Measurement and Bio-dynamic Model Development of Seated Human Subjects Exposed to Low Frequency Vibration Environment

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Abstract

In this study, the effect of posture, vibration magnitude and frequency on seat-to-head (STH) and back support-to-head (BTH) transfer functions has been studied under vertical sinusoidal vibration. Twelve healthy male subjects were participated in experimental work to measure vertical vibration transmitted to the occupants head in three representative postures (erect, vertical back on and forward lean on table) under three magnitudes of vibration (0.4, 0.8 and 1.2 m/s² r.m.s.) in frequency range 1 to 20 Hz. From collected data sets, the effect of vibration magnitude, vibration frequency and postures on STH and BTH transmissibility’s and phase has been drawn over the prescribed frequency range. The result suggested that inclusion of all possible variables in optimal design of vehicle seat, suspension and comfort analysis most benefit for better design and analysis. The comparison of experimental and model response reveals that both models matched with mean experimental data sets most closely and the models provide best description about biodynamic response study of seated human subjects under vertical whole body vibration.

Keyword: Human Vibration, Seated posture, seat to head transmissibility, low frequency vibration

1. Introduction

Whole body vibration causes a complex distribution of vibration within the body and unpleasant sensations giving rise to discomfort or annoyance result in impaired performance and health risk. This distribution of vibration is dependent on extrinsic, intrinsic variables, interfaces between the body and the vibration environment. While travelling by vehicles: cars, buses, trains, ships and airplanes, there are many factors that cause discomfort, such as pressure at seat interface, sitting posture, vibration, noise, visual effects, humidity, temperature, etc. Among this, exposure to whole body vibration causes a complex distribution of vibration within the body and unpleasant sensations giving rise to discomfort or annoyance result in impaired performance (e.g. degraded vision) and health risk (e.g. tissue damage or deleterious physiological change). This distribution of vibration is dependent on extrinsic and intrinsic variables, interfaces between the body and the vibration environment. Extrinsic variables are variables those express the state or environment of the dynamics system such as magnitude, frequency, direction etc and intrinsic variables refers to the human subject natural behavior, characteristic and condition (age, posture, gender, weight, and etc). The intrinsic variables further categorized into two: Intra-subject variability and Inter-subject variability. Inter-subject variability describes the changes between different subjects or individuals and comprises
population type (age, sex, size, fitness etc.), experience, expectation, arousal, motivation, and body dynamic response. Intra-subject variability is differences within a single individual and includes alterations of body posture, position and orientation of in person.

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 different vibration environment. 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 [1]. The main objective of the study of human response to vibration is the definition of an engineering model of the response of the body [2]. 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. 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 models have been developed with this method since it is simple to analyze and easy to validate with experiments. Wei and Griffin [3] developed alternative four lumped parameter models (two 1DOF and two 2DOF) of vertical apparent mass of the seated human body. The optimum parameters were derived from the mean measured apparent masses of 60 subjects (24 men, 24 women, 12 children) and concluded that the two DOF model provides an apparent mass similar to that of the human body. Mitsunori et al. [4] have developed a synthetic vibration model reproducing the relations between the physical, psychological and physiological reactions of the human body exposed to external vibrations. Transmission ratios of the vibration of each body part to the seat were estimated through the simulation of the vibration system. And, the physiological and psychological reactions to the vibration were easily predicted by using the multiple regression equations with the transmission ratios as the explanation variables. Liang and Chiang [1], 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. Based on the analytical study and experimental validation, a four DOF model developed by Wan and Schimmels [5] 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 [6] was suggested. Kim, et al. [7], developed a bio-mechanical lumped parameter model of the human body for the vibration transmissibility and apparent mass exposed to vertical vibration in sitting posture. Finally the authors concluded that the model depict the apparent mass and head transmissibility better than other models especially the head rotational transmissibility.

The FE models hypothesize that the human body consists of numerous finite elements whose element properties were mainly obtained from experiments on human corpses. In a finite element model the system to be modeled is
divided 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. Tazaki and Griffin [8] developed a two dimensional model of human biomechanical responses to whole body vibration by using the finite element method. It is suggested that an increase in contact area between the buttocks and the thighs and the seat surface, when changing posture from erect to slouched, may decrease the axial stiffness beneath the pelvis, with a non-linear force deflection relationship of tissue resulting in decreases in the natural frequencies.

