Seat-to-Head Transmissibility and Reading Discomfort of the Seated Subjects Exposed to Whole Body Vibration

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The transmission of vibration from the vibrating interface to various organs of the human body may influence their functioning during the vibration exposure. Therefore, an experimental study on a vibration simulator has been performed to find the effects of vibration on reading performance, and also to establish the relationship between seat-to-head transmissibility (STHT) with reading difficulty and reduction in reading performance. Twelve seated male subjects were exposed to sinusoidal vibration with three magnitudes (0.5, 1.0 & 1.5 m/s2 rms) at seven different frequencies (4, 5, 6.3, 10, 16, 20, and 25 Hz) in three independent directions (vertical, fore-and-aft, and lateral). The results show that three output measures - STHT, reduction in reading performance, and perceived difficulty in reading - are significantly affected by the frequency of vibration in each direction. All three measures have shown the peak at 4 or 5 Hz in three independent directions of vibration. Another peak at 25 Hz has also been observed for reduction in performance and perceived reading difficulty in vertical direction vibration. The results also show decrease in resonance frequency of the transmissibility with an increase in vibration magnitude, which represents nonlinear behaviour in biodynamic response by the human body.

1. INTRODUCTION

There are diverse effects of whole body vibration (WBV) exposure on the human body, such as discomfort, performance difficulty in various sedentary activities, and health effects. The biodynamic response of the human body to WBV may be used for the quantification of the diverse effects of vibration exposure.[10] Biodynamic responses are measured in terms of two functions: the 'to the body' function, and the 'through the body' function. The 'through the body' function describes the transmission of vibration from the input point to the various segments of the human body during the WBV exposure. The STHT measurement has been found to be appropriate for describing seated body responses to higher frequency vibration.[27]

The STHT measurement may be considered for the quantification of the activity discomfort in the WBV environment. The transmissibility is measured as the ratio of output acceleration to the input acceleration.[10]

$$\text{STHT} T_{STH}(f) = \frac{a_{head}(f)}{a_{seat}(f)}; \qquad (1)$$

where $a_{head}(f)$ is acceleration at the head, and $a_{seat}(f)$ acceleration at the seat.

A large number of experimental studies[6,7,11,17,18,21,22,25] have focused on the transmissibility of vibration to various parts of the human body, such as seat-to-head, pelvis, lumber/cervical, etc., with a broad range of experimental conditions. Griffin and Whitham have observed the significant effect of individual variability on transmissibility of WBV through the seated subjects.[6] Many previous studies[17,19,27] have shown the relationship between STHT and Apparent Mass (APMS) of the seated subjects exposed to WBV with various experimental conditions, *e.g.* vibration magnitude, frequency range, vibration type, subject's anthropometric data, etc. The measured data in these studies have revealed nonlinearities in both APMS and STHT responses, and also shows stronger effects of hand position, backrest conditions, etc. In the field studies of Bhiwapurkar, *et al.*[1] and studies of Indian and Swedish trains by Khan and Sundström,[12] reading activity has been found to be the most preferable of all sedentary activities- *i.e.* writing, sketching, eating, etc.- to the passengers while travelling. Also, most passengers reported reading discomfort due to the train vibrations in response to a questionnaire used in these studies. Bhiwapurkar, *et al.*,[3,4] conducted the laboratory experiment on reading of a word chain in English, a Hindi newspaper, and an English e-paper under vibration exposure by measuring subjective and objective responses. The results revealed a strong influence of the WBV on the performance reduction in reading performance and increase in perceived difficulty. Experiments on reading and writing activity[3,4,8,12] show the strong influence of vibration amplitude and vibration frequency on the performance of these activities. The studies also show that a moderate level of discomfort has been found at low magnitudes of WBV. These results depend upon various conditions, such as sitting posture, direction of vibration, type of task to be performed, etc. Wollstrom observed a decrease in the reading performance in fore-and-aft (x-axis) vibrations between 5.6 and 11 Hz frequencies; however, the effect was only present when a seat with a backrest was used.[29] So backrests may be a critical part for vibration transmitted to the head, and may be the cause of the problem.

Most of the human body sensors, *e.g.* the eyes, tongue, etc., are located in the head and play a crucial role in the reading tasks performed by the seated subjects. The functioning of these organs of human body during the task performance is also affected by the WBV exposure.[10] In the present experimental study, an attempt has been made to establish the relationship between STHT and perceived difficulty and decrement in reading performance for the seated subjects in the vibration environment. It was hypothesized that the transmission of vibration to the head would affect reading difficulty, and this would also be reflected in the reading performance.

