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Apparent Mass and Seat-to-head Transmissibility Responses of Seated Occupants under Single and Dual Axis Horizontal Vibration

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Abstract: The apparent mass and seat-to-head-transmissibility response functions of the seated human body are investigated under exposures to fore-aft (*x*), lateral (*y*), and combined fore-aft and lateral (*x* and *y*) axis whole-body vibration. The experiments were performed to study the effects of hands support, back support and vibration magnitude on the body interactions with the seat pan and the backrest, characterised in terms of fore-aft and lateral apparent masses and the vibration transmitted to the head under single and dual-axis horizontal vibration. The data were acquired with 9 subjects exposed to two different magnitudes of vibration applied along the individual *x*- and *y*- axis (0.25 and 0.4 m/s^2 rms), and along both the-axis (0.28 and 0.4 m/s^2 rms) in the 0.5 to 20 Hz frequency range, and analyzed to derive the biodynamic responses. A method was further derived to obtain total seated body apparent mass response from those measured at the backrest and the seatpan. The results revealed coupled effects of hands and back support conditions on the responses, while the vibration magnitude effect was relatively small. For a given postural condition, the biodynamic responses to dual-axis vibration could be estimated from the direct- and cross-axis responses to single-axis vibration, suggesting weakly nonlinear behaviour.

Key words: Apparent mass, Seat-to-head-transmissibility, Seated occupants, Single and dual axis horizontal vibration

Introduction

The biodynamic responses of the seated occupants exposed to whole body vibration (WBV) have been widely investigated in terms of apparent mass (APMS) or driving-point mechanical impedance, seat-to-head vibration transmissibility (STHT) and absorbed power, under broad ranges of vibration and postural conditions[1–6]. The majority of these studies focus on response analyses of seated body exposed to vertical vibration although a few have investigated the responses to fore-aft (x) and lateral (y) vibration[1, 3]. Furthermore, most of the studies have been limited to single-axis vibration and response measurements in the direction of the applied vibration. Only a few recent studies have measured the seated occupants apparent mass responses to orthogonal dual and three-axis vibration[5–7] and only a single study has obtained cross axis responses of seated occupants exposed to dual-axis vibration[7]. Studies on horizontal biodynamics have mostly considered a sitting posture without a back support with only few exceptions[6–8]. The vast majority of the studies reporting the biodynamic responses of subjects seated with back support have primarily focused on the body interactions with the seatpan alone, although the backrest is known to serve as an important secondary driving-point[3, 9].

Although both the back and hands supports are representative of typical sitting postures for vehicle drivers, the effects of both the supports on the biodynamic responses to single and dual-axis horizontal vibration have not been quantified. A single study on horizontal biodynamics has shown considerable influence of hands support on the fore-aft apparent mass at the seatpan, while the body interactions with the back support were not considered[5]. The studies under single axis vibration have shown high magnitudes of biodynamic forces at the seatpan measured along the fore-aft direction under vertical vibration and vice versa, suggesting coupled movements of the human body in the sagittal (x-z) plane under either fore-aft

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or vertical vibration[7, 9, 11]. However, significantly smaller lateral forces at the seatpan were observed under the fore-aft or vertical vibration[7, 9, 11] suggesting weaker coupling between the *x*- and *y*-, and *y*- and *z*- axis responses. The vehicular vibration encompasses multi-axis whole-body vibration including translational and rotational components. The cross-axis biodynamic responses of the seated body observed under single-axis vibration would contribute to the total APMS and STHT responses to multi-axis vibration.

