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Relationship between measured apparent mass and seat-to-head transmissibility responses of seated occupants exposed to vertical vibration

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Abstract

The "to-the-body" and "through-the-body" biodynamic response functions of the seated human body exposed to vertical vibration are measured and analyzed in an attempt to identify relationships between the apparent mass and seat-to-head transmissibility measures. The experiments involved 12 male subjects exposed to three magnitudes of whole-body vertical random vibration ($0.25, 0.5, 1.0\,\mathrm{m/s^2}$ rms acceleration) in the 0.5–15 Hz frequency range, and seated with three back support conditions (none, vertical and inclined), and two different hands positions (hands in lap and hands on the steering wheel). The vertical apparent mass and seat-to-head transmissibility responses were acquired during the experiments, where the head acceleration was measured using a light and adjustable helmet-strap mounted accelerometer. The results showed that both the measured responses show good agreements in the primary resonances, irrespective of the back support condition, while considerable differences between the normalized apparent mass and seat-to-head transmissibility could be seen in the secondary resonance range for the two back supported postures. The seat-to-head transmissibility responses are further shown to be relatively sensitive to back supported postures compared with that of apparent mass responses. Relatively stronger effects of hands position were observed on the seat-to-head transmissibility responses compared with the apparent mass responses under back supported conditions. From the results, it is further concluded that seat-to-head transmissibility emphasizes the biodynamic response in the vicinity of the secondary resonance compared to the apparent mass. The seat-to-head transmissibility measure is thus considered to be more appropriate for describing seated body response to higher frequency vibration.

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1. Introduction

Apparent mass (APMS), driving-point mechanical impedance (DPMI), seat-to-head vibration transmissibility (STHT) and absorbed power have been widely used to characterize response characteristics of the seated subjects exposed to vibration. These functions describe "to-the-body" force–motion relationship at the

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human–seat interface, while the transmissibility function describes ''through-the-body'' vibration transmission properties. Although all these functions describe the body response to vibration, ''to-the-body'' and ''through-the-body'' functions yield considerably different information. Consideration of both types of functions may thus provide a better understanding of physical responses of the seated body to whole-body vibration (WBV), and could provide better means for formulating reliable biodynamic models.

Over the years, a quantity of the two types of biodynamic data has been generated by different investigators using different measurement methods under various sitting conditions, and types and magnitudes of whole-body vibration. The reported data on both types of measurements have shown significant differences that are mostly attributable to differences in test and analyses methods, experiment design, and subjects' anthropometry, nature of whole-body vibration and muscles tension, employed in individual studies [1–6]. Two studies (e.g. Refs. [7,8]) presented a review of the reported data, and demonstrated significant variabilities among both datasets. The variabilities in seat-to-head transmissibility were particularly extreme. Apparent mass, ratio of force to acceleration at the driving-point, has been more frequently used to characterize the ''to-the-body'' biodynamic response to vertical or horizontal vibration, since it permits greater convenience for measurement and performing necessary corrections to account for inertia force due to seat structure [2,9]. Moreover, apparent mass based on driving-point measurements alone, yields considerably smaller variability among the data sets when compared to that observed in seat-to-head transmissibility. It was further concluded that apparent mass responses yield lesser variability in the primary resonant frequency compared to that observed from driving-point mechanical impedance responses [10]. Consequently, the vast majority of the studies have focused on measurements of apparent mass responses, while the seat-to-head transmissibility measurements have been the subject of relatively fewer studies.

Although it is recognized that knowledge of a relationship between different forms of biodynamic functions would facilitate an understanding of vibration response of the human body [10–12], this relationship has not yet been thoroughly established, most likely due to excessive inter-subject variability of the measured seat-to-head vibration transmissibility responses. Only a few studies have attempted to identify relationships between the biodynamic functions (e.g., Refs. [10,13]). Boileau et al. [13] investigated the relationships between driving-point mechanical impedance and seat-to-head transmissibility functions based upon 11 reported one-dimensional lumped parameter models. The majority of the models showed differences in frequencies corresponding to peak magnitudes of the two functions, which were expressed as resonant frequencies. The majority of the models considered, however, did not include the head substructure for evaluating seat-to-head transmissibility responses. The biomechanical models proposed by Patil and Palanichamy [14] and Payne and Band [15] with head substructure revealed 0.1 Hz difference in the primary resonant frequencies observed from the seat-to-head transmissibility and the apparent mass magnitudes. Wu et al. [10] investigated a relationship between the APMS/DPMI and seat-to-head transmissibility functions based upon four biodynamic models, ranging from single- to three-degrees of freedom models. It was shown that both the normalized apparent mass and seat-to-head transmissibility functions provide very similar fundamental resonant frequency, while the frequencies of higher modes of the higher order models differed. The apparent mass response was normalized with respect to seated body mass. The structures of models employed in this study, however, did not include a head substructure.

Although both the apparent mass and seat-to-head transmissibility response functions relate to the seated occupant responses to whole-body vibration, the two responses have shown some differences in resonant frequencies that are generally identified from the peak response magnitudes [7,8,16]. Synthesis of measured data presented in ISO-5982 [16] exhibits considerable differences in primary resonant frequency in the apparent mass and the seat-to-head transmissibility responses. Such differences may be inherent to ''to-the-body'' and ''through-the-body'' responses of the biological system to vibration or may be attributed to differences in subjects' anthropometry and methods used to characterize the two measures. Moreover, the two measures have been acquired either by different investigators or during different test sessions that may also involve different subjects. The measurements of two functions under carefully controlled identical conditions could yield considerable insight into relationship between them, by reducing contributions due to inter- and intra-subject variabilities. Moreover, characterization of both ''to-the-body'' and ''through-the-body'' response functions for same subjects under identical test conditions could provide a better understanding of body response to whole-body vibration. In recent years, only one study has measured both functions with the same experimental condition using eight subjects exposed to vertical whole-body vibration, while a relationship between the two functions was not attempted [17]. Moreover, the seat-to-head transmissibility responses were measured using a bite-bar revealed excessively inter-subject variability.

Reported studies have invariably shown important influences of type and level of vibration, and sitting posture and muscles tension on both types of responses to whole-body vibration. The relations between the two biodynamic functions are thus also expected to depend upon the sitting and vibration conditions. The vast majority of the studies, however, have considered sitting with an unsupported back. Only a few studies have characterized vibration responses of seated body against an inclined back support, particularly the seat-to-head transmissibility [18]. Considering that the automotive seats are designed with inclined seat pan and backrest to provide comfortable and controlled sitting posture, the reported biodynamic data would be insufficient for identifying a relationship between the two types of functions. A study of seated body responses to vibration and the relationships between the two biodynamic functions, while sitting against a vertical or an inclined back support, thus forms an essential task.

In this study, the vertical apparent mass and seat-to-head transmissibility response characteristics of seated subjects are derived through measurements of total biodynamic force at the seat pan, and motions of the seat pan and head along the applied input acceleration direction, using 12 male subjects. The data were acquired under three different back support conditions and two different hands positions representative of drivers and passengers-like postures. The measurements were performed to establish the influences of back support condition, hands position and vibration magnitude on the acquired measures. Relationships between the measured vertical apparent mass and seat-to-head transmissibility biodynamic responses of the seated occupants under vertical vibration are investigated as functions of sitting posture and excitation conditions.

