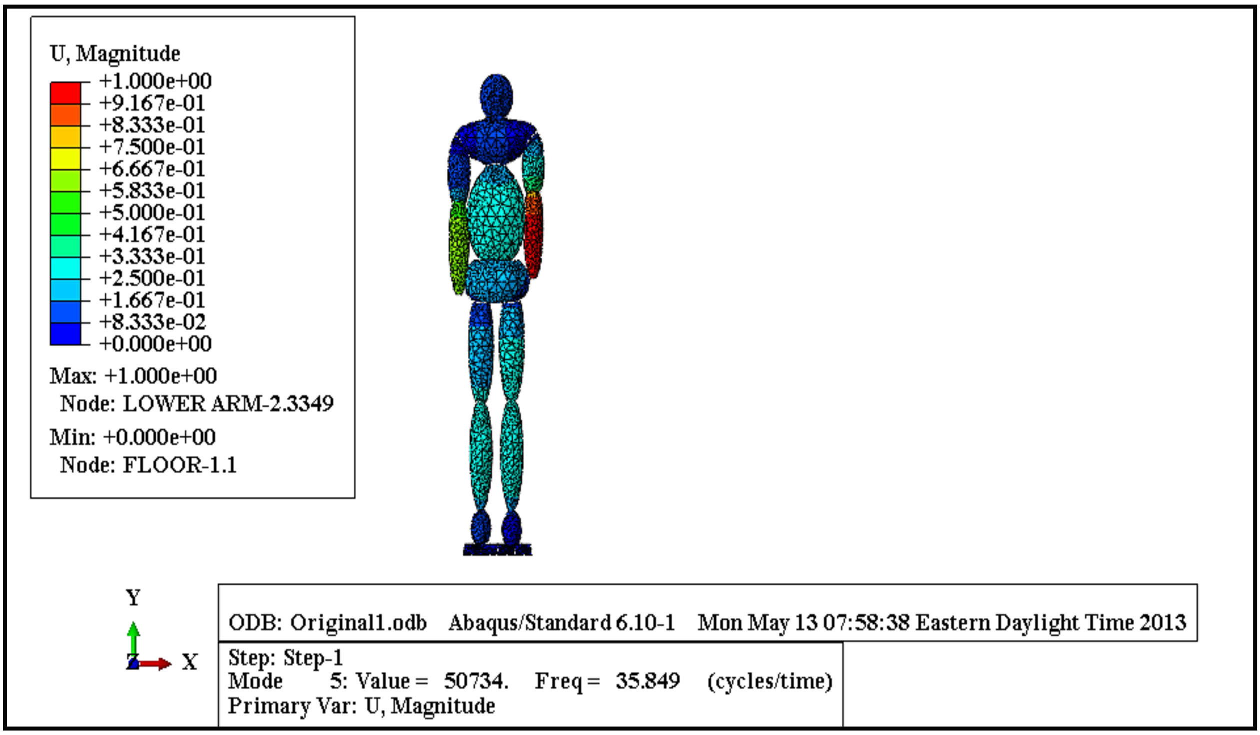

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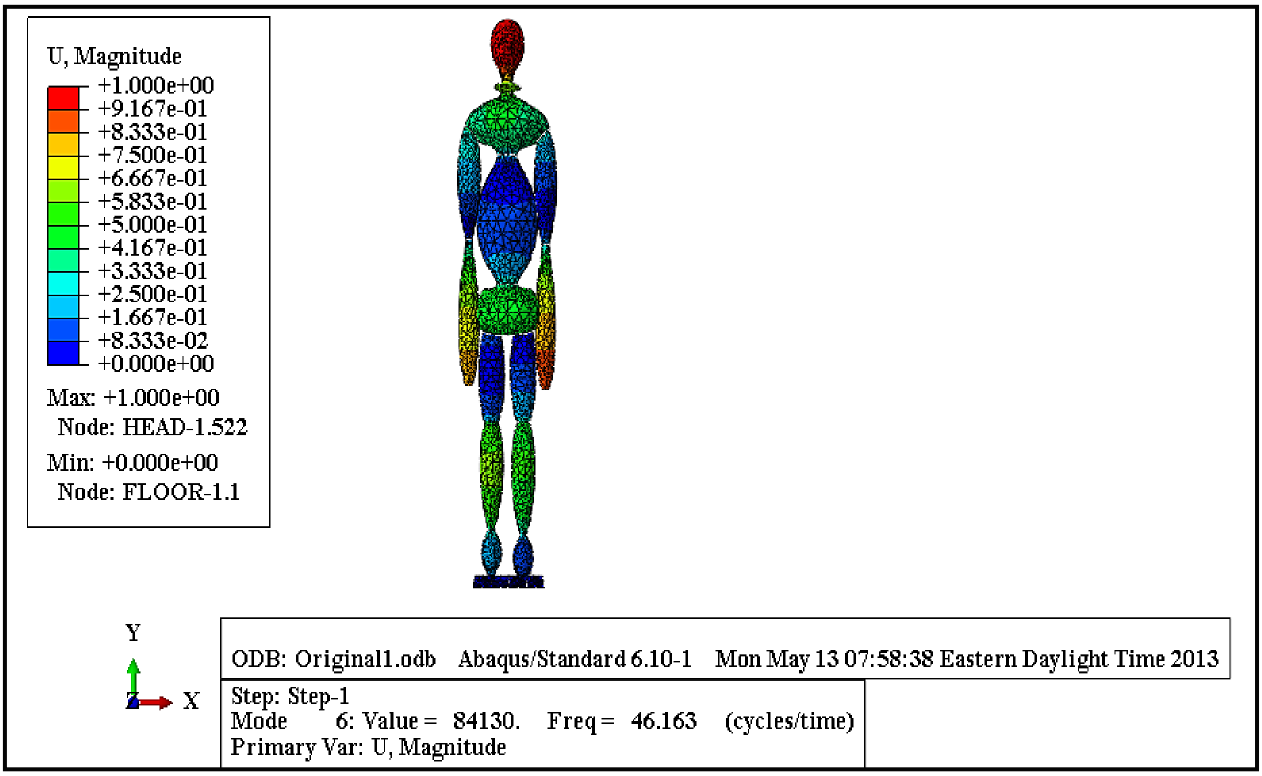

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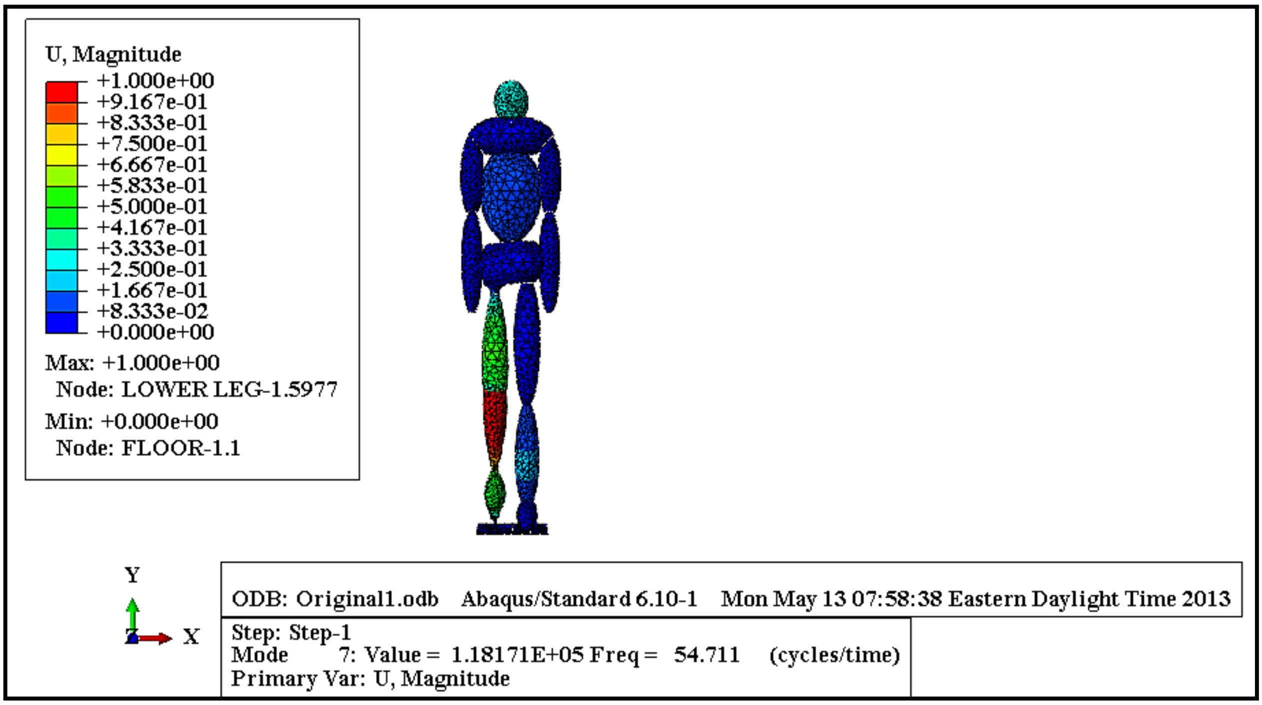

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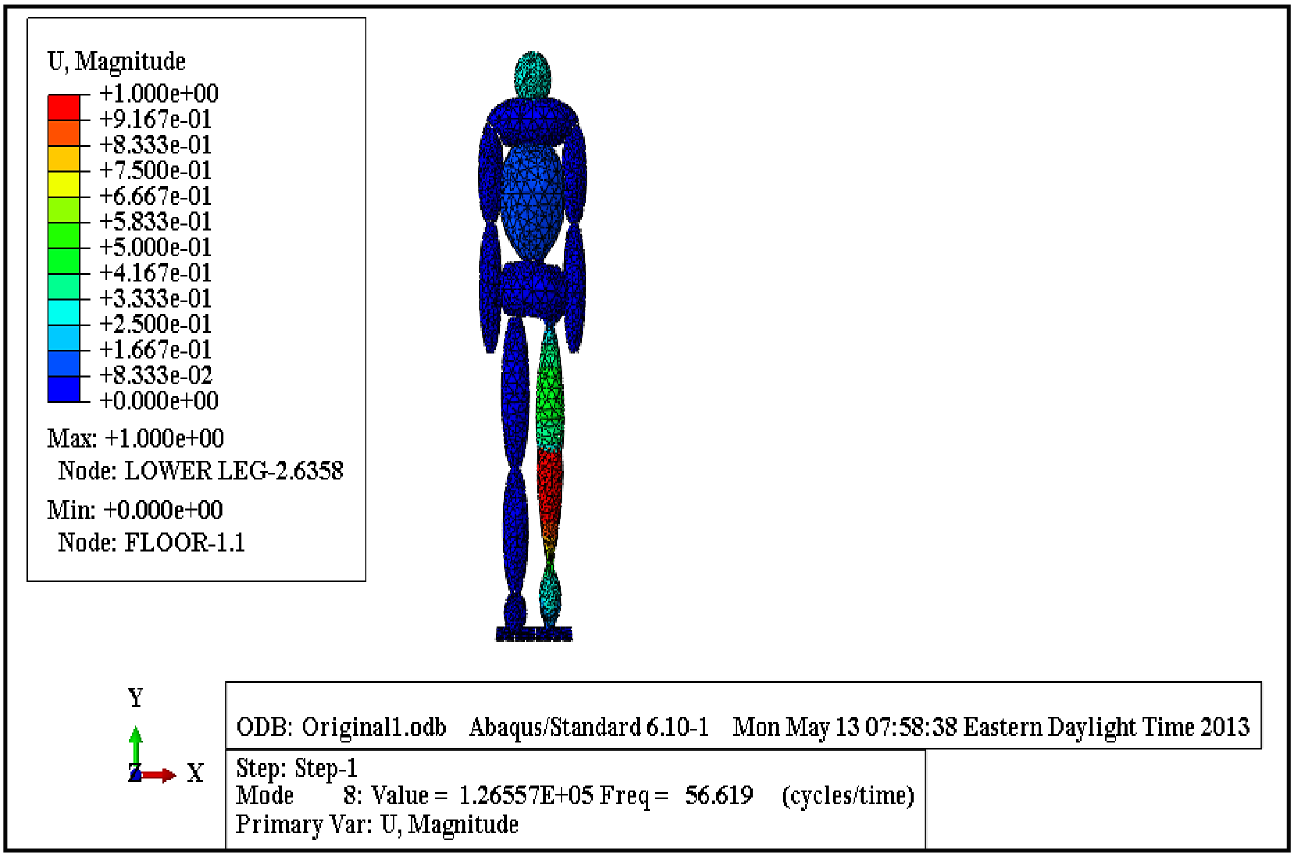

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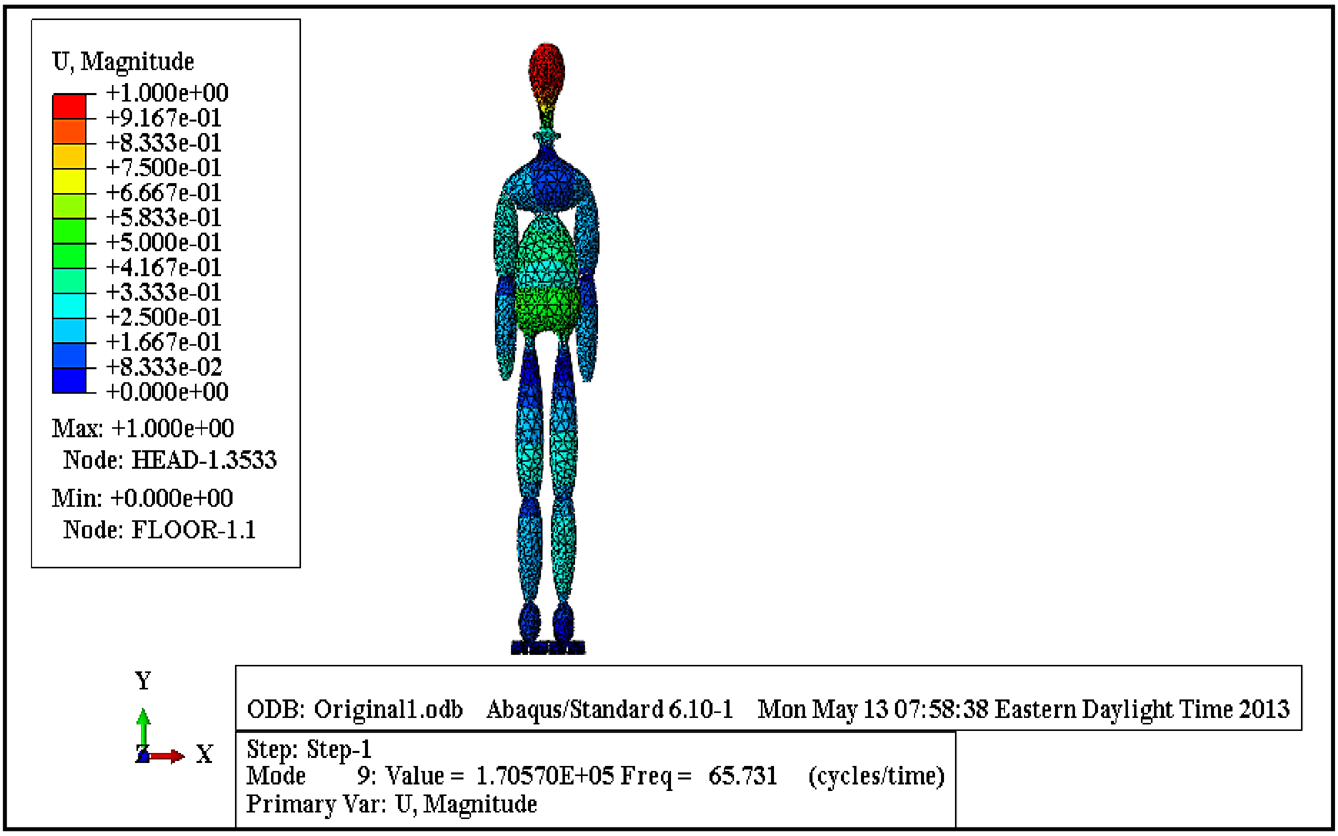

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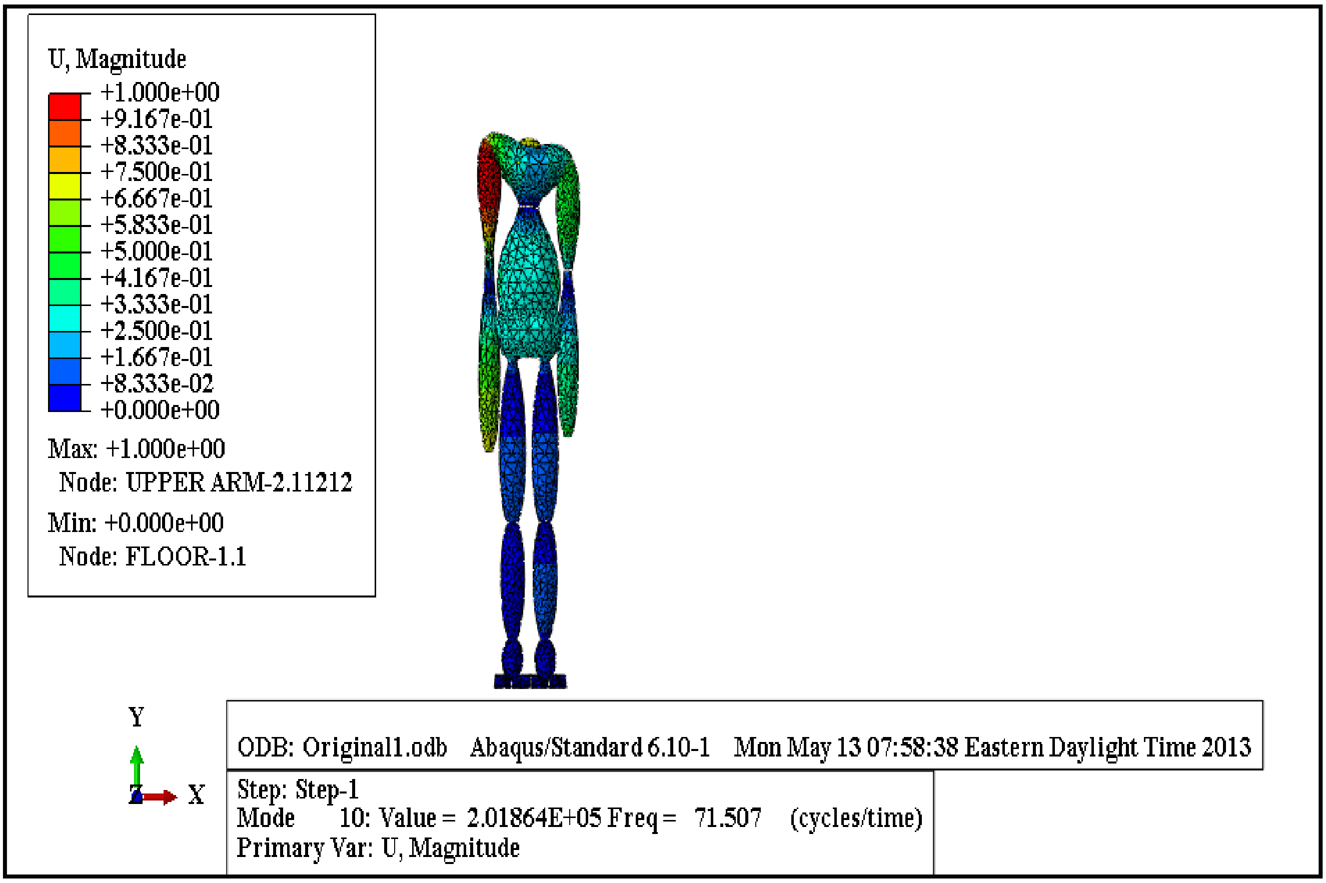