The international standard ISO 2631-1[12] defines identical weighting for assessing the exposure to both *x*- and *y*- axis vibration. It has been shown that the proposed W_d-weighting correlates reasonably well with the biodynamic responses of the body seated without a back support[4]. The biodynamic responses of the occupants seated with a back support and exposed to fore-aft WBV, however, differed significantly from those corresponding to sitting with a back support and exposed to lateral vibration[1, 3, 4, 6, 8]. The characterisation of biodynamic responses of the body seated assuming typical driving postures (back and hands supports) is thus essential for defining adequate frequency weightings for exposure assessments. Furthermore, the studies of upper body interactions with the back support together with the cross-axis biodynamic responses are vital for enhancing the seated body responses to single and dual-axis horizontal vibration. Only a few studies, however, have considered the backrest as the second important driving point and obtained the APMS responses at the backrest under fore-aft vibration[3, 8]. A single study has reported the upper body interactions in terms of cross-axis APMS along all the three axes under fore-aft vibration[8].

Recent studies on seated occupants biodynamic to dual and three-orthogonal axis vibration have consistently reported similar seatpan APMS response trends, but slightly lower resonant frequencies and magnitudes compared to the single axis APMS responses[5–7]. These studies have considered either back supported or hands supported postures, although not both, and did not attempt measurements at the backrest and vibration transmitted to the head. The measurements of STHT responses have been limited to only single axis vibration where two studies have measured responses along 6-axes (3 translational and 3 rotational) of the occupants seated with unsupported and supported back postures[13, 14]. These studies reported substantial head motions mainly in the mid-sagittal plane and have mostly shown increased head motions with the addition of the back support under individual fore-aft and vertical WBV. The lateral WBV mainly caused lateral head motions and revealed minimal effect of the back support. On the basis of the 'to-the-body' and 'through-the-body' biodynamic responses to vertical vibration, it has been suggested that the two measures (APMS and STHT) tend to emphasize different modal responses of the seated body[15]. Both the measures are thus essential for describing the seated body responses to WBV. The STHT responses tend to emphasize the contribution to higher vibration modes compared to the APMS responses. This may partly be attributed to reduced contributions of the resonant oscillations of the low-inertia body substructures to the driving-point force. The transmissibility measures should thus be considered more appropriate for describing higher frequency vibration modes of the seated body and for developing higher order models.

Owing to the observed differences in the STHT and APMS responses measured in different laboratories under different test conditions with subjects of different anthropometry, simultaneous measurements of driving-point and vibration transmissibility responses have been suggested to yield more reliable biodynamic responses[15, 16]. A few studies have measured both the biodynamic functions, either simultaneously or sequentially[17, 18], while only one has explored the relationship between the two simultaneously measured responses to vertical vibration[15]. This study concluded that the STHT and APMS responses under vertical WBV correlate well in terms of peak magnitudes and corresponding frequencies. However, such comparisons have not been attempted under horizontal vibration.

The aim of this study is to characterise the seated body responses to single and dual-axis horizontal vibration in terms of the simultaneously measured fore-and-aft and lateral STHT and APMS responses, while the APMS responses for the back supported posture are characterised at both the driving-points formed by the buttock-seatpan and the upper-body-backrest interfaces. The influences of the hands and back supports on the measured responses are investigated and relationships between the measured APMS and STHT responses are explored in terms of peak response magnitudes and corresponding frequencies.

Methods

Exposure conditions and subjects

A rigid seat and a steering column were installed on a 6-DOF whole-body vibration simulator (IMV Corp.) for measurements of biodynamic responses to single and dual-axis horizontal vibration. A 600×400 mm^2 force plate (Kistler 9281C) served as the seatpan at a height of 450 mm from the simulator platform. Another 450 mm high force plate served as the backrest, which was fabricated using three 3-axis force sensors (Kistler 9317B). The two force plates were used to acquire the forces developed at the two driving-points (seatpan and backrest) along the *x*, *y* and *z* directions. The platform vibration was measured by a three-axis accelerometer (Bruel and Kjaer 4506A) aligned with the translational axes of vibration. The head vibration was measured using a three-axis micro-accelerometer (Analog Devices ADXL-30) mounted on a light-weight helmet strap proposed by Wang *et al*[19]. The frequency response characteristics of the helmet strap acceleration measurement system were measured by mounting the strap on the rigid seat subject to white-noise (flat power spectral density) two-axis horizontal vibration in the 0.5–20 Hz range. The results revealed nearly unity magnitude and negligible phase in the frequency range of interest (0.5–20 Hz).