Multi-body human models are made of several rigid bodies interconnected by pin (two-dimensional) and/or ball and socket (three-dimensional) joints, and can be further separated into kinetic and kinematic models. Pranesh et al. [9] developed a 14 inertial segments and 14DOF multi-body dynamic model of the seated human body to study the driving point, vibration transmissibility and energy absorption responses to whole-body vertical vibration in the mid-sagittal plane. Teng et al. [10] examined the dynamic response of the human body in a crash event and assesses the injuries sustained to the occupant’s head, chest and pelvic regions. Yoshimura et al. [11] determined the detail measurement of human response to vibration, and modeling of seated 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 to the spinal column for seated subjects.

Although a number of experimental and analytical study have been investigated to characterize the effect of inter-subject and intra-subject variabilities on transmission of vibration through seated human subjects, none of the studies have attempted to consider the most widely used postures in vehicles, while performing sedentary activities. This study targeted three representative postures (backrest, erect and forward lean on table) and under three magnitudes (0.4, 0.8, 1.2 m/s² r.m.s.) of vibration under a frequency range 1-20Hz were considered as representative of those likely prevail in wide range of vehicles. Moreover, the study attempt to validate two lumped parameter models using the seat to head (STH) and back support to head (BTH) transmissibility and the corresponding phase difference.

2. Experimental Setup

The study was conducted on the vibration simulator in natural laboratory environment, developed as a mockup of a railway vehicle, in Vehicle Dynamics Laboratory, IIT Roorkee, India. The vibration simulator is located in a room with sound absorbing materials placed on the walls to obtain reduced noise environment. It consists of a platform made up of stainless steel corrugated sheets of size 2 m × 2 m, on which a chair have been securely fixed. The weight of the platform is supported by four helical springs placed under each of its corner. The Electro-Dynamic Vibration shakers are used to provide longitudinal, lateral and vertical motion to the platform. The vibration exciter had a force capacity of 1000 N with a stroke length of 25 mm (p-p), Fig. 2.1. In the performed experiment, the sinusoidal vertical vibration signal, generated by the controller was used to excite the shaker. For simplicity and safety reasons the internal positioning accelerometer of the shaker was continuously used for motion feedback.

3. Method and Analysis
Twelve healthy male subjects participated in the experiment with age between 20-37 years, height 160-182 cm tall and weighs 57-93 kg. Subjects sat on the flat rigid surface of a seat 470 mm above their feet. Each subject was exposed to three vibration magnitudes (0.4, 0.8 and 1.2 m/s² r.m.s.) at 1, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 8, 10, 12.5, 16 and 20 Hz sinusoidal frequency in three different sitting postures(erect, backrest contact and leaning forward on table). The 60 s vibration stimuli were given to the subject under the above vibration conditions. The three postures used in experiment are shown in Fig. 2.2. In order to determine STH transmissibility function, the seat pad accelerometer was placed on the surface of the rigid seat beneath the subject’s ichial tuberosities to measure seat vibration. Accelerometer was also mounted on plastic helmet to register head vibration. Data from accelerometers HBM B12/200 were conditioned and acquired through data acquisition system into Labview Signal Express software at 1K sampling rate.

![Schematic diagram of vibration simulator and accessories](image)

4. Results

4.1 Effect of Vibration Magnitude on Seat-to-Head Transmissibility

Figs. 4.1, 4.2, 4.3 compare mean vertical seat-to-head transmissibility responses for twelve subjects while exposed to three excitation levels (0.4, 0.8, 1.2 m/s² r.m.s.) under three postures (Erect, vertical backrest, forward lean on table), respectively. The results distinctly reveal that resonance in seat-to-head transmissibility of erect and forward lean on table posture visibly tends to shift to a lower frequency with increasing vibration magnitude. This suggests that in erect and forward lean on table posture the upper body part exhibits more softening tendency under higher magnitudes of vertical vibration.
Fig. 4.1 Mean STH transmissibility for 12 subjects exposed to vertical sinusoidal vibration at 0.4, 0.8 and 1.2 m/s² r.m.s in erect sitting posture.