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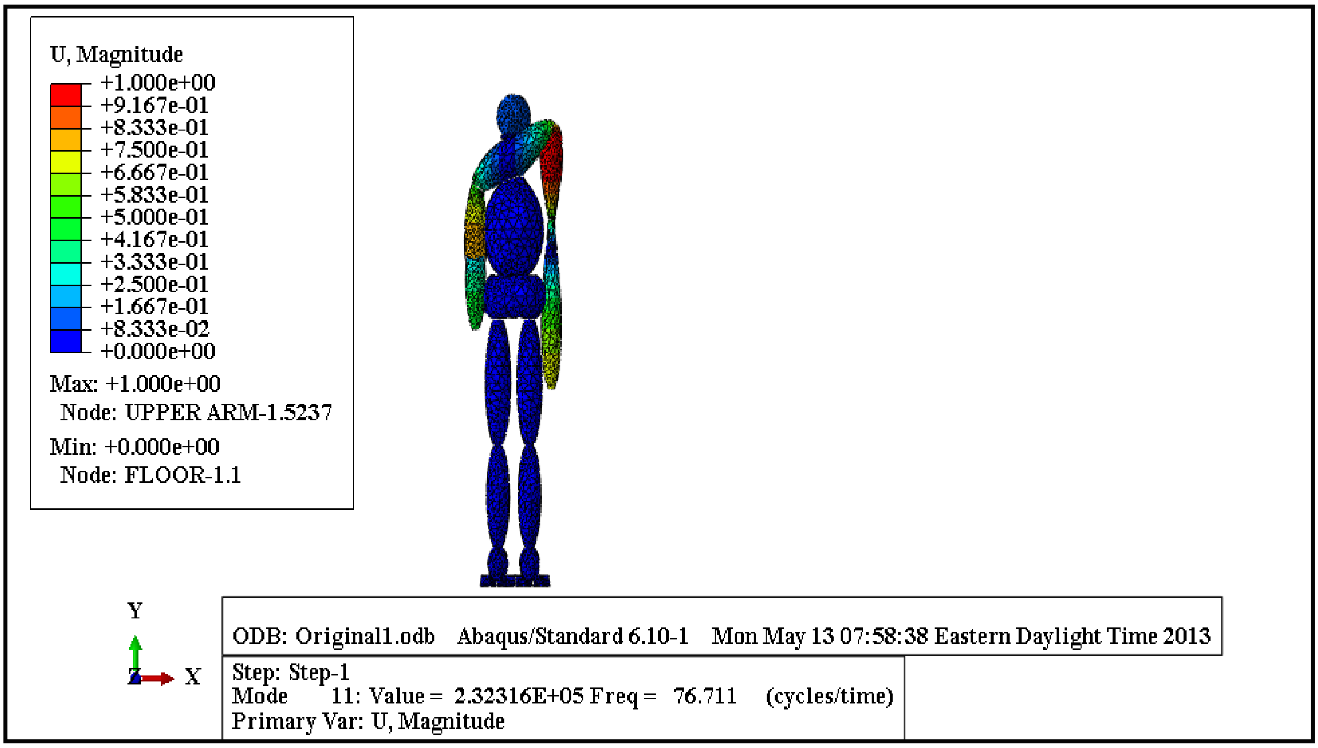
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Y
Z
X
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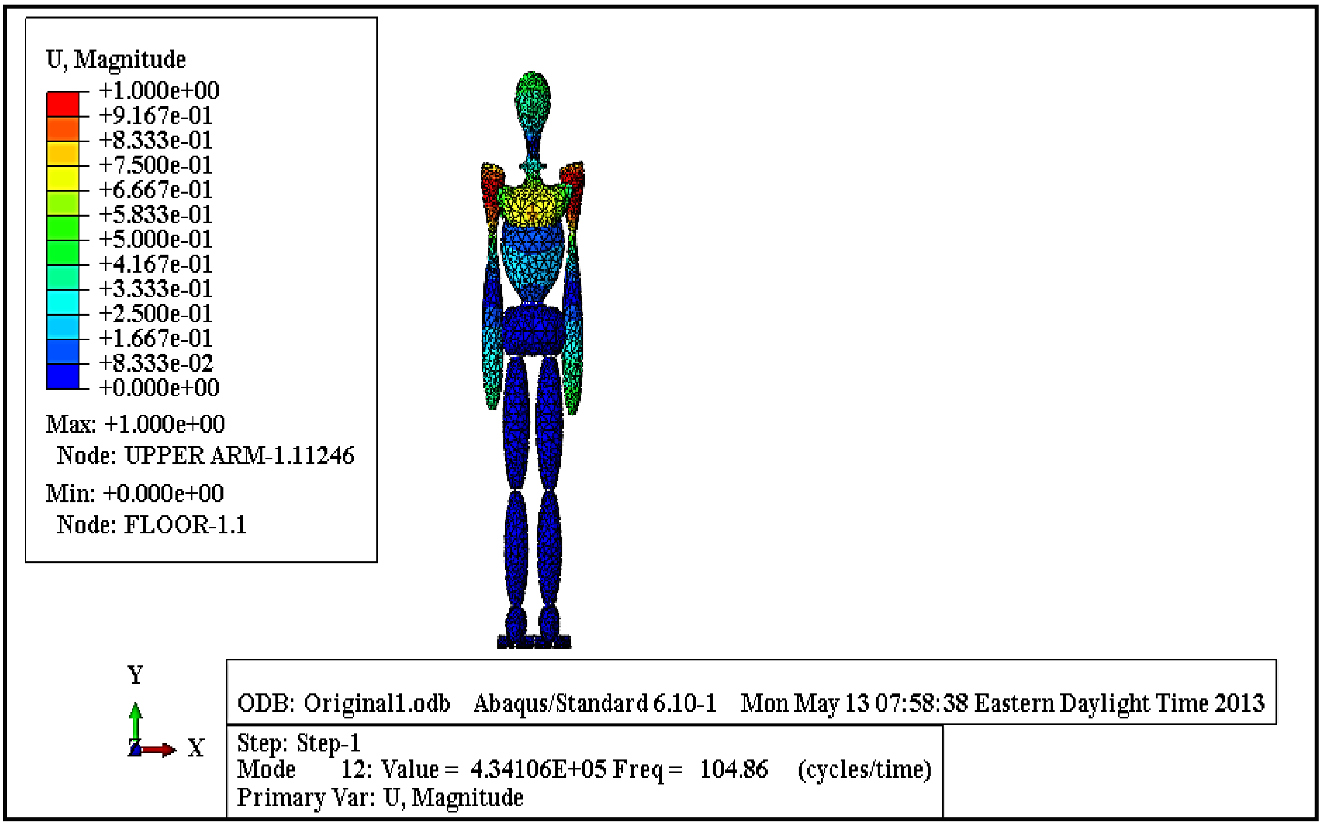
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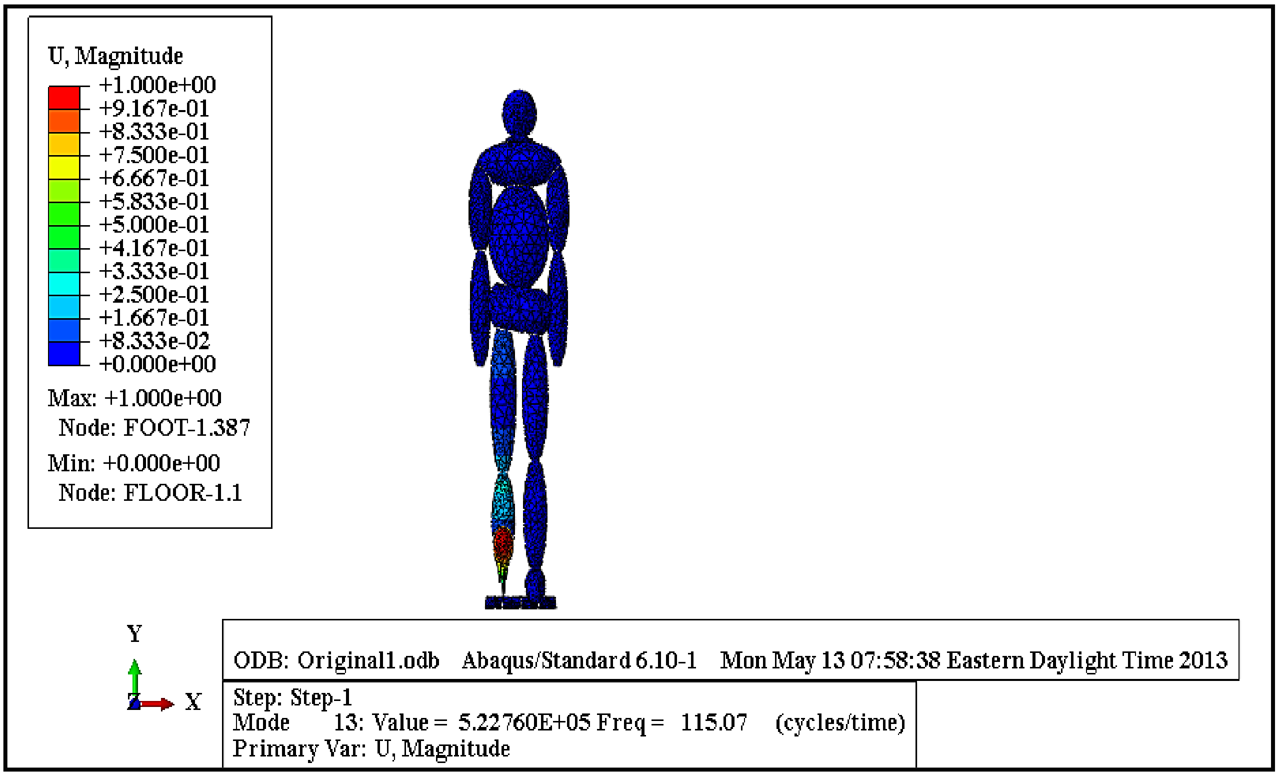
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X
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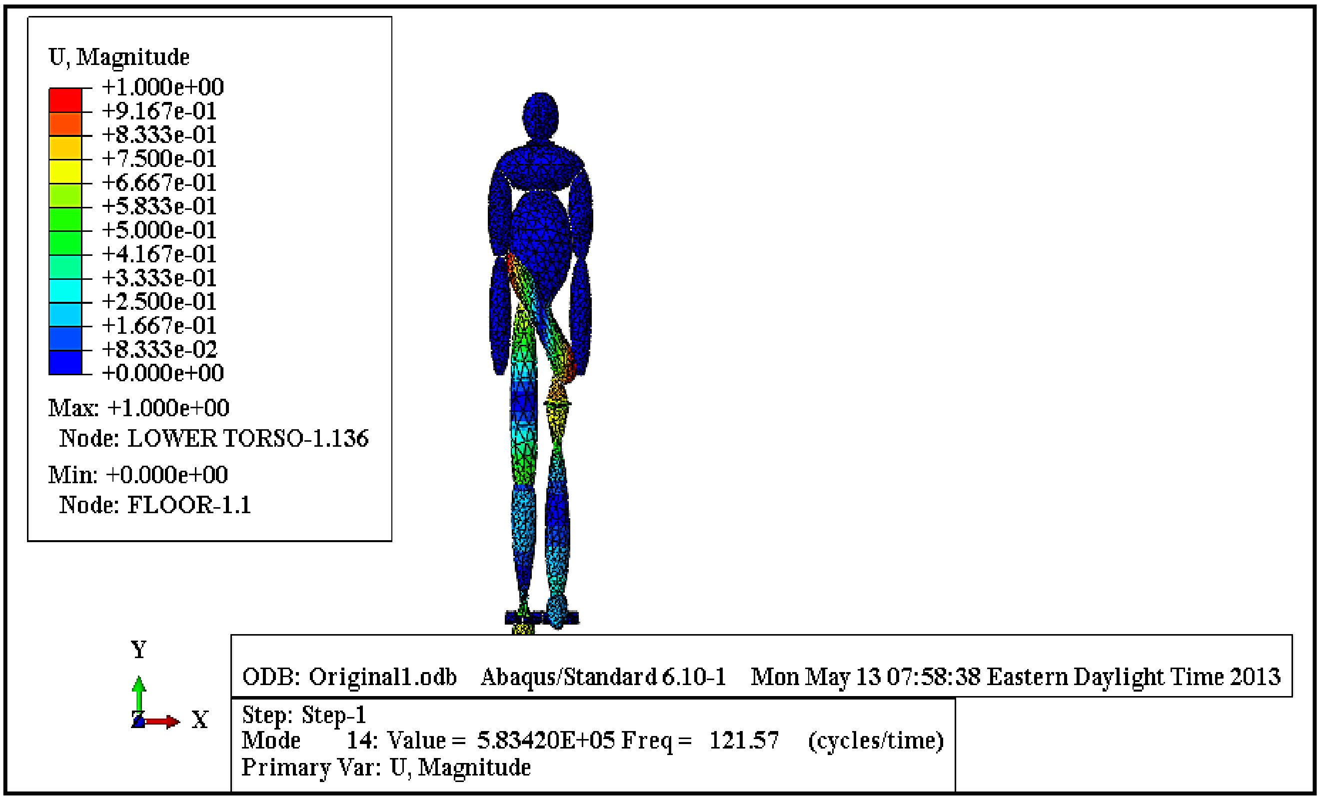
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Min: +0.000e+00
Node: FLOOR-1.1
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Z
X
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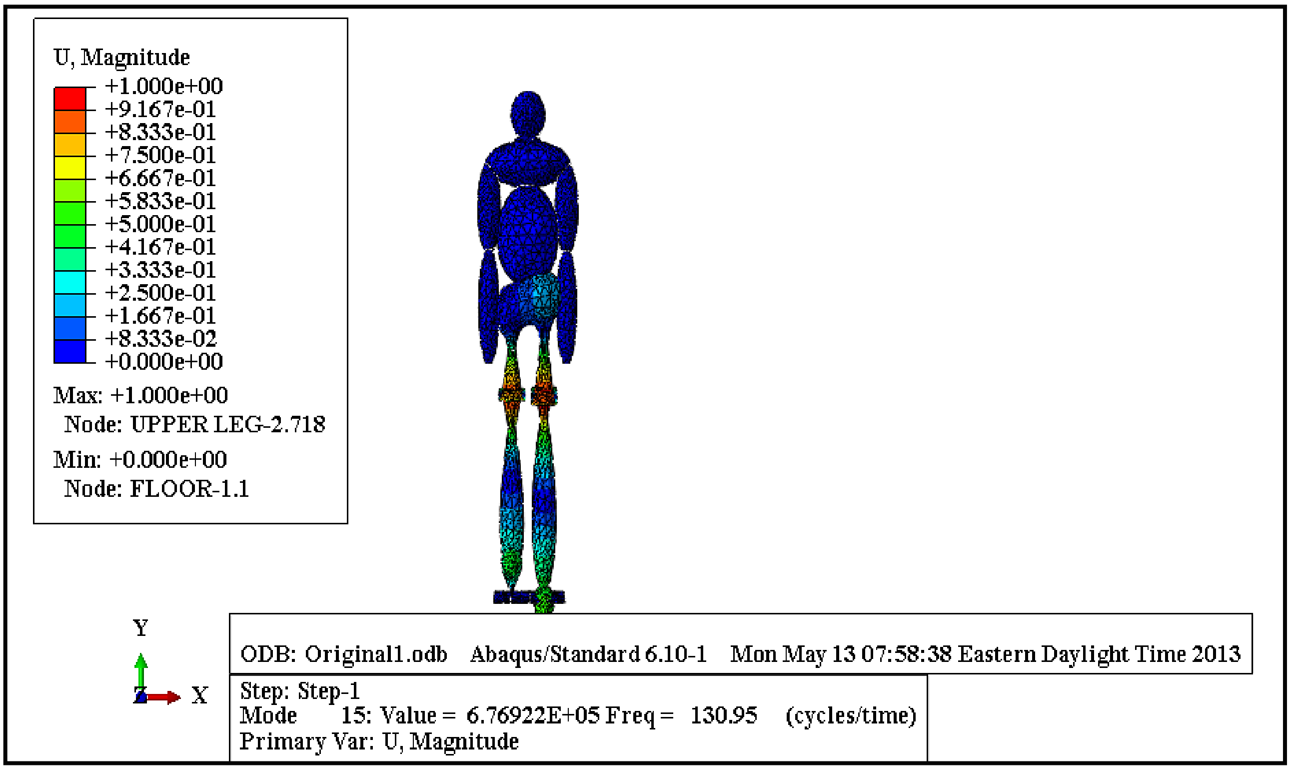


Fig 5.20 (a to o) - 15 modes and its natural frequencies with maximum and minimum displacements on human body segments.

5.3 DYNAMIC RESPONSE ANALYSIS OF HUMAN BODY USING FINITE ELEMENT METHOD FOR DIFFERENT POSTURES.

Fundamentally in most of the research studies in past the evaluation technique for the assessment of ride comfort has been studied experimentally with the measurement of time domain and frequency domain responses with the appropriate weighting filter by ISO 2631-4, (2001) conducting measurements and taking the subjective responses using scales.

The literature reveals ISO 2631 (1985) has been criticized because: 1) the standard lacks empirical support in many areas, 2) the use of the same shape of frequency weights of the three criteria (levels) is an oversimplification of the true situation, and 3) the dependency exposure duration or timing of exposure during pregnancy on adverse pregnancy outcomes is unknown and concluded with further study for standards improvement.

The amplitude dependence of resonance frequency and transmissibility plays a very important role in evaluating the ride comforts and this was observed by Koizumi et al., (2002) and they clarify the relation between ride comfort and dynamic characteristics of the human body in a standing posture from questionnaires and frequency responses of some of the body parts. For this purpose, excitation experiments are conducted employing sinusoidal waves and reproduced train floor vibrations.

Suggs et al. (1969) developed the transmissibility or apparent mass of the human body, although this was the simple model but not sufficient to study the potential injury. FEM techniques were used by Pankoke et al (1998) to develop an advanced model of a sitting man. The model focuses its detail on the lumbar spine region modelling the individual vertebrae and including the muscles of the lower back region as multiple springs. Remaining model was represented by rigid bodies having mass so that computational time can be reduced. Three different postures, mainly upright, relaxed as in case of lorry drivers and slumped forward as in case of crane operator were considered for the development of above model. Both weight and height could be easily adjusted in the model. At test data frequencies up to about 7 Hz the body model was validated against experimental data for the overall motion. Forces in the lumbar region of the spine were predicted by Pankoke et al. (1998) using the model and same FE model were used by Seidel et al., (2001) to determine the loads in the spine during whole body vibration. Further validation was carried out by them with experimental data on different model. Thus the model and its assumption were found valid. For other type of model the validation using internal forces within the spine is quite difficult.

In the present study, the objective is to study and analyze the vibration signatures in time domain and frequency domain under low frequencies from 0 – 25 Hz under excitation conditions of 1m/s^2 acceleration and body weight of 75 Kg using finite element method. The model is being developed using finite element method and the dynamic response analysis of a human body in two postures, ie, normal standing posture, holding rod posture is being studied to measure transmissibility of accelerations from floor to head, floor to knee. The fast Fourier transform technique is performed to analyze the responses in time domain and frequency domain.

In modelling the body of a standing man, the spring stiffness are considered to be acting in and permitting the vibrations in vertical and lateral direction only and the axial elastic modulus of the ellipsoids is approximated as a geometric mean of the elastic moduli of bones and tissues (Nigam and Malik, 1987). The geometric models of the human body take part a important role in analyzing the human response to the vibration platform in industries, vehicles and also in product design, allowing industrial products such as cars, furniture and clothing to be custom-designed for an individual’s body shape (Bischoff and Kobbelt, 2002). The present model is constructed in 3D geometry based on Nigam and Malik, (1987). These solid ellipsoidal models define the volume of the object they represent, and hence density of each part is being calculated. A human body is in reality not a homogeneous mass, the bulk (average) densities of different body segments are nearly the same (Bartz and Gianotti, 1975).

The element type used in finite element method is C3D10 quadratic hexahedron element, and each individual part consists of a corresponding number of elements and nodes. Young's modulus and poisson's ratio for different parts of the assembly is assumed as E = 13.02 MN/m^2 and $\mu = 0.25$ (Nigam and Malik, 1987).

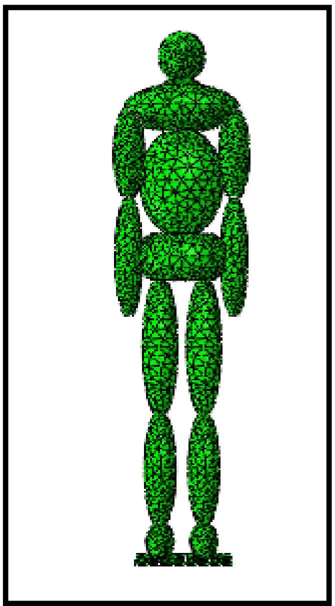
5.4 DYNAMIC RESPONSE ANALYSIS OF A STANDING HUMAN UNDER LOW FREQUENCY VIBRATIONS IN VERTICAL DIRECTION AND LATERAL DIRECTION

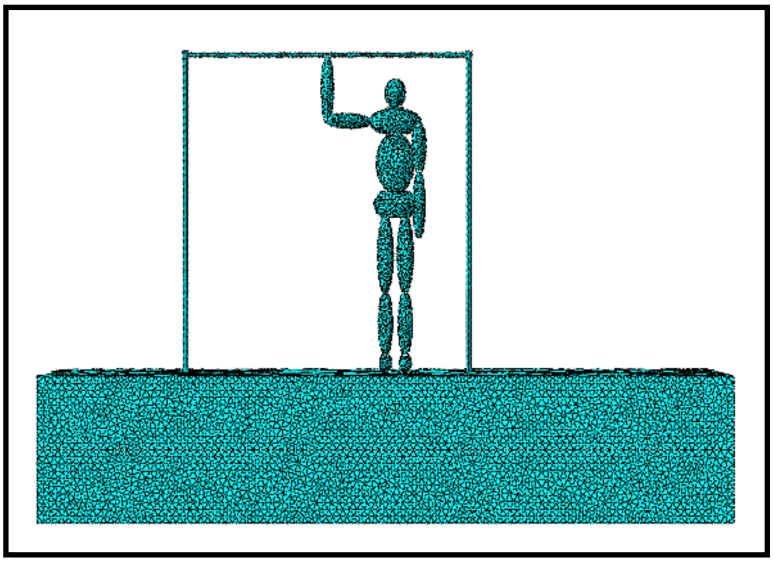
Matsumoto et al., (1998) studied the dynamic response of the standing human body exposed to vertical vibration and also the influences of posture and vibration magnitude by the assessment of experimental data and mathematical models in the frequency range of 0.5 – 50 Hz at vibration magnitudes from 0.125 to 2.0 m/s^2 r.m.s for normal standing posture and found principal resonance in the frequency range of 4 – 6 Hz and reported in their studies that, the principal resonance of the standing body is utmost affected by the dynamic response of the viscera and also induced by rotational motions at the leg joints and the deformation of the tissue of the foot sole. About the study on bending motion of the spine, the results shown resonance peaks in the lumbar spine, occurs at the principal resonance frequency but makes a small influence to the apparent mass resonance in standing postures.

5.4.1 Normal standing posture and holding rod posture

The number of studies has been performed in the whole body vibration study to investigate the influence of vibration on humans, and concluded with lack of complete understanding due to various changes in health, comfort and activity interference that have been observed.

The most of the studies concerned of about experimental analyses and mathematical models instead of finite element models to study the effect of magnitude on different body segments. Hence in the present work the acceleration of the head and knee with the





application of force on the foot is simulated using (ABAQUS 6.10) With the analysis of the results in time domain and frequency domain plots.

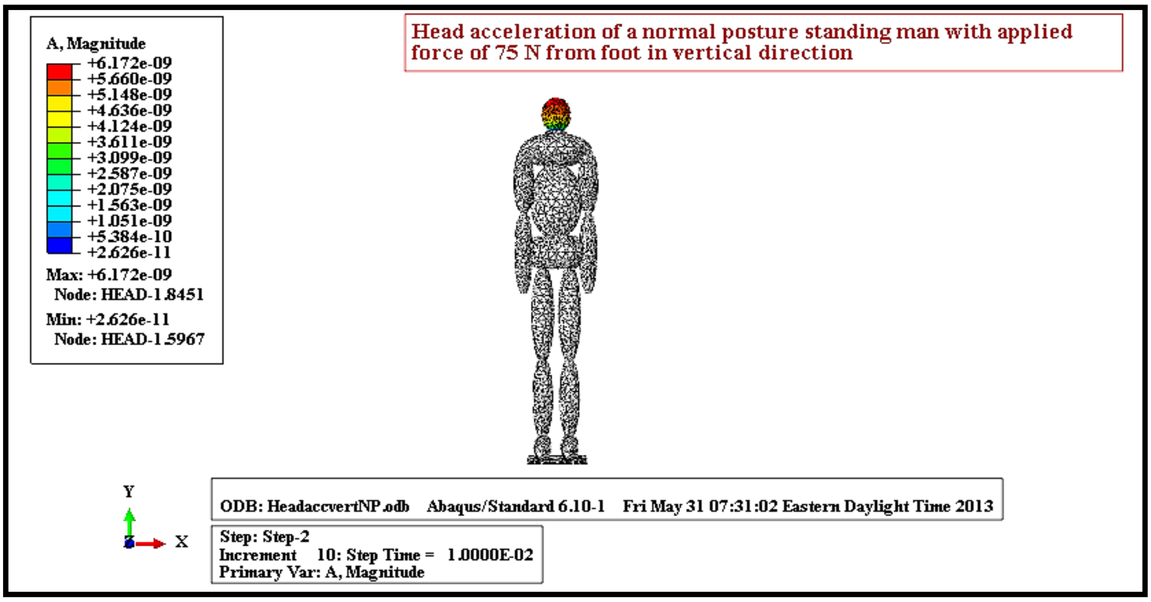
Fig 5.21 - Normal standing posture.

The two postures with normal standing human (Fig. 5.21) and a man holding the rod (Fig. 5.22) in standing posture is developed using finite element (FE) model in the present study for the dynamic response analysis of the human body in vertical as well as lateral directions to investigate the transmissibility of acceleration to body segments specifically to the head and knee while the model is simulated with the application of force excitation.

Fig 5.22 - Holding rod posture human body

5.5 EFFECT OF HEAD ACCELERATION OF TIME DOMAIN AND FREQUENCY DOMAIN RESPONSE IN VERTICAL DIRECTION.

In general, analysis of transmission of vibration to the human body segments is a difficult phenomenon because of nonlinearities in the human tissue system. The present finite element (FE) model concentrated on predicting the fundamental frequency of vibration and the peak acceleration on the human body segment (head) considering linear behavior of human tissues. Normal standing posture (Fig. 5.23) and holding rod posture (Fig. 5.22) with excitation of $1 m/s^2$ and body mass of 75 kg were considered. The obtained results have been used for



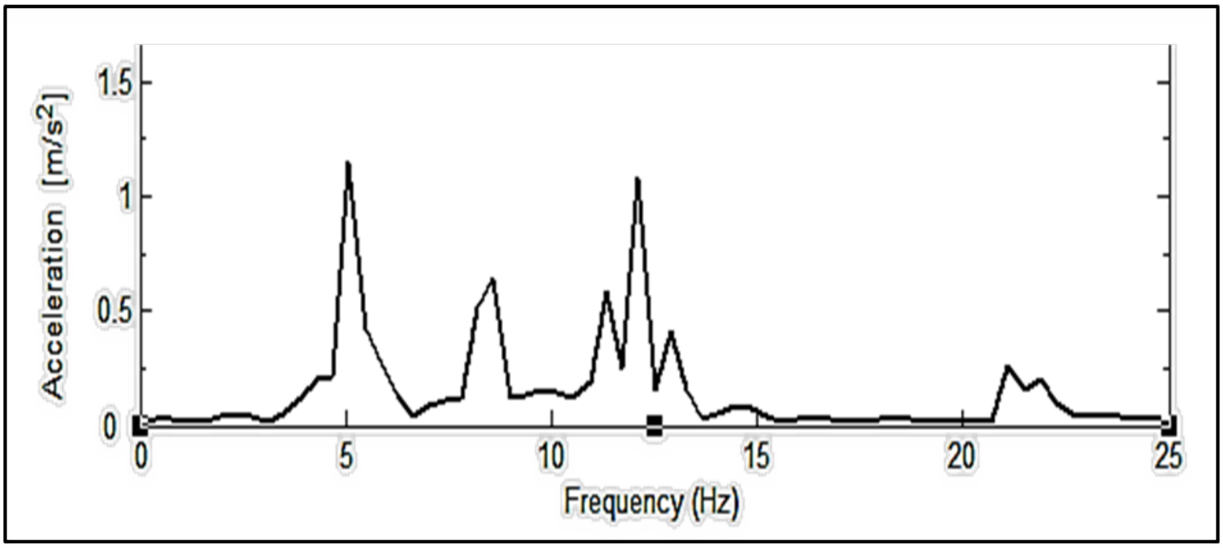
assessing how the transmission of accelerations (due to vibrations) to head is affected due to sinusoidal input.