A total of 9 healthy adult male subjects with average age 30.4 yr (22–55 yr), body mass 63.4 kg (57–69 kg) and height 173.4 cm (162–179 cm), participated in the experiments. The subjects had no prior history of back pain. Each subject was informed about the purpose of the study, experimental set up and usage of the emergency stop that would suppress the stimulator motion in a ramp-down manner, when activated. The experiment protocol had been approved by an ethics research committee prior to the study.

The measurements were performed for each subject assuming: (i) two different back support conditions (seated with no back support-NB; and with lower back against a vertical backrest-B0); (ii) two different hands positions (with lower arm horizontal to the platform and hands on steering wheel-HS; hands on lap- HL); and (iii) two different levels of un-weighted vibration applied along the individual x- and y- axis (0.25 and 0.4 m/s^2 rms acceleration), and along the dual-axis (0.28 and 0.4 m/s^2 rms acceleration) in the frequency range of 0.5–20 Hz. The broad-band random vibration along the single and dual-axis were synthesized to achieve nearly flat power acceleration power spectral density (PSD) in the 0.5–20 Hz range, and comparable magnitudes of single- and dual-axis vibration. The dual-axis vibration were synthesised to yield 0.28 and 0.4 m/s^2 along each axis, with overall rms accelerations of 0.4 and 0.57 m/s^2, respectively. Each vibration exposure lasted for 60 s and each subject was asked to put on a cotton lab coat to ensure uniform friction between the back and the backrest across the subjects.

Each subject was asked to wear the head-accelerometer strap and adjust its tension to ensure a tight but comfortable fit, while the accelerometer orientation was appropriately adjusted by the experimenter to ensure its alignment with the basicentric axis system and was visually monitored before and during the vibration exposure. Furthermore, each subject was asked to maintain constant head posture by looking at a fixed visual marker in the line of sight during the vibration exposure. The subject was asked to sit comfortably with average thigh contact on the seatpan and lower legs oriented vertically with feet on the vibrating platform. The feet support was adjusted to provide the desired sitting posture for each subject.

Data acquisition and analyses

The seatpan and backrest force, and platform and head acceleration data were acquired in the PulseLabShop™ (Bruel & Kjaer) and analysed to derive APMS and STHT biodynamic responses of seated body to single- and dual-axis horizontal vibration. The APMS response to single-axis vibration was computed from:

$$M_{kl}\left(j\omega\right)=\frac{S_{a_k F_l}}{S_{a_k}};\ k=x,\ y \text{ and } l=x,\ y \tag{1}$$

Where M_{kl} $(j\omega)$ defines the complex APMS response corresponding to excitation frequency ω. $S_{a_k F_l}$ is the cross-spectral density of the force measured at the driving-point along direction l (l=x, y) and the acceleration a_k (k = x, y) at the platform and S_{a_k} is the auto spectral density of acceleration a_k. The above equation would yield direct-axis response for k=l and the cross-axis APMS response for k≠l. The direct and cross-axis components of the APMS at the seat back were also computed in a similar manner by considering the force measured at the backrest. For dual-axis vibration, the total APMS response at the seatpan and the backrest was computed from the total measured force along an axis due to excitation along both the axis and the acceleration along the axis of the measured force, such that:

$$M_k\left(j\omega\right)=\frac{S_{a_k F_k}}{S_{a_k}};\ k=x,\ y \tag{2}$$

In the above equation, M_k is the complex APMS along axis k (k=x,y) due to vibration applied along both the axis, and $S_{a_k F_k}$ is the cross-spectral density of the force and accelartion measured along the same axis. The APMS of the rigid seat and the backrest structures were initially computed through measurements of forces at the pan and backrest under single- and dual-axis vibration. The magnitudes of the APMS of both the structures were observed to be constant in the entire frequency range (0.5–20 Hz) with nearly zero phase between the measured force and acceleration signals. Furthermore, the magnitudes of cross-axis APMS of the seat structure under single axis vibration along the x- and y-axis were mostly negligible. The measured APMS responses of the seat and the backrest were subsequently applied to the data obtained for the seat-human subjects in order to perform inertial corrections to the responses measured at the pan and the backrest using the reported methodology[1, 2)].