Fig. 4.2 Mean STH transmissibility for 12 subjects exposed to vertical sinusoidal vibration at 0.4, 0.8 and 1.2 m/s² r.m.s in vertical backrest posture.

The seat-to-head transmissibility magnitude results suggest that the mean body resonance for the erect and forward lean on table postures decreases by approximately 0.5 Hz (from 5.5 to 5 Hz) and 0.4 Hz (from 5.65 to 5.25 Hz) respectively, when vertical excitation magnitude is increased from 0.4 to 1.2 m/s² r.m.s, Fig. 4.1, 4.3. Similarly, the mean seat-to-head transmissibility shows that body resonance frequency of vertical backrest posture also shifts, but very small, Fig 4.2.

In all postures, mean STH transmissibility increases with increasing vibration magnitude at body resonance frequencies which approximately lies between 4.5 to 6 Hz. For the frequency range above body resonance zone, erect posture mean STH transmissibility increases with increasing vibration magnitude Fig.4.1 For vertical backrest posture the mean STH transmissibility indicates higher for lower magnitudes of vibration in the frequency range of 6 to 12 Hz and in contrary exhibit higher STH transmissibility for higher magnitude beyond frequency 12 Hz, Fig. 4.2.
In forward lean on table posture the mean STH transmissibility in a frequency range of 6 to 9Hz exhibit higher for lower magnitude of vibration and show very small effect of vibration magnitude beyond 9Hz. Fig.4.3. In general the effect of vibration magnitude on mean STH transmissibility in erect posture is higher than others postures, at body resonance frequency. The result in vertical backrest posture reveals that mean STH transmissibility variation due to vibration magnitude attain maximum in the frequency range 6 to 10Hz.

![Graph showing STH transmissibility for different vibration magnitudes](image)

**Fig. 4.3** Mean STH transmissibility for 12 subjects exposed to vertical sinusoidal vibration at 0.4, 0.8 and 1.2 m/s$^2$ r.m.s in forward lean on table sitting posture.

### 4.2 Effect of Vibration Magnitude on Back-to-Head Transmissibility

When a subject is in a backrest sitting posture, the lower part of the body is supported by the seat and the upper part of body is lean to back support. The backrest support contributes to decrease the muscle tensions and maintains the sitting posture relatively relaxes. Also there comes a significant amount of vibration input through the backrest. Thus, it is naturally reasonable to include the effect of this source of vibration to the body. In order to investigate this effect back-to-head (BTH) transmissibility was determined for twelve subjects. The mean BTH transmissibility reveal that, the peak value frequency decreases as magnitude increases. The peak value frequency under vibration magnitude of 0.4 m/s$^2$ r.m.s. laid at 5Hz and of 0.8, 1.2 m/s$^2$ r.m.s. at 4.5, 4Hz respectively, figure 4.4.
Figure 4.4 Mean BTH transmissibility for 12 subjects exposed to vertical sinusoidal vibration at 0.4, 0.8 and 1.2 m/s² r.m.s in backrest sitting posture

4.3 Effect Of Posture On Seat-To-Head Transmissibility

Figs. 4.5, 4.6, 4.7 compare the mean vertical seat-to-head transmissibility magnitude responses of twelve subjects exposed to excitation level of 0.4, 0.8, 1.2m/s² r.m.s., respectively, measured with three different postures (erect, vertical backrest, and forward lean on table). It is clearly noticeable that the difference between mean STH transmissibility of the three postures decreases and the body resonant frequency also closer to each other as the magnitude of vibration increases.

Figure 4.5 Mean STH transmissibility for the three postures exposed to vertical sinusoidal vibration of magnitude 0.4m/s² r.m.s.

For all the three postures, the mean STH transmissibility increases at resonance frequency with increasing vibration magnitude, figure 5 to 7. It is observed that the mean STH transmissibility’s of all three postures steadily increased up to resonance frequency and decreased generally for higher frequencies. There was a decrease in the resonance frequency with increase in vibration magnitude for erect and leaning on table postures.
Fig. 4.6 Mean STH transmissibility for the three postures exposed to vertical sinusoidal vibration of magnitude 0.8m/s² r.m.s.