5.5.1 Normal standing posture

The normal standing posture of human body is developed using finite element method as shown in Fig 5.23 and is analyzed for the measurement of head acceleration. The human body is excited with a sinusoidal input having acceleration of 1 m/s^2. This acceleration is attained by subjecting the body to a force of 75 N from the base of foot in vertical (z) direction. Fig. 5.24 represents the head vibration in time domain due to sinusoidal input for time duration of 2 sec. It is seen that the peak amplitude of vibration is 1.3 m/s^2. Fig. 5.25 represents the FFT of head vibration. The resonance peaks were analyzed for the frequency in the range of 0 – 25 Hz and the principal resonance peak is observed at 5 Hz. For the other peaks the corresponding values of frequencies and the amplitudes have been identified as are as follows: 8 Hz – 0.7 m/s^2, 11 Hz – 0.6 m/s^2, 12 Hz – 1.2 m/s^2, 13 Hz – 0.4 m/s^2 and 21 Hz – 0.25 m/s^2.

Fig 5.23 – FTHT transmissibility of a normal standing posture man with applied force of 75 N from foot in vertical direction.

Fig 5.24 – Time domain plots of floor to head transmissibility FTHT for normal standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.



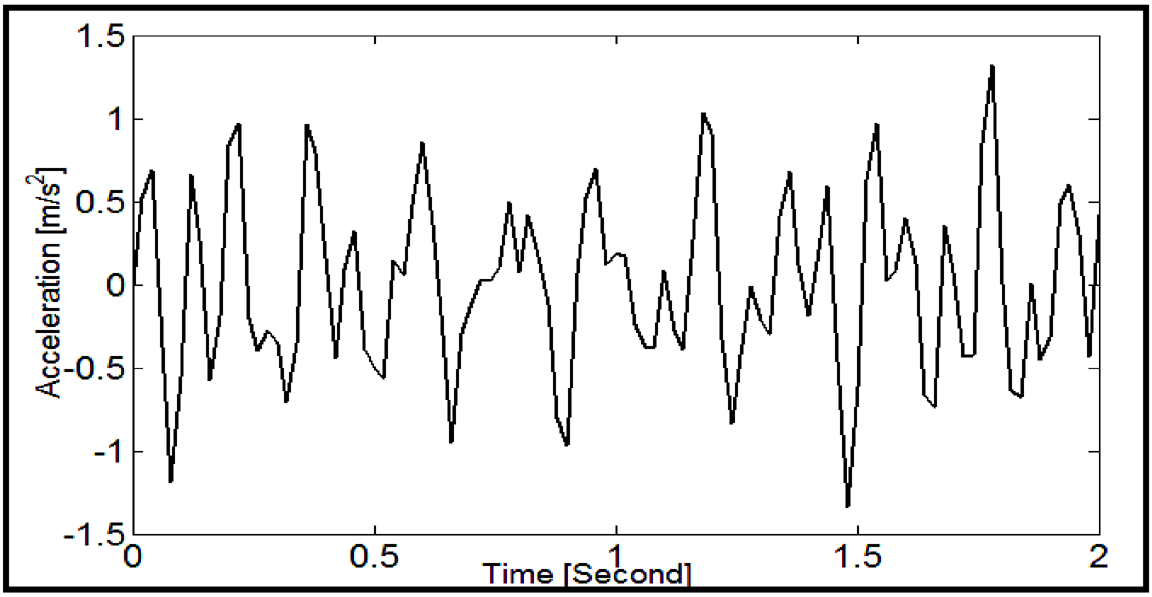
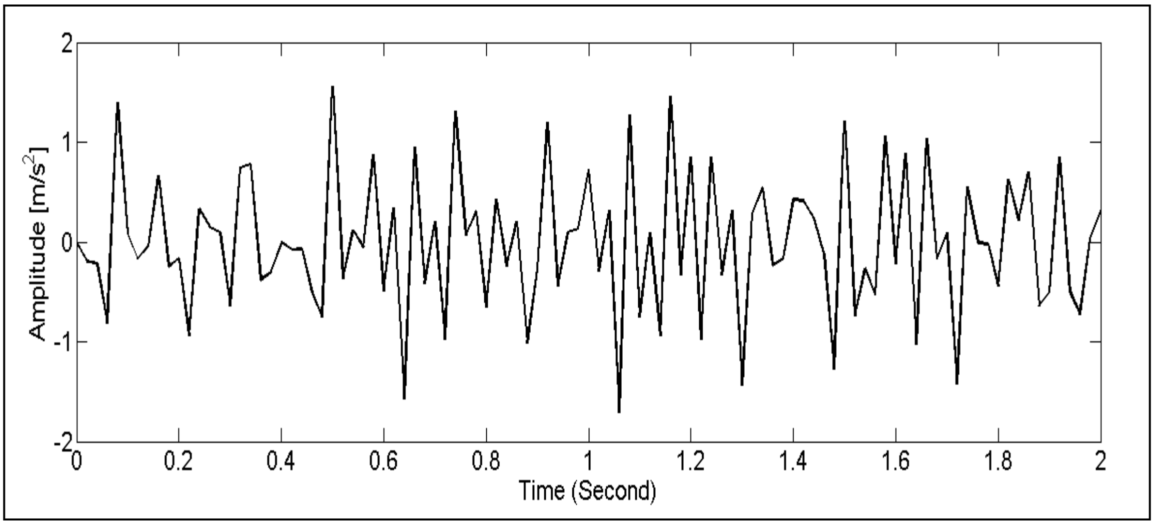


Fig 5.25- Frequency domain plots of floor to head transmissibility for normal standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

5.5.2 Holding rod posture

From the Fig. 5.26 and Fig. 5.27 it has been observed that the head acceleration is measured in the time domain and frequency domain plots. The holding rod standing posture human



body is developed using finite element method and analyzed for the measurement of knee acceleration when the body is subjected to force of 75 N from the base of foot in vertical (z) direction. From the Fig 5.26 it has been observed that the behavior of vibration is sinusoidal in nature and the acceleration measured for time duration of 2 sec gives the peak acceleration of 1.6 m/s^2 and from the Fig 5.28 the resonance peaks were analyzed for the frequency range from 0 – 25 Hz and it has been observed that the resonance peaks starting from the principal resonance peak of 22 Hz. For the other peaks the corresponding values of frequencies and the amplitudes have been identified as are as follows: 5 Hz – 0.8 m/s^2, 12 Hz – 1.4 m/s^2, 17 Hz – 0.9 m/s^2 and 19 Hz – 0.6 m/s^2.

Fig 5.26 - Time domain plots of floor to head FTHT transmissibility for holding rod standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

Fig 5.27 - Frequency domain plots of floor to head transmissibility FTHT for holding rod standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

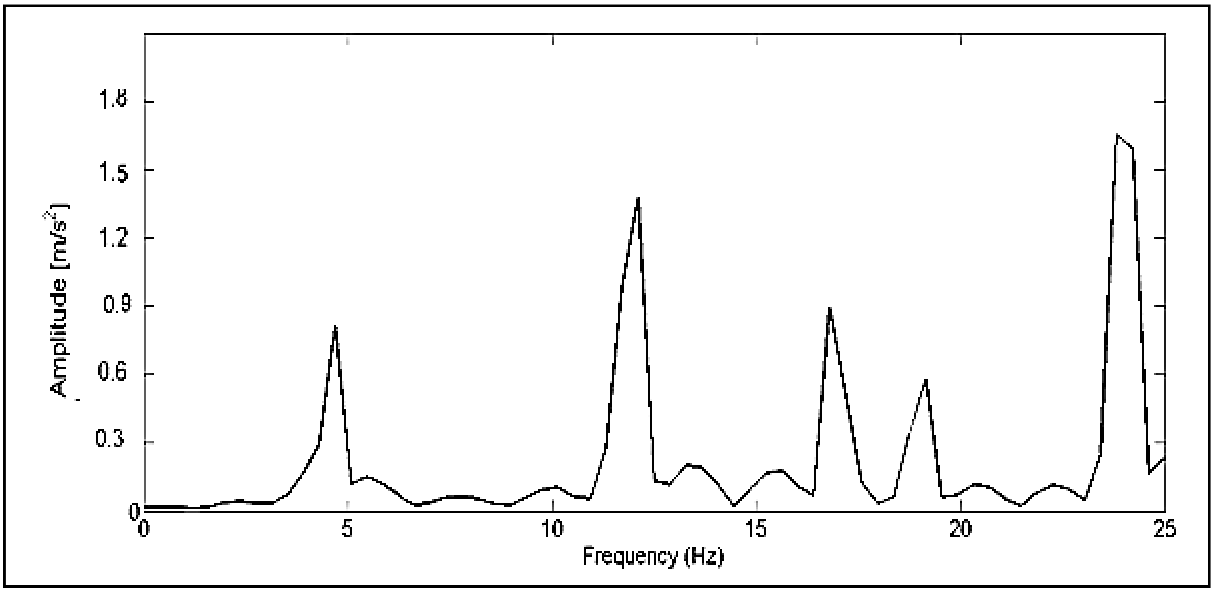


Table 5.6 summarizes the frequency response of the head in vertical direction for sinusoidal excitation for two postures.

Table 5.6 – Summary of frequency response in vertical direction (FTHT)

Transmissibility	**Resonance frequencies (Hz)**	**Amplitude (m/s^2)**	**Remark**
FTHT for normal standing posture	05	1.30	Amplification
	08	0.70	Attenuation
	11	0.60	Attenuation
	12	1.20	Amplification
	13	0.40	Attenuation
	21	0.25	Attenuation
FTHT for holding rod posture	05	0.8	Attenuation
	12	1.4	Amplification
	17	0.9	Attenuation
	19	0.6	Attenuation
	22	1.6	Amplification

5.6 EFFECT OF KNEE ACCELERATION OF TIME DOMAIN AND FREQUENCY DOMAIN RESPONSE IN VERTICAL DIRECTION

The present finite element (FE) model is also used for assessing the transmission of accelerations (due to vibrations) to knee due to sinusoidal input. This input is the same as described for head acceleration in section 5.5. Fig 5.28 shows the knee acceleration due to sinusoidal input for a normal standing posture of the subject.

5.6.1 Normal standing posture

Fig. 5.29 represents the knee vibration in time domain due to sinusoidal input for time duration of 2 sec. It is seen that the peak amplitude of vibration is 6.0 m/s^2. Fig. 5.30 represents the FFT of knee vibration. The resonance peaks were analyzed for the frequency in the range of 0 – 25 Hz and the principal resonance peak is observed at 12 Hz. Other than the principal peak there is only one more peak (5.5 m/s^2) occurring at a frequency of 20 Hz.

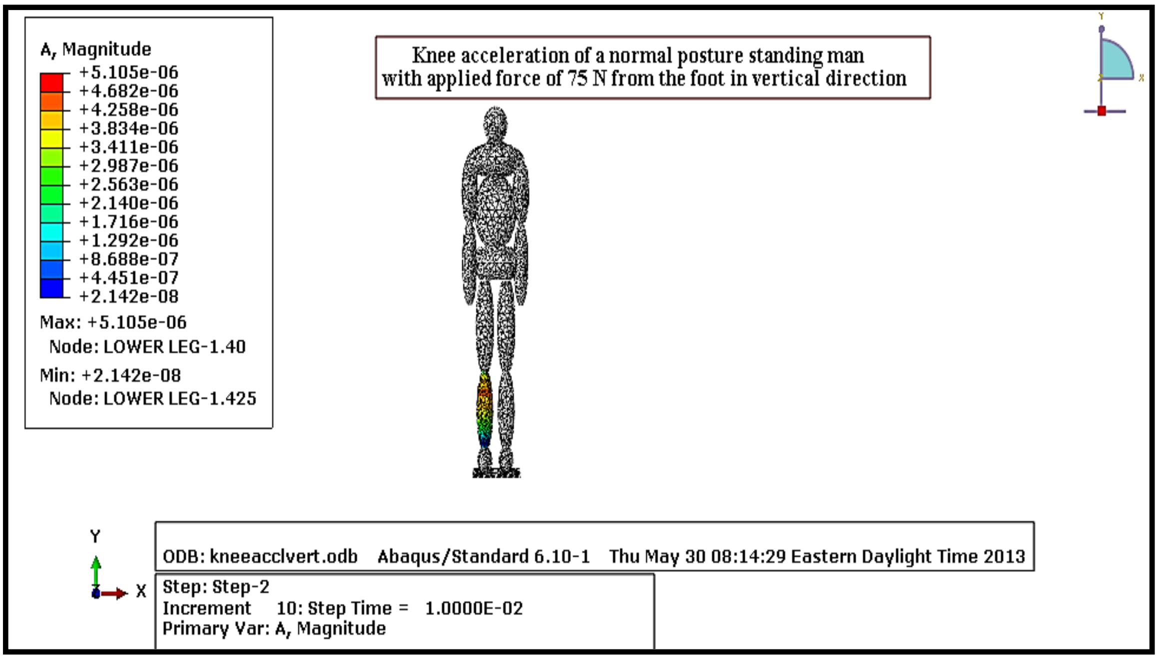


Fig. 5.28 - Knee acceleration of a normal posture standing man with applied force of 75 N from the foot in vertical direction.

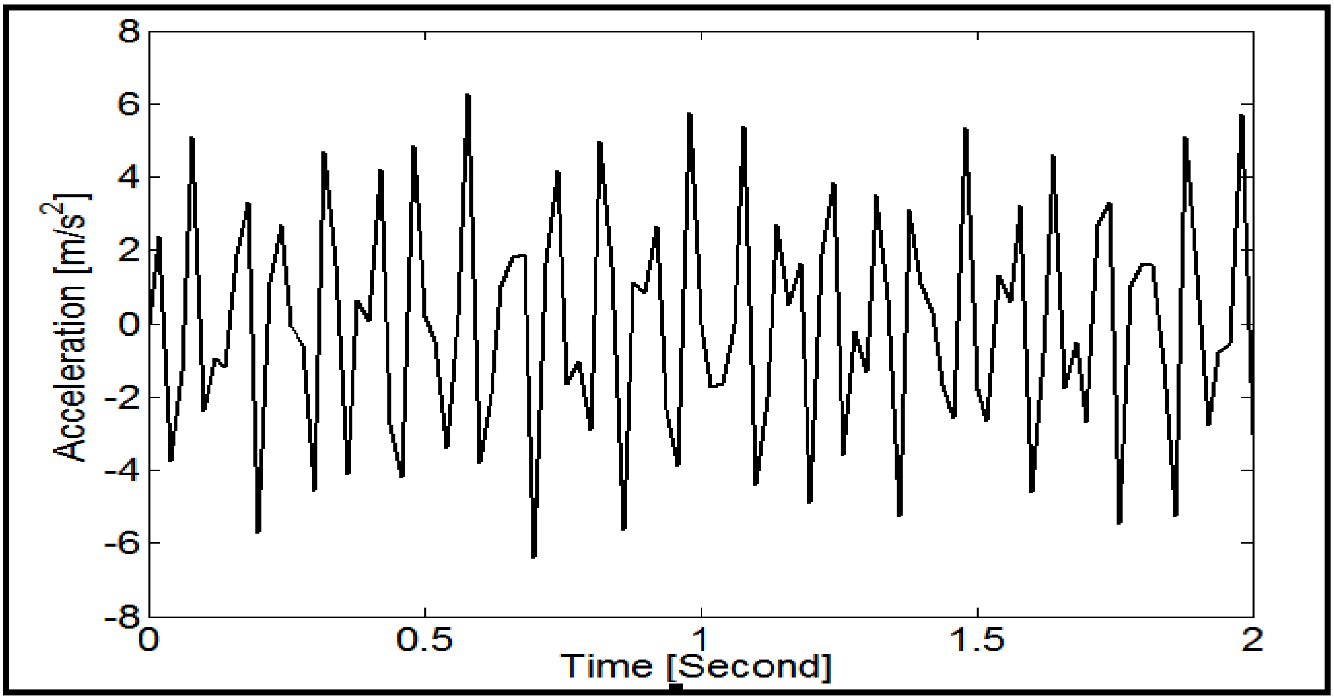


Fig 5.29 - Time domain plots of floor to knee transmissibility FTKT for normal standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

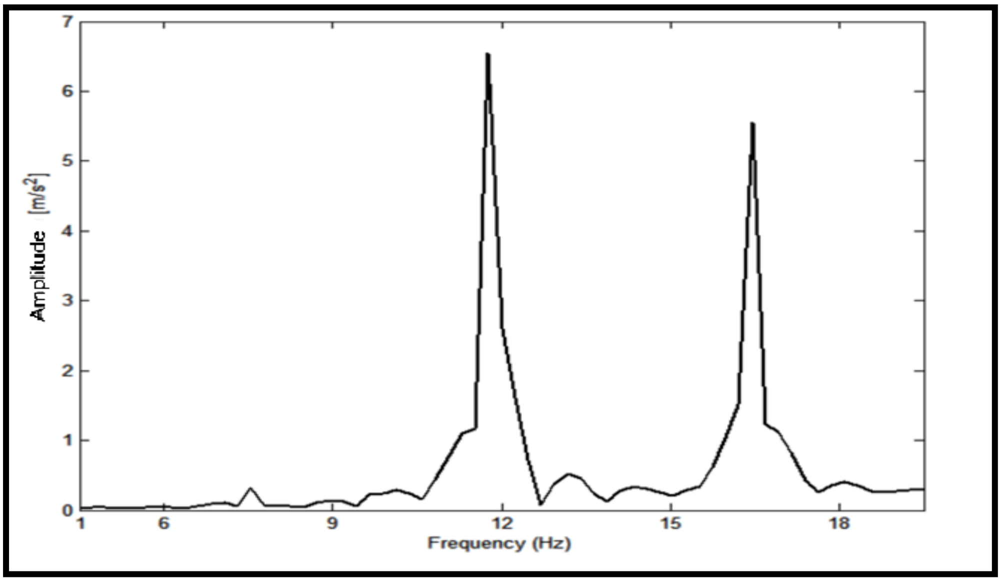


Fig 5.30- Frequency domain plots of floor to knee transmissibility FTKT for normal standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

5.6.2 Holding rod posture

Fig. 5.31 represents the knee vibration in time domain due to sinusoidal input for time duration of 2 sec. It is seen that the peak amplitude of vibration is 4.2 m/s^2. Fig. 5.32 represents the FFT of knee vibration. The resonance peaks were analyzed for the frequency in the range of 0 – 25 Hz and the principal resonance peak is observed at 17 Hz. Other than the principal peak there is only one more peak (4.0 m/s^2) occurring at a frequency of 12 Hz.

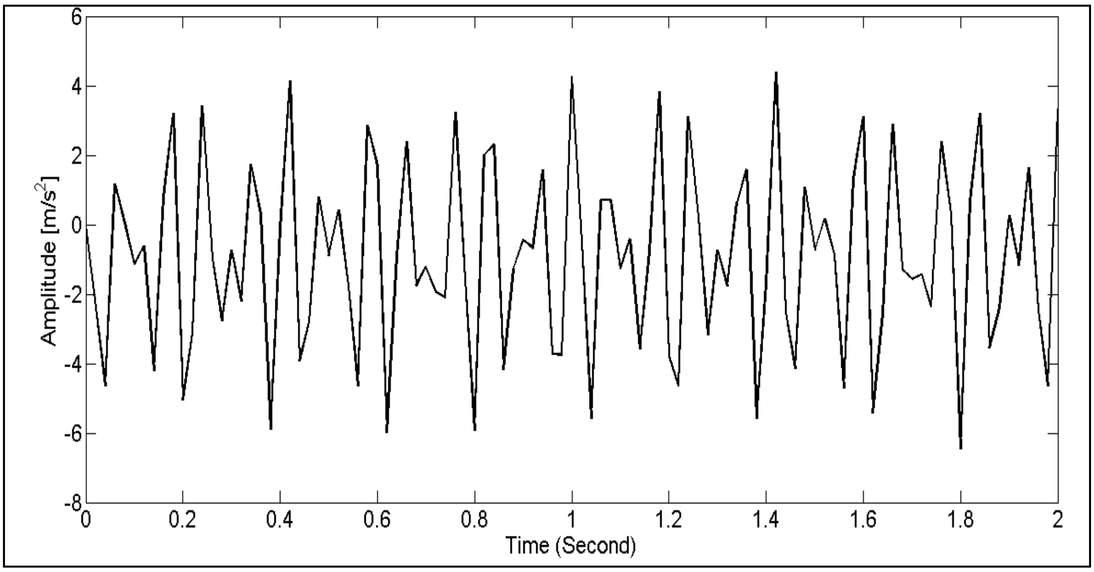


Fig 5.31 - Time domain plots of floor to knee transmissibility FTKT for normal standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

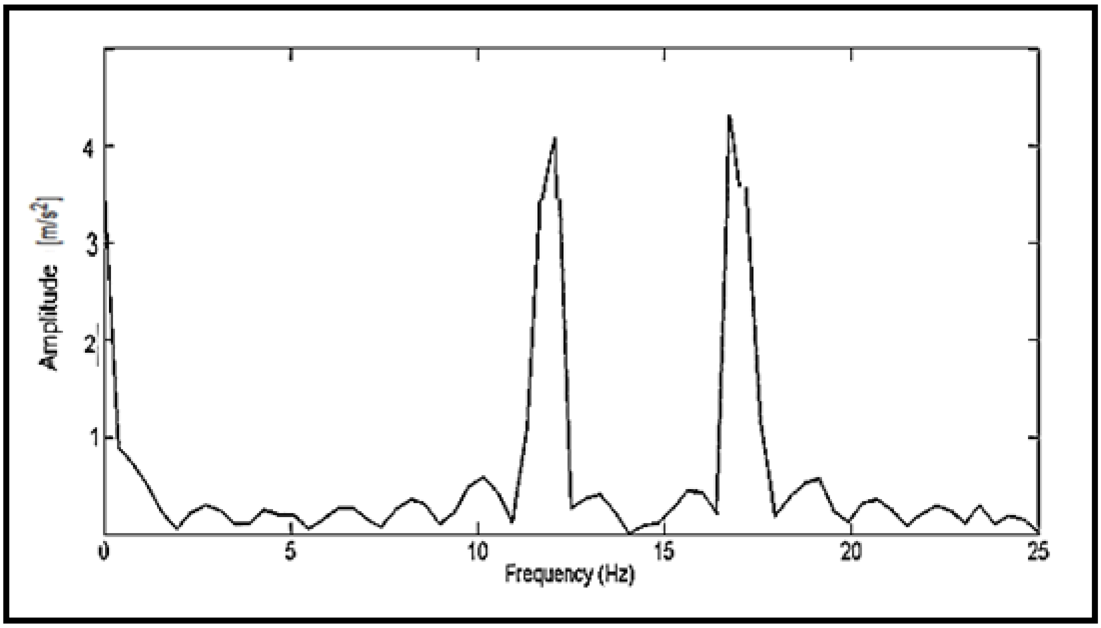


Fig 5.32 – Frequency domain plots of floor to knee transmissibility FTKT for normal standing human exposed to vertical sinusoidal vibration at 1 m/s^2 r.m.s.

Table 5.7 summarizes the frequency response of the knee in vertical direction for sinusoidal excitation for two postures.

Table 5.7 – Summary of frequency response in vertical direction (FTKT)

Transmissibility	**Resonance frequencies (Hz)**	**Amplitude (m/s^2)**	**Remark**
FTKT for normal standing posture	12 20	6.00 5.50	Amplification Amplification
FTKT for holding rod posture	12 17	4.0 4.2	Amplification Amplification

5.7 EFFECT OF HEAD ACCELERATION OF TIME DOMAIN AND FREQUENCY DOMAIN RESPONSE IN LATERAL DIRECTION

5.7.1 Normal standing posture

From the Fig. 5.33 and 5.34 it has been observed that the head acceleration is measured in the time domain and frequency domain plots. The normal standing posture human body is developed using finite element method and analyzed for the measurement of head acceleration when the body is subjected to force of 75 N from the base of foot in lateral (y) direction. Since the mass of the subject is 75 kg, a force of 75 N in lateral direction is applied to attain an acceleration of 1 m/s^2. By constraining the movement in other two directions, i.e, (X-longitudinal and Z-vertical) the FE human model is allowed to vibrate in lateral (y) direction. From the Fig 5.33 it has been observed that the behavior of vibration is sinusoidal in nature and the acceleration measured for time duration of 2 sec gives the peak acceleration of 3 m/s^2 and from the Fig 5.34 the resonance peaks were analyzed for the frequency range from 0 – 25 Hz and it has been observed that the principal resonance peak of 12 Hz with acceleration values of 3 m/s^2 found.