2. METHODOLOGY

2.1. Experimental Setup

This experimental study has been conducted on the vibration simulator available in the vehicle dynamics laboratory, MIED, IIT Roorkee, India. This vibration simulator was developed as a mock-up of a train compartment, and was used in many previous studies.[1–4,7,13] The vibration simulator consists of a platform of the size 2 × 2 m, made of stainless steel sheets, and can be excited with the help of three electrodynamic vibration shakers in three directions: vertical (z-axis), lateral (y-axis) and fore-and-aft (x-axis). The sinusoidal vibration can be generated by each vibration shaker having a capacity of 1000 N force and maximum stroke length (peak-peak) of 25 mm. These shakers are computerized and controlled with the help of three amplifiers and three controllers. An accelerometer is attached to the shaker to provide continuous motion feedback to each individual controller via a signal conditioning unit. A table and two rigid chairs have been fixed rigidly on the platform of the vibration simulator (shown in Fig. 1). The height of the seat surface from the floor is 45 cm. None of the accessories attached to the platform had shown any resonance within the frequency range under study, in any of three directions. The platform vibrations were measured for the monitoring of the vibration signals by using a tri-axial accelerometer (PCB PEZIOTRONICS-356A32), and the signals were conveyed to the LabVIEW software via a data acquisition device (NI cDAQ-9174). The air conditioned environment at 26 °C temperature was maintained in the simulator lab with working illumination well above 250 Lux. The illumination from all the direct and indirect light sources was well distributed. The two test subjects were seated on the chairs at a specific time and were excited with the same frequency as the platform. The frequency of the vibrations produced on-board railway vehicles ranges from 1 to 25 Hz, which is also a critical range for human beings.[10,20]

2.2. Subjects and Methods

A total of twelve healthy male subjects were involved in the present experimental study. The details of the anthropometric data of the subjects are given in the Table 1. All the participants were students (either undergraduates, graduates, or research scholars) of the institute, had normal eyesight (normal visual acuity 6/6 vision), and were fluent in reading the English language. All the subjects participated voluntarily, and before participation, all the subjects were required to sign the written consent letter. Approval for conducting the experiment on the subjects was obtained from the Institute Human Ethical Committee of IIT Roorkee. A screening questionnaire was filled by the participating subjects related to their personal backgrounds, levels of education, fitness, and musculoskeletal disorders.[14] All the subjects were free from any musculoskeletal disorders and were found to be suitable for the experimental task.

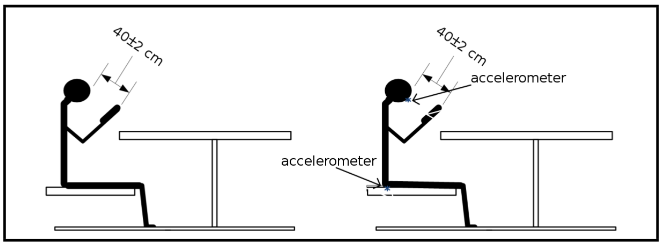

Figure 2. Erect upright posture maintained during the (a) reading task, and (b) measurement of STHT.

The sinusoidal vibration in each independent axis was generated at frequencies 4, 5, 6.3, 10, 16, 20, and 25 Hz with the help of computerized controllers at three levels of vibration magnitude: 0.5, 1 and 1.5 m/s^2 rms (un-weighted). A total of 63 vibration conditions (7 vibration frequencies, 3 vibration magnitudes in 3 mono axes) were given to the vibrating platform, and three responses to STHT - perceived difficulty in reading and reading performance - were measured. For one vibration condition, a one-minute break was provided to the subject to reduce fatigue. The whole experiment was completed in two different sessions of 2 hours each.

Both the subjects maintained an erect upright posture throughout the experiment for the reading task, and had the reading material in their hands, as shown in Fig. 2. The normal viewing distance of 40±2 cm between the subjects' eyes and the reading material was maintained by each subject throughout the experimentation.[15,16]

The experimental task performed by the subjects involved reading a printed paragraph in English on A4 size paper at a normal speed. The paragraphs of 300 words were selected from leading English newspapers. Most of the leading newspapers use Nimrod MT font type and 7.5- to 10-point font sizes for the news content. For the present study, Nimrod MT font type and 8 font sizes had been selected for the reading task. To avoid learning the effect, different articles were used for the reading task for each vibration exposure. The test subjects were asked to sit in the prescribed posture.