The lowest transmissibility occurred with the backrest posture and highest transmissibility occurred in erect posture under all magnitude of vibration undertaken at resonance frequency. The peak value frequency (resonance frequency) for backrest posture was lesser than the peak value frequency of other postures. The peak value frequency for erect and leaning forward on table posture was decreased as vibration magnitude increases while there is no clear indication for backrest posture. It was also observed that the lean forward on table posture shows more mean STH transmissibility in the frequency range of 6 to 9 Hz and backrest posture exhibit more STH transmissibility for higher frequencies.

Fig. 4.7 Mean STH transmissibility for the three postures exposed to vertical sinusoidal vibration of magnitude 1.2m/s² r.m.s.

4.4 Head Helmet Relation

There are two most popular methods to measure head vibration: bite bar (measured at mouth using accelerometer mounted on bite bar/plate) and helmet (collected from accelerometer mounted on helmet). Many studies have been used bite bar [12, 13-15] and helmet has been also used in many studies [16-19]. In this study the easiest method to measure head acceleration (helmet) were used.

In order to determine STH and BTH transmissibility functions, accelerations were measured at the seat–buttock interface, back and back support interface and on the head. Head vibration was measured using the accelerometer
mounted on plastic helmet. Since there is relative motion between the head and the helmet it is necessary to analyze error induced. It is analyzed by the use of averaged plots of transmissibility transfer function of head helmet system, shown in Fig. 4.8. Acceleration data of head helmet system, given in Fig. 4.8, were measured under sinusoidal excitation on one subject, repeated five times and then averaged. The subject is a member of the tested group. It is found that above 10Hz the errors increases and the maximum error take place at approximately 20 Hz, of resonance frequency, because, in that point, the magnitude of transmissibility attain highest and this should be taken into consideration while analyzing the data in the frequency domain. To be more specific, frequencies above 10Hz will not be desirable to consider for further analyses.

![Graph showing Head-Helmet Transmissibility and Phase Difference](image)

Fig 4.8  Head helmet transmissibility and phase difference under 1.2m/s^2 r.m.s magnitude of vibration.

5. Bio-Mechanical Model

Bio-mechanical models may either seek to describe the form of body motion caused by vibration or seek to provide a simple mathematical summary for the response of the body. Human body in sitting posture can be modeled with different modeling techniques consisting of several masses, translational/rotational spring and dampers and different joints. In this study, 9DOF two lumped parameter model ((Model-A, Model-B), were proposed in order to describe human response to vertical vibration in sitting postures. The models targeted erect (Model-B) and backrest (Model-A) postures as shown in Fig 5.1.

These modes are a lumped parameter models developed in order to study the response of seated human body to the vertical and horizontal whole body vibration. Model-A (9DOF) consists of five segments of mass interconnected by six (6) sets of vertical and horizontal springs and dampers and connected to seat and back support by four (4) and two (2) vertical and horizontal springs and dampers respectively, with total mass of 72kg. The parameters such as mass segment, stiffness, and dampers are described in Table 5.1 for their respective representation in the models. Model-A represent seated human subject supported with vertical back support and Model-B signify erect posture without backrest posture. The main difference between Model-A and Model-B is attributed to postural difference which resulted in parameter difference. Consequently, in Model-B the springs and dampers between body and back support (k_{4h}, k_{4v}, c_{4h}, and c_{4v}) are eliminated.
Table 5.1 Symbolic representation of human model parameters for (Model-A, Model-B)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1$</td>
<td>Upper Leg(left + right)</td>
</tr>
<tr>
<td>$m_2$</td>
<td>Pelvic</td>
</tr>
<tr>
<td>$m_3$</td>
<td>Viscera (Soft abdominal body parts)</td>
</tr>
<tr>
<td>$m_4$</td>
<td>Upper Torso (Including hands)</td>
</tr>
<tr>
<td>$m_5$</td>
<td>Head and neck</td>
</tr>
<tr>
<td>$c_{4h}$, $c_{4v}$</td>
<td>Back horizontal and vertical dampers</td>
</tr>
<tr>
<td>$c_{2h}$, $c_{2v}$</td>
<td>Pelvic vertical and horizontal dampers</td>
</tr>
<tr>
<td>$c_{1h}$, $c_{1v}$</td>
<td>Upper leg vertical and horizontal dampers</td>
</tr>
<tr>
<td>$k_{4h}$, $k_{4v}$</td>
<td>Back horizontal and vertical springs</td>
</tr>
<tr>
<td>$k_{2h}$, $k_{2v}$</td>
<td>Pelvic vertical and horizontal springs</td>
</tr>
<tr>
<td>$k_{1h}$, $k_{1v}$</td>
<td>Upper leg vertical and horizontal springs</td>
</tr>
<tr>
<td>$c_{21}$ up to $c_{54}$</td>
<td>The respective dampers between body segments</td>
</tr>
<tr>
<td>$k_{21}$ up to $k_{54}$</td>
<td>The respective springs between body segments</td>
</tr>
</tbody>
</table>