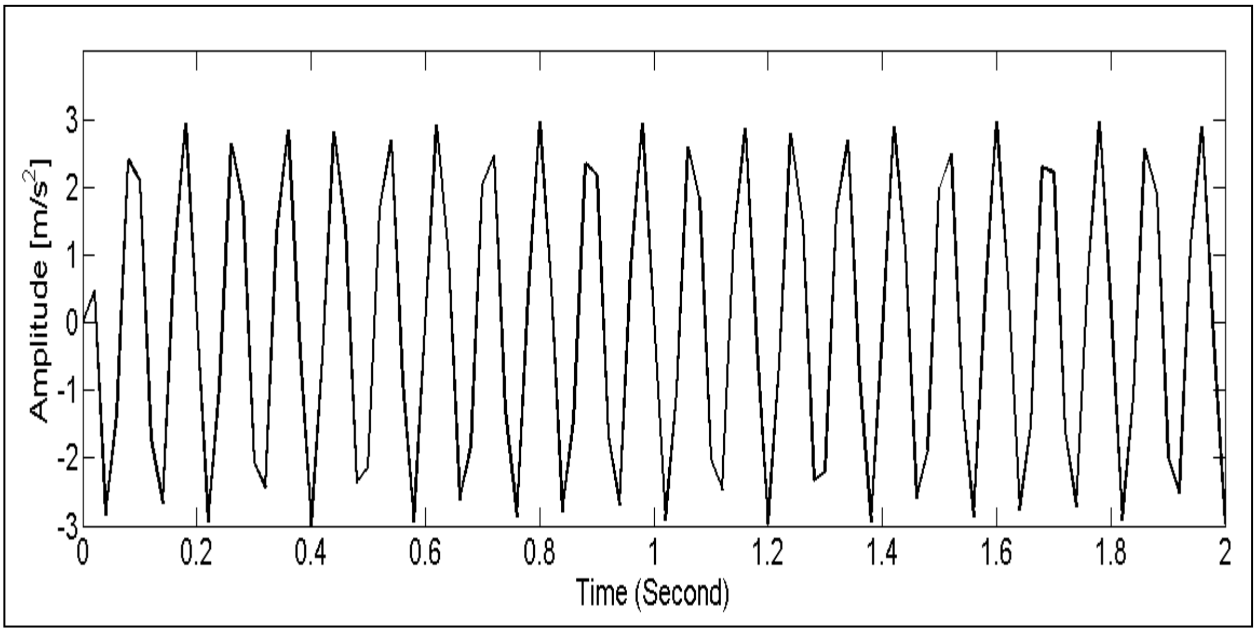


Fig 5.33 - Time domain plots of floor to head transmissibility FTHT for normal standing human exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

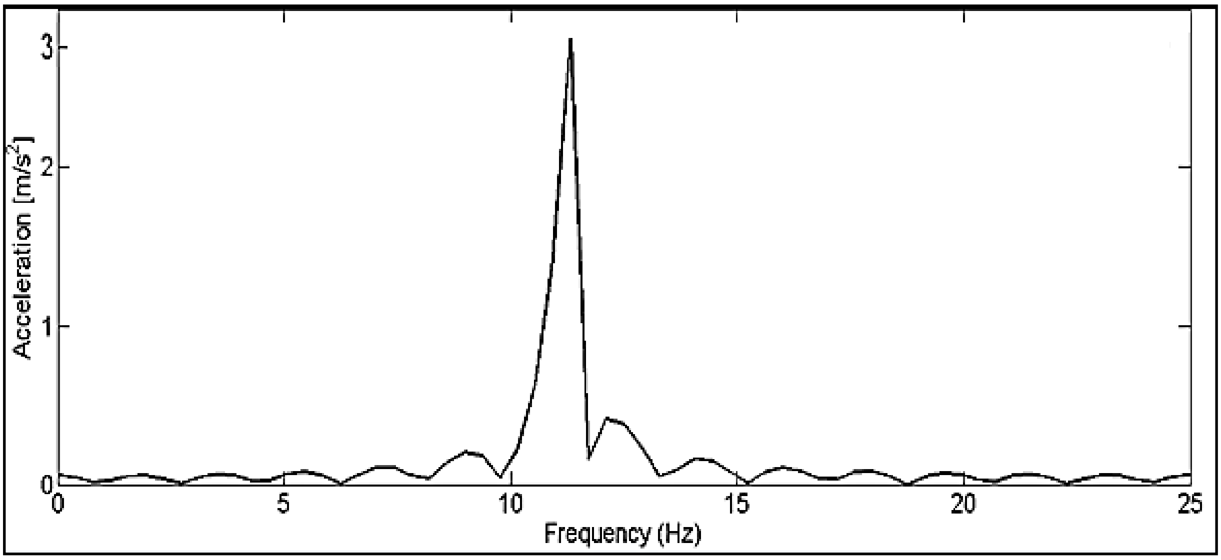


Fig 5.34 - Frequency domain plots of floor to head transmissibility FTHT for normal standing human exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

5.7.2 Holding rod posture

From the Fig. 5.35 and Fig. 5.36 it has been observed that the head acceleration is measured in the time domain and frequency domain plots. From the Fig 5.35 it has been observed that the behavior of vibration is sinusoidal in nature and the acceleration measured for time duration of 2 sec gives the peak acceleration of 1.7 m/s^2 and from the Fig 5.36 the resonance peaks were analyzed for the frequency range from 0 – 25 Hz and it has been observed that the resonance peaks starting from the first resonance peak of 24 Hz. For the other peaks the corresponding values of frequencies and the amplitudes have been identified as are as follows: 5 Hz – 0.83 m/s^2, 12.5 Hz – 1.4 m/s^2, 17.5 Hz – 0.9 m/s^2 and 19 Hz – 0.6 m/s^2.

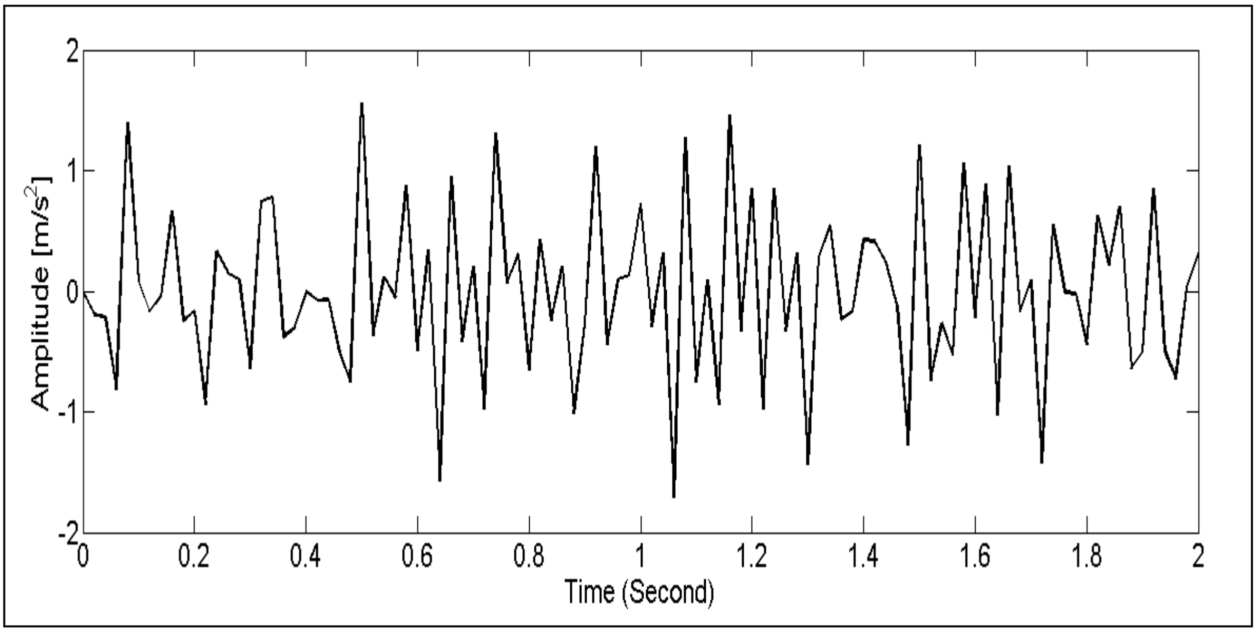
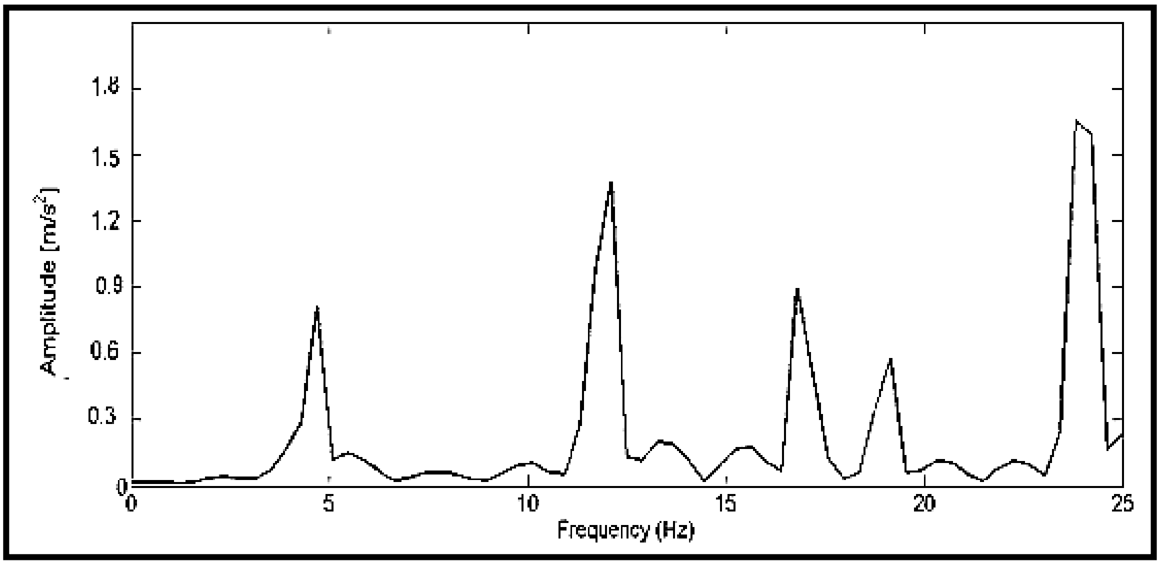


Fig 5.35 -Time domain plots of floor to head transmissibility FTHT for normal standing



human exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

Fig 5.36 Frequency domain plots of floor to head transmissibility FTHT for holding rod standing human exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

Table 5.8 summarizes the frequency response of the head in lateral direction for sinusoidal excitation for two postures.

Table 5.8 – Summary of frequency response in lateral direction (FTHT)

Transmissibility	**Resonance frequencies (Hz)**	**Amplitude (m/s^2)**	**Remark**
FTHT for normal standing posture	12	3.00	Amplification
FTHT for holding rod posture	05.0 12.5 17.5 19.0 24.0	0.83 1.40 0.90 0.60 1.70	Attenuation Amplification Attenuation Attenuation Amplification

5.8 EFFECT OF KNEE ACCELERATION OF FREQUENCY DOMAIN RESPONSE IN LATERAL DIRECTION

5.8.1 Normal standing posture

From the Fig. 5.37 and 5.38 it has been observed that the knee acceleration is measured in the time domain and frequency domain plots. From the Fig 5.37 it has been observed that the behavior of vibration is sinusoidal in nature and the acceleration measured for time duration of 2 Sec gives the peak acceleration of 2.35 m/s^2 and from the Fig 5.38 the resonance peaks were analyzed for the frequency range from 0 – 25 Hz and it has been observed that the resonance peaks starting from the first resonance peak of 17 Hz. Other than the principal peak there is only one more peak (0.7 m/s^2) occurring at a frequency of 14 Hz

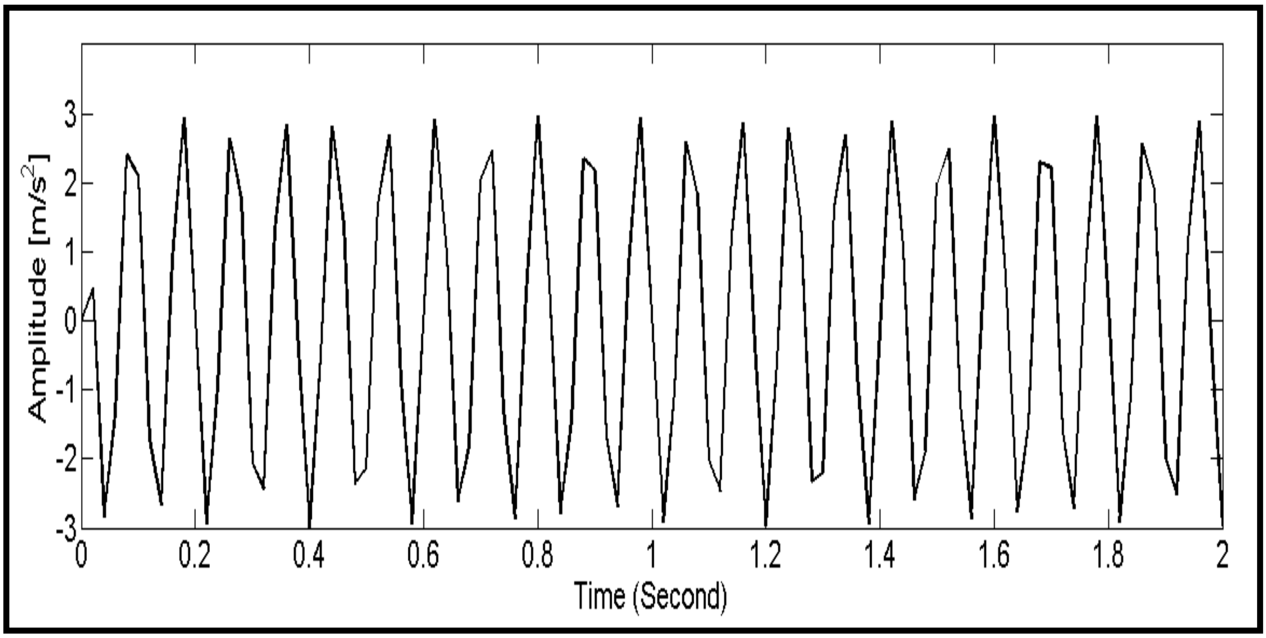


Fig 5.37 Time domain plots of floor to knee transmissibility for normal standing human exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

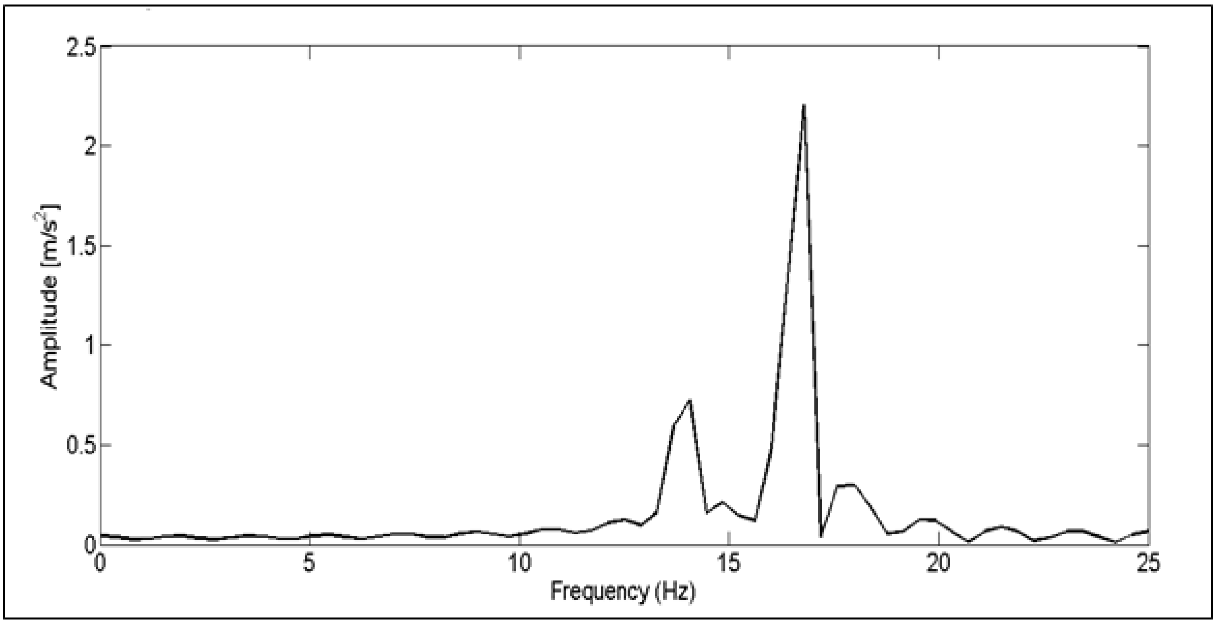


Fig 5.38 Frequency domain plots of floor to knee transmissibility for normal standing human exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

5.8.2 Holding rod posture

From the Fig. 5.39 and 5.40 it has been observed that the knee acceleration is measured in the time domain and frequency domain plots. From the Fig 5.39 it has been observed that the behavior of vibration is sinusoidal in nature and the acceleration measured for time duration of 2 Sec gives the peak acceleration of 2.3 m/s^2 and from the Fig 5.40 the resonance peaks were analyzed for the frequency range from 0 – 25 Hz and it has been observed that the principal resonance peak found at 15 Hz with 2.3 m/s^2.

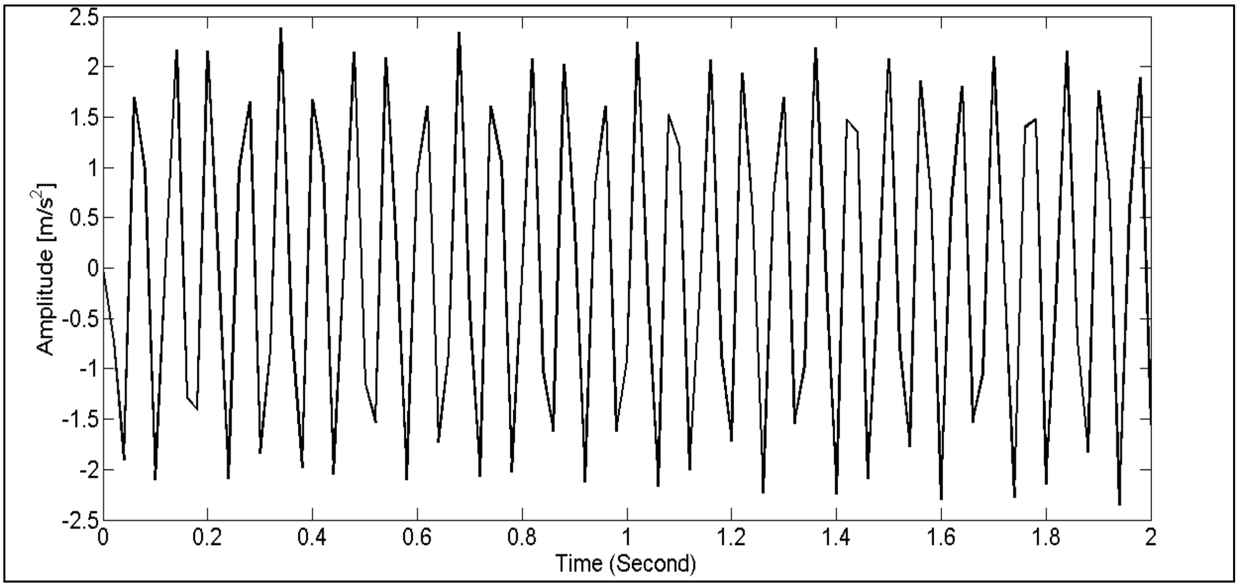


Fig 5.39 - Time domain plots of floor to knee transmissibility for holding rod exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s.

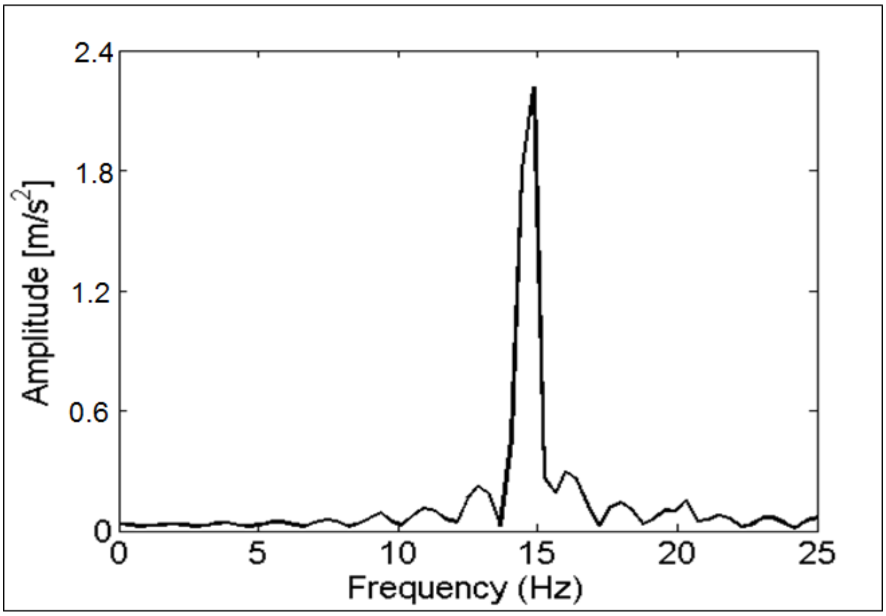


Fig 5.40 - Frequency domain plots of floor to knee transmissibility for holding rod standing posture exposed to lateral sinusoidal vibration at 1 m/s^2 r.m.s

Table 5.9 summarizes the frequency response of the knee lateral direction for sinusoidal excitation for two postures.

Table 5.9 – Summary of frequency response in lateral direction (FTKT)

Transmissibility	**Resonance frequencies (Hz)**	**Amplitude (m/s^2)**	**Remark**
FTKT for normal standing posture	14 17	0.70 2.35	Attenuation Amplification
FTKT for holding rod posture	15	2.3	Amplification

5.9 SITTING POSTURE FINITE ELEMENT MODEL

5.9.1 Introduction

In past research studies on the seated human body most of the work has been carried using mathematical models and using laboratory setups for the measurement of dynamic response. The finite element model and 3-Dimensional multibody models dynamic simulations of a seated human body was reported by Liang and Chiang, (2008). In the present work the objective is to develop a computational seated human body using finite element method and to extract mode shapes its deflections and respective natural frequencies in modal analysis. The 4 – DOF biomechanical model with rigid bodies connected by springs and dampers was developed by Boileau and Rakheja, (1998). The four masses represent the following four body segments: the head and neck (M1), the chest and upper torso (M2), the lower torso (M3), and the thighs and pelvis in contact with the seat (M4). The mass due to lower legs and the feet is not included in this representation, assuming they have negligible contributions to the biodynamic response of the seated body. The stiffness and damping properties of thighs and pelvis are (K4) and (C4), the lower torso are (K3) and (C3), upper torso are (K2) and (C2), and head are (K1) and (C1).

Table 5.10 - Mass, stiffness and damping properties of 4 DOF model (Boileau and Rakheja, 1998).

Biodynamical Parameters of the 4DOF model		
Mass (kg)	**Damping Coeff. (kN-sec/m)**	**Stiffness Coeff. (kN/m)**
M1 = 05.31	C1 = 0.400	K1 = 310.00
M2 = 28.49	C2 = 4.750	K2 = 28.490
M3 = 08.62	C3 = 4.585	K3 = 162.80
M4 = 12.78	C4 = 2.064	K4 = 90.000

5.9.2 Finite element modal analysis of seated human body

The geometry of the seated posture human body developed and assigned mass properties using the data given by Boileau and Rakheja, (1998). The 3–dimensional segment of seated human body geometry is constructed using solid modeling software Pro-E (Fig. 5.41) and imported to ANSYS 11.0. The material was analyzed as a linear elasic, isotropic material by assigning the mass, spring stiffness and damping properties using solid 42 element and combin14 spring damper element (ANSYS 11.0) adopted with free meshing. The seated backest is constrained in all the degrees of freedom (DOF) and analyzed for mode shape and frequencies.