The reading performance was assessed on the basis of the time taken to complete the reading task at various vibration conditions. A digital stopwatch was used to count the time taken for task completion. The perceived difficulty in the reading task was assessed with the help of Borg's CR-10 scale, which consists of nine labelled and eight unlabelled points (depicted in Table 2). The value ranges from a minimum of '0' to

Table 1. Anthropometric data of 12 volunteer male subjects who participated in the study

	Age (Years)	Height (cm)	Seated Height (cm)	Weight (Kg)	Seated weight (Kg)	Arm length (cm)	Lower leg length (cm)
Mean	26.5	172.1	133.5	70.9	53.6	58.9	50.8
Standard deviation	2.4	5.7	1.9	4.0	2.5	1.7	1.1

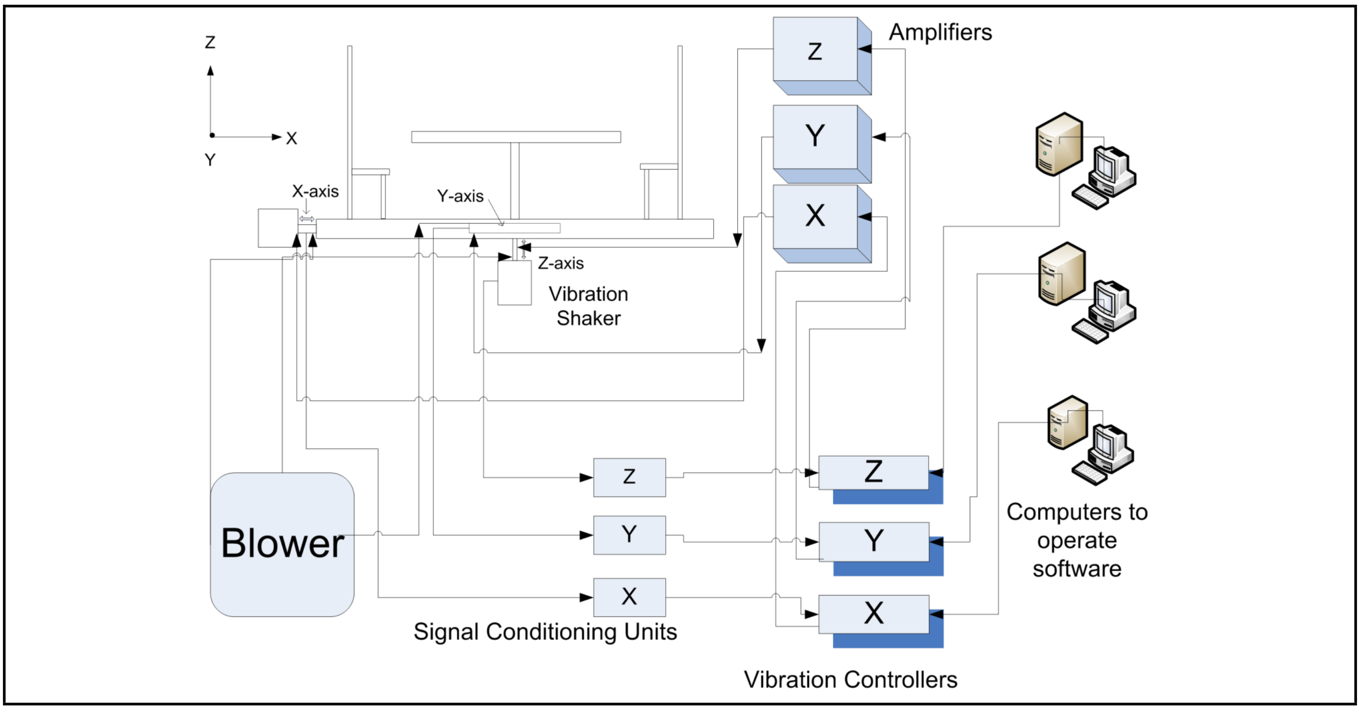

Figure 1. Schematic diagram of computerized controlled vibration simulator.

Table 2. Borg's CR-10 scale.

0	Nothing at all
0.3	
0.5	Extremely weak
0.7	
1	Very weak
1.5	
2	Weak
2.5	
3	Moderate
4	
5	Strong
6	
7	Very strong
8	
9	
10	
•	Absolute maximum

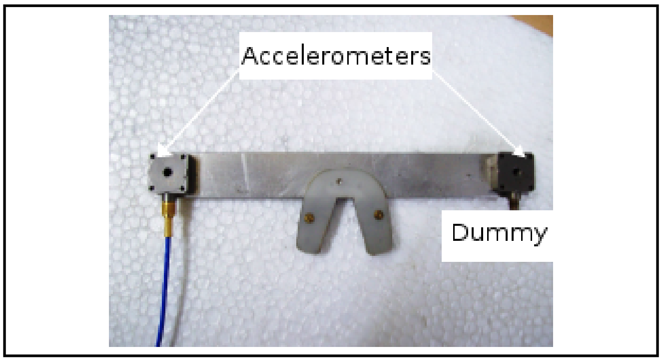

Figure 3. Sterilize bite-bar.

a maximum of '10' for this scale. The point after 10 can also be selected by the subjects depending upon their choice.^{5}

For the measurement of acceleration at the seat and Ischial-tuberosite interface, a seat-pad accelerometer was placed on the seat. The acceleration of the head was measured with the help of a bite bar on which an accelerometer was mounted. The bite bar consisted of a light-weight, alloy steel strip, approximately 21 cm long, which was screwed on to a U-shaped bite plate made of Perspex material, as illustrated in Fig. 3. The weight of the accelerometer was balanced by mounting the dummy accelerometer. The sterilized bite bar was gripped by the subjects in their teeth during the measurement of the STHT responses. The signals from the accelerometers were acquired with the help of a nine-channel data acquisition system (**NI cDAQ-9174**) and further processed with the help of LabVIEW software.