The fore-and-aft and lateral STHT responses were computed in a similar manner from the measured head and seat accelerations, such that:

$$T_{kl}\left(j\omega\right)=\frac{S_{a_k a_l}}{S_{a_k}};\ k=x,\ y \text{ and } l=x,\ y \tag{3}$$

Where T_{kl} $(j\omega)$ defines the complex direct (k=l) or cross-axis (k≠l) vibration transmissibility corresponding to excitation frequency ω. $S_{a_k a_l}$ is the cross-spectral density of acceleration signal measured at the head along direction l (l= x, y), and the source vibration a_k along direction k (k=x, y).

The analyses were performed using a band width of 100 Hz with a resolution (Δf) of 0.125 Hz, accounting for 27 linear averages. The coherence between the response signals along the axis of applied vibration were continually monitored, which were generally close to 1.0 for the APMS measures but lower for the STHT measures at frequencies above 7 Hz.

Total seatpan APMS response

The biodynamic force measured at the seatpan revealed strong coupling with the backrest force, when a back supported posture was considered. The majority of the studies reporting seatpan APMS response of the seated occupants employed the force plate at the seat base, where the measured force responses F_{px} and F_{py} would represent the total body interactions (seatpan and backrest) together with the intertia force due to the seat structure along the x- and y- axis, respectively[1, 3)]. In some studies, the force plate itself served as the seatpan to obtain the seatpan APMS responses, as in the present study. In this case the forces imparted on the backrest due to the upper body would not be reflected in the measured seatpan forces, as illustrated in Fig. 1. Let f_{px} be the total inertia-corrected force developed at the seatpan measured below the seat and f_{bx} be the inertia-corrected biodynamic force at the backrest under x-axis vibration. The total biodynamic force would be the sum of the forces developed at the pan f'_{px} and the backrest, as seen in Fig. 1, such that:

$$f_{px}(t) = f'_{px}(t) + f_{bx}(t) \tag{4}$$

Greater upper body interaction with the back support would thus yield lower seatpan APMS response. Considering relatively larger magnitude of the fore-aft backrest APMS the effect of coupling on the seatpan APMS would be quite pronounced. It should be noted that the force measured at the backrest is not influenced by the location of the seatpan

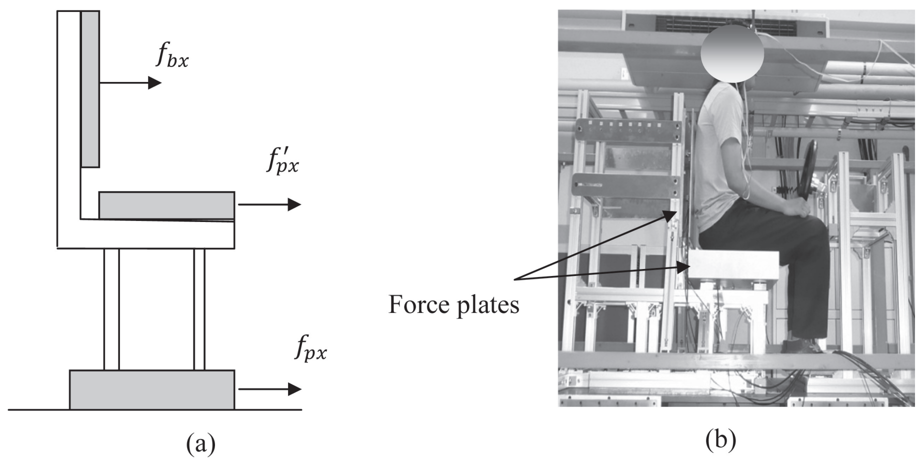


Fig. 1. (a) Schematic of the test seat with force plate serving as the seatpan: f'_{px} and f_{bx} are forces measured at the seatpan and backrest, respectively, and f_{px} is the total force; (b) Experimental setup showing the subject seated with back supported posture and the locations of force-plates.