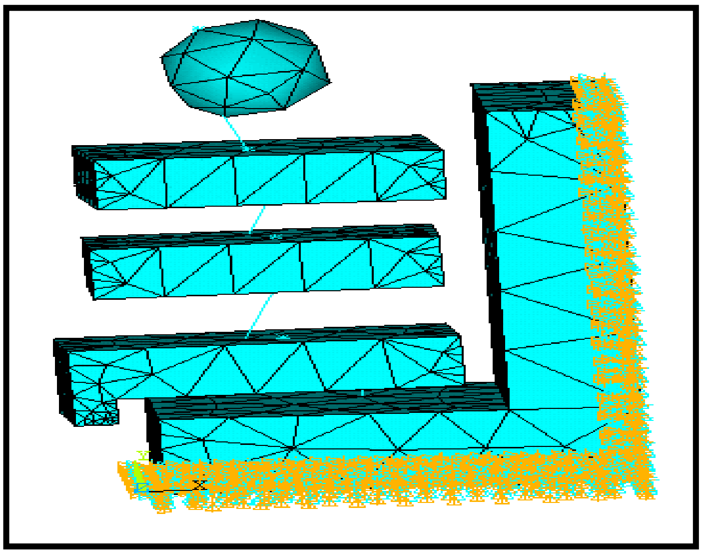


Fig. 5.41 - Discrete finite element seated human body model

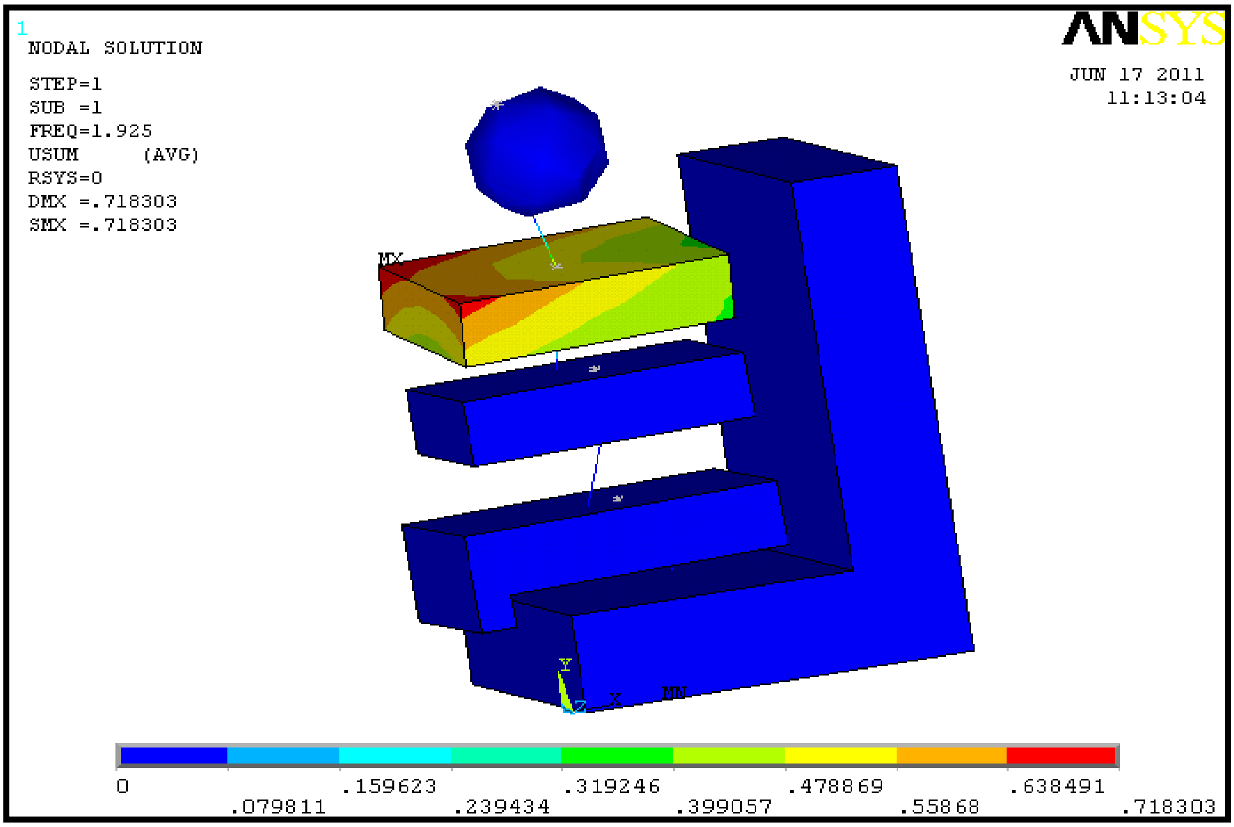


Fig. 5.42 First mode of a seated human body

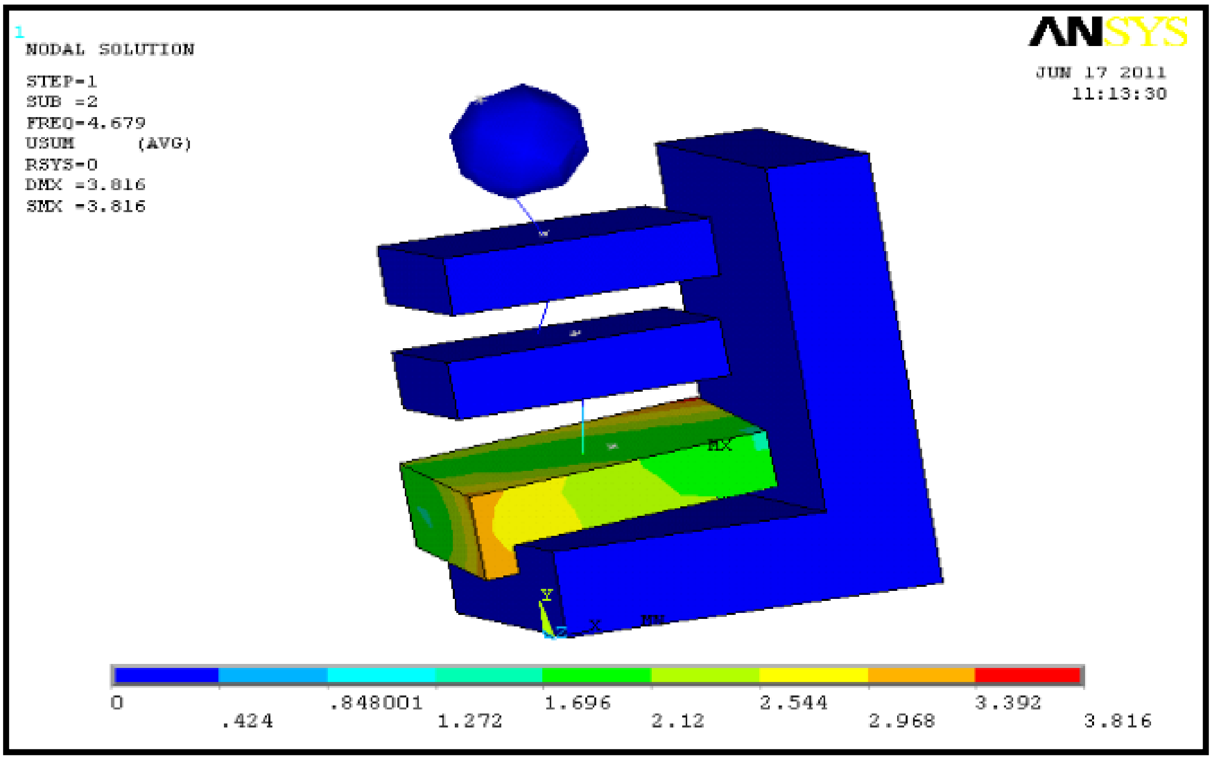


Fig. 5.43 Second mode of a seated human body

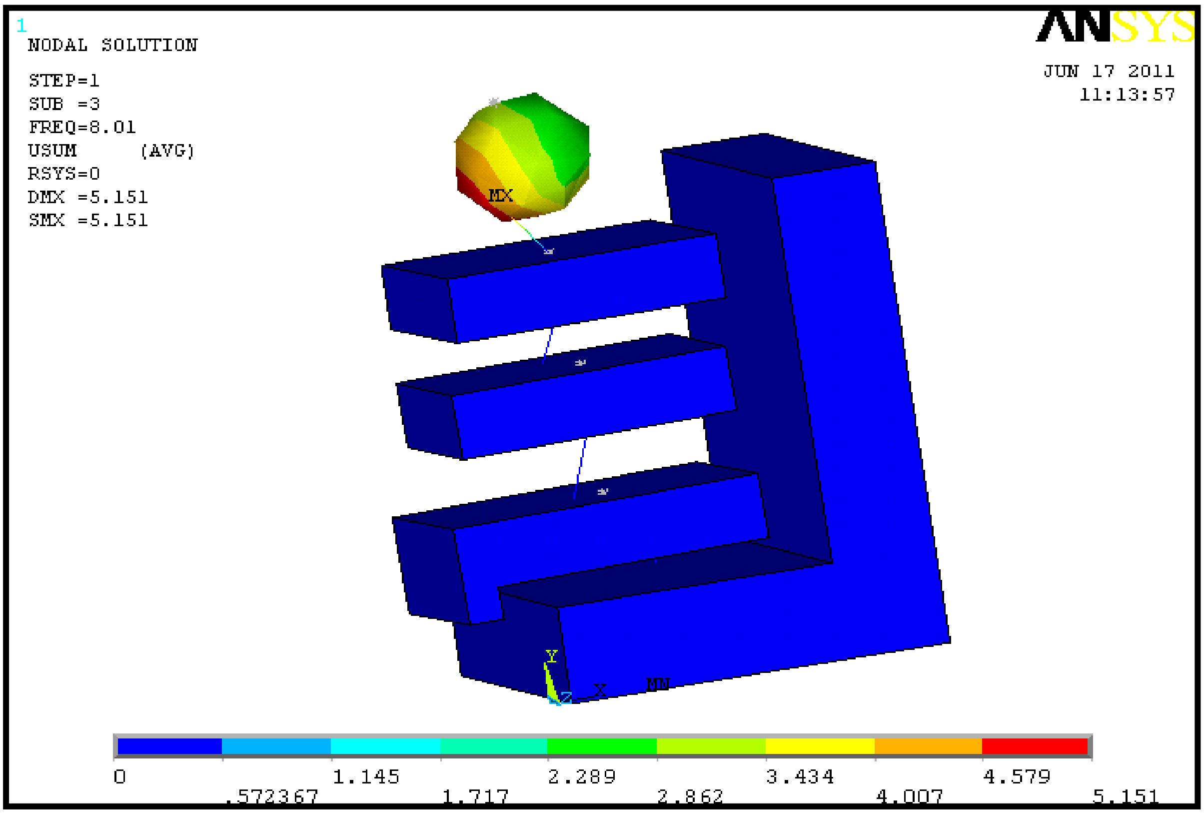


Fig. 5.44 - Third mode of a seated human body

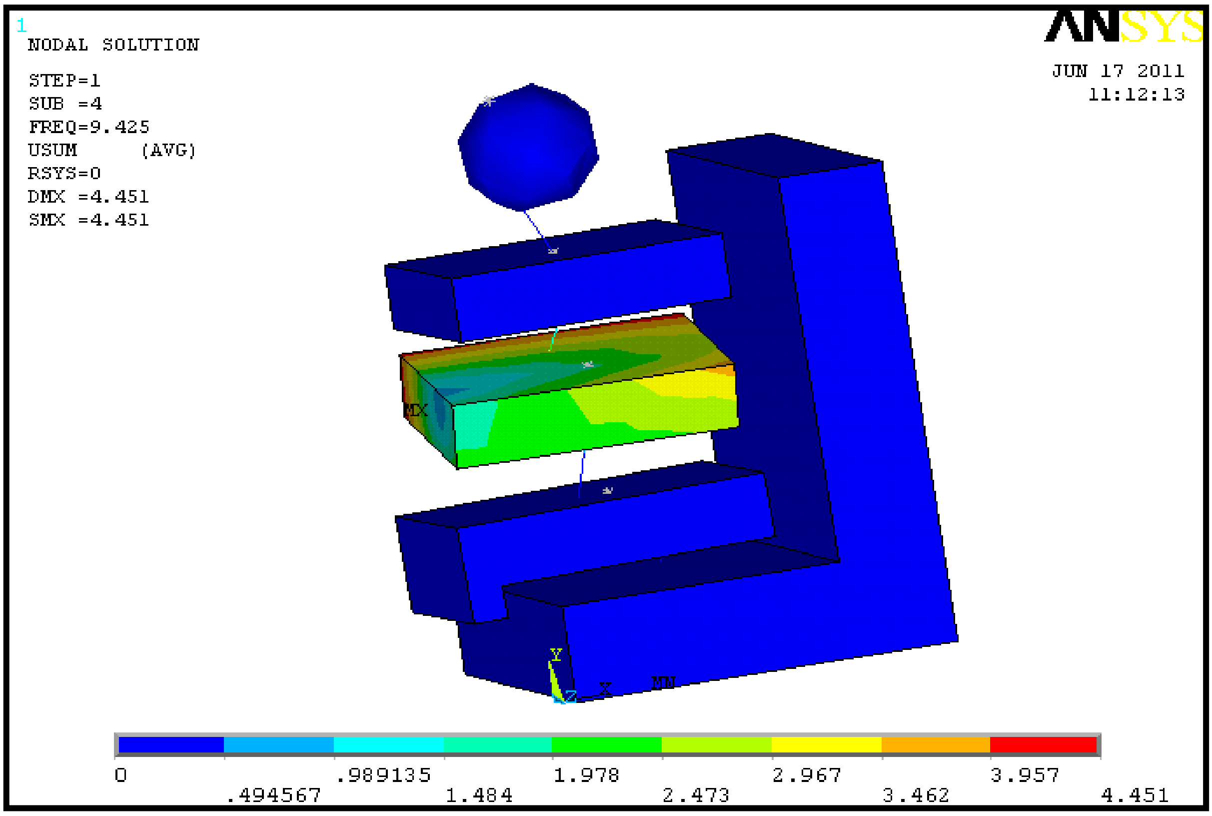


Fig. 5.45 - Fourth mode of a seated human body

Table 5.11 - Representation of natural frequencies and deflections for extracted modes

Mode numbers	Natural frequencies (Hz)	Deflection (mm)
1	1.925	0.718
2	4.679	3.816
3	8.010	5.151
4	9.425	4.451

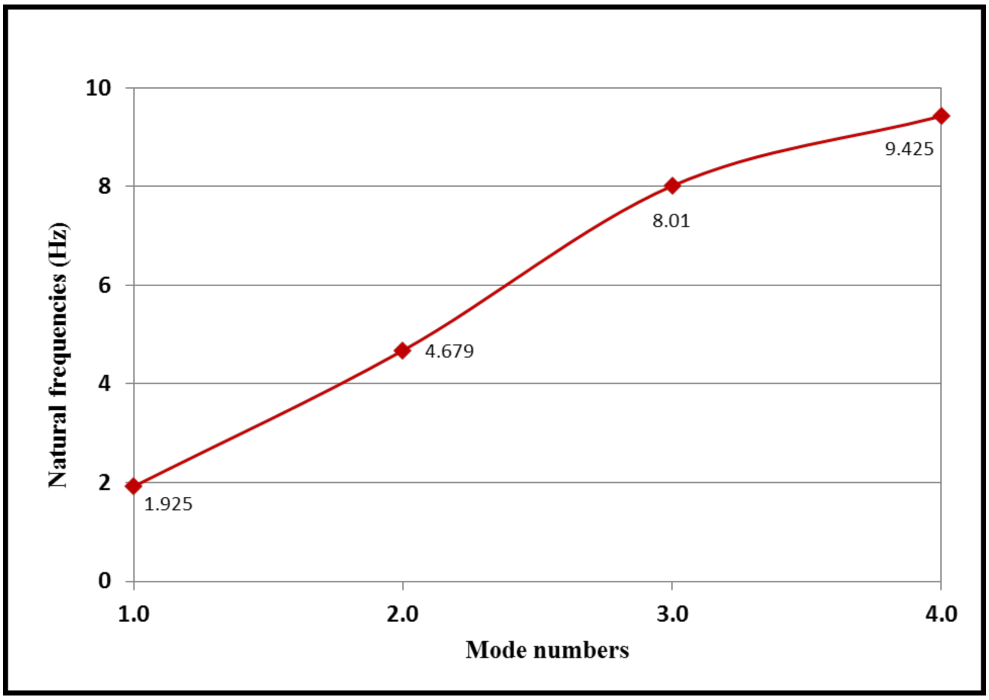


Fig. 5.46 - Finite element seated human body natural frequencies for the extracted modes.

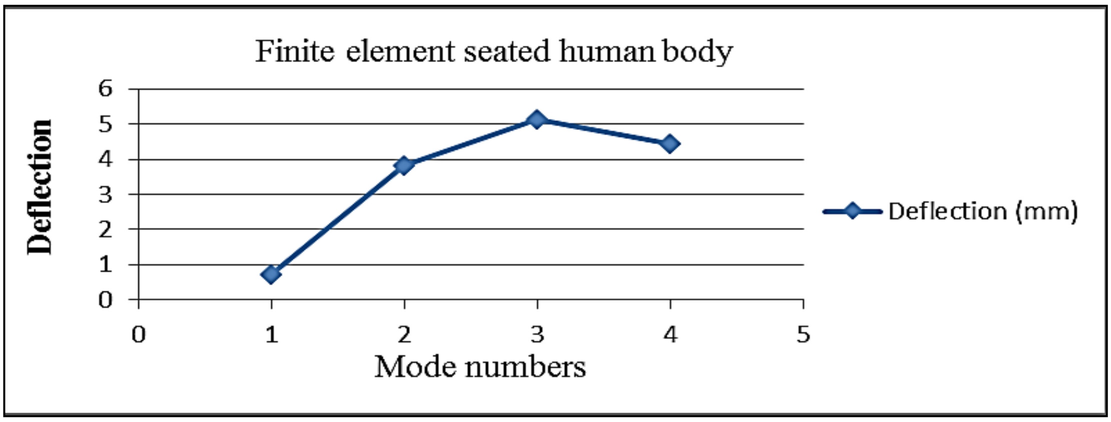


Fig. 5.47 – Finite element seated human segments deflections for the extracted modes.

The modal frequency and mode shape deflections of the model is obtained through the ANSYS simulation. Fig. 5.46 represents natural frequencies for four modes extracted from the (FE) model of seated human body. Fig. 5.47 shows that the maximum displacement occurs in the third mode shape with value being 5.15 mm and minimum displacement occurs in the first mode with the value being 0.718 mm. Fig. 5.42 – 5.45 represents the mode shape and natural frequency of different masses. The natural frequencies for various masses are: 1.92 Hz on upper torso (M2), 4.679 Hz on thighs (M4), 8.01 Hz on head (M1) and 9.425 Hz on lower torso (M3).

The analysis shows that frequency 4.679 Hz on thighs (M4) characterizes the principal resonance of the STHT. At 8.01 Hz, the head rotational mode appeares and affects the secondary resonance in the STHT. The representation of deflection (mm) and natural frequencies (Hz) with respect to their extracted modes is shown in Table. 5.11.

5.10 CONCLUSION

For the fundamental understanding of the transmission of vibration and body dynamic mechanisms at frequencies below 25 Hz, a continuous (FE) model of normal standing posture and holding rod standing posture have been developed. These FE models has been constructed in 3 dimension with the elements representing the segments of human body.

For the developed continuous (FE) model principal resonance findings have been analysed for the transmission of vibrations from foot to head (FTH) and foot to knee (FTK). These findings are in vertical (z) and lateral (y) directions while considering the excitation in the respective directions for two postures of the continuous (FE) standing human model.

⇒ **Normal standing posture**

- For FTHT with excitation magnitude of 1.0 m/s^2 in the vertical direction (z), the first mode of resonant frequency occurs at 5 Hz. At this frequency, the maximum acceleration of head is identified as 1.3 m/s^2.
- For FTHT with excitation magnitude of 1.0 m/s^2 in the lateral direction (y), only a single peak is observed at frequency of 12 Hz at the magnitude of 3.0 m/s^2.
- For FTKT with excitation magnitude of 1.0 m/s^2 in the vertical direction (z), two peaks are observed. The principal resonance frequency occurs at 12 Hz and has a magnitude of 6.0 m/s^2.
- For FTKT with excitation magnitude of 1.0 m/s^2 in the lateral direction (y), two peaks are observed. The principal resonance frequency occurs at 17 Hz and has a magnitude of 2.35 m/s^2.

⇒ **Holding rod posture**

- For FTHT with excitation magnitude of 1.0 m/s^2 in the vertical direction (z), the first mode of resonant frequency occurs at 22 Hz. At this frequency, the maximum acceleration of head is identified as 1.6 m/s^2.
- For FTHT with excitation magnitude of 1.0 m/s2 in the lateral direction (y), only a single peak is observed at frequency of 24 Hz at the magnitude of 1.7 m/s^2.

- For FTKT with excitation magnitude of 1.0 m/s^2 in the vertical direction (z), two peaks are observed. The principal resonance frequency occurs at 17 Hz and has a magnitude of 4.2 m/s^2.
- For FTKT with excitation magnitude of 1.0 m/s^2 in the lateral direction (y), two peaks are observed. The principal resonance frequency occurs at 15 Hz and has a magnitude of 2.3 m/s^2.

The conclusions from the present study suggests that the transmission of vibration to the knee is more predominant than the transmission of vibration to head due to the full extension of knees in the two adopted postures. But, when the knees are in bent postures i.e., due to flexion of knees the transmission of vibration to the human spine and head segment can be attenuated.

⇒ **Sitting posture**

- A discrete (FE) model of seated human body posture is developed and principal resonance findings for the same have been analysed.
- The modal frequency and mode shape deflections of the model clearly exhibited the maximum displacement occured in the third mode shape with value being 5.15 mm and minimum displacement occurs in the first mode with the value being 0.718 mm.
- The maximum and minimum displacements of the human body suggest that the amplification of vibration is more on thighs (M4) due to the supporting structure seat and attenuation of vibration is on head (M1) due to the inherent damping.
- The third mode corresponds to lower torso and the first mode corresponds to head. In the second mode the natural frequency of 4.679 Hz is observed.

The conclusions from the present study suggested that since, the resonance frequency is of the prime importance in low frequency vibration to study human discommfort. The obtained frequency of 4.679 Hz, which is almost near to the 5 Hz is been considered has the better result in the developed discrete FE model.

CHAPTER 6

BIODYNAMIC MODEL STUDY ON HUMAN COMFORT

6.1 INTRODUCTION

Vibration impacts human health, activities and comfort. Innumerable studies, both experimental and analytical have been conducted to determine bio-dynamic response so as to create a better working environment. As far as the response to vibration exposure in various conditions is concerned, the analytical studies find favor over the experimental, in that the simulations save time, cost and energy and moreover eliminate the ethical difficulties associated with human participation.

Humans are most sensitive to WBV under low-frequency excitation in seated posture. Therefore, biodynamic of seated human subjects has been topics of interest over the years and a number of mathematical models have been established. While much research has been performed on building up specific biodynamic models based on certain experimental data under prescribed testing conditions, a thorough investigation of mathematical human models in seated posture has not yet received the same level of attention.

Lumped-parameter models deliberate the human body as several concentrated masses unified by springs and dampers. This category of model is simple to analyze and easy to validate with experiments. But, the disadvantage is the limitation to one-directional analysis. Over the years, plenty of mathematical models have been established with different degrees of complexity depending on the analysis objective. Also, many data have been generated by different investigators to characterize these response functions using widely varying experimental conditions (Liang and Chiang, 2006, 2008).

Many human body models have been proposed to assess the impact of WBV, the driver suspension seat performance, the dynamic loads transmitted to the spinal structure, etc. These models range from simple single-degree of freedom to complex nonlinear multi- degree of freedom models (Nigam and Malik (1981, 1987, 1989); Nigam, (1990, 1996)). Majority of the models proposed in the literature are lumped parameter models, where the parameters are identified from the measured biodynamic response data. The model parameters in the majority of the studies are identified from the seat to head transmissibility (STHT) or driving point mechanical impedance (DPMI) and have been widely used in conjunction with curve-fitting algorithms. Multiple sets of model parameters may thus be derived such that the model response correlates reasonably well with the measured data. In the present study the biodynamic models of sitting and standing posture were constructed with lumped mass spring system. In the case of 5 DOF sitting posture lumped parameter model driving point mechanical impedance (DPMI), seat to head transmissibility (STHT), effect of human body mass, effect of stiffness and effect of damping constant is reported. Whereas, in the 15 DOF standing posture lumped mass spring model the system is solved to obtain the natural frequencies for the (15 × 15) mass and spring matrix using MATLAB. The obtained frequencies were analyzed for human comfort.

6.2 5 DOF MODEL

This study encompasses the development of a five DOF lumped-parameter-model and computation of seat to head transmissibility. The results have been compared with four DOF model developed by Boileau and Rakheja, (1998). The human model in sitting posture consists of five mass segments interconnected by five sets of springs and dampers, Fig. 6.1.