2. Measurement and analysis methods

A schematic representation of the experimental setup used in this study is shown in Fig. 1. The setup consists of a whole-body vehicle vibration simulator (WBVVS) capable of producing vertical vibration of deterministic as well as random nature. The whole-body vehicle vibration simulator comprises two vertical electro-hydraulic actuators with a number of safety control loops that limit the peak displacement, peak force and peak acceleration to preset levels. A rigid seat is installed on the whole-body vehicle vibration simulator platform through a force platform to measure the total dynamic force developed by the occupant and the seat. A steering column is installed on the whole-body vehicle vibration simulator to allow for experiments to be conducted under a driver-like sitting posture. The experiments were conducted using a rigid seat with a configuration representative of that used for automotive seats. The seat consisted of a $500 \times 450\,\text{mm}^2$ flat seat

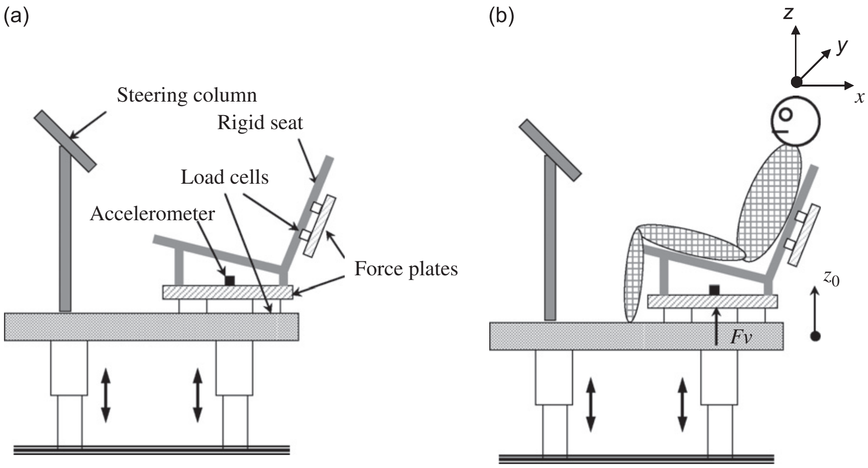


Fig. 1. Schematic representation of experimental setup: (a) the seat, force platform and accelerometer arrangements for measurements of apparent mass (APMS) and seat-to-head transmissibility; and (b) sitting posture and head motion measurement.

pan installed at an angle of 77° with respect to the vertical (z) axis. The experiments were performed to measure vertical vibration transmitted to the occupants head seated without a backrest, and leaning against a vertical and an inclined backrest forming an angle of 24° with respect to the z-axis.

The seat assembly is instrumented to measure the total body force acting on the seat base along the z-axis. The force plate at the seat base was fabricated using four Kistler load cells with a summing junction. Two identical 222 N force transducers (Sensotec, model 41), together with a summing junction were also installed between the backrest and the tubular support structure of the seat to measure the forces along an axis normal to the back support surface. Fig. 1(a) illustrates the location of the load cells supporting the seat. The seat and the force platform were positioned to achieve the overall center of gravity of the seat–occupant system near the geometric center of the force sensors. A single-axis accelerometer (Analog Devices Model ADXL05 EM-1) was installed on the whole-body vehicle vibration simulator to measure the acceleration due to vertical vibration at the driving point. The primary resonance frequency of the assembly comprising seat with its support structure, and the vibration platform with the steering column was measured as 21 Hz.

A three-axis accelerometer was used in a light-weight helmet-strap mounting system to acquire the head vibration along the three translational axes. The frequency response characteristics of the system have been presented in Ref. [18]. The measurements were performed for each subject assuming three different back support conditions: (i) sitting with no back support, NBS; (ii) sitting with upper body supported against a vertical backrest, VBS; and (iii) sitting against the inclined backrest, IBS. Fig. 1(b) illustrates the inclined back support condition. Under each back support condition, the subjects were also asked to assume two different hands positions: hands in lap (referred to as "LAP") representing a passenger-like sitting posture, and hands on the steering wheel (referred to as "SW") representing the driver-like sitting posture. Each subject was asked to wear the head-accelerometer band and adjust its tension to ensure a tight but comfortable fit. The experimenter made the necessary adjustments to ensure appropriate orientation of the head accelerometer, using a level. Each subject was asked to sit comfortably with average thigh contact with upper legs comfortably supported on the seat pan and lower legs oriented vertically with feet on the vibrating platform, assuming the desired posture. Each subject was further asked to maintain a steady head position by staring straight ahead at his self-image in a mirror, which was located on the wall around 4 m away from the test subject. Meanwhile the subject's posture during each trial was visually checked by the experimenter to ensure consistency.

A total of 12 healthy adult male volunteers, aged between 25 and 39 years, took part in the experiment. The subjects had no prior known history of musculo-skeletal system disorders. The subjects' mass ranged from 66.4 to 99.6 kg, with mean mass of 77.3 kg and standard deviation of the mean of 10.1 kg. The standing height of the subjects varied from 1.64 to 1.83 m. The physical characteristics of test subjects are summarized in Table 1. Prior to the tests, each subject was informed about the purpose of the study, experimental set up and usage of a hand-held emergency stop, which could suppress the platform motion in a ramp-down manner, when activated. Each subject was given written information about the experiment and was requested to sign a consent form that was previously approved by a Human Research Ethics Committee.

The vibration simulator was operated using the synthesized white-noise vibration spectrum in the 0.5–15 Hz frequency range. Three different levels of broad-band excitations were synthesized to yield overall rms acceleration values of 0.25, 0.5 and 1 m/s^2. Table 2 summarizes the test matrix used in this study, which combines both the excitation and postural variations. The acceleration signals measured at the seat base and the head (vertical, lateral and fore-and-aft directions) together with the seat base and backrest force signals were acquired in a multi-channel data acquisition and analysis system (Bruel & Kjær Pulse 6.0 system).

Table 1
Physical characteristics of test subjects involved in the measurements

$N = 12$	Mean	Standard deviation	Minimum	Maximum
Age (years)	30.75	6.02	25	39
Weight (kg)	77.26	10.12	66.4	99.6
Height (m)	1.74	0.06	1.64	1.83

Table 2
Test matrix used in measurements

White noise excitation	0.25 0.5 1.0 m/s^2 rms (0.5–15 Hz)	0.25 0.5 1.0 m/s^2 rms (0.5–15 Hz)	0.25 0.5 1.0 m/s^2 rms (0.5–15 Hz)
Back support condition	No back support (NBS)	Vertical back support (VBS)	Inclined back support (IBS)
Hands position	LAP, SW	LAP, SW	LAP, SW

LAP—hands in lap, SW—hands on steering wheel.

The data corresponding to each measurement were acquired over a period of 56 s (25 averages with an overlap of 75%). The data analyses were performed using a bandwidth of 100 Hz and resolution of 0.125 Hz. Each experiment was performed twice, and the results were compared to ensure reasonable repeatability.

The primary purpose of the experiments in this study was to derive both the apparent mass and seat-to-head transmissibility biodynamic responses under identical experimental conditions for the same subject and sitting posture. Due to the limitation of the number of available analyzer channels, the measurements were performed in two sessions. The first session involved the apparent mass measurement at the pan and the backrest, while the seat-to-head transmissibility data were acquired during the second session. In order to maintain a relatively consistent sitting posture, the back force was strictly monitored in both sessions for the back supported postures. For the same posture and subject, the time interval between two sessions of measurements was generally less than one hour. The static force signals acquired from the seat base and backrest force sensors, were also recorded prior to and after each test, and were compared to examine the consistency in the subject posture.