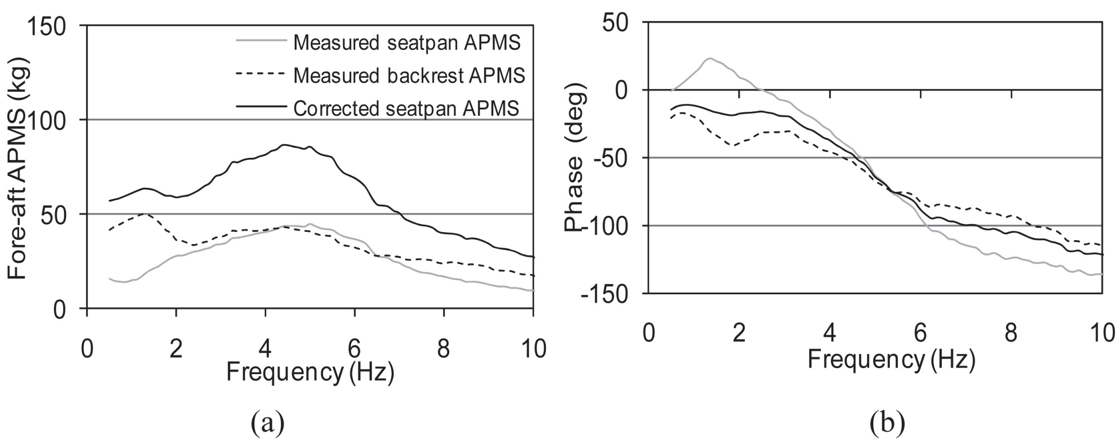


Fig. 2. Mean measured fore-aft backrest and seatpan APMS, and corrected-seatpan APMS magnitude and phase responses of occupants seated with back support and exposed to fore-aft vibration of 0.25 m/s^2 rms acceleration magnitude.

force measurement system. Considering equal magnitudes of broadband vibration applied at the backrest and seatpan along the fore-aft axis, and multiplying the terms in Eq. (4) by the complex conjugate of acceleration $a_x^*(f)$ yields:

$$a_x^*(f)\ F_{px}(f) = a_x^*(f)\ F'_{px}(f) + a_x^*(f)\ F_{bx}(f) \tag{5}$$

Where F_{px}, F_{bx} and F'_{px} are the Fourier transforms of f_{px}, f_{bx} and f'_{px}, respectively. Eq (5) can be expressed in terms of cross-spectral densities of the measured forces and accelerations, and auto-spectral density of the acceleration, as:

$$S_{a_xF_{px}}(f) = S_{a_xF'_{px}}(f) + S_{a_xF_{bx}}(f) \tag{6}$$

$$\frac{S_{a_xF_{px}}}{S_{a_x}}(f) = \frac{S_{a_xF'_{px}}}{S_{a_x}}(f) + \frac{S_{a_xF_{bx}}}{S_{a_x}}(f) \tag{7}$$

Where $S_{a_xF_{px}}(f) = \frac{1}{T}E[a_x^*(f)F_{px}(f)]$, $S_{a_x}(f) = \frac{1}{T}E[a_x^*(f)a_x(f)]$ and T = $1/\Delta f$ is the duration of measurement. The above yields following relationship between the APMS of the seated body measured at the seatpan (M_{px}) and the backrest (M_{bx}):

$$M_{px}(f) = M'_{px}(f) + M_{bx}(f) \tag{8}$$

Where M'_{px} and M_{bx} are the apparent mass responses based on the forces measured at the seatpan and the backrest, respectively, such that:

$$M'_{px}(j\omega) = \frac{S_{a_xF'_{px}}}{S_{a_x}}\ ;\ \text{and}\ \ M_{px}(j\omega) = \frac{S_{a_xF_{bx}}}{S_{a_x}} \tag{9}$$