5.1 Derivation of Equation of Motion

The equations of motion describing the system dynamic behavior are derived for the models using Newton second law of motion and written in general and simplified matrix form as:

Eq. (5.1)
where, $M$, $D$, and $K$ are mass matrix, damping matrix, and stiffness matrix respectively. $a$, $v$, and $d$ are acceleration, velocity and displacement vectors of each segments. $s_i$ source of excitation or excitation vector and $j$ implies number of independent coordinate system or number of degree of freedom.

All the matrices and vectors can be further represented as follows:

Mass matrix

Damping matrix

Where

Stiffness matrix

where,
In the above system equations of motion, \( x_0 \) represent the seat vertical and forward horizontal displacement and like wise represent the vertical and forward displacement at back support back interface. In model-B are taken as zero.

It has to be mentioned that the mass matrix is diagonal. The stiffness and damping matrices are symmetric with respect to diagonal elements, depending on the biomechanical properties of seated human body model. To solve system equations of motion in frequency domain, the all initial condition are kept zero. Then, it is possible to transform the equations from time domain to (s) domain using Laplace transform which is straight forward to solve in frequency domain.

5.2 Solving for Response Functions

In order to study the response of human to vibration, the bio-dynamic response function of each model should be derived. In this study, the seat to head (STH) and back support to head (BTH) transmissibility and the corresponding phase difference are selected for model validation. Before, model parameters search these transfer functions (both STH and BTH transfer functions for Model-A) and (STH transfer function for Model-B) should be known. The expression for seat to head and back support to head transfer functions were symbolically derived from equations of motion using Wolfram Mathematica 7.0. From which model parameters were searched. After all parameters are optimized, the transfer functions were taken to MatLab 7.8 for graphic simulation of the models.

The vertical seat to head (STH) transfer function of each model (Model-A, Model-B) was expressed in frequency domain as follow:

\[
T_{STH}(f) = \frac{Z_s(f)}{Z_0(f)}
\]

Eq. (5.2)

where, \( T_{STH}(f) \) seat to head transfer function, \( Z_s(f) \) vertical head acceleration or displacement, and \( Z_0(f) \) seat acceleration or displacement all in frequency domain.

Likewise back support to head transfer functions also expressed as:

\[
T_{BTH}(f) = \frac{Z_s(f)}{Z_{01}(f)}
\]

Eq. (5.3)
where, $T_{BTH}(f)$ back support to head transfer function, $Z_5(f)$ vertical head acceleration or displacement, and $Z_{01}(f)$ vertical back support acceleration or displacement all in frequency domain.

### 5.3 Model Parameters

To analyze the bio-dynamic response of the models, the models parameters should be known. The masses and geometric parameters of the model could be determined from standard anthropometric data [20, 21]. While this data can vary considerably from one person to another, there are patterns and averages which can be useful in most analyses [22]. In this work all the mass segments and geometric parameters were determined from anthropometric data provided by Houston (2009), [22]. The average anthropometric data of the subjects involved in experimental study were found 72kg and 172cm, using these average data, the segments mass and geometry were calculated as tabulated in Table 5.3, 5.4.