Vertical apparent mass is derived from the spectral analyses of the data, namely, the complex ratio of cross-spectral density between the vertical acceleration and force measure at the seat base, and the auto-spectral density of the vertical seat acceleration:

$$M_v(\mathrm{j}\omega) = S_{\ddot{z}_0 F_v}(\mathrm{j}\omega)/S_{\ddot{z}_0}(\mathrm{j}\omega), \tag{1}$$

where $M_v(\mathrm{j}\omega)$ is referred to as "vertical apparent mass" corresponding to the excitation frequency of ω. $S_{\ddot{z}_0 F_V}(\mathrm{j}\omega)$ is the cross-spectral density of the total force measured (F_v) at the seat base along the vertical z-axis and the acceleration due to excitation $\ddot{z}_0$. $S_{\ddot{z}_0}$is input acceleration auto-spectral density.

The measured force F_v comprises components due inertia force of the force plate and the seat structure, and biodynamic force of the seated occupant. The measured apparent mass responses of the seat and the subject were thus inertia corrected using the methodology described in the reported studies [2,5]. For this purpose, the vertical apparent mass responses were initially measured with test seat alone, which were subsequently applied to perform the inertia cancellation of the measured biodynamic response of the seat and supporting structure, and the subject.

The analysis of the head acceleration data was limited to vertical axis acceleration alone. The vertical seat-to-head transmissibility is evaluated as the complex ratio of cross-spectral density between the seat acceleration and the vertical head acceleration, and the auto-spectral density of the seat acceleration, such that

$$T_v(\mathrm{j}\omega) = S_{\ddot{z}_0 \ddot{z}}(\mathrm{j}\omega)/S_{\ddot{z}_0}(\mathrm{j}\omega), \tag{2}$$

where $T_v(\mathrm{j}\omega)$ is referred to as "vertical STHT", and $S_{\ddot{z}_0 \ddot{z}}(\mathrm{j}\omega)$ is the cross-spectral densities of head acceleration along the z direction with the vertical seat base acceleration $\ddot{z}_0$.

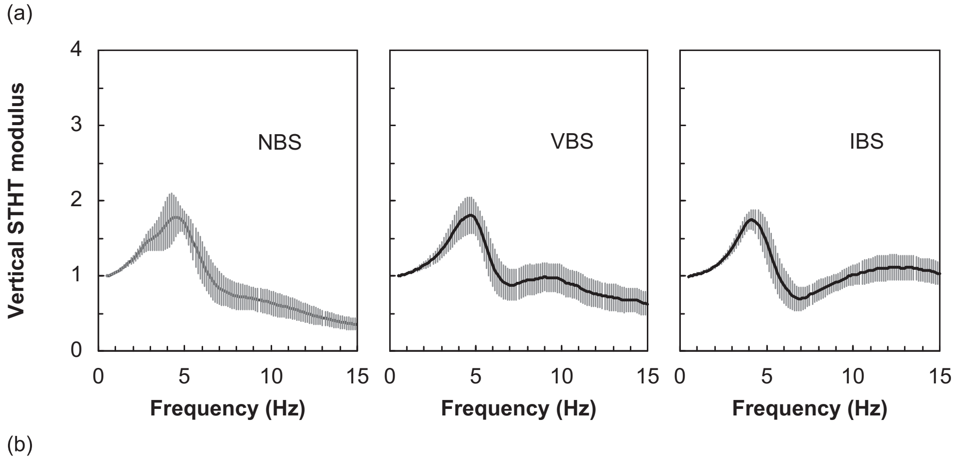
The coherence between the forces and accelerations were constantly monitored during the experiments [19]. A measurement was rejected when coherence value was observed to be below 0.8 within the entire frequency range. The analyzer software was also programmed to continually display the rms acceleration due to excitation in the third-octave frequency bands, which was monitored to ensure consistent excitation.

Multi-factor ANOVA was performed using the SPSS software to verify the statistical significance level of the main factors upon the vertical apparent mass and seat-to-head transmissibility responses. These included the three excitation levels, three back support conditions (no back support, vertical back support and inclined back support), and two hands positions (hands in lap and steering wheel).

3. Results and discussions

3.1. Vertical seat-to-head transmissibility responses

The data acquired in this study was analyzed to establish vertical seat-to-head transmissibility (T_v) responses of 12 subjects seated assuming three different back support conditions and both hands postures. The inter-subject variabilities [18] were also evaluated in the measured data. Despite considerable scatter between the seat-to-head transmissibility responses of different subjects, the peak moduli occur in the 4–5 Hz frequency range for all subjects, irrespective of the back support conditions, often referred to as the primary resonant frequency of the seated body. As an example, the mean seat-to-head transmissibility magnitude and phase curves with standard deviations of the mean as error bars of 12 subjects seated with three different back support conditions and hands in lap posture, while exposed to 1 m/s^2 rms acceleration, are presented in Fig. 2. The results revealed considerable effects of back support conditions on the magnitudes of acceleration transmitted to the head. At frequencies below the primary resonance, a larger dispersion of the moduli of the T_v was observed for the no back support and vertical back support postures than with the inclined back support posture. At frequencies around the primary resonance, the vertical seat-to-head transmissibility responses with the inclined back support exhibit smallest scatter, while relatively larger variations were observed under the no back support condition. For the no back support posture, the coefficient of variation of T_v modulus was in the vicinity of 20% near the primary resonance, which reduced to nearly 12% and 7% for the vertical back support and inclined back support posture respectively. The phase responses also revealed



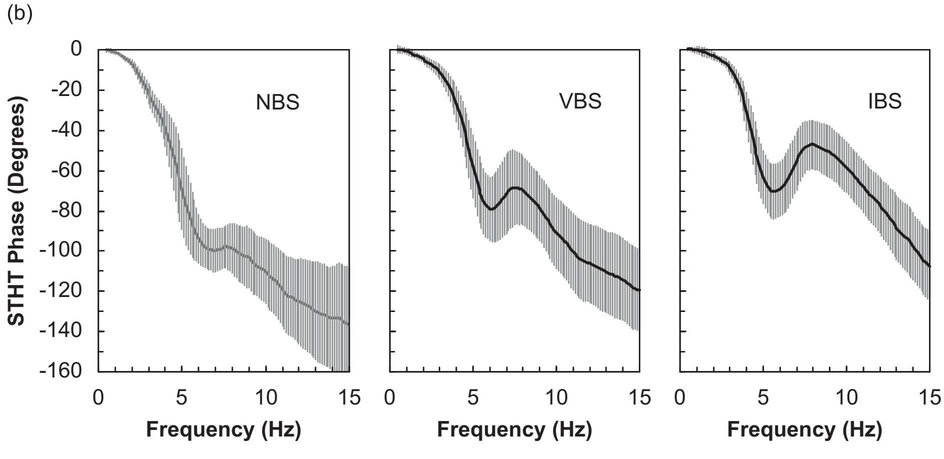


Fig. 2. Mean curves and standard deviation scatters of the vertical seat-to-head transmissibility (STHT) magnitude and phase responses for 12 subjects measured at 1.0 m/s^2 rms excitation under three back support conditions with hands in lap posture: (a) magnitude and (b) phase. NBS is no back support, VBS is vertical back support and IBS is inclined back support.

consistent trends and similar degrees of scatter of variability. The no back support posture resulted in larger variability of the data at higher frequencies.