The total direct- and cross-axis seatpan APMS responses along the lateral (y-) axis were also derived using the same methodology, such that:

$$M_{pk,l}(f) = M'_{pk,l}(f) + M_{bk,l}(f);\ k{=}x,\ y \text{ and } l{=}x,\ y \tag{10}$$

As an example, Fig. 2 illustrates the mean fore-and-aft seatpan and backrest APMS magnitude and phase responses of the subjects seated with a back support and exposed to a_x=0.25 m/s^2. The results derived from the inertia-corrected measured data show that the seatpan APMS magnitude is either lower or comparable to the backrest APMS magnitude. The magnitude of the total seatpan APMS, M_{px}, derived using Eq (10) is considerably higher than the measured APMS, M'_{px} as shown in Fig. 2 (a). The phase response at the seatpan is also altered by the proposed method, as seen in Fig. 2(b).

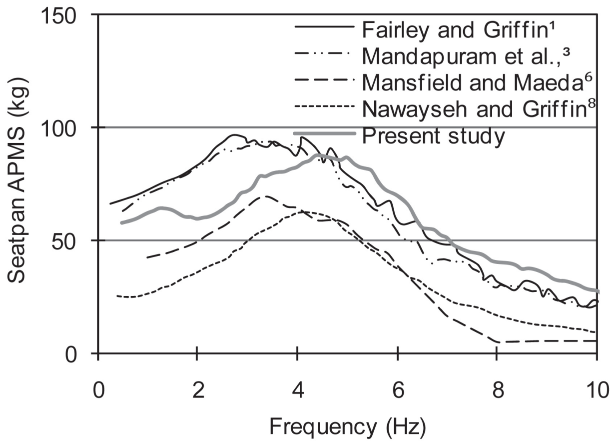


Fig. 3. Comparison of reported APMS magnitude of subjects seated with a back support and exposed to fore-aft vibration, and the corrected APMS in the present study (0.25 m/s^2).

The studies employing force plate as the seatpan[6, 8], generally, report lower magnitudes of the fore-and-aft APMS of the body seated with a back support, compared to those based on force measurement at the seat base[1, 3], as illustrated in Fig. 3. This is directly attributable to the coupled effects of the forces developed at the seatpan and the backrest. The total mean APMS magnitude response derived using Eq. (10) approached those reported in[1, 3] (Fig. 3).

Normalisation factors

The APMS response characteristics of the seated human body exposed to WBV are known to be influenced by many anthropometric, excitation and seat related factors. A number of studies on vertical and horizontal APMS have mostly attributed the dispersion in the APMS data to variations in the body mass, particularly at low frequencies. The measured APMS is thus frequently normalized with respect to either the body mass supported by the seat, or by the APMS magnitude at a low frequency, e.g., 0.5 to 1 Hz[20, 21] in order to study the effects of other contributing factors such as nature of WBV, sitting posture and seat geometry[15, 22]. Such normalisation, however, cannot decouple the dynamic contributions due to body mass variations. While the APMS responses obtained under vertical WBV have been widely normalised using the low frequency magnitude, such normalisation has been discouraged for horizontal APMS due to presence of a very low frequency resonance, near 0.7 Hz, particularly under the NB posture[1]. Furthermore, the effective body mass supported by the seat along a horizontal axis could not be quantified through static measures.

Furthermore, the body mass supported by the seatpan is affected by the human tendency to maintain the desired posture. It has been reported that subjects tend to stiffen their upper body and legs under fore-aft WBV exposures to maintain contact with the seat, which yields greater contact between the thighs and the seatpan[3]. Considering the participation of legs, particularly the thighs, under fore-aft WBV, the sum of masses due to the upper body and thighs is considered as the normalisation factor for the direct APMS responses under fore-aft WBV. The upper body comprising the head, neck, thorax and arms, and thighs contribute to the seatpan biodynamic response of the seated occupants with the hands in lap postures. The normalization factor of 87.8% of the total body mass was estimated from the anthropometric data, which includes the proportions due to upper body (67.8%) and thighs (20%)[23]. The resulting fore-aft normalised APMS magnitudes were nearly unity at low frequencies. The same normalisation factor were also applied to the seatpan lateral APMS data, although the subjects maintained average thigh contact with the seat pan during exposure to lateral vibration. The normalised lateral APMS were thus generally lower. The occupants seated with the hands on steering wheel transfer a portion of the arms weight from the seatpan to the rigid steering wheel. The normalising factor for this posture was thus appropriately reduced to 77.8% of the total body mass by considering the arms mass as 10% of the total body mass.