A model of sitting position of human is built in the form of system (mechanical type) containing springs and dampers which are interconnected. The model is shown in the Fig. 6.1 consists of five sets of springs and dampers. The five mass segments interconnected by five sets of springs and dampers, with total mass of 74.46 kg. The five masses represent the following body segments: head (m_1), upper torso including hands (m_2), thorax and back (m_3), diaphragm and abdomen (m_4) and two legs and pelvis (m_5). The stiffness and damping properties of two legs and pelvis are (k_5) and (c_5), abdomen and diaphragm are (k_4) and (c_4),the thorax and back are (k_3) and (c_3), upper torso including two hands (k_4) and (c_4), and head are (k_1) and (c_1). The schematic of the model is shown in Fig 6.1 and biomechanical parameters of the model are listed in Table 6.1.

6.2.1 Basic assumptions

The following assumptions have been made in defining the biodynamic model of the seated human subjects:

1. The mass of the seat is neglected and the displacement which occurs at the seat is same as at the pelvis.
2. A human subject is considered to be sitting without backrest support, irrespective of the hands position.
3. Body masses are range between 49 – 94 kg.
4. Feet are supported and vibrated.
5. Analysis constrained to vertical direction.

6. The human model is subjected to sinusoidal vibration excitation in the range 1–20 Hz below 5 m/s^2 amplitude.

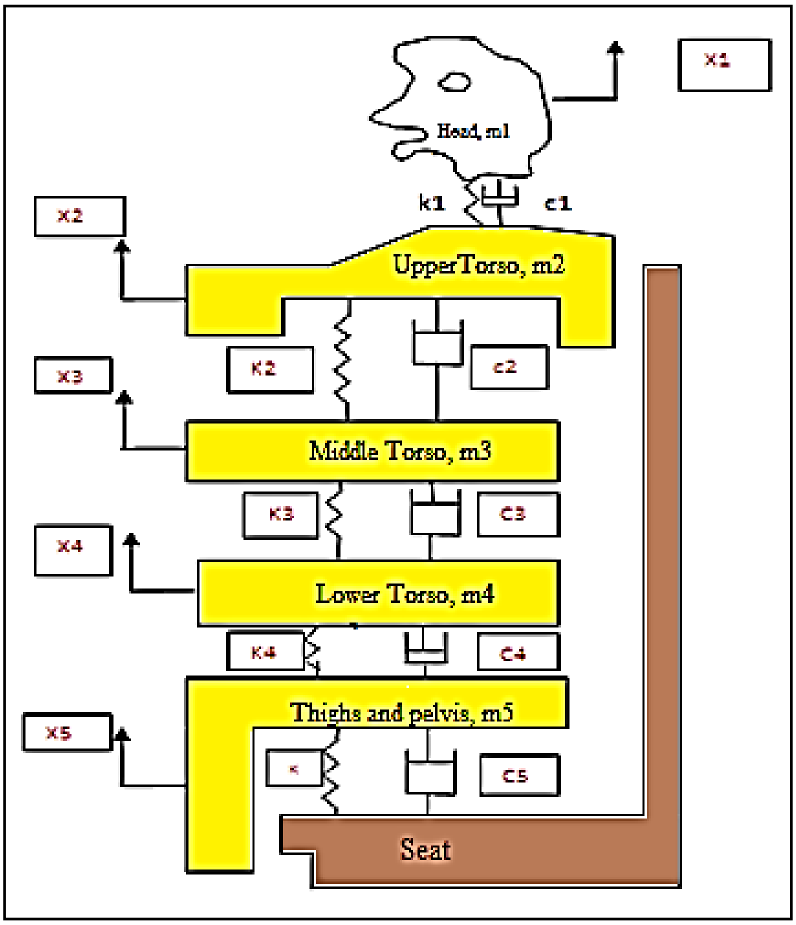


Fig. 6.1 - 5 DOF Model

Table. 6.1 Symbolic representations of human model parameters of 5 DOF Model.

Parameters	**Representation**
m_1	Mass of head
m_2	Upper torso
m_3	Middle torso
m_4	Lower torso
m_5	Thighs and pelvis

k_1, c_1	Spring and damper properties between head and upper torso.
k_2, c_2	Spring and damper properties between upper torso and middle torso.
k_3, c_3	Stiffness and damping properties between middle torso and lower torso.
k_4, c_4	Stiffness and damping properties between lower torso and thighs-pelvis.
k_5, c_5	Stiffness and damping properties between thighs-pelvis to the seat
x_1, x_2, x_3, x_4, x_5	Displacements of all the masses with respect to vertical direction.

6.2.2 Derivation of governing equations

Considering the free body diagrams of each of the masses, and applying Newton's second law, the equations of motion are as follows:

$$\left.\begin{aligned}
&m_1\ddot{x}_1 + k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) = 0 \\
&m_2\ddot{x}_2 + k_1(x_2 - x_1) + c_1(\dot{x}_2 - \dot{x}_1) + k_1(x_2 - x_3) + c_2(\dot{x}_2 - \dot{x}_3) = 0 \\
&m_3\ddot{x}_3 + k_2(x_3 - x_2) + c_1(\dot{x}_3 - \dot{x}_2) + k_3(x_3 - x_4) + c_2(\dot{x}_3 - \dot{x}_4) = 0 \\
&m_4\ddot{x}_4 + k_3(x_4 - x_3) + c_3(\dot{x}_4 - \dot{x}_3) + k_4(x_4 - x_5) + c_4(\dot{x}_4 - \dot{x}_5) = 0 \\
&m_5\ddot{x}_5 + k_4(x_5 - x_4) + c_5(\dot{x}_5 - \dot{x}_4) = k_5 x_5 + c_5\dot{x}_5 = 0
\end{aligned}\right\} \quad 6.1$$

6.2.3 Parameter search using curve fitting technique

Biodynamic responses can be analyzed from the details of the model parameters. The body part masses of the model could be determined from prevailing anthropometric data Kitazaki and Griffin, (1998); Matsumoto and Griffin, (2001). Huston, (2009) propounded that while the data of previous studies can differ considerably from one person to another, there are patterns and averages which can be beneficial in most analyses.

In this study, all the mass sections are determined from standard human body's anthropometric data provided by Huston, (2009). The average anthropometric data of the subjects involved in experimental study were found for mean mass of 74.46 kg and using these mean data, the segment masses were calculated as tabulated in Table 6.2. Many biodynamic models have been derived using trial-and-error curve-fitting techniques over specific frequency range, such that the error between the calculated and measured biodynamic response function is reduced, Wolfram, (1996). A nonlinear model fit parameter search method which is based on the above error minimization, provided within Wolfram Mathematica 7.0 (Wolfram research, Inc) is employed to determine the model parameters. Using this search method, the model parameters are optimized by decreasing the square error sum of STHT difference functions (Eqn. 6.4) over the frequency range of 1-20 Hz. The model which can provide a rational relationship with the transmissibility features is derived.

$T(j\overline{w})$ is the transmissibility of vibration motion relationship for transmission of vibration through the body in seating posture. The response function of STHT is given by:

$$STHT\ H(j\overline{w}) = \frac{a_{H(j\overline{w})}}{a_{S(j\overline{w})}} = \frac{x_{1(j\overline{w})}}{x_{5(j\overline{w})}} \qquad (6.2)$$

Where, $H(j\overline{w})$ represents STHT of complex nature, $a_{H(j\overline{w})}$ represents acceleration response normally measured in case of seated occupant at the head, and $a_{S(j\overline{w})}$ represents response for acceleration at the point of driving.

Driving Point mechanical impedance of model is:

$$DPMI\ Z(j\overline{w}) = \frac{F_{(j\overline{w})}}{V_{(j\overline{w})}} = \left| \left(c_5 + \frac{k_5}{j\overline{w}} \right) \frac{x_{5(j\overline{w})}}{x_{1(j\overline{w})}} - \left(c_5 + \frac{k_5}{j\overline{w}} \right) \right| \qquad (6.3)$$

where, $Z(j\overline{w})$ represents DPMI of compex form, $F(j\overline{w})$ and represents force required for transmission of vibration and $V(j\overline{w})$ represents velocity due to response at the point of driving, respectively. $\overline{w}$ represents angular frequency in rad/sec, and *j* represents phase of complex nature.

The square error sum of STHT (E1) over the frequency range of 1-20 Hz is given as

$$E_1 = \left[\int_{f_1}^{f_n} (T_e(f) - T_m(f))^2\, df \right] \qquad (6.4)$$

where, T_e and T_m are the experimental and model STHT respectively.

Considering assumed value of parameters related to model based on range of values for stiffness and damping coefficients from the various studies, the transmissibility values are obtained using Eqn. 6.2. The sum of squared errors for total range of frequency is examined at every sequence of search, and then re-initiation of the methodology with improved values of parameter, when the error crosses the limit as of the earlier search.

As the computed error reaches some minimal value termination of search takes place. The uniqueness of parameter set of model is verified for optimization performed with variable starting values in all circumstances. Model parameters for seated subject identified the solution of problem optimization for average mass of population (i.e. 74.46 kg).

Table. 6.2 Biodynamic parameters of 5 DOF model

Biodynamic parameters of 5 DOF model		
Mass (kg)	**Damping Coeff. (N-s/m)**	**Stiffness Coeff. (kN/m)**
m_1 = 05.31	c_1 =1400	k_1 = 310
m_2 = 28.69	c_2 =2850	k_2 = 183
m_3 = 08.62	c_3 =3585	k_3 = 250
m_4 = 10.00	c_4 =3585	k_4 = 250
m_5 = 21.84	c_5 =1700	k_5 = 010

The equations of motion for the model can be expressed in matrix form as follows:

$$[m]\{\ddot{x}\}+[c]\{\dot{x}\}+[k]\{x\}=[f] \tag{6.5}$$

where [*m*], [*c*] and [*k*] are (n × n) mass, damping and stiffness matrices, respectively; and [*f*] is the force vector due to external excitation.

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

$$[c]=\begin{bmatrix} c_1 & -c_1 & 0 & 0 & 0 \\ -c_1 & c_1+c_2 & -c_2 & 0 & 0 \\ 0 & -c_2 & c_2+c_3 & -c_3 & 0 \\ 0 & 0 & -c_3 & c_3+c_4 & -c_4 \\ 0 & 0 & 0 & -c_4 & c_4+c_5 \end{bmatrix}$$

$$[k]=\begin{bmatrix} k_1 & -k_1 & 0 & 0 & 0 \\ -k_1 & k_1+k_2 & -k_2 & 0 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 & 0 \\ 0 & 0 & -k_3 & k_3+k_4 & -k_4 \\ 0 & 0 & 0 & -k_4 & k_4+k_5 \end{bmatrix}$$

$$[f]=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ k_5 x_{seat} + c_5 x_{seat} \end{bmatrix}$$

By taking the Fourier transform of the equation (6.5), the following matrix form of equations can be obtained:

$$[X\ (jw)] = \{[K]-\omega^2\ [M]+jw[C]]^{-1}\ \{F(jw)\} \qquad (6.6\ )$$

where [X (jw)] and {F (jw)} are the FFT vectors of {x}, {f}. 'ω' is the excitation frequency and x_5 is the displacement of seat. Vector {X(jw)} contains complex displacement responses of (n×n) mass segments as a function of 'w'($\{X_1(jw),X_2(jw),X_3(jw)\ldots.X_n(jw)\}$).

{F(jw)} consists of complex excitation forces on the mass segments as a function of 'w' as well.

6.2.4 Model responses

- Effect of the stiffness coefficient: In order to investigate the effect of pelvis stiffness on the response behavior of the human body the pelvic stiffness k_5 is varied by 40% below and above from the given value shown in Fig. 6.2 and 6.3.

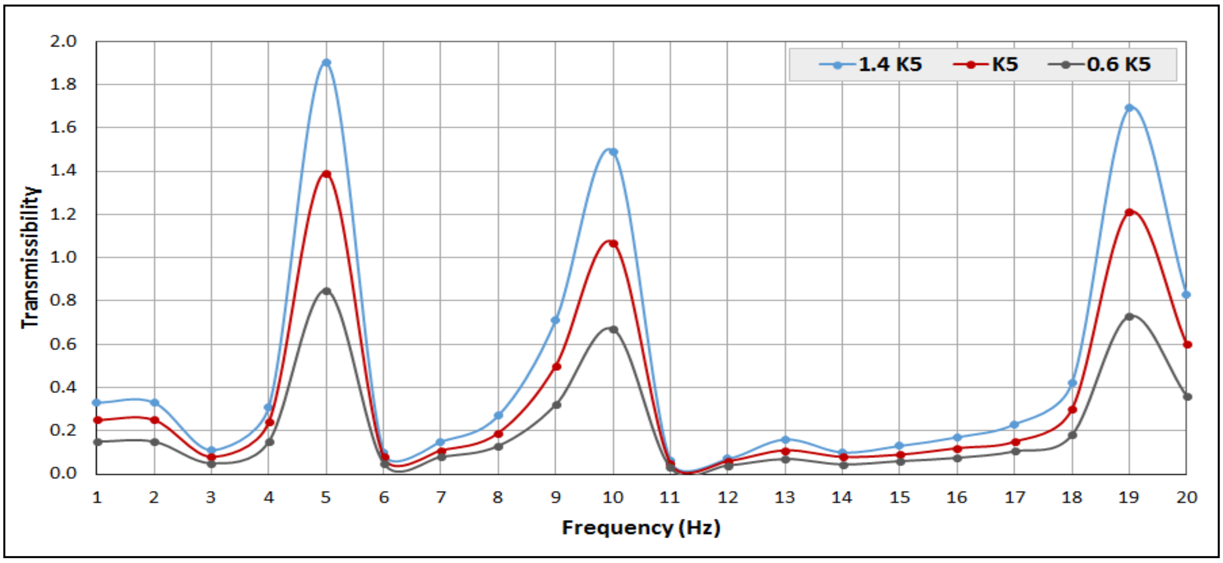


Fig. 6.2 Effect of the variation of stiffness between the pelvis and seat (k_5) on STHT

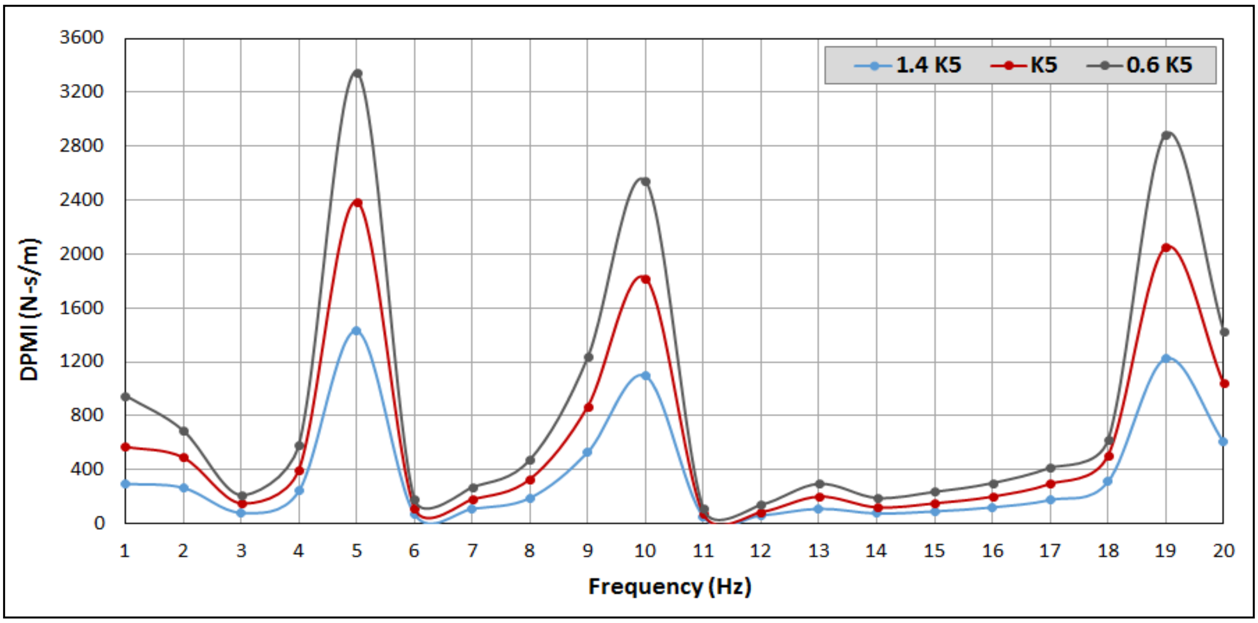


Fig. 6.3 Effect of the variation of stiffness between the pelvis and seat (k_5) on DPMI

- Effect of the damping constant:

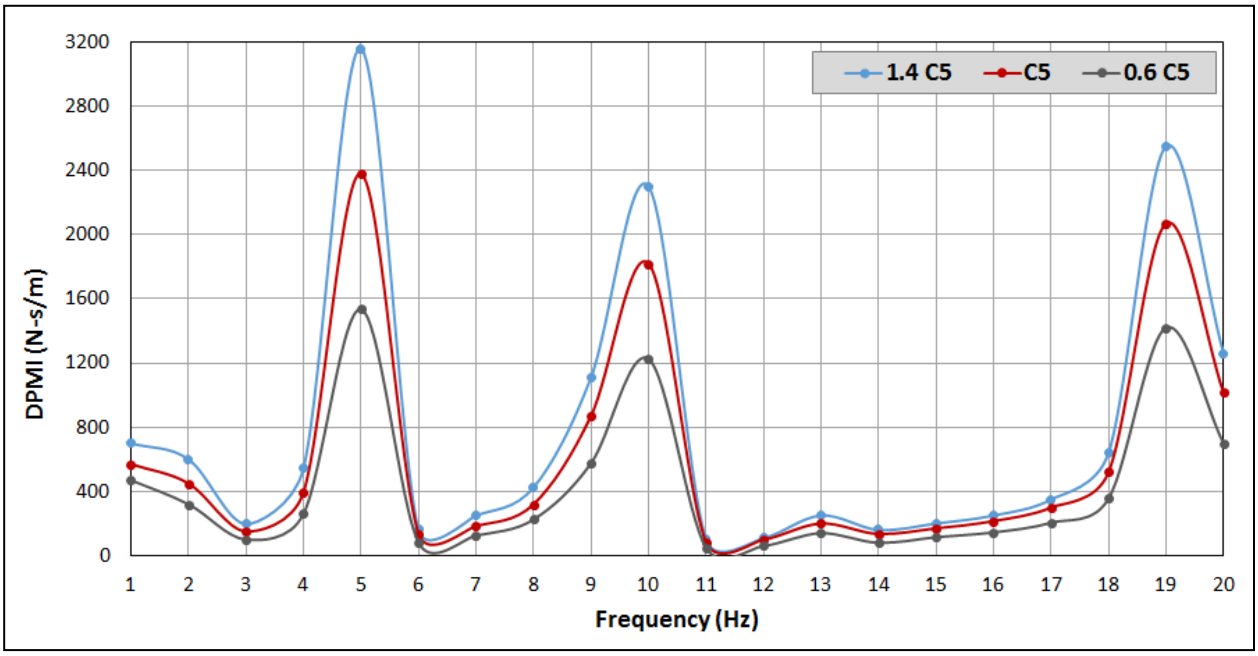


Fig. 6.4 - Effect of variation in damping constant between the pelvis and the seat (k_5) on STHT

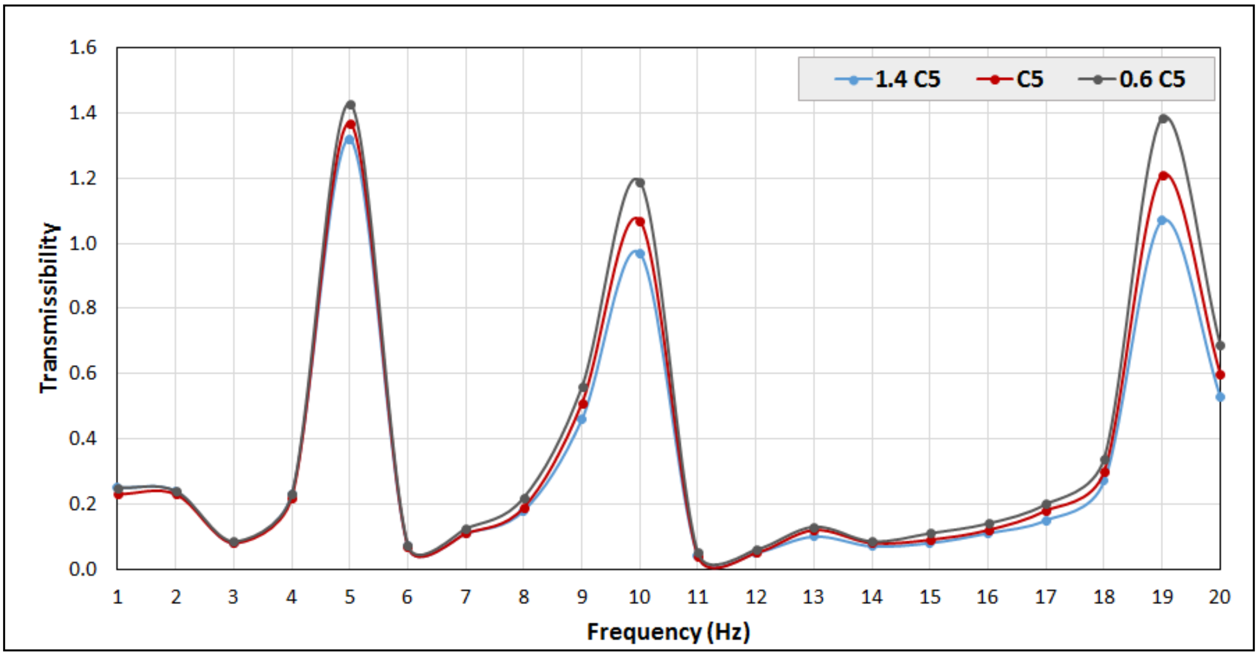


Fig. 6.5 - Effect of variation in damping constant between the pelvis and the seat (k_5) on DPMI

- Effect of human body mass:

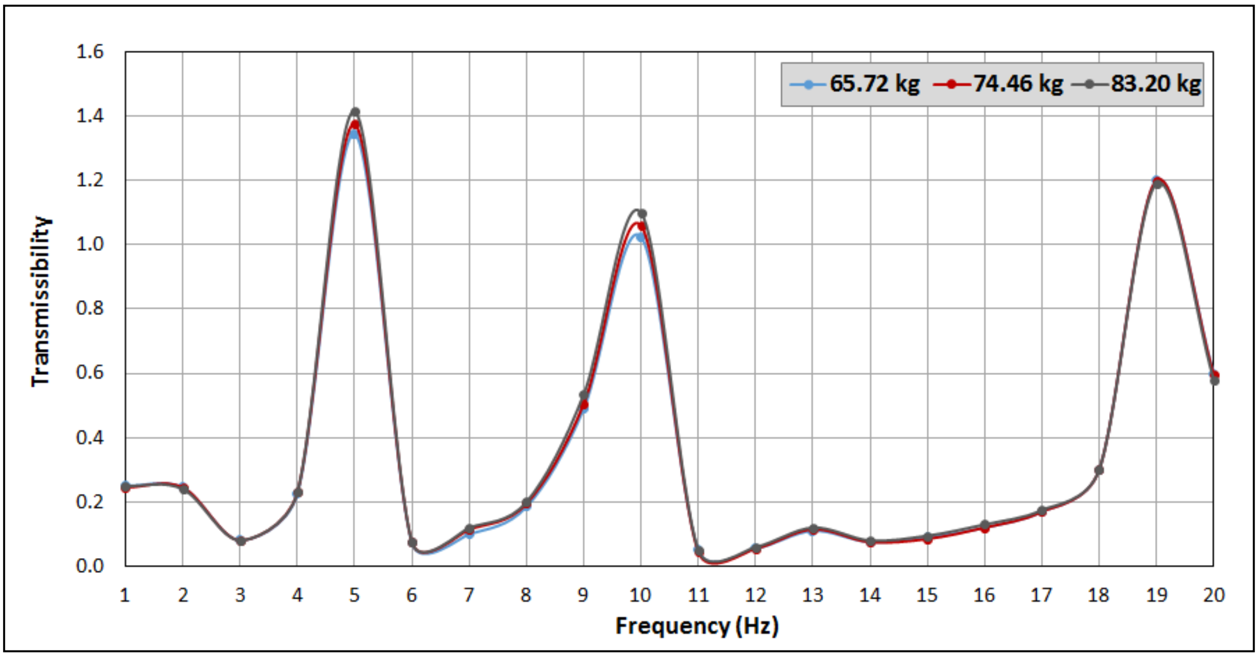


Fig 6.6 - Effect of the mass on the STHT

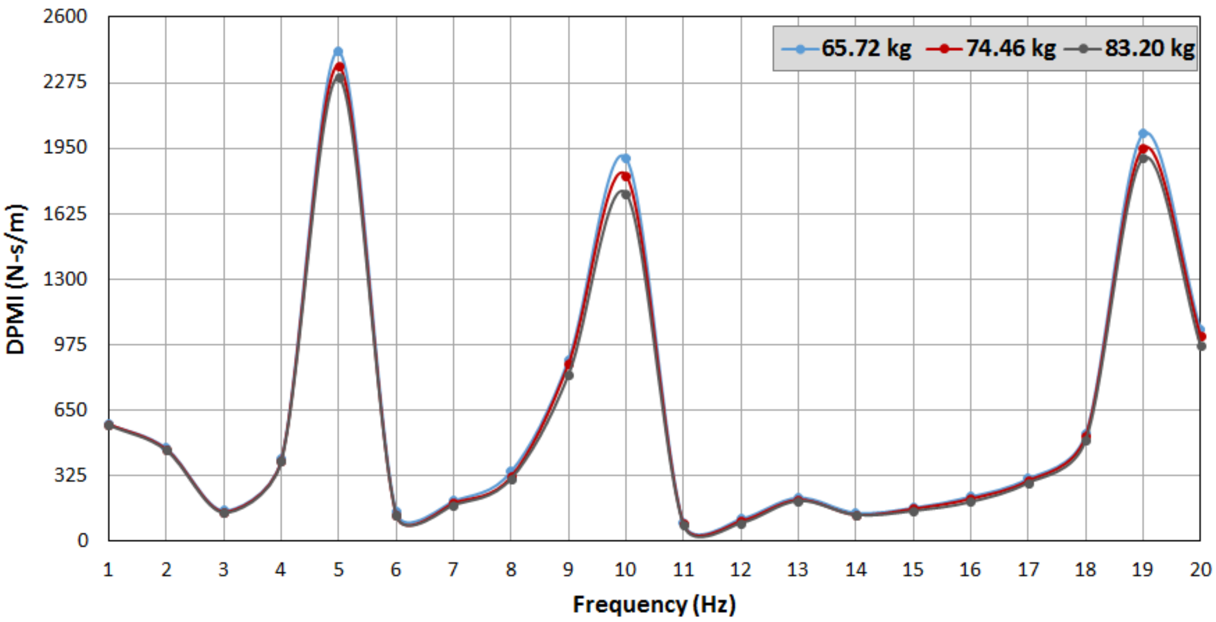


Fig 6.7 - Effect of the mass on the DPMI

The different total body mass (65.32, 74.46 and 83.2 kg.) from the literature of Huston, (2009) are used to investigate the effect of mass on the behavior of human body (STHT, DPMI). As shown in the Fig. 6.6 and 6.7.