The effects of various factors, such as vibration magnitude, frequency, and direction, were analysed by the general linear model (GLM) for repeat measurements. A factorial analysis of variance (ANOVA) was performed using a statistical package for social sciences (SPSS Inc., Chicago, USA, version 16). The results at the level of $p<0.05$ and $p<0.01$ were considered 'Significant' and 'highly significant', respectively. To analyse all the gathered responses, these were manually fed to the statistical software SPSS 16.

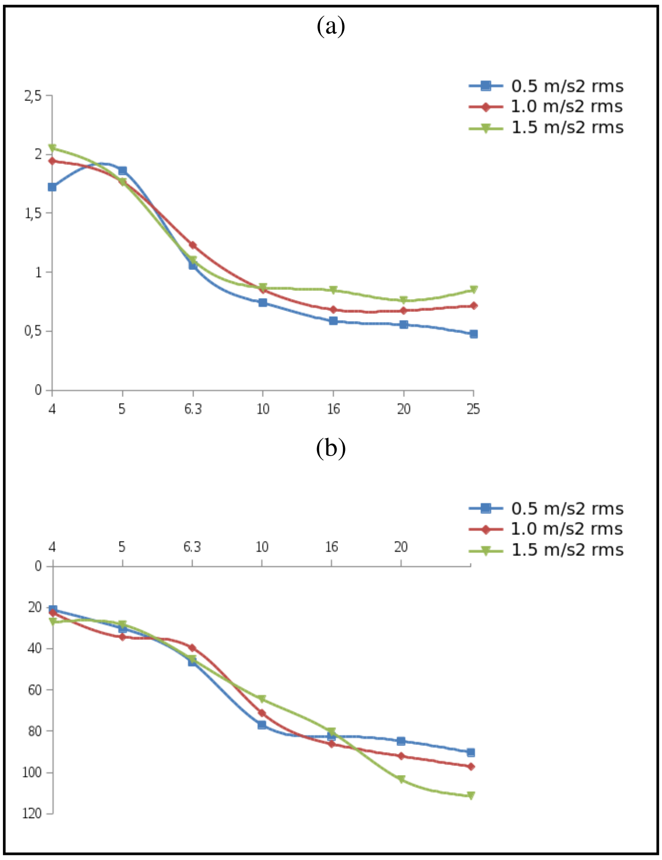

Figure 4. (a) Mean STHT and (b) phase (degree) of 12 subjects measured at 0.5, 1.0, 1.5 m/s^2 rms in vertical direction.

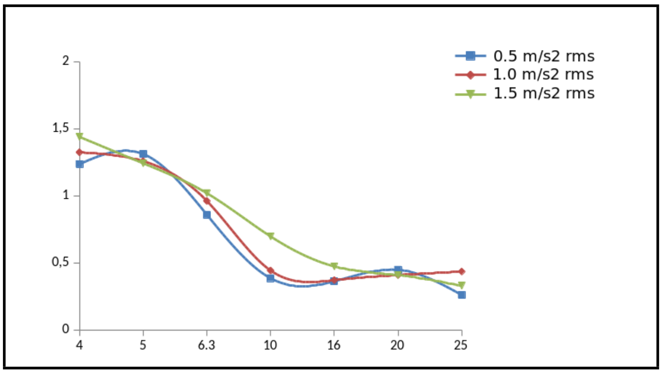

Figure 5. Mean STHT of 12 subjects measure at 0.5, 1.0, 1.5 m/s^2 rms in lateral direction.

3. RESULTS

3.1. Effect of Vibration on STHT

The mean STHT and phase responses were shown for all the three vibration magnitudes in vertical, lateral, and fore-and-aft directions, and are depicted in Figs. 4–6. Only the values of the phase for the vertical direction are shown in Fig. 4(b). The peak was observed around 4–5 Hz for the mean STHT responses for vibration in all the three directions, as shown in Figs. 4–6.

The STHT was found to decrease after 5 Hz frequency in the vertical direction of vibration for all vibration magnitudes. Statistically, highly significant differences have been observed between STHT responses at 4–5 Hz and other frequencies of vibration ($p<0.01$). The STHT responses at 4 and 5 Hz frequency are not found to be significantly different ($p>0.05$). The overall effect of the frequency of vibration is highly significant ($p<0.01$), as specified in Table 3.