The vertical seat-to-head transmissibility responses clearly reveal the presence of a second resonance in the 9–11 Hz range, although it is far more pronounced for the back supported postures. The second mode frequency under inclined back support posture, however, is considerably higher. A number of reported biodynamic response studies have also suggested the presence of this secondary peak. Matsumoto and Griffin [17] found the second peak between 6 and 9 Hz for vertical vibration transmissibility of seat to L4 and to the pelvis under the no back support posture. Similarly, Mansfield and Griffin [20] found the second resonant peak in the 8–10 Hz range, while investigating the seat to spine and pelvis acceleration transmissibilities under vertical whole-body vibration. A second resonance frequency occurring in the vicinity of 11 Hz under the inclined back support and hands on steering wheel posture has also been reported on the basis of the measured apparent mass biodynamic responses [5]. Nawayseh and Griffin [21] also observed the presence of a second resonance peak of relatively small magnitude in the 10–15 Hz range in the fore-and-aft cross-axis apparent mass response measured at both the seat and the backrest, which was considered to be consistent with the rotational mode of the pelvis and the lower upper body (T11-L3).

3.2. Vertical apparent mass responses

Fig. 3 illustrates mean magnitude and phase responses of vertical apparent mass (M_v) responses measured for 12 subjects seated with three different back support conditions and hands in lap posture, while exposed to 1 m/s^2 rms acceleration excitation. The figure also shows standard deviation of the means as the error bars. The scatter in the M_v magnitude response tends to be higher at lower frequencies prior to the primary resonance, which can be mostly attributed to variations in the body masses. But at frequencies above the primary resonance, the scatter in the magnitude responses is relatively small, irrespective of the back support

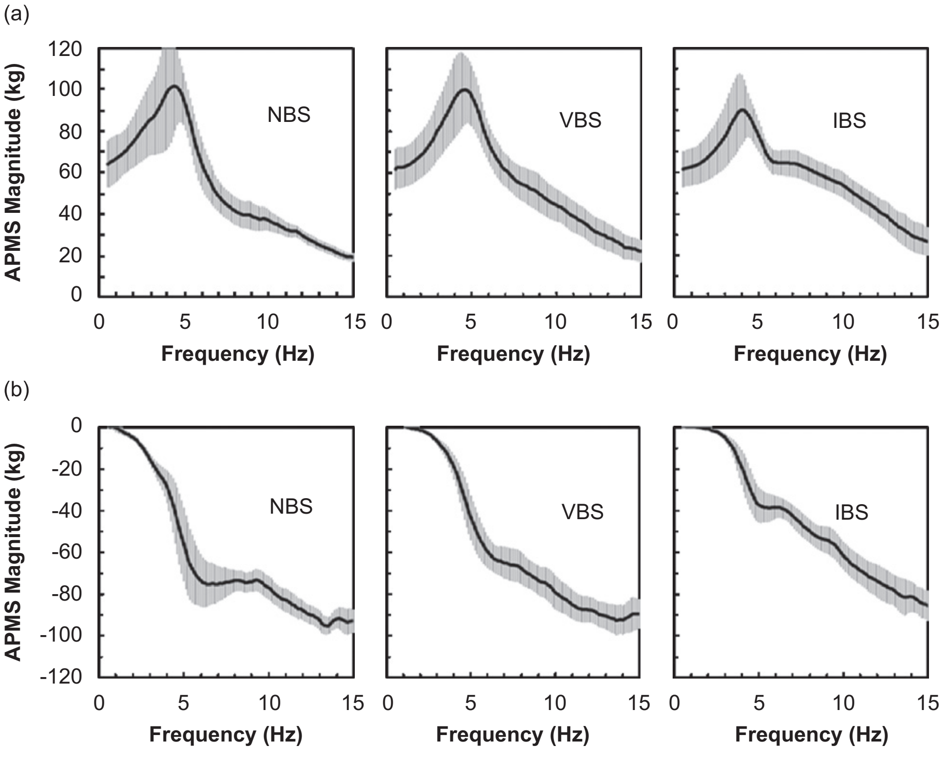


Fig. 3. Mean curves and standard deviation scatters of the vertical apparent mass (APMS) magnitude and phase responses for 12 subjects measured at 1.0 m/s^2 rms excitation under three back support conditions with hands in lap posture: (a) magnitude and (b) phase. NBS is no back support, VBS is vertical back support and IBS is inclined back support.

conditions. The corresponding scatter in the phase response, however, shows the opposite trend compared with magnitude response, irrespective of the back support condition. Similar degrees of scatter and consistent trends in the magnitude and phase data were also observed for other test conditions involving different excitation magnitudes and hands on steering wheel.

Despite the scatter between the apparent mass magnitude responses of different subjects, the peak magnitude of M_v occurs in the 3.75–5.75 Hz frequency range for all subjects, irrespective of the back support condition, which is referred to as the primary resonant frequency of the seated body. The "vertical apparent mass" responses (M_v) exhibit a notable second resonance in the 7–10 Hz frequency range only for some subjects, when sitting assuming vertical back support posture. This secondary peak is thus not as clear as it was observed in the mean seat-to-head transmissibility response. The magnitude responses of all the subjects, however, reveal a distinct second peak in the 7–10 Hz frequency range under inclined back support posture. Moreover, the magnitude of this secondary peak becomes higher for the back supported postures as compared with the no back support posture.

The strong dependence of the apparent mass magnitude response on the body mass has been reported in several studies [2,5,22]. The magnitude responses are thus frequently normalized with respect to either static seated mass or apparent mass magnitude at a very low frequency (e.g. 0.5 Hz) such that the apparent mass responses of subjects of different body masses can be directly compared [2,12]. Besides, the dimensionless characteristics of normalized apparent mass data would facilitate the analysis of its relationship with the measured seat-to-head transmissibility. The mean normalized vertical apparent mass magnitude responses of 12 subjects together with the standard deviation of the mean error bars are illustrated in Fig. 4 for all the three back support conditions. The normalization resulted in lower coefficient of variation in magnitude in the low frequency, and below 20% near the primary resonance, irrespective of the sitting posture and excitation magnitudes.

3.3. Effects of contributing factors on measured biodynamic responses

The results presented in Figs. 2–4 suggest that the back support condition strongly affects both the seat-to-head transmissibility and apparent mass responses. Furthermore, the hands position may also influence both the responses, while little has been reported in the literature on the influences of such factors. The human body shows a highly nonlinear response to vibration. A common finding associated with the driving-point biodynamic functions is a reduction in the primary resonance frequency with increase in the vibration magnitude [3,4,20]. However, little has been reported on the influence of vibration magnitude on the seat-to-head transmissibility responses. Mansfield and Griffin [20] demonstrated the nonlinearity of the seat vibration transmitted to various body segments of the seated body, namely the viscera, pelvis and lumbar spine. The measured data were thus analyzed to study the effects related to different experimental conditions considered in this study.