Table 1. Normalization factors (% of body mass), based on anthropometry[23]

Response		NB-HL	NB-HS	B0-HL	B0-HS
Seatpan APMS	Fore-aft	87.8	77.8	87.8	77.8
	Lateral	87.8	77.8	87.8	77.8
Back APMS	Fore-aft	-	-	67.8	57.8
	Lateral	-	-	54.3	44.3

The proportion of the upper body mass contributing to the APMS obtained at the backrest, however, differs with the axis of vibration. Under fore-aft vibration, the entire upper body is considered to contribute; a normalisation factor of 67.8% of the total body mass is thus assumed. Under lateral vibration, a relatively smaller portion of the upper body, however, tends to slide along the backrest, which was evident from the relatively lower magnitudes of the lateral APMS measured at the backrest. Unlike under the fore-aft vibration, the backrest offers little resistance to the upper body lateral movement. It is thus assumed that the contribution of the pelvic mass to the low frequency lateral apparent mass would be very small. Considering the pelvic mass of 13.5% of the total body mass, the normalisation factor of 54.3% of the total body mass is assumed for the backrest APMS responses to lateral WBV. However, the defined normalisation factors based on the anthropometry alone may yield some error due to small changes in the sitting posture such as leaning forward. The direct- and cross-axis APMS responses of each individual subject corresponding to each experimental condition were normalised using the normalisation factors summarised in Table 1, although a sound basis for normalisation of the cross-axis data is yet to be explored.

Multi-factorial analyses of variance (ANOVA) were performed on the corrected APMS and STHT data using SPSS to identify the statistical significance levels of the main factors such as the hands support, back support and the excitation magnitude.

Relationship between responses to single- and dual-axis vibration

The application of vibration along a single axis also yields biodynamic forces due to along the other axis. This is evident from reported the cross-axis APMS responses[7, 8, 10].

Assuming nearly linear response under a given excitation magnitude and posture, the APMS and STHT responses to multi-axis vibration may be evaluated from superposition of the direct- and cross-axis responses. Considering the seated body as a multiple input-multiple output system, the total APMS response can be evaluated from the resultant forces along x- and y- axis due to simultaneous x- and y- axis excitations, such that:

$$\bar{F}_x(f) = F_{xx}(f) + F_{xy}(f);\ \bar{F}_y(f) = F_{yy}(f) + F_{yx}(f) \qquad (11)$$

Where $\bar{F}_x$ and $\bar{F}_y$ are the Fourier transforms of the total biodynamic forces along x- and y- axis respectively. F_{ij} are the Fourier transforms of the biodynamic forces developed along axis i (i=x,y) due to single-axis vibration applied along j (j=x,y). F_{ij} represents the direct component of the biodynamic force for i=j and cross-axis component for $i \neq j$. For the seated body exposed to single axis vibration along the x- and y- axis, let $M_{xi}(f)$ represent the linear transfer function between the force F_{xi} and the acceleration $a_i(f)$ along axis i (i=x,y), such that:

$$F_{xi}(f) = M_{xi}(f)a_i(f) \qquad (12)$$

Where M_{xi} represents the direct-axis APMS due to single axis excitation along x-axis (i=x), and the cross-axis APMS under single axis excitation along y-axis (i=y). The resultant force $\bar{F}_x$ under simultaneous dual axis vibration (x and y) can be derived using Eqs (11) and (12), as:

$$\bar{F}_x(f) = \Sigma_{i=x,y} M_{xi}(f)a_i(f) \qquad (13)$$

Let $\bar{F}_x^*$, M_{xi}^* and a_i^* be the complex conjugates of $\bar{F}_x(f)$, $M_{xi}(f)$ and $a_i(f)$, respectively. The square of the modulus of the resultant force can be written as:

$$\bar{F}_x^*(f)\bar{F}_x(f) = [\Sigma_{i=x,y} M_{xi}^*(f)a_i^*(f)][\Sigma_{i=x,y} M_{xi}(f)a_i(f)] \qquad (14)$$