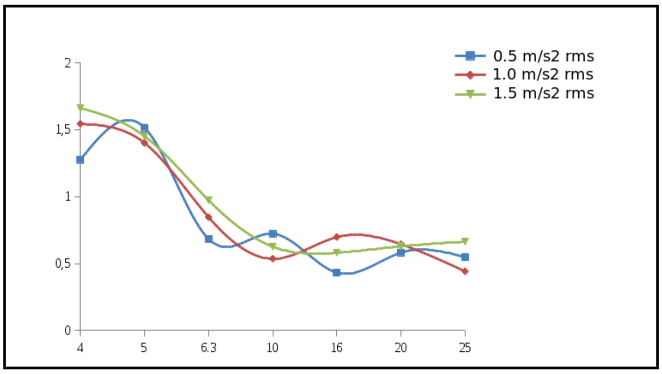

Figure 6. Mean STHT of 12 subjects measure at 0.5, 1.0, 1.5 m/s^2 rms in fore-and-aft direction.

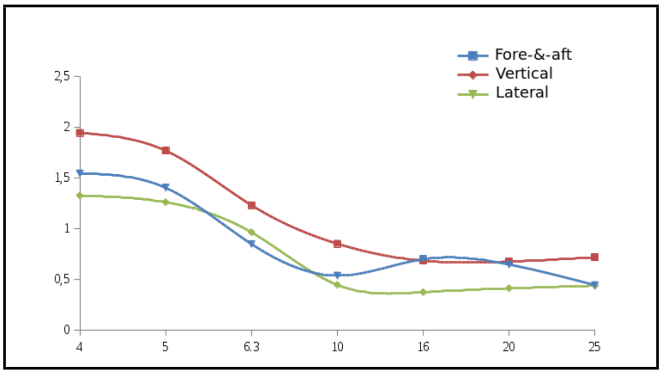

Figure 7. Comparisons of mean STHT responses for 1.0 m/s^2 rms in vertical, fore-and-aft, and lateral vibration.

No significant differences were observed in STHT responses for lateral and fore-and-aft vibrations. At a vibration magnitude of 0.5 m/s^2 rms, the peak in STHT was observed at 5 Hz frequency for all the considered directions. At vibration magnitudes 1.0 and 1.5 m/s^2 rms, the peak was observed around 4 Hz for the vertical and lateral directions. There is a decrease in resonance frequency with an increase in vibration magnitude, which is also evident in many previous studies.[7,17,19] This shows the nonlinear softening characteristics of three human body under the exposure of vibration.

The results also revealed that STHT for vertical vibration was significantly higher than that in lateral and fore-and-aft vibration at 1 m/s^2 rms vibration magnitude up to the 1ower frequency range, *i.e.* up to 10 Hz only ($p<0.05$), as shown in Fig. 7.

3.2. Effect of Vibration on Reduction in Reading Performance

Figures 8–10 show the effect of vibration frequency on the reduction in reading performance for all the vibration magnitudes. The decline in reading performance was found to be greater with the increase in vibration magnitude in all the directions of vibration, as shown in Figs. 8–10. The greatest drop in reading performance was observed around 4–5 Hz frequency for all directions and vibration magnitudes ($p<0.01$). The decline in reading performance decreases with the increase in

Table 3. Test of within-subject effects of experimental variables in repeated-measure analysis.

Seat-to-head Transmissibility (STHT)					
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Direction	10.404	2	5.202	11.478	.000
Magnitude	2.972	2	1.486	5.649	.010
Frequency	164.401	6	27.400	84.697	.000
Direction * Magnitude	.145	4	.036	.172	.951
Direction * Frequency	3.239	12	.270	.879	.570
Magnitude * Frequency	3.065	12	.255	1.365	.191
Direction * Magnitude Frequency	2.355	24	.098	.518	.972
Percentage Reduction in reading performance					
Direction	189.410	2	94.705	2.554	.012
Magnitude	3848.626	2	1924.313	48.872	.000
Frequency	30159.175	6	5026.529	135.100	.000
Direction * Magnitude	255.200	4	63.800	1.719	.043
Direction * Frequency	905.005	4.971	182.075	2.764	.027
Magnitude * Frequency	2678.784	12	223.232	6.635	.000
Direction * Magnitude Frequency	798.303	24	33.263	1.128	.113
Perceived Difficulty in reading					
Direction	39.784	2	19.892	43.061	.000
Magnitude	635.722	2	317.861	627.932	.000
Frequency	839.779	6	139.963	322.900	.000
Direction * Magnitude	8.179	1.000	8.179	7.512	.018
Direction * Frequency	20.975	1.000	20.975	5.721	.034
Magnitude * Frequency	469.164	12	39.097	124.990	.000
Direction * Magnitude Frequency	12.147	1.000	12.147	1.785	.206