From the Fig. 6.2 it has been observed that transmissibility increases in comparision to the actual k5 value with 1.4 k_5 and decreases with 0.6 k_5. The maximum transmissibility value observed at 5 Hz with the transmissibility value of 1.9 for 1.4 k_5 and with 0.6k_5 the transmissibility value observed at 0.85.

From the Fig. 6.3 it has been observed that DPMI decreases in comparision to the actual k_5 value with 1.4 k_5 and increases with 0.6 k_5. The maximum DPMI observed at 5 Hz with the 3300 N-s/m for 0.6 k_5 and with 1.4 k_5 the DPMI observed at 1400 N-s/m.

From the Fig. 6.4 it has been observed that DPMI increases in comparision to the actual C5 value with 1.4 k_5 and decreases with 0.6 k_5. The maximum DPMI observed at 5 Hz with the 3200 N-s/m for 1.4 k_5 and with 0.6 k_5 the DPMI observed at 1500 N-s/m.

From the Fig. 6.5 it has been observed that transmissibility decreases in comparision to the actual k_5 value with 1.4 k_5 and increases with 0.6 k_5. The maximum transmissibity value observed at 5 Hz with the transmissibility value of 1.3 for 1.4 k_5 and with 0.6 k_5 the transmissibility value observed at 1.43.

From the Fig. 6.6 it has been observed that DPMI increases for 65.72 kg and decreases for 83.20 kg. The maximum DPMI observed at 5 Hz with the 2400 N-s/m for 65.72 kg and 2280 N-s/m observed for 83.20 kg.

From the Fig. 6.7 it has been observed that transmissibilty decreases for 65.72 kg and increases for 83.20 kg. The maximum transmissibilty observed at 5 Hz with 1.4 for 83.20 kg and observed 1.38 for 65.72 kg.

6.3 15 DOF MODEL

The standing posture model in 3-Dimension is developed with five percent truncated ellipsoidal segments using anthropometric data. Mass and stiffness values for these segments are considered and Young's modulus is derived using elastic moduli of bones and tissues developed by Nigam and Malik, (1987).

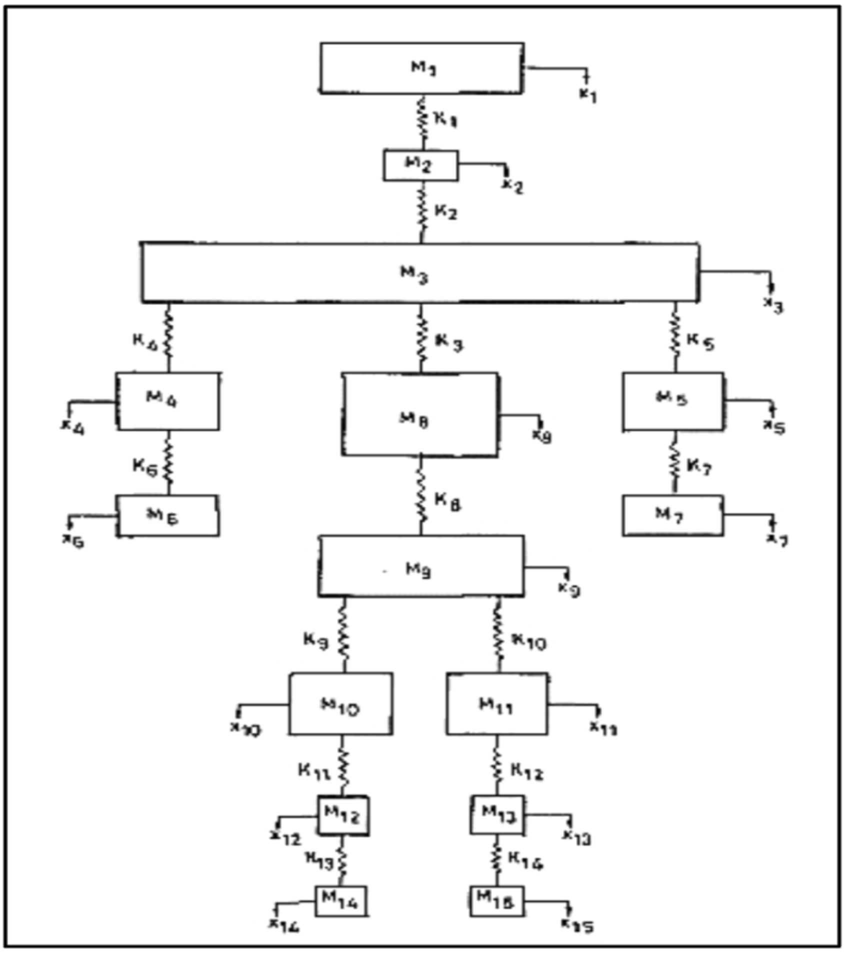


Fig. 6.8 15 DOF Model

6.3.1 Free body diagrams of 15 DOF lumped parameter model

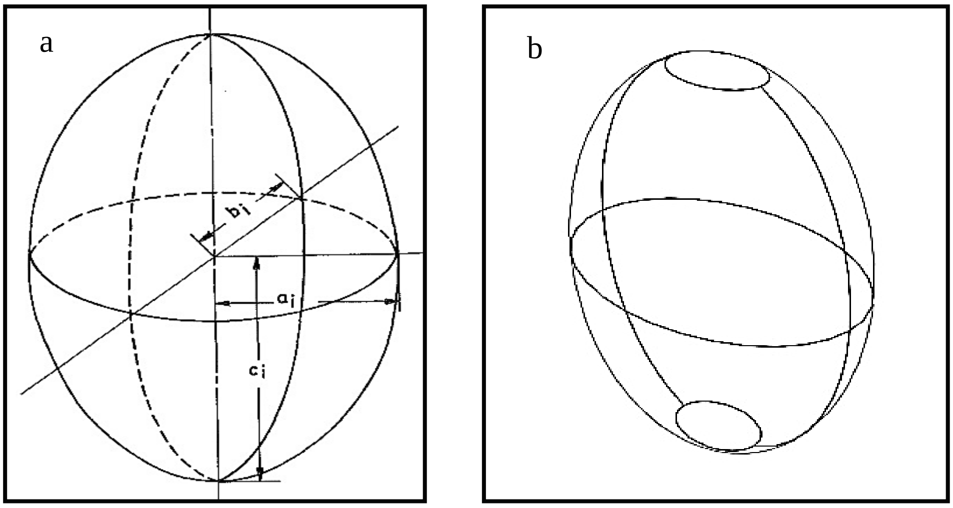
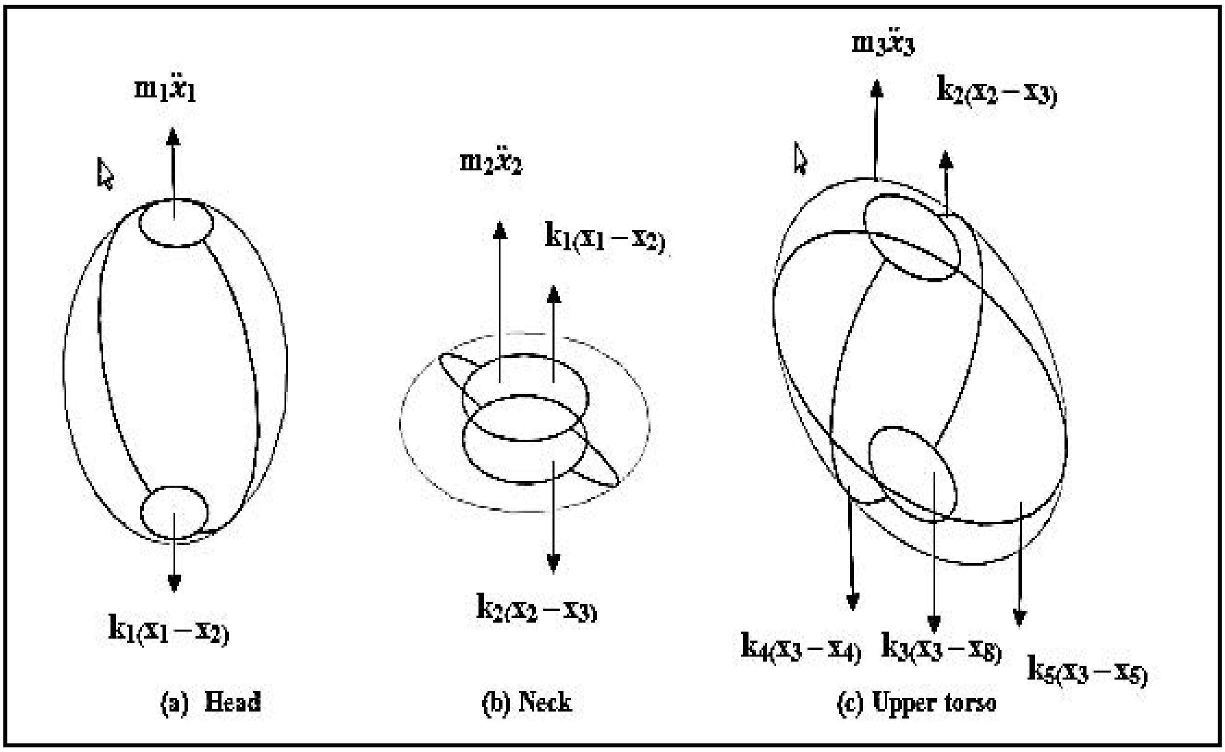
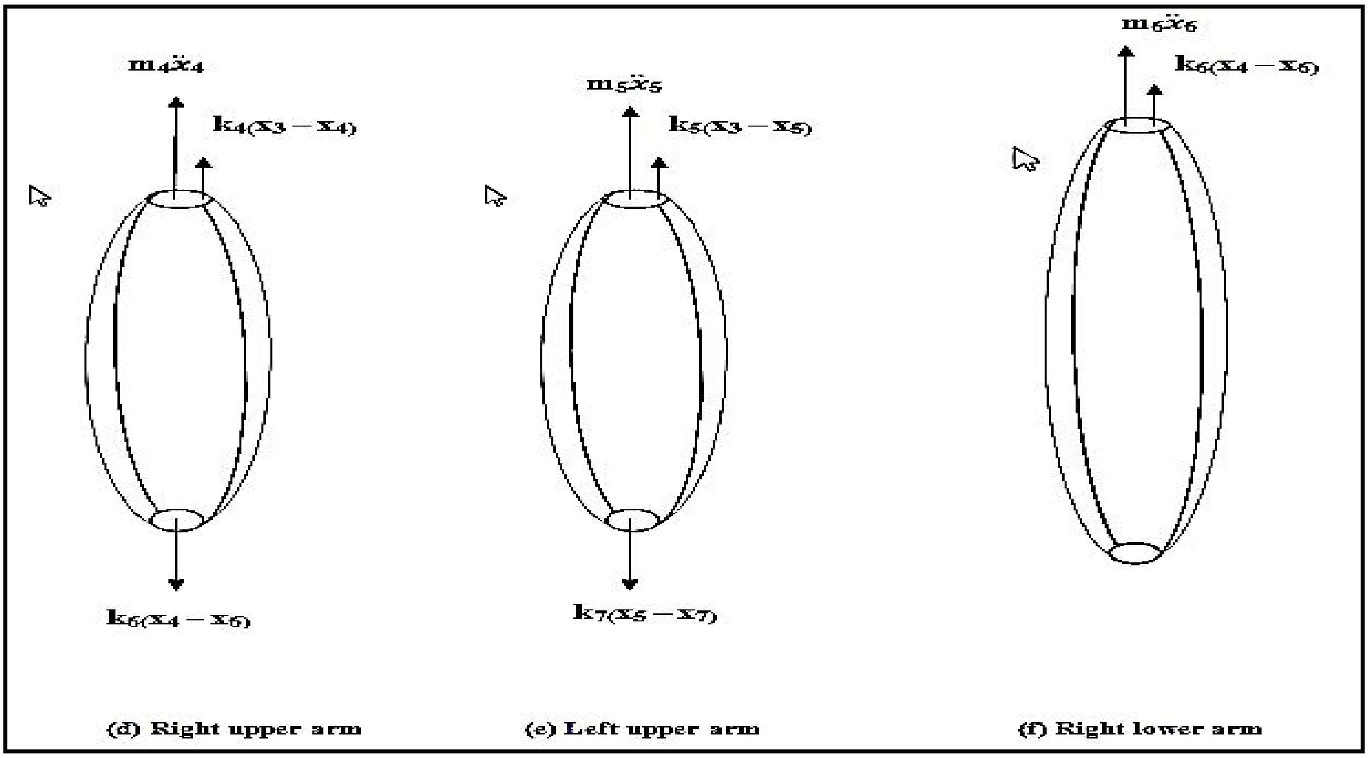


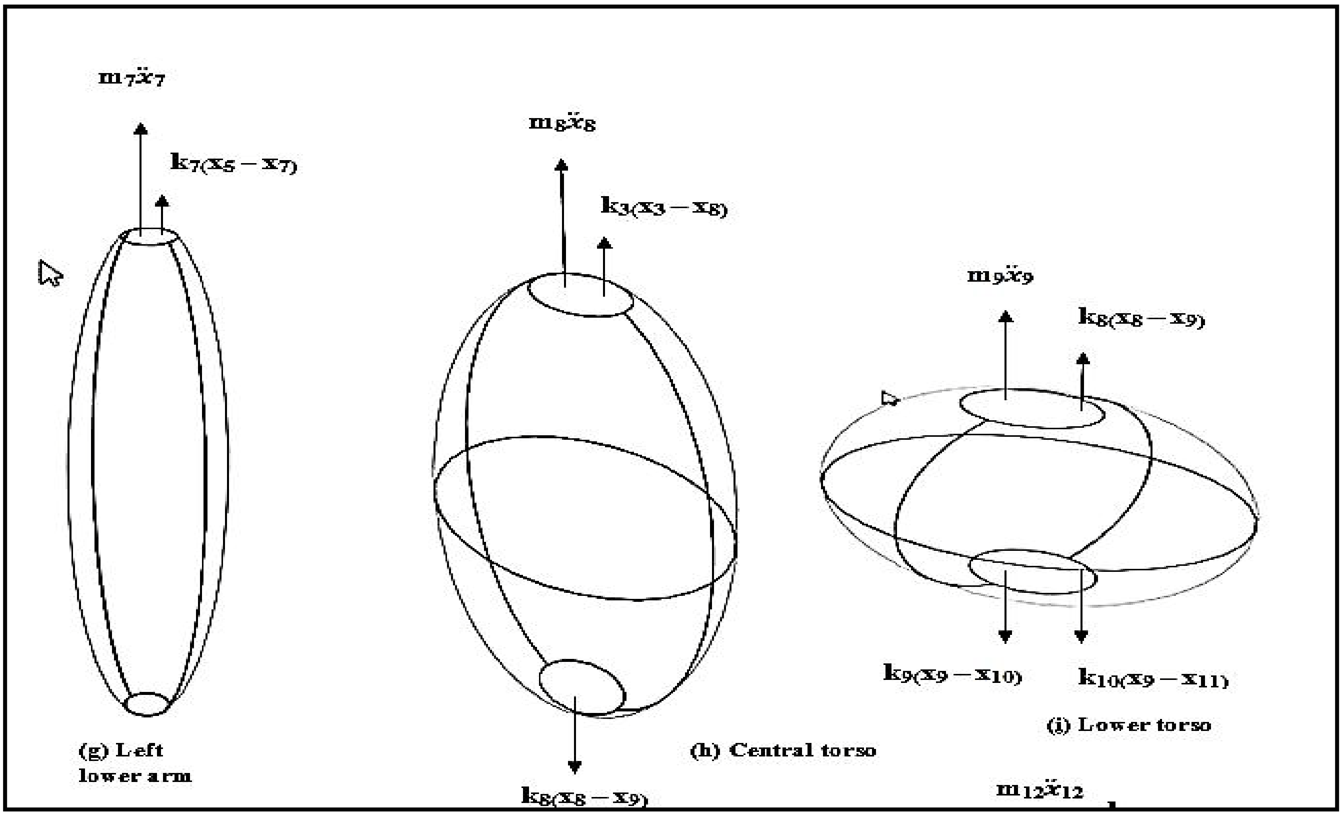
Fig. 6.9 (a) Ellipsoid and (b) truncated ellipsoid with 5 %

Free body diagrams

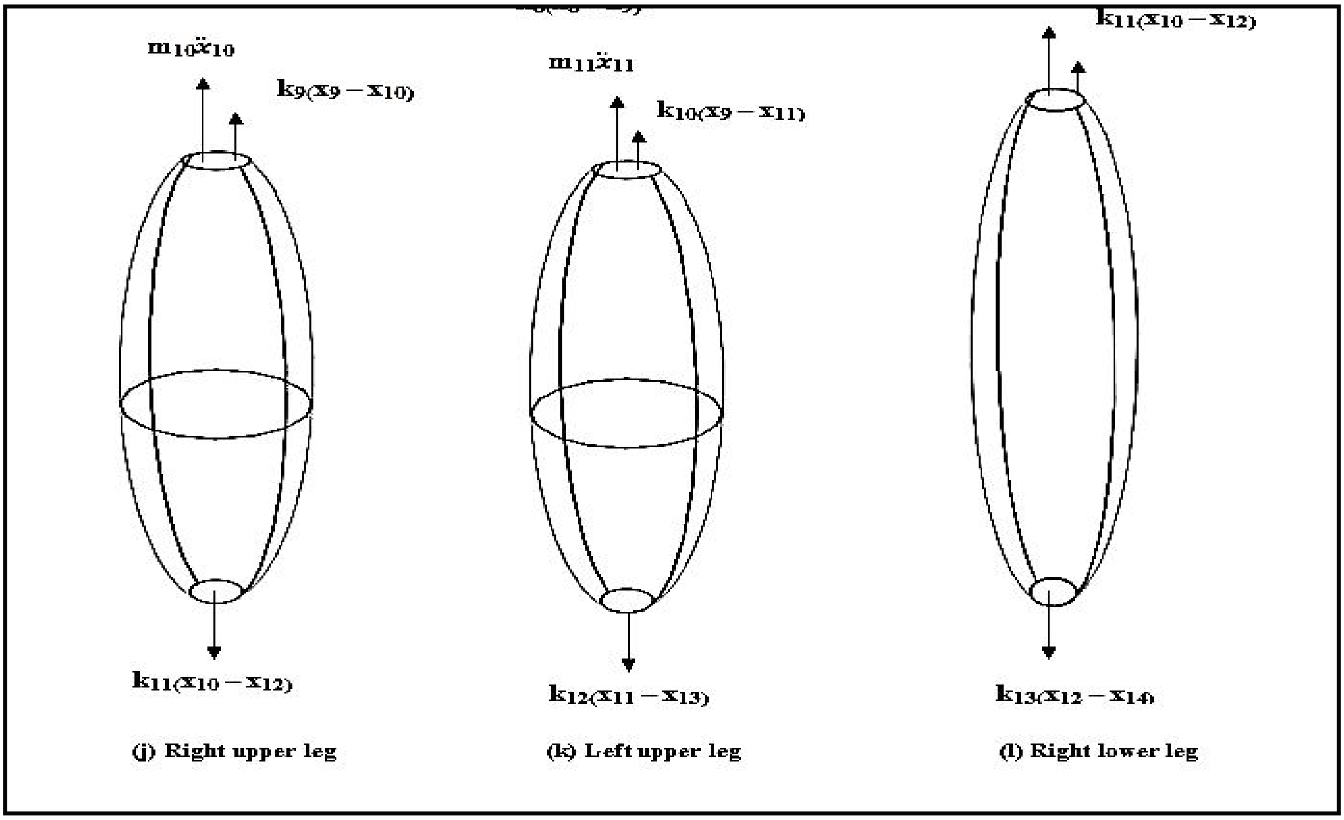




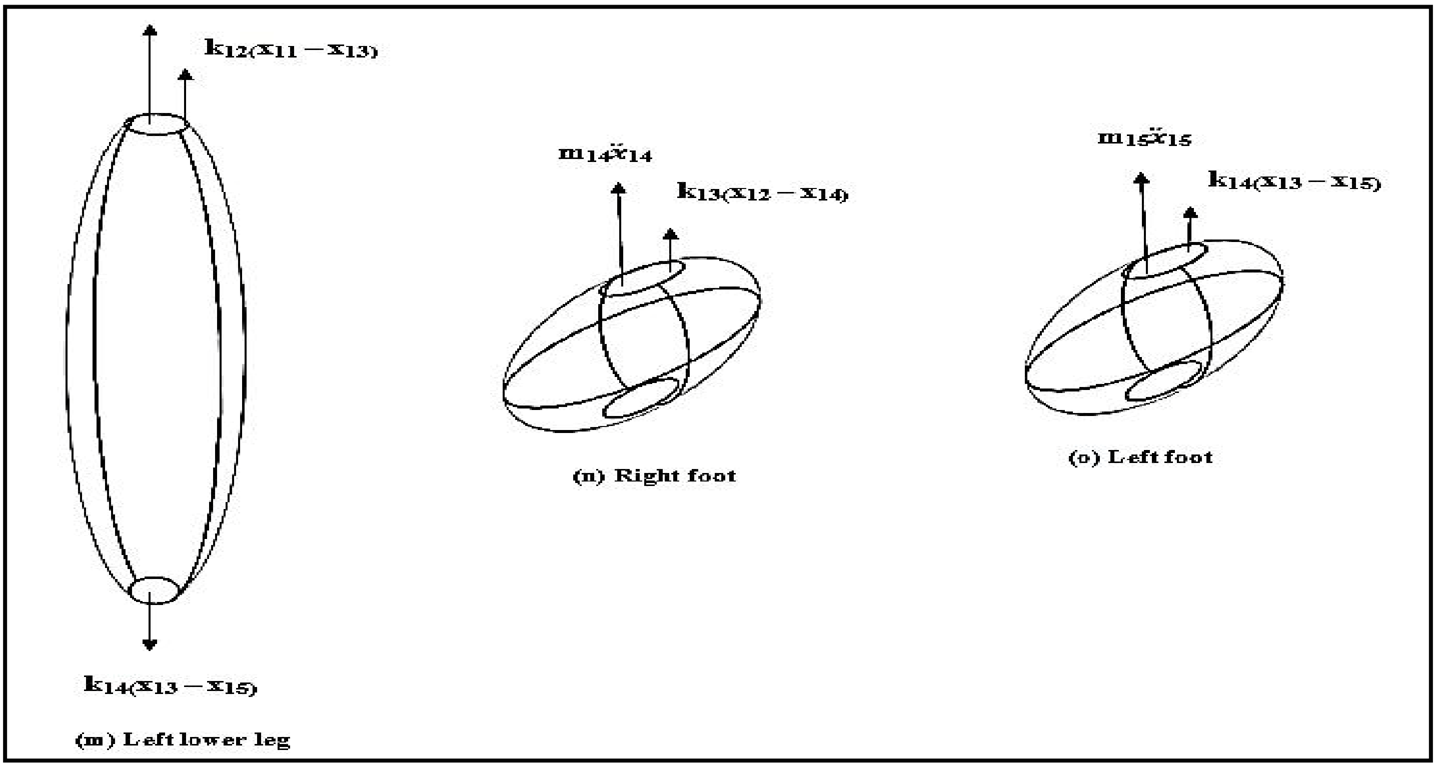
(d) Right upper arm (e) Left upper arm (f) Right lower arm



(g) Left lower arm (h) Central torso (i) Lower torso



(j) Right upper leg (k) Left upper leg (l) Right lower leg



(m) Left lower leg (n) Right foot (o) Left foot

Fig. 6.10 - Free body diagrams of 15 DOF lumped parameter model

Fig. 6.9 (b) represents the ellipsoidal human segments with 5 % truncation. The dimensions and anthropometry data are considered from Nigam and Malik, (1987). Fig 6.10 represents the free body diagrams for the individual segments of 15 DOF normal standing posture human body.