For uncoupled excitations along the x- and y- inputs, the above can be expressed as:

$$S_{\bar{F}_x}(f) = \Sigma_{i=x,y}\, |M_{xi}(f)|^2\, S_{a_i}(f) \qquad (15)$$

Where $S_{\bar{F}_x}$ and S_{a_i} are the auto spectral densities of the total force along the x-axis, and acceleration along axis i (i=x,y). Eq (15) yields the resultant APMS $\bar{M}_x$ along the x- axis under simultaneous dual-axis vibration, as:

$$|\bar{M}_x(f)|^2 = |M_{xx}(f)|^2 + |M_{xy}(f)|^2\, \frac{S_{a_y}(f)}{S_{a_x}(f)} \qquad (16)$$

In similar manner, the resultant APMS $\bar{M}_y$ along y-axis under simultaneous dual axis vibration can be obtained as:

$$|\bar{M}_y(f)|^2 = |M_{yy}(f)|^2 + |M_{yx}(f)|^2\, \frac{S_{a_x}(f)}{S_{a_y}(f)} \qquad (17)$$

The resultant APMS under identical magnitudes of x- and y-axis vibration could be simply derived as the sum of direct and cross-axis APMS under single axis vibration. The magnitudes of x- and y-axis WBV in most work vehicles, however, differ considerably. For instance, the frequency-weighted x- and y- axis vibration of an off-road tractor during ploughing have been reported to vary in the 0.3 to 1.3 m/s^2 and 0.2 to 0.6 m/s^2 ranges, respectively, while those of a forklift truck lie in the 0.1 to 0.9 and 0.1 to 2.5 m/s^2 ranges, respectively[24, 25]. Relatively higher magnitudes of lateral vibration would yield greater contribution of the cross-axis APMS to the resultant APMS along the x-axis but smaller to the APMS along the y-axis.

The seat-to-head transmissibility responses to dual-axis horizontal vibration may also be related to the responses to single-axis vibration in a similar manner, such that:

$$|\bar{T}_x(f)|^2 = |T_{xx}(f)|^2 + |T_{xy}(f)|^2\, \frac{S_{a_y}(f)}{S_{a_x}(f)} \qquad (18)$$

$$|\bar{T}_y(f)|^2 = |T_{yy}(f)|^2 + |T_{yx}(f)|^2\, \frac{S_{a_x}(f)}{S_{a_y}(f)} \qquad (19)$$

Where $\bar{T}_x$ and $\bar{T}_y$ represent the resultant STHT responses along x- and y- axis to dual-axis horizontal vibration, and T_{ij} defines STHT response along axis i (i=x,y) to single-axis excitation along axis j (j=x,y).

Owing to the equal magnitudes of the uncorrelated broad-band random vibration inputs considered in this study the ratios $\frac{S_{a_x}(f)}{S_{a_y}(f)}$ and $\frac{S_{a_y}(f)}{S_{a_x}(f)}$ are considered equal to unity.

Results

The APMS and STHT magnitude responses of individual subjects to single and dual-axis horizontal vibration revealed strong dependence upon the back support, hands position, direction of excitation and vibration magnitude. Considerable scatter among the individual data acquired for each test condition was observed, and it was particularly significant in the cross-axis components. The peak APMS and STHT magnitudes, however, occurred within narrow frequency ranges for all subjects for both single and dual-axis vibration responses. The coefficient of variation (*CoV*) obtained for