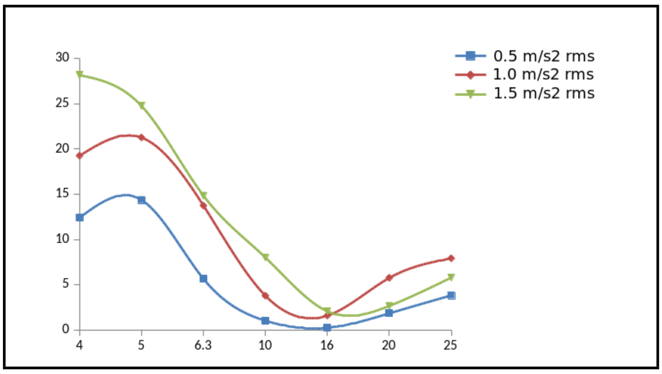

Figure 8. Mean percentage reduction in reading performance of 12 subjects measure at 0.5, 1.0, 1.5 m/s^2 rms in vertical direction.

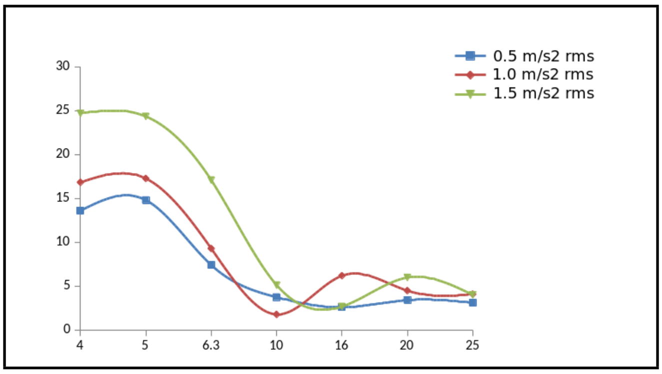

Figure 9. Mean percentage reduction in reading performance of 12 subjects measure at 0.5, 1.0, 1.5 m/s^2 rms in lateral direction.

frequency up to 16 Hz frequency. The comparable decline in reading performance was observed at 25 Hz for all vibration magnitudes in the vertical direction only. Comparing the vibration in three directions, the decline in reading performance in the vertical direction is significantly higher at lower frequencies ($p<0.05$), as shown in Fig. 11.

3.3. Effect of Vibration on Perceived Difficulty in Reading

Figures 12,–14 show the effect of vibration frequency on the perceived difficulty in reading for all three vibration magnitudes. The perceived difficulty in reading progressively increases with an increase in vibration magnitude in each direction. Highly significant differences were observed for the perceived difficulty in reading for all the considered vibration magnitudes in each direction, up to the lower frequency range, *i.e.* 10 Hz ($p<0.01$). The perceived difficulty in reading for vertical vibration is significantly greater than in lateral and fore-and-aft directions up to lower frequencies, *i.e.* up to 10 Hz ($p<0.05$) (Figure 15). The maximum perceived difficulty has been observed at 5 Hz for all the considered vibration magnitudes in all directions. Considerable reading difficulty was also observed at 25 Hz, but in the vertical direction only. The perceived difficulty in reading is very low at higher frequencies for lateral and fore-and-aft vibration.

3.4. Results from Statistical Analysis

The within-subject design of repeated measurement analysis was used to evaluate the overall effects of all the independent variables, *i.e.* vibration magnitude, direction, and frequency, of the three dependent variables such as STHT, perceived difficulty in reading, and reduction in reading performance. The overall effects of the independent variables and their interaction on dependent variables are shown in Table 3. Table 3 shows the significance value ($p<0.05$) of all the independent variable and their interaction for the measured re-

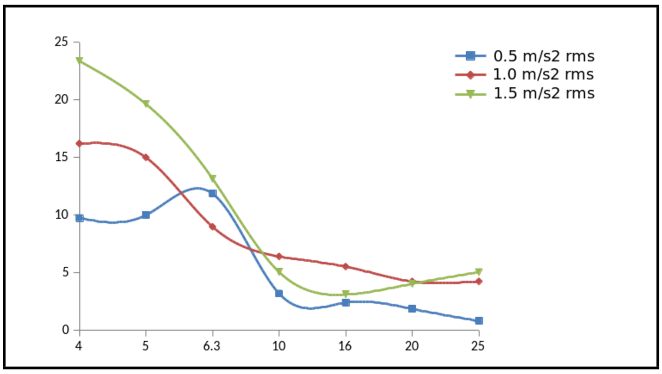

Figure 10. Mean percentage reduction in reading performance of 12 subjects measure at 0.5, 1.0, 1.5 m/s^2 rms in fore-and-aft direction.