6.3.2 Derivation of governing equations

The equations of motion describing the system dynamic performance are derived for the models using Newton second law of motion and written in general and simplified matrix form as follows in (eq. 6.7).

$$\left.\begin{aligned}
&m_1\ddot{x}_1 + k_1 x_1 - k_1 x_2 = 0\\
&m_2\ddot{x}_2 - k_1 x_1 + (k_1 + k_2) x_2 - k_2 x_3 = 0\\
&m_3\ddot{x}_3 - k_2 x_2 + (k_2 + k_3 + k_4 + k_5) x_3 - k_4 x_4 - k_5 x_5 - k_3 x_8 = 0\\
&m_4\ddot{x}_4 - k_4 x_3 + (k_4 + k_6) x_4 - k_4 x_4 - k_6 x_6 = 0\\
&m_5\ddot{x}_5 - k_5 x_3 + (k_5 + k_7) x_5 - k_7 x_7 = 0\\
&m_6\ddot{x}_6 - k_6 x_4 + k_6 x_6 = 0\\
&m_7\ddot{x}_7 - k_7 x_5 + k_7 x_7 = 0\\
&m_8\ddot{x}_8 - k_3 x_3 + (k_3 + k_8) x_8 - k_8 x_9 = 0\\
&m_9\ddot{x}_9 - k_8 x_8 + (k_8 + k_9 + k_{10}) x_9 - k_9 x_{10} - k_{10} x_{11} = 0\\
&m_{10}\ddot{x}_{10} - k_9 x_9 + (k_9 + k_{11}) x_{10} - k_{11} x_{12} = 0\\
&m_{11}\ddot{x}_{11} - k_{10} x_9 + (k_{10} + k_{12}) x_{11} - k_{12} x_{13} = 0\\
&m_{12}\ddot{x}_{12} - k_{11} x_{10} + (k_{11} + k_{13}) x_{12} - k_{13} x_{14} = 0\\
&m_{13}\ddot{x}_{13} - k_{12} x_{11} + (k_{12} + k_{14}) x_{13} - k_{14} x_{15} = 0\\
&m_{14}\ddot{x}_{14} - k_{13} x_{12} + k_{13} x_{14} = 0\\
&m_{15}\ddot{x}_{15} - k_{14} x_{13} + k_{14} x_{15} = 0
\end{aligned}\right\} \qquad (6.7)$$

6.3.3 Solving equations in MATLAB for natural frequencies

The mathematical model consisting of fifteen degree of freedom standing human body is been solved for obtaining natural frequencies. In the model, mass of each rigid element equals the mass of the corresponding segments developed by Nigam and Malik, (1987). The model is considered with the case of free vibrations with mass and stiffness only. Where, [M] and [K] are respectively mass and stiffness matrices of order 15 × 15. For solving 15 × 15 matrices MATLAB is used and Eigen values were obtained. The computed natural frequencies of the model are as follows:

$$m\ddot{x} + kx = 0 \qquad (6.8)$$

$$\mathbf{[M] =} \begin{bmatrix}
\mathrm{m}_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & \mathrm{m}_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & \mathrm{m}_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \mathrm{m}_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & \mathrm{m}_5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \mathrm{m}_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_9 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_{10} & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_{11} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_{12} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_{13} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_{14} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \mathrm{m}_{15}
\end{bmatrix}$$

$$\mathbf{[K] =} \begin{bmatrix}
k_1 & -k_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-k_1 & k_1+k_2 & -k_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -k_2 & k_2+k_3+k_4+k_5 & -k_4 & -k_5 & 0 & 0 & -k_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_4 & k_4+k_6 & -k_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_5 & 0 & k_5+k_7 & 0 & -k_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -k_6 & 0 & k_6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -k_7 & 0 & k_7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -k_3 & 0 & 0 & 0 & 0 & k_3+k_8 & -k_8 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_8 & k_8+k_9+k_{10} & -k_9 & -k_{10} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{10} & k_{10}+k_{12} & 0 & -k_{12} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{10} & 0 & k_{10}+k_{11} & 0 & -k_{12} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{11} & 0 & k_{11}+k_{13} & 0 & -k_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{12} & 0 & k_{12}+k_{14} & 0 & -k_{14} \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{13} & 0 & k_{13} & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -k_{14} & 0 & k_{14}
\end{bmatrix}$$

$$\left[\ddot{X}\right]^T = \left[\ddot{x}_1 \quad \ddot{x}_2 \quad \ddot{x}_3 \quad \ddot{x}_4 \quad \ddot{x}_5 \quad \ddot{x}_6 \quad \ddot{x}_7 \quad \ddot{x}_8 \quad \ddot{x}_9 \quad \ddot{x}_{10} \quad \ddot{x}_{11} \quad \ddot{x}_{12} \quad \ddot{x}_{13} \quad \ddot{x}_{14} \quad \ddot{x}_{15}\right]$$

and

$$[X]^T = [\, x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7 \quad x_8 \quad x_9 \quad x_{10} \quad x_{11} \quad x_{12} \quad x_{13} \quad x_{14} \quad x_{15} \,]$$

The first fifteen natural frequencies can be computed as

f_1 = 0 Hz, f_2 = 13.82 Hz, f_3 = 14.35 Hz, f_4 = 23.92 Hz, f_5 = 25.22 Hz,

f_6 =28.77 Hz, f_7 = 29.53 Hz, f_8 = 40.29 Hz, f_9 = 53.32 Hz, f_{10}=58.27 Hz,

f_{11} =58.29 Hz, f_{12} =79.81 Hz, f_{13} = 165.6 Hz, f_{14} = 165.6 Hz, f_{15} = 507.9 Hz.

6.3.4 Results and Discussions

The validity of the proposed modeling was well assessed on the basis of a comparison of the frequency values with the available experimental data from in vivo studies. At the outset, a comparison may be made with some experimentally observed resonance peaks observed by Goldman and Von Gierke, (1961). These values correspond to discrete segments of a human body. Thus, a peak resonance near 12 to 14 Hz suggests mass-spring combination of upper torso; a peak between 20 and 30 Hz corresponds to the head resonance; hand resonance corresponds to frequency peak in between 30 Hz and 40 Hz; eye ball resonance occurs between 60 and 90 Hz; fundamental frequency of skull occurs in between 300 to 400 Hz with higher modes occurring in between 600 to 900 Hz. It is obvious that the computed frequencies lie in the range of the experimental resonance values The human vibration effects are mainly considered from 0 -80 Hz and there is very little information on the effects of exposure to WBV above 80 Hz. Natural frequencies obtained from 15 DOF lumped parameter model completely matches with the Nigam and Malik, (1987) model results.

CONCLUSION

The modeling procedure presented in this study involves several simplifying assumptions. The important being the approximation of the body segments to ellipsoidal bodies, truncation of the ellipsoids for evaluating segment stiffness, and the approximation of segment elastic modulus as a geometric mean of bone and tissue elastic modulii. However, with the adopted approximations the proposed modeling procedure seems to give a fairly good estimate of the primary natural frequencies. Damping, though inherently present in a human body, has been ignored in the present study. Also, the vibrating body has been assumed to be in the standing posture. The un-damped resonant frequencies are important parameters of any vibratory system as they signify the location of the frequency response peaks of an externally excited system. In the present approach, model structure is laid on anthropomorphic model of a human body. As such a particular posture of a human body does not seem to be a restriction for present modeling as long as an anthropomorphic model for the posture can be worked out. However, refinements in the model are being sought to account for damping and consider other body postures to make modeling approach more realistic and general.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

Comprehensive analyses are presented in chapter 3 to chapter 6, for transmission of vibration to different body segments in standing and sitting postures with their effects on postures, vibration magnitude, inter subject variability, etc., under the sections of field study, experimental study, finite element study and biodynamic study, respectively.

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~~The detail analysis of field study, experimental study, finite element study and biodynamic study, for transmission of vibration to different body segments in standing and sitting postures with their effects on postures, vibration magnitude, inter subject variability, has been made in the previous chapters 3 to chapter 6.~~ The conclusions from the previous chapters have been summarized and deliberated in this chapter. Further, ~~the~~ recommendations are made for future research studies~~y was made~~ based on the conclusions from the previous chapters~~ in detail~~.

7.1 FIELD STUDY ON HUMAN COMFORT

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In the study about ride comfort and reading activity comfort, the percentage of discomfort due to vibration and noise on sedentary activities was quantified. The vibration measurements have been made on the floor and seat of the buses and unweighted rms acceleration was acquired for analysis of discomfort. From the analysis following important aspects can be highlighted:

- The questionnaire analysis identified vibration as the~~a~~ ~~disturbing~~ factor causing maximum discomfort for reading activity conducted in all the three bus routes.
- The ~~P~~pilot study revealed that of all the postures the ‘sitting with backrest’ and ‘foot rested on floor’ postures caused most reading discomfort, which could be attributed~~ due~~ to the excitation of human body by supporting structures. Further, it was observed that the vibration amplification is more for the ‘sitting with backrest’ as compared to ‘foot rested on floor’ posture~~s~~.
- Moreover,~~Pilot study revealed~~ the maximum acceleration for seated and standing postures were measured as~~to be~~ 2.85 m/s^2 and 2.64 m/s^2 ~~for standing postures~~respectively.

This field study has~~will~~ thus highlighted~~s~~ the passenger preferences~~needs~~ for reading comfort~~able~~onboard public transport buses~~ride~~. Based on these preferences~~needs,~~ improvements can be suggested to bus operators or bus manufacturers.

7.2 HUMAN COMFORT ANALYSIS USING EXPERIMENTAL STUDY

For evaluating human comfort, an experimental study ~~in a ‘mock-up of commuter’s section’~~ was carried out on a vibration simulator~~for various subjects. The~~and vibrations transmitted to different locations on human subjects~~segments~~ were measured. Following are the significant outcomes of this work:

Standing postures

The subjects were exposed to vertical sinusoidal excitations of 1 m/s^2 in the frequency range of 3-15 Hz. The transmission of vibrations from FTH and FTK was measured in vertical and lateral direction and analyzed for the two postures, viz., ‘holding the handle’ and ‘holding the handrail’, as found in public transport ~~Indian~~ buses.

- The mean floor to head transmissibilty (FTHT) in normal standing posture exposed to vertical sinusoidal excitation of 1 m/s^2 is observed to be 1.98 at 5 Hz.
- Investigations for FTHT and floor to knee transmissibilty (FTKT) measures of biodynamic responses were made through measurements for standing humans with exposure to whole body vibration. Six adult male subjects ~~who were adult male, and~~ were considered in varying standing posture conditions ~~were considered~~.
- The effects of vibration on the two postures ‘while holding the handle’ and ‘while holding the handrail’ as found in Indian buses were measured. ~~Excitation magnitude is 1 m/s^2 r.m.s in the frequency range of 3-15 Hz.~~
- In vertical direction vibrations, the resonance peak is found at 5 Hz at the head and at the knee in both the postures, and in lateral direction the resonance peak is observed ~~at~~ near 6 Hz at the~~of~~ head in both the postures.
- The resonance peak is observed at 8 Hz ~~of~~at knee in lateral direction vibrations~~is observed at 8 Hz~~ in both the postures. For the subject holding handle there is a significant decrease in the FTHT value and the minimum is 0.01m/s^2 which is observed in the lateral direction.
- The FTHT ~~floor-to-head transmissibility~~ of different subjects in vertical direction is slightly increased while holding the handle as compared to while holding the handrail.

It is also observed that the transmissibility is increased in lateral as well as in vertical direction in both the postures while compared to the normal standing posture.

Sitting postures

The STHT transmissibility measures of biodynamic responses of seated occupants ~~inhabitants~~ exposed to whole body vibration were examined through measurements performed with 6 adult male subjects, and with varying sitting postures. Measured vertical seat to head transmissibility biodynamic responses were characterized to examine the effects of the two postures~~:~~ (erect posture and inclined back rest posture), excitation magnitudes (0.4, 0.8, 1.2 m/sec^2 r.m.s in the frequency range from 3-12 Hz) and sitting with two hands on the lap. STHT transmissibilty measures of seated human with erect posture ~~human~~ exposed under three vibration magnitudes were conducted~~exposed~~ and resonance frequency observed to be 5 Hz. STHT transmissibilty of inclined seated posture under exposure to three vibration magnitudes ~~exposed~~ revealed that~~and~~ the resonance frequency value decreases with increase in vibration magnitude~~observed~~. The shift in the frequency though, is more obvious in the back held postures. This could be interpreted as~~proposed that~~ the upper body being held against a back support presents more relaxing tendency under higher magnitudes of vertical vibration. The STHT transmissibilty also revealed that primary resonance frequency decreases by approximately 1 Hz (from 5 Hz to 4 Hz) from the erect posture to inclined posture for 1.2 m/sec^2 r.m.s vibration magnitude.

7.3 ANALYSIS OF HUMAN COMFORT USING FINITE ELEMENT METHOD

~~The present FE models has been constructed in 3 dimension with the elements representing the segments of human body.~~ The developed continuous FE models of standing human ~~posture~~ and ~~discrete FE model of~~ seated human body postures ~~principle resonance findings~~ have~~s~~ been analysed with their respective modes and found that the results are almost consistent with the lumped 15 DOF parameter model and lumped 5 DOF parameter models from the present study (Chapter. 6). For the fundamental understanding of the transmission of vibration and body dynamic mechanisms at frequencies below 25 Hz, the continuous FE models of normal standing posture and holding rod standing posture have~~s~~ been developed. The transmission of vibration i.e., FTHT, FTKT has been found in vertical (~~z~~Z) and lateral (Y~~y~~) excitation for the considered two postures of continuous FE model.

In a normal standing posture~~(z)~~ FTHT was computed~~,~~ with a vertical vibration magnitude of 1.0 m/s^2 rms, the first mode of resonant frequency was observed at 5 Hz ~~was observed at 1.4 m/s^2~~ and the ~~corresponding~~ further resonance modes were found at frequencies ~~(~~8, 11, 12, 13 and 21~~)~~ Hz respectively. Whereas~~,~~ for the FTKT, the~~each~~ resonance peak was observed for the acceleration transmissibility measured at~~in to~~ the knee. U~~u~~nder the first mode of resonant frequency 12 Hz the acceleration at the knee was found 6.5 m/s^2 and the another resonance mode has been found at 17 Hz.

For the~~In a~~ normal standing posture,~~(y)~~ FTHT was computed for lateral vibrations, it has been observed that the ~~behavior of vibration is sinusoidal in nature and the acceleration measured for time duration of 2 sec gives the~~ peak acceleration of 3 m/s^2 was observed. ~~and from the~~ The frequency response ~~the resonance peaks were~~ analyses~~zed~~ for the frequency range from 0 – 25 Hz revealed~~and it has been observed~~ that a~~the~~ principal~~e~~ resonance peak at~~of~~ 12 Hz with acceleration values of 3 m/s^2 ~~found~~. Whereas for~~,~~ FTKT it has been observed that the resonance peaks start~~ing~~ from the first ~~resonance~~ peak at~~of~~ 14 Hz with~~and~~ ~~each resonance peak was observed for~~ the acceleration transmissibility measured at ~~in to~~ the knee and ~~under~~ the first mode of resonant frequency is observed at 14 Hz at the acceleration amplitude of 3 m/s^2 ~~at the knee was found 3 m/s^2~~.

For the~~In a~~ holding rod standing posture~~(z)~~ FTHT was computed for vertical direction, with a vibration magnitude of 1.0 m/s^2 rms, the first mode of resonant frequency was found at 5 Hz but the peak was observed for the acceleration transmissibility ~~in to~~ measured at the head under the fifth mode of resonant frequency 22 Hz with 1.6 m/s^2 acceleration and the other resonance modes were found at frequencies ~~(~~12, 17, 19~~)~~ Hz respectively. Whereas, for FTKT, it has been observed that ~~the behavior of vibration is sinusoidal in nature and~~ the acceleration measured ~~for time duration of 2 sec~~ gives a~~the~~ peak value of acceleration of 4 m/s^2 at the~~under~~ resonance peak of 12 Hz and the second resonance peak of 17.5 Hz at 4.2 m/s^2 acceleration amplitude.~~.~~

In the standing posture holding the rod with FTHT computed for lateral direction, it has been observed that the head acceleration of 1.7 m/s^2 for the first mode occurred at resonant frequency of 5 Hz and the other consecutive modes were found at frequencies 12.5, 17.5, 19 and 24 Hz respectively.

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~~In a holding rod standing posture(y) FTHT, it has been observed that the head acceleration measured for time duration of 2 sec and each resonance peak was observed for the acceleration transmissibility in to the head under the first mode of resonant frequency 5 Hz the acceleration at the head was found 1.7 m/s^2 and the other resonance modes were~~

~~found at frequencies (12.5, 17.5, 19 and 24) Hz respectively.~~ Whereas~~,~~ for FTKT, it has been observed that the peak knee acceleration ~~measured for time duration of 2 Sec gives the peak acceleration~~ of 2.4 m/s^2 ~~and the resonance peaks were analyzed for the frequency range from 0 – 25 Hz found~~with principal~~e~~ resonance peak at 15 Hz ~~with 2.4 m/s^2~~.

The conclusions from the present study suggest~~ed~~ that the transmission of vibration to the knee is more predominant than the transmission of vibration to head due to the full extension of knees in the two adopted postures. But, when the knees are in bent postures i.e., due to flexion of knees the transmission of vibration to the human spine and head segment can be attenuated. Discrete finite element FE model has been developed to mainly understand the natural frequencies of lumped masses and the obtained results suggested that 8.01 Hz head rotational mode appeared and affects to the secondary resonance in the STH transmissibility

7.4 ANALYSIS OF HUMAN COMFORT USING BIODYNAMIC MODELS

Bio-dynamic studies (model development) can hypothetically save the time to perform experiments, save energy, save setup cost and totally remove the ethical difficulties associated with humans ~~take~~ taking part in the experimentation~~.~~.

The un-damped resonant frequencies are important parameters of any vibratory system as they signify the location of the frequency response peaks of an externally excited system. In the present approach, model structure is laid on anthropomorphic model of a human body. As such a particular posture of a human body does not seem to be a restriction for present modeling as long as an anthropomorphic model for the posture can be worked out. However, refinements in the model are being sought to account for damping and consider other body postures to make modeling approach more realistic and general.

- Three different values of pelvis damping c_5 is used in the present model , and value ± 40 % are used to investigate the effect of pelvis damping constant on the response behaviors of the human body STHT , DPMI as shown in the fig. (3.4). It is observed that the pelvis constant, the biodynamic response characteristics of the seated human body STHT and DPMI are decreased which is observed at the 10 Hz frequency.
- Three different values of pelvic stiffness k5 is used in the present model and the value ± 40 % are used to investigate the effect of pelvis stiffness on the response behavior of the human body. STHT , DPMI and has been observed that the pelvic stiffness ,the biodynamic response characteristics of the seated human body STHT and DPMI are increased

- The different total body mass (65.32, 74.46 and 83.2kg.) are used to investigate the effect of mass on the behavior of human body STHT, DPMI and has been observed that increasing the mass of the human body the biodynamic response characteristics of the seated human body STHT and DPMI slight increased has been observed.
- From the 5 DOF current model it is concluded that the change in the human body mass, pelvic stiffness and pelvic damping coefficient give a remarkable change with directly proportional to seated human body mass and pelvic stiffness coefficient and inversely proportional to the seat to pelvic interface damping coefficient in the biodynamic response behaviors of the seated human body.
- Natural frequencies of 15 DOF lumped parameter model obtained results perfectly matches with the Nigam and Malik, (1987) model results solved analytically using Jacobi method .

7.5 FUTURE SCOPE

Eventhough substantial attempt have been paid on field study, experimental, analytical and computational response studies in this thesis, more precise results may be possible if some advances or modifications to the current model are obtained.

- The main aim of this field study is to increase knowledge on passenger needs and to be able to suggest improvements on bus comfort. The suggested improvements will support bus operators and bus manufacturers in their work. In future using proper weighting filters vibration measurements can be made and good suspension seats would be designed for reducing vibrations in buses.
- In Indian public transport buses the common people travel more and the commuter’s are including pregnant women and small childrens. So, further study is very essential on the estimation of vibration exposure and investigation of injury risks from the source of noise, amplitude and frequency on pregnant women and small childrens.
- Investigate the potential of using eye and hand movements as an indicator of task difficulty for reading, operating mobile, and other sedentary activities like drinking water under vibration exposure.
- Investigate the effects of random multi axis vibration on other activities such as eating, drinking and sleeping.

- Test the subjective difficulty from the pseudo semantically related word chains against semantically unrelated word chains to find reading difficulty.
- Establish applicable weighting filters for different postures and activities.
- Evaluating ride comfort on Indian buses by measuring weighted acceleration amplitudes at various human-surface interfaces like seat-pan, seat-back and in inclined sitting postures backrest etc.
- This study was totally limited to vertical axis and lateral axis, which dominate the response of humanbody. However, adding other directions and running exciters in dual axis and multi axis influence in the response study and model validation may be better represent the realistic condition. Thus, it will enhance model application domain and may be increase the accuracy over which it claims apply.
- With the help of force plate, which help us to find the force at seat-though interface, it may be possible to validate all models in this study, with mechanical impedances (driving point mechanical impedance and apparent) and absorbed power. These may increase the accuracy of the model.
- Different types of the cushioning materials on the chair can be used to calculate the transmissibility and effect of the cushioning material can be ensured.
- The study can be extended to off road vehicles in order to understand the behavior of human body system in sitting posture while driving earth moving vehicles like trucks, excavators and other earth moving equipments.
- Previous studies reported that females are more sensitive to certain frequencies of vibration than males, with regard to comfort. Therefore, a similar study could merit investigation using both male and female subjects to quantify the effect of gender on activity comfort and transmissibility more accurately.
- In order to improve the accuracy of FEM models the exploration of work are still necessary in proper assignment of material properties to human tissue structure because of its complexity in converting biological aspect human physiology in to biomechanical sysmtems.
- Finite element analysis can be implemented to study the transmissibility of vibrations to knee in full extension and flexion postures of knees in sinusoidal and random vibrations.

- From the present study it has been observed that the total mass which is resting on the floor acts as a force of impact on the floor, Hence, when stiffness increases the frequency increases and when stiffness decreases frequency decreases and it is noticed that the upper body is having lesser deflection compared to lower body segments in vivo.
- The nonlinear stiffness and damping can be taken in the modelling and the vibration signature analysis can be done.

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