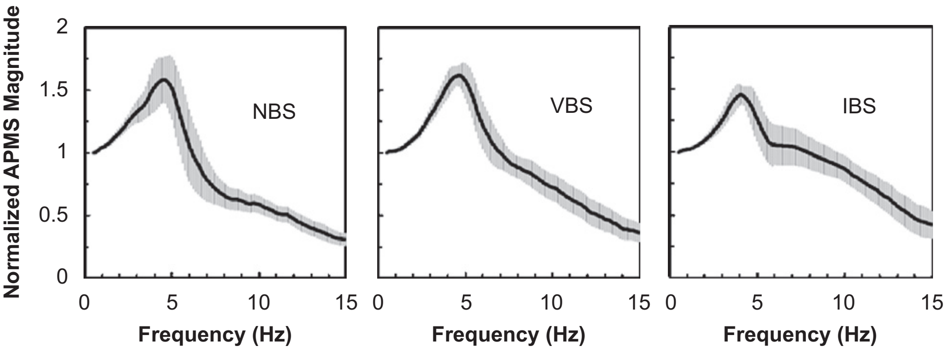


Fig. 4. Mean curves and standard deviation scatters of 12 subjects in the normalized vertical apparent mass (APMS) responses under 1.0 m/s^2 rms excitation with three back support conditions and hands in lap postures. NBS is no back support, VBS is vertical back support and IBS is inclined back support.

Although a few studies have explored the influence of variation in the body mass and size on the seat-to-head transmissibility [23,24], a definite influence of such factors, however, could not be established due to considerable variations in the measured seat-to-head transmissibility responses of individuals. The seat-to-head transmissibility results attained in this study have revealed little effects of body mass, which was consistent with the observations reported in the published studies [7,23]. Owing to the strong dependence of the apparent mass on the body mass, which cannot be entirely eliminated through normalization [25], the analyses were performed for a subset of data containing those acquired for a smaller subject population of comparable body mass. For this purpose, the data acquired for a total of six subjects with body mass ranging from 70.5 to 79.96 kg (mean = 75.58 kg; standard deviation = 2.90 kg) were selected from the ensemble of 12 subjects in order to examine the influence of postural factors variations. The analyses based on this selected subset of data are expected to eliminate the strong inter-subject variability arising from variations in the anthropometric variables, such as the body mass. The effects of excitation levels and posture-related factors are characterized by analyzing the seat-to-head transmissibility and normalized apparent mass responses of six selected data sets in the following sections.

3.3.1. Effect of vibration magnitude on seat-to-head transmissibility and apparent mass

Figs. 5(a) and (b) compare the normalized vertical apparent mass and seat-to-head transmissibility responses measured with hands in lap for the six subjects while exposed to three excitation levels under three

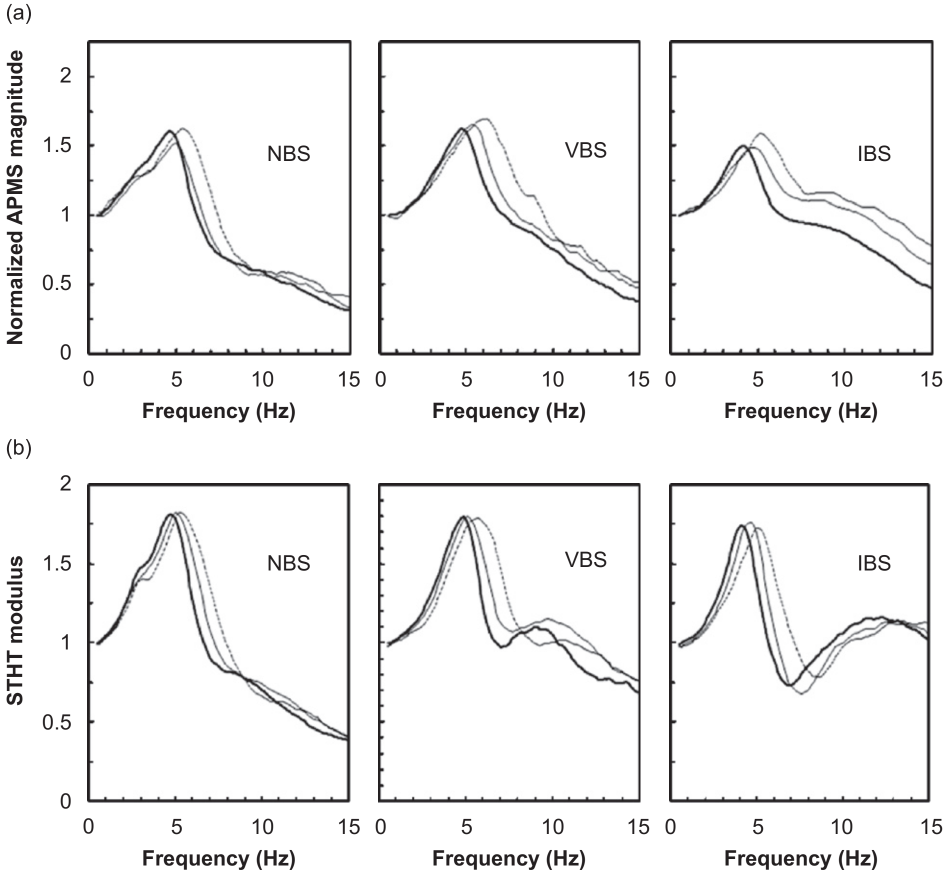


Fig. 5. Influence of excitation magnitude on mean vertical apparent mass (APMS) and seat-to-head transmissibility (STHT) responses of six subjects with hands in lap posture: (a) vertical normalized apparent mass (APMS) magnitudes; (b) vertical seat-to-head transmissibility. ━━ 1.0 m/s^2 rms; ―― 0.5 m/s^2 rms; ---- 0.25 m/s^2 rms. NBS is no back support, VBS is vertical back support and IBS is inclined back support.

back support conditions. The results distinctly reveal that the primary resonance in both apparent mass and seat-to-head transmissibility tends to shift to a lower frequency with increasing vibration magnitude, irrespective of the back support condition. The ANOVA results also show significant effects ($p<0.0001$) of excitation magnitudes upon the primary resonance frequencies for both measures. Similar trends were also observed for the apparent mass and seat-to-head transmissibility phase responses. The shift in the frequency however, is more evident for the back supported postures. This suggests that the upper body supported against a back support exhibits more softening tendency under higher magnitudes of vertical vibration. The posture effect was observed to be significant on both apparent mass and seat-to-head transmissibility ($p<0.0001$). The secondary resonant frequency in the vertical apparent mass response, which is more evident with the vertical and inclined back supports, also decreases with increasing vibration magnitude. The same trend can also be observed from the seat-to-head transmissibility. The apparent mass magnitude results suggest that the mean primary resonance for the inclined back support and hands in lap posture decreases by approximately 1.07 Hz (from 5.29 to 4.22 Hz), when vertical excitation magnitude is increased from 0.25 to 1.0 m/s^2 rms. The seat-to-head transmissibility also revealed similar reductions in the primary resonance frequency, which for the inclined back support posture decreased by approximately 1.13 Hz (from 5.43 to 4.30 Hz). Under the same back support condition, the steering wheel posture yields relatively larger differences compared with hands in lap posture ($p<0.005$). The apparent mass responses reveal that the mean primary resonance for the inclined back support and steering wheel posture decreases by approximately 1.28 Hz (from 5.51 to 4.23 Hz), with increasing vertical excitation magnitude from 0.25 to 1.0 m/s^2 rms. Similarly, the seat-to-head transmissibility also revealed that the primary resonance frequency decreased by approximately 1.29 Hz (from 5.59 to 4.30 Hz) for the inclined back support and steering wheel posture.