Each segment in model-A, model-B, is interconnected by linear translational vertical and horizontal springs and dampers. The thigh and pelvic segments are assumed to be connected to the seat surface with horizontal and vertical linear spring-dampers to simulate the flexibility at buttock tissue. The same principle is considered for backrest support and upper torso contact.

In all models the damping and stiffness coefficients may have nonlinear properties to represent nonlinear properties of the body components. However in this work, these parameters are assumed to have linear properties for simplicity. It is obvious that the damping and stiffness parameters could not be determined directly from standard data. This is partly because each combination of spring and damper do not necessarily represent a particular anatomical segment of the body. In addition, the stiffness and damping properties of most soft tissues in the living human body are difficult to measure and are not available in the literature.

### 5.4 Parameter Search

The bio-mechanical model parameters are obtained by trying to match the model simulation to the experimental data. In this study seat to head (STH) and back to head (BTH) transmissibility and phase difference functions were used to search the parameters. Some horizontal spring and dampers such as $c_{1h}$, $c_{2h}$, $c_{3h}$, $k_{1h}$, $k_{2h}$, and $k_{3h}$ were estimated from literature [7, 23]. Other parameters in all models (model-A, model-B) were optimized by minimizing the square error sum of seat to head (STH) and back to head(BTH) transmissibility and phase difference functions over the frequency range 1-10Hz.

\[
E_1 = \left[ \int_{f_1}^{f_2} (T_{STH}^e(f) - T_{STH}^o(f))^2 \, df \right] 
E_2 = \left[ \int_{f_1}^{f_2} (P_{STH}^e(f) - P_{STH}^o(f))^2 \, df \right] 
E_3 = \left[ \int_{f_1}^{f_2} (T_{BTH}^e(f) - T_{BTH}^o(f))^2 \, df \right] 
E_4 = \left[ \int_{f_1}^{f_2} (P_{BTH}^e(f) - P_{BTH}^o(f))^2 \, df \right] 
\]

Eq. (5.4)
Where, $T_{STH,e}$, $T_{BTH,e}$, $P_{STH,e}$, and $P_{BTH,e}$ are the experimental seat to head (STH) and back to head (BTH) transmissibilities and phase angles respectively. $T_{STH,m}$, $T_{BTH,m}$, $P_{STH,m}$, and $P_{BTH,m}$ are the model seat to head (STH) and back to head (BTH) transmissibilities and phase angles respectively. Whereas, $E_1$, $E_2$, $E_3$, $E_4$ were the square error sum of Seat to head (STH) and back to head (BTH) transmissibility and phase difference functions over the frequency range 1-10Hz. Each model parameters were determined using the same principle and tabulated as in Table 5.3, 5.4.

Table 5.3 9DOF Lumped parameter model (Model-A) backrest posture parameters

<table>
<thead>
<tr>
<th>Mass</th>
<th>kg</th>
<th>Stiffness</th>
<th>N/m</th>
<th>Damping</th>
<th>Ns/m</th>
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<td>$c_{1v}$</td>
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<td>$k_{1h}$</td>
<td>15.00</td>
<td>$c_{1h}$</td>
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<tr>
<td>$m_3$</td>
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<td>$k_{2v}$</td>
<td>151625.00</td>
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<td></td>
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Table 5.4 9DOF Lumped parameter model (Model-B) erect posture parameters

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<thead>
<tr>
<th>Mass</th>
<th>kg</th>
<th>Stiffness</th>
<th>N/m</th>
<th>Damping</th>
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5.5 Model Responses

5.5.1 Vertical Seat-to-Head Transfer Function in Erect Posture
In this study Model-B was developed to represent the subjects sitting in erect posture. The model was developed using the mean STH transmissibility and STH phase difference of 12 subjects exposed to sinusoidal vibration of magnitude \(1.2 \text{m/s}^2\) r.m.s. as measured in experiment.