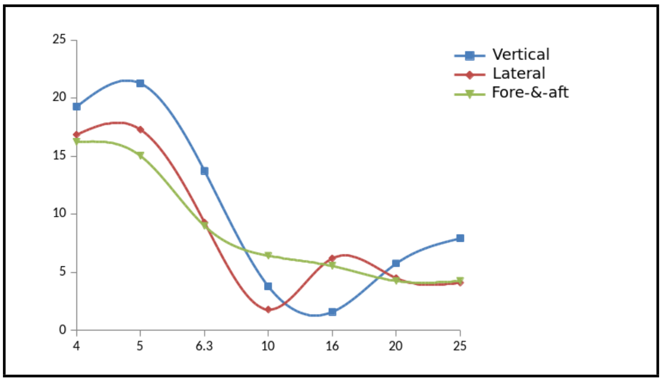

Figure 11. Comparisons of mean percentage reduction responses for 1.0 m/s^2 rms in vertical, fore-and-aft and lateral vibration.

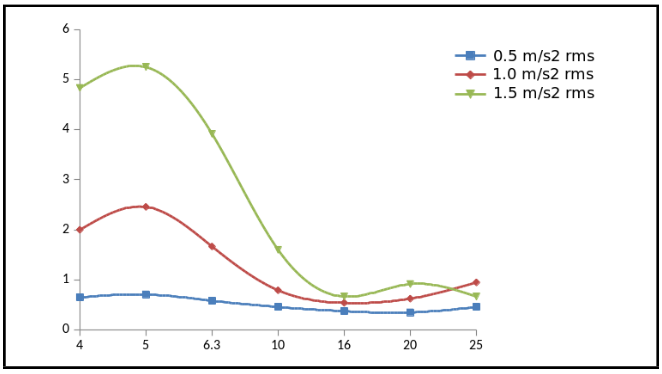

Figure 13. Mean level of perceived difficulty in reading of 12 subjects measured at 0.5, 1.0, 1.5 m/s^2 rms in the lateral direction.

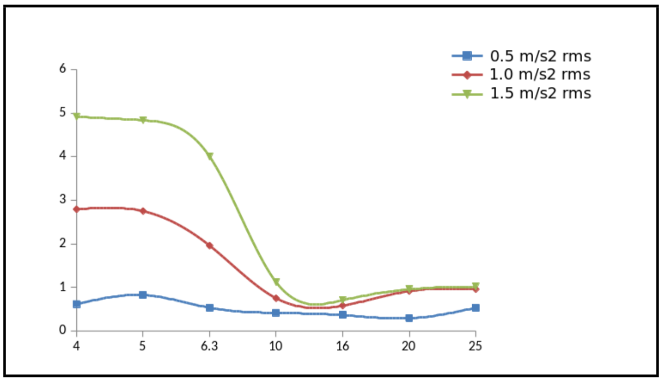

Figure 14. Mean level of perceived difficulty in reading of 12 subjects measured at 0.5, 1.0, 1.5 m/s^2 rms in fore- and-aft direction.

sponses, which indicate that the variables and their interactions are strongly responsible for the results. The vibration direction, magnitude, and frequency have significant effects on the STHT, reduction in performance, and perceived difficulty responses ($p<0.05$), as illustrated in the Table 3. The interactions of variables, *i.e.* vibration direction, magnitude, and frequency, have insignificant effects on the STHT responses. The two-way interactions of variables, *i.e.* vibration direction, magnitude, and frequency, have significant effects on the reduction in performance and perceived difficulty responses.

4. DISCUSSION

In the research used in this paper, none of the studies were observed to relate STHT to reading discomfort at the same vibration environment and posture from the best knowledge of the author. This study has shown that the STHT and reading discomfort are related to each other during the vibration exposure. The STHT, percentage reduction in reading performance, and perceived difficulty in reading have shown higher values around 4–5 Hz frequency for all the vibration directions and magnitudes. The results also revealed that the response decreases with an increase in frequency up to 10–16 Hz, and it is almost constant at least up to 25 Hz.