3.3.2. Effect of hands position on the seat-to-head transmissibility and apparent mass

Figs. 6(a) and (b) compare the mean normalized vertical apparent mass and mean vertical seat-to-head transmissibility magnitude responses of six subjects, respectively, measured with two hands position (in lap and on the steering wheel), while exposed to excitation level of 1.0 m/s^2 rms. The hands position revealed relatively larger differences in the normalized apparent mass magnitude and vertical seat-to-head transmissibility occurring around the primary resonance for the no back support condition, as opposed to the vertical back support and inclined back support conditions ($p<0.005$). For the back supported postures, the effect was significant in the 6–9 Hz frequency range, which is also evident in Fig. 6. The results show relatively stronger effects of hands position on the seat-to-head transmissibility compared to the apparent mass magnitude response. This is clearly evident for the no back support posture in the vicinity of the primary resonance and could be attributed to the vibration entering the hands, which yields greater contribution to the head vibration, whereas its contribution to the biodynamic force developed at the seat pan is small. For the back supported postures, the coupling between the hands and the steering wheel tends to be relatively weaker, which yields small effects on the resonant responses, particularly for the seat-to-head transmissibility ($p>0.05$). An earlier study has shown greater effects of hands position on the apparent mass response of subjects seated against an inclined back support and exposed to lower magnitudes of vertical vibration (0.25–1 m/s^2 rms in the 0.5–40 Hz range) [5]. It was shown that sitting against an inclined back support with hands on steering wheel posture causes higher resonance and lower peak magnitude of the apparent mass compared to those attained for subjects seated with hands on lap. The results attained in the present study show relatively smaller differences in the resonance frequencies, which is due to relatively larger levels of broad-band random vibration used in studies compared to those employed in the reported studies [5].

3.3.3. Effect of back support condition on seat-to-head transmissibility and apparent mass

Fig. 7 illustrates comparisons of mean normalized apparent mass and seat-to-head transmissibility attained for the three back support conditions (no back support, vertical back support and inclined back support) under exposure to 1.0 m/s^2 rms excitation and the hands in lap posture. Both the apparent mass and seat-to-head transmissibility responses exhibit similar trends with regard to the effects of back support. The ANOVA results showed significant effects of three back support conditions upon the primary resonance frequencies ($p<0.0001$) obtained from both the measures, while the significant effects were also evident at frequencies

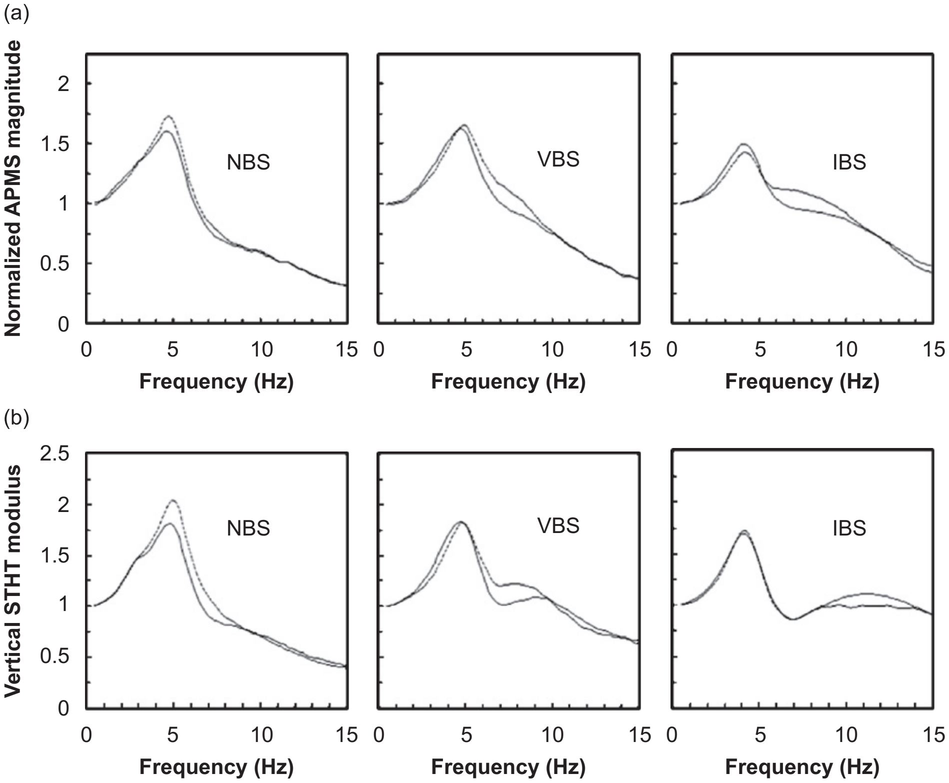


Fig. 6. Influence of hands position on mean vertical apparent mass (APMS) and seat-to-head transmissibility (STHT) responses of six subjects: (a) vertical normalized apparent mass (APMS) magnitudes; (b) vertical seat-to-head transmissibility (STHT). ——— hands in lap; ------- hands on the steering wheel. NBS is no back support, VBS is vertical back support and IBS is inclined back support.

above the primary resonance ($p<0.01$). The apparent mass data reported for occupants sitting on a rigid seat representing the commercial vehicle seat geometry with considerable lower backrest angle (12° with respect to the vertical axis) and horizontal pan, however, revealed a somewhat opposite trend [25]. The data showed a slightly higher resonant frequency with the inclined back support. The seat used in the present study is designed with pan angle of 13° with respect to horizontal and backrest angle of 24° with respect to the vertical axis. These suggest that the seat geometry could also influence the biodynamic response of the vibration-exposed seated subject, since it directly affects the sitting posture and upper body support. The secondary resonance for the inclined back support, on the other hand, occurs at a relatively higher frequency than those for the no back support and vertical back support postures, which is evident from the seat-to-head transmissibility responses. The peak seat-to-head transmissibility (T_v) and normalized vertical apparent mass (M_v) responses corresponding to this secondary resonance are significantly higher for the inclined back support condition than those for the other support conditions. In the 0.5–3 Hz frequency range, the no back support posture yields relatively higher value of seat-to-head transmissibility and normalized apparent mass modulus. The seat-to-head transmissibility response under no back support condition also exhibits presence of smaller peak in 2–3 Hz, which is also evident in the apparent mass response for the same posture. This frequency has been attributed to the upper body mode around 2 Hz in the fore-and-aft direction [26]. Both the moduli are higher at frequencies above 10 Hz for the back supported postures. The results presented in Fig. 7 suggest that the seat-to-head transmissibility greatly emphasizes the second mode response of the body compared to the apparent mass magnitude, particularly for the back supported postures. This may suggest relatively lower contributions of this mode to the biodynamic force developed at the seat pan. The single-degree-of freedom biodynamic models may thus be inadequate to describe the seat-to-head transmissibility or apparent mass responses under back supported postures. This observation confirms with the conclusions