Due to the effect of head-helmet relationship the model validation was restricted to the frequency range 1 to 10Hz. Fig 5.3(a) illustrate STH transmissibility of Model-B which compared with mean, lower limit, and upper limit experimental data sets. Since model parameters were found using mean values the comparison has to be good agreement with it. The seat-to-head (STH) transmissibility characteristics, presented in Fig. 5.3(a) reveal good agreement between the model response (analytical) and the target values (mean value). The model response exhibits a resonant peak of 2.20 at 5.0 Hz; the corresponding target value (mean value) is 2.20 at 5.0 Hz. Also relatively good agreement is observed for the phase response over the frequency range 1.0 to 10.0 Hz as shown in Fig. 5.3(b).

The seat-to-head transmissibility magnitude increases with increasing frequency up to the main body resonant frequency, near about 5 Hz. The magnitude of transmissibility tends to decrease at frequencies higher than the resonant frequency as usually reported for human body. The model phase response slowly increase for lower frequencies and followed by high slope increase up to 10Hz.

![Graph](image)

**Fig. 5.3** Comparison of the vertical seat-to-head vibration transmissibility and phase difference characteristics computed from the Model-B (erect posture) with those defined mean value, lower limit and upper limits of 12 subject’s response experimental data sets.
5.5.2 Vertical Seat-to-Head Transfer Functions in Backrest Posture

The nine degree-of-freedom model (Model-A) developed in this research work for vertical backrest posture under vertical sinusoidal vibration of magnitude 1.2m/s\(^2\) r.m.s. analytical result were compared with experimental work conducted in the same condition. Fig. 5.4 (a) and (b) shows the comparison between experimental data sets (lower limit, upper limit and mean value) and theoretical result from model. The simulation result and mean experimental results reveal that resonance frequency of head lies around 5 Hz for both case and the pear value of seat-to-head transmissibility hits 1.65 and 1.69 at resonance frequency respectively.

The simulation results in both STH transmissibility and phase over the frequency range 1 up to 10Hz show good agreement with experimental results Fig. 5.4 (a) and (b). It is observed from figure 5.4 (b) that the phase difference increment hits maximum at resonance frequency in other word the curve slope hits maximum at peak value frequency.

![Graph (a)](attachment:image1)

![Graph (b)](attachment:image2)

Fig. 5.4 Comparison of the vertical seat-to-head vibration transmissibility and phase difference characteristics computed from the Model-A (backrest posture) with those defined mean value, lower limit and upper limits of 12 subject’s response experimental data sets.
From above mathematical simulation and graphical representation, it is clear that all models could provide good degree of estimation or prediction of human response to vibration in frequency range 1-10 Hz. Though, small deviations of peak value frequency and peak value from experimental data sets, all models best estimate the experimental results.

5.5.3 Vertical Back Support-to-Head Transfer Functions in Backrest Posture

People usually use backrest posture while traveling, because this posture decreases the muscle tension and maintains the sitting posture relatively relaxed. Since the upper body part bends over the back support there comes a significant amount of vibration input at back support. In order to investigate the effect of this vibration experimental work and model considering of this situation were developed. Model (Model-A) consider back-to-head (BTH) transmissibility and phase in order to study the effect of external excitation through back support in vertical direction.

![Graph of Transmissibility](image1)

![Graph of Phase Angle](image2)

**Fig. 5.5** Comparison of the vertical Back support-to-head vibration transmissibility and phase difference characteristics computed from the Model-A (backrest posture) with those defined mean value, lower limit and upper limits of 12 subject’s response experimental data sets.
Fig. 5.5 (a) and (b) illustrates that BTH transmissibility and phase difference of Model-A has good agreement with experimental data sets. The simulation result were compared with an upper limit, lower limit and mean value of the experimental results and the model response (simulation result) has close conformity with the mean value of experimental data sets. The peak value frequency of both experimental and simulation result were found the same (4Hz) and the peak value of analytical result was slightly smaller than experimental result and found to be 1.78 and 1.81 respectively. The phase difference simulated also match with mean measured value result very closely as shown in Fig. 5.5 (b).

5.5.4 Performance of the Models

The performance of each model was examined by evaluating how the model meets the experimental result of the transmissibility and phase angle. The performance of each model was evaluated using the function known as goodness-of-fit (\( \xi \)). This function is used to evaluate the prediction accuracy of each analytical human model in comparison with experimental results [1]. The ratio of the root-mean-square error to the mean value is calculated with the following equation response.

\[
\xi = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{\tau_m - \tau_c}{\tau_m} \right)^2
\]

Where \( \tau_m \) is the test datum, \( \tau_c \) is the calculated result from each model, and N is the number of test data points used in the comparison, (14) for this study. When \( \xi \) is equal to 1 or 100%, the fit of predicted results to test data is perfect.