The results show the various trends between STHT, reduction in performance, and perceived difficulty responses. As the vibration magnitude increases, the peak in STHT responses occurs at lower frequencies. This decrease in STHT resonance frequency with an increase in vibration magnitude has been observed in the present study, which shows the nonlinear behaviour of transmissibility. The nonlinear behavior of

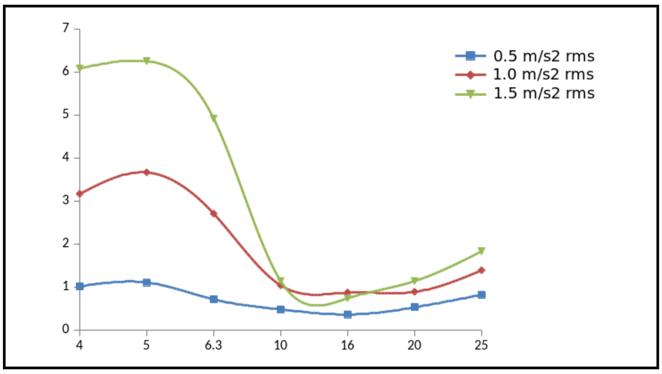

Figure 12. Mean level of perceived difficulty in reading of 12 subjects measured at 0.5, 1.0, 1.5 m/s^2 rms in the vertical direction.

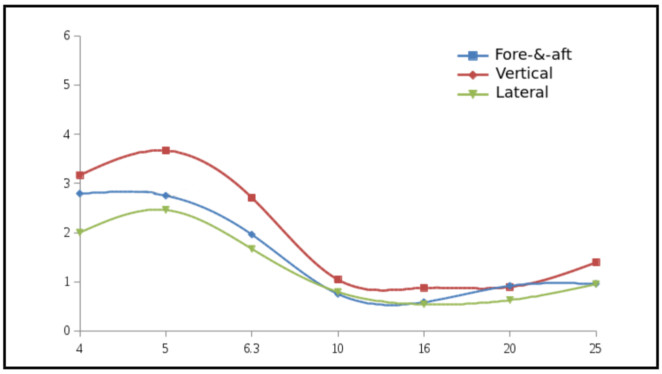

Figure 15. Comparisons of mean level of perceived difficulty in reading for 1.0 m/s^2 rms in vertical, fore-and-aft and lateral vibration.

transmissibility has been discussed previously in many studies.19,26,27 Mansfield and Griffin,[19] showed the nonlinear behaviour of apparent mass and transmissibility to the viscera, pelvis, and lumbar spine, and it was observed that the dynamics of tissues, the bending and buckling of the spine, and some complex responses of the body may be the cause for nonlinearity in biodynamic responses.

The results show that both the percentage reduction in reading performance and the perceived difficulty are found to increase with an increase in vibration magnitude in each independent direction. This finding is consistent with many previous studies.[2,3,28,29] The frequency of vibration also has highly significant effects on the reduction in reading performance and the perceived difficulty in reading. The reduction in reading performance and perceived difficulty have the highest value around 4–5 Hz. Eye movements of the subjects are affected by the whole body vibration depending upon the magnitude and vibration frequency. The performance with respect to reading is largely dependent upon the eye movements of the subjects.[10] The legibility reduces as the image moves faster across the retina, which is due to the unstable image on the retina.[24] The lines which make up the letters and rows overlap with each other at higher magnitudes of whole body vibration, which in turn reduces the reading performance of the subjects.

The results show a considerable decline in reading performance and an increase perceived difficulty in reading at 25 Hz frequency in the vertical direction. Most of the subjects feel agitation in the eyes at around 20–25 Hz frequency. This agitation in the eyes may be attributed to the resonance of the eyeballs or the internal structure of the head of the seated subjects under the exposure to WBV at 25 Hz frequency.

The reading discomfort is quantified with the help of the percentage reduction in reading performance and perceived difficulty in reading. The results for these two quantifying parameters show the maximum value of reading discomfort occurs around 4–5 Hz frequency of WBV in three independent axes. The STHT also observed the peak around 4–5 Hz frequency in all the three considered directions of vibration. So, both STHT and reading discomfort show the maximum values at the resonant frequency of the human body. Considerable reading discomfort was also shown around 25 Hz frequency, which may be attributed to the resonance of the eyeballs of the subjects. The reading discomfort may be affected by other frequencies which may be the resonance frequencies for the subjects' internal organs or structure of the head. The vibrations for the internal organs and eyes are difficult to measure. At the resonance frequencies, *i.e.* around 4–5 Hz of human body, the seated test subjects feel higher reading discomfort during WBV exposure.

5. CONCLUSION

The extent of decline in the reading performance depends upon magnitude, direction, and frequency of vibration. Vibration magnitude and frequency contribute most to the reduction in reading performance and perceived difficulty in reading. The decline in reading performance increases with an increase in vibration magnitude in each direction of vibration. The three measured responses - STHT, percentage reduction in reading performance, and perceived difficulty in reading - are most affected around 4–5 Hz frequency of whole body vibration, which means that the, transmission of vibration to the head and various parts of the head affects the reading performance of the seated subjects. In vertical vibration, reading performance is to some extent affected around 25 Hz frequencies. STHT has shown nonlinear behaviour with respect to vibration magnitude. Principal resonance in STHT occurs at around 4–5 Hz for seated subjects.

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