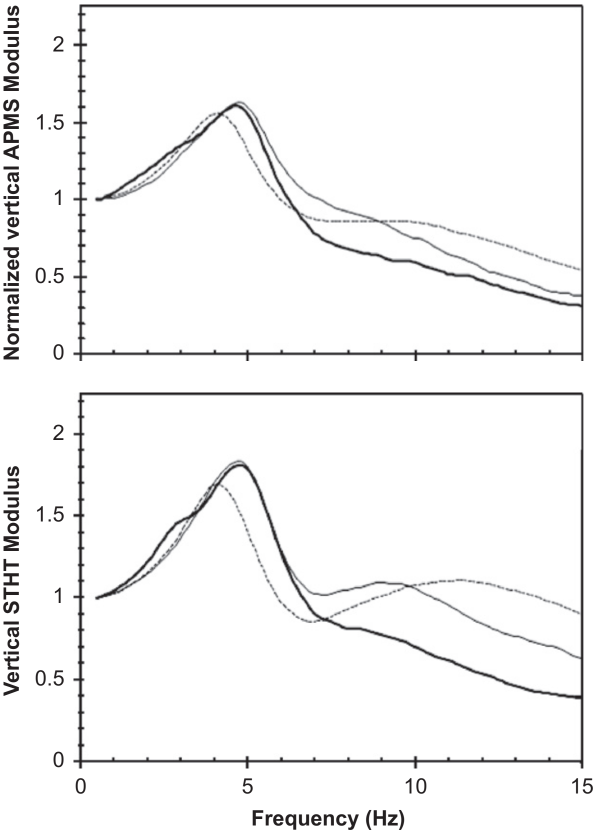


Fig. 7. Influence of three back support conditions on mean apparent mass (APMS) and vertical seat-to-head transmissibility (STHT) responses of six subjects: ▬▬ no back support; ▬▬ vertical back support; - - - - inclined back support (hands in lap: excitation: 1.0 m/s^2 rms).

drawn on the basis of analyses of analytical models [10], although the analysis did not include the back support effects.

3.4. Peak variation analyses of the apparent mass and seat-to-head transmissibility

Table 3 summarizes the mean values of the primary resonant frequencies observed from the measured "vertical apparent mass" and "vertical seat-to-head transmissibility" responses attained under different combinations of experimental conditions, together with the standard deviations of the means. Both the measures exhibit very similar values of primary resonant frequencies for all the conditions considered. The differences in the frequencies estimated from peak apparent mass modulus and the seat-to-head transmissibility is in the order of 6% for the hands in lap posture that occurs for no back support, and 10% for the steering wheel posture that occurs for vertical back support posture. The two measures generally yield closest frequencies under inclined back support conditions, irrespective of the hands position. The mean primary resonant frequencies observed from both responses decrease with increasing excitation magnitude, irrespective of hands position and back support condition, as observed in Fig. 5. The vertical back support condition generally exhibits highest mean frequency for both hands positions, while inclined back support condition yields lowest frequency. The apparent mass magnitude responses reveal greater softening tendency for the back supported postures irrespective of the hands position. From the mean apparent mass responses, the difference in mean primary resonant frequency attained under lowest and highest excitation amplitude considered in this study is observed to be 1.23 Hz for the vertical back support and hands in lap postures, and

Table 3
Primary resonance frequencies (mean and standard deviation) for both vertical apparent mass (APMS) and vertical seat-to-head transmissibility (STHT)

Back support condition	No back support			Vertical back support			Inclined back support		
Excitation (m/s^2 rms)	0.25	0.5	1.0	0.25	0.5	1.0	0.25	0.5	1.0
Mean and standard deviation of the primary resonant frequency									
Vertical APMS									
LAP	5.61	4.99	4.76	5.92	5.19	4.69	5.29	4.70	4.22
	0.48	0.69	0.46	0.60	0.48	0.43	0.48	0.42	0.28
SW	5.78	5.11	4.84	6.26	5.77	5.07	5.51	4.91	4.23
	0.45	0.59	0.36	0.76	0.73	0.43	0.63	0.51	0.31
Vertical STHT									
LAP	5.63	5.06	4.66	5.58	4.94	4.69	5.43	4.83	4.30
	0.59	0.43	0.43	0.63	0.33	0.36	0.74	0.47	0.35
SW	5.97	5.25	4.89	6.08	5.22	4.76	5.59	4.97	4.30
	0.58	0.32	0.33	0.86	0.62	0.46	0.73	0.40	0.37

LAP—hands in lap, SW—hands on steering wheel.

Table 4
p values obtained from a three-factor (B, E and H) analysis of variance of the peak primary resonance of vertical apparent mass (APMS) and seat-to-head transmissibility (STHT)

Measure	Factors						
	B	E	H	$B*E$	$E*H$	$B*H$	$B*E*H$
APMS	0	0	0.001	0.411	0.705	0.143	0.955
STHT	0	0	0.003	0.687	0.391	0.522	0.938

B = back support conditions (NBS, VBS, IBS); E = excitation (root mean square accelerations: 0.24, 0.5, 1.0 m/s^2); and H = hands position (in lap (LAP) or steering wheel (SW)). NBS is no back support, VBS is vertical back support and IBS is inclined back support.

1.28 Hz for the inclined back support and steering wheel posture. For identical back support condition, the steering wheel posture generally yields relatively larger difference in frequency compared with the hands in lap posture. The difference in the frequencies between the hands in lap and steering wheel postures diminishes under higher magnitude excitations for the back support conditions. Both the apparent mass and seat-to-head transmissibility responses reveal this trend. The above findings again suggest greater softening effect of increasing magnitude for the steering wheel posture. The greater softening tendency observed for inclined back support and steering wheel condition is most likely attributed to the well-supported upper body and more stable posture.

The results further show that standard deviation of the primary resonance tends to decrease as the excitation magnitude increases for both "vertical apparent mass" and "vertical seat-to-head transmissibility" frequencies. The standard deviations of the means for vertical apparent mass and seat-to-head transmissibility frequencies generally tend to be considerably higher under lower excitation magnitude of 0.25 m/s^2 rms, when compared to those under higher excitations, irrespective of the hands position and back support condition. Moreover, the inclined back support posture yields relatively lower deviations compared to no back support and vertical back support condition, which help achieve more controlled sitting posture.

Table 4 summarizes the results attained from three factors ANOVA of the vertical primary resonances obtained from the seat-to-head transmissibility and apparent mass responses in view of the back support condition (B), hands position (H) and excitation magnitude (E), and their interactions. The results clearly show significant effects ($p < 0.005$) of all three factors upon the primary resonance frequencies obtained from both the measures, as indicated in previous discussion. The results also show insignificant interactions among the main factors.

3.5. Relationship between the apparent mass and the seat-to-head transmissibility

The measured apparent mass and seat-to-head transmissibility responses exhibit comparable mean values of primary resonant frequencies, irrespective of the posture and excitation conditions considered (Table 3). The magnitude and phase responses of the two measures, however, are different over the frequency range considered irrespective of back support conditions. It has been shown that single degree of freedom (sdof) biodynamic models yield identical normalized apparent mass and seat-to-head transmissibility magnitude and phase responses [10]. The results obtained in this study suggest that the measured ‘‘to-the-body’’ and ‘‘through-the-body’’ biodynamic response characteristics cannot be fully described by sdof biodynamic models.