The goodness-of-fits of Model-A is 92.40% in STH transmissibility for frequency range of 1-10Hz. Phase goodness-of-fits of Model-A is found 87.43% in frequency range 1-10Hz. In same model the goodness-of-fit in BTH transmissibility and phase is found to be 94.73% and 82.96% in frequency range 1-10 Hz.

The prediction accuracy of Model-B is found 88.27% and 80.00% in STH transmissibility and phase angle over the frequency range 1-10 Hz.

In general, the maximum goodness-of-fit in STH transmissibility and phase is obtained in Model-A. In addition the BTH transmissibility and phase also predicted best in Model-A.

6. Discussion

This study concentrated on three representative postures and under three magnitudes of vibration. This postures (backrest, erect and forward lean on table) and magnitudes (0.4, 0.8, 1.2 m/s^2 r.m.s.) under a frequency range of 1-20Hz are considered as representative of those likely prevail in wide range of vehicles.

Financially and ethnically it is not visible to conduct experimental work for each and every desired studies on human response to vibration. Consequently, a number of biodynamic models have been proposed in the literature to characterize the whole-body vibration response of seated subjects. This study targeted to include both magnitude and phase of STH and BTH transfer functions in estimating the model parameters.
Using averaged experimental work conducted under vibration magnitude of 1.2 m/s$_{2}$ r.m.s., two bio-dynamic models seek to represent human sitting postures are proposed in this work. Since the model parameters optimization were depend on STH and BTH transmissibility and phase angles, the simulated result and mean, lower limit and upper limit of experimental data sets were compared. Both models responses and simulated results have good agreement with mean value or averaged experimental data sets.

The study of human response to vibration in sitting posture is usually linked with transportation in which people are exposed to whole body vibration. In vehicle seat environment identifying the whole body vibration discomfort zone is very essential in optimal design of vehicle seat and suspension as well. Indeed, seat having the optimum dynamic properties is one which minimizes the unwanted vibration responses of the human in the relevant vibration environment. The three important factors combined to determine the seat dynamic efficiency are vibration environment, seat dynamic response and response of the human body. This study helps to determine the response of human body in vertical direction under stated frequency range and magnitude.

7. Conclusion

It is apparent that vibration affects human health, performance, activities and comfort. In bio-dynamic response studies both experimental and analytical works are conducted to create comfortable, luxury, good performance and healthy environment, which needs better understanding of human response to vibration. All postures considered in this study have firm relation with our daily life while traveling. In the study of bio-dynamic response of seated human subject, both posture and vibration magnitude has significant effect.

The results from all postures show that the transmissibility magnitude increases with increasing frequency up to the main body resonant frequency, near about 5 Hz. The magnitude of transmissibility tends to decrease at frequencies higher than the resonant frequency. Resonance in seat-to-head transmissibility of erect and forward lean on table posture visibly tends to shift to a lower frequency with increasing vibration magnitude. This suggests that in erect and forward lean on table posture the upper body part exhibits more softening tendency under higher magnitudes of vertical vibration.

- The analytical study or bio-mechanical modeling of seated human subject under vibration magnitude of 1.2m/s$^2$ in mentioned postures has been developed and validated against experimental work.
- The parameters search or model development has been dependent on frequency range 1-10Hz, for which 10-20Hz has been omitted due to head-helmet relationship.
- From simulation results and graphical representation, it is clear that the models could provide good degree of estimation or prediction of human response to vibration in frequency range 1-10 Hz. Though, small deviations of peak value frequency and peak value from experimental data sets, all models best estimate the experimental results.
- In general, the maximum goodness-of-fit in STH transmissibility and phase is obtained in Model-A. In addition the BTH transmissibility and phase also predicted best in Model-A. In general, both experimental and analytical works conducted in this study helps in optimal design of vehicle seats and suspensions, and comfort analysis under vertical whole body vibration.
8. References