While the reported studies, despite their differences, have consistently observed the primary resonance in the 4–6 Hz range, some studies have identified a second resonance in biodynamic responses in the 8 and 12 Hz range [2,5,20,21]. The presence of this higher mode in the biodynamic response, however, is less clear and the variability between the reported frequencies and corresponding peak magnitude is much higher. The second resonance at about 8 Hz may be corresponded to pitching modes of the pelvis and the second visceral mode, as suggested by Kitazaki and Griffin [27]. Measured apparent mass and seat-to-head transmissibility responses in this study clearly reveal this particular secondary resonance in the frequency range 7–11 Hz. This secondary resonance, however, cannot be more clearly observed from apparent mass responses. The apparent mass magnitude responses do not clearly show the contributions of this second mode, particularly for no back support and vertical back support conditions. The seat-to-head transmissibility measure may thus be more appropriate for describing seated body responses to higher frequency vibrations, particularly when back support condition is considered.

The biodynamic responses of the seated body to whole-body vibration in terms of apparent mass have been shown to exhibit nonlinearity with respect to vibration magnitude [2,20,21]. The results attained in this study show similar reductions in primary resonance frequencies observed from both the apparent mass and seat-to-head transmissibility responses with increasing in vibration magnitude (Fig. 5). Furthermore, the back support conditions and hands position were found to have similar effects on measured apparent mass and seat-to-head transmissibility moduli over the entire frequency range considered (Figs. 6 and 7).

The relationship between the normalized vertical apparent mass and seat-to-head transmissibility moduli is further illustrated in Fig. 8 for three back support conditions with hands in lap posture and 1.0 m/s^2 rms. It is evident that for all the back support conditions, the primary resonances are nearly identical, while the second mode frequencies either differ or not always evident from both the curves. For the no back support posture, the measured seat-to-head transmissibility tends to be relatively higher than normalized apparent mass magnitude over the entire frequency range, irrespective of hands position. The differences in magnitudes of the two measures are nearly consistent at frequencies above 9 Hz. The peak magnitudes of normalized apparent mass and seat-to-head transmissibility corresponding to primary resonance decrease when inclined back support is used. For the two back support postures, similar trends are observed only up to 5 Hz, including the primary resonance. At higher frequencies, there are quite large differences between the normalized apparent mass and seat-to-head transmissibility magnitudes for the two back supported postures. The seat-to-head transmissibility responses emphasize the biodynamic response in the vicinity of secondary resonance compared to the apparent mass responses, suggesting greater transmission of higher frequency vibration to the head under back supported postures. The no back support posture, on the other hand, yields lowest head vibration at higher frequencies. The seat-to-head transmissibility responses suggest lower overall damping due to seated body under no back support condition, and considerably high damping under back supported conditions.

4. Conclusions

The similarities and differences in the apparent mass and seat-to-head vibration transmission measures of biodynamic responses of seated occupants exposed to whole-body vertical vibration were investigated through

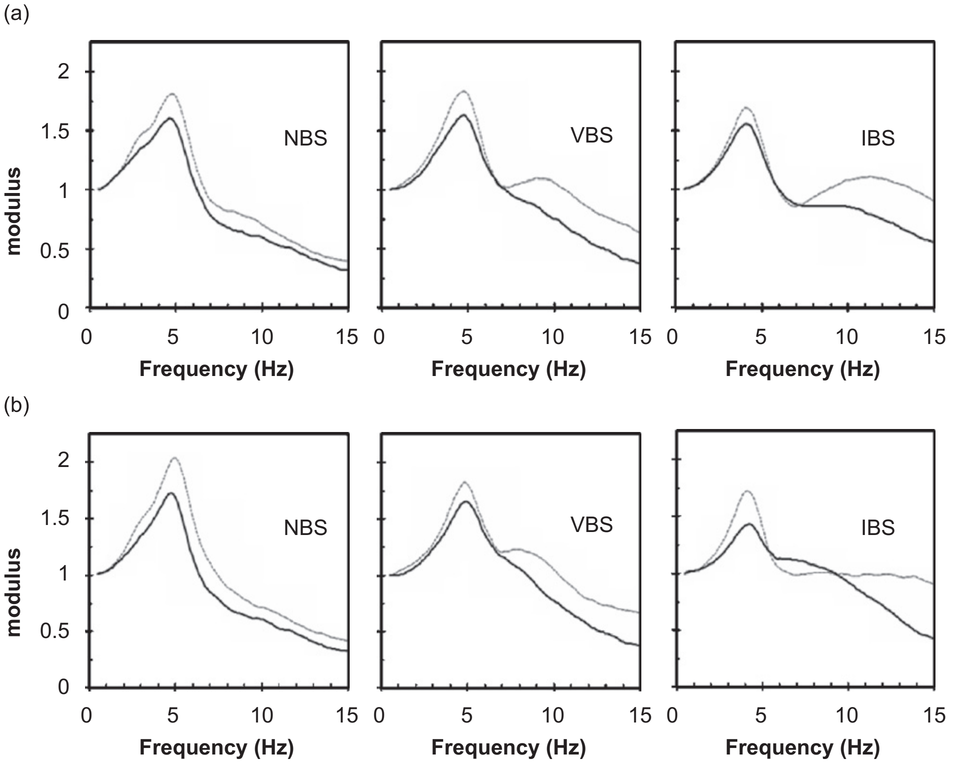


Fig. 8. Comparison of seat-to-head transmissibility (STHT) and normalized apparent mass (APMS) moduli responses (excitation: 1.0 m/s^2 rms): (a) hands in lap; (b) hands on the steering wheel. —— apparent mass; - - - - seat to head transmissibility. NBS is no back support, VBS is vertical back support and IBS is inclined back support.

measurements performed with 12 adult male subjects, and varying sitting conditions. Measured vertical seat-to-head transmissibility and apparent mass biodynamic responses were further characterized to examine the effects of three main factors: back support condition (no back, vertical back and inclined back supports), excitation magnitude (0.25, 0.5, 1.0 m/s^2 rms white noise in the 0.5–15 Hz frequency range) and two hands position (Hands in lap and hands on the steering wheel). Owing to the strong effects of the body mass, the analyses of measured apparent mass responses are performed on a subset of data attained for six subjects with body mass in the 70.5–79.96 kg range. The measured data revealed nonlinearities in apparent mass and seat-to-head transmissibility responses. The results showed relatively stronger effects of hands position on the seat-to-head transmissibility compared with the apparent mass magnitude responses under back supported postures. The results further showed strong influences of three back support conditions on both the vertical apparent mass and the seat-to-head transmissibility responses. The vertical apparent mass and the seat-to-head transmissibility magnitudes in the vicinity of the secondary resonance (7–11 Hz) tend to be higher for the back supported postures. Measured apparent mass and seat-to-head transmissibility responses showed good agreements as far as the primary resonances are concerned irrespective of the back support condition, while considerable differences between the normalized apparent mass and seat-to-head transmissibility magnitudes were found in the secondary resonance range for the back supported postures. The seat-to-head transmissibility responses emphasize the biodynamic response in the vicinity of secondary resonance compared to the apparent mass responses. Under back supported postures, the seat-to-head transmissibility measure emphasizes the response under higher frequencies, while the secondary peaks are not clearly evident from the apparent mass magnitude. The seat-to-head transmissibility measures should thus be considered more appropriate for describing seated body responses to higher frequency vibration, and development of higher order models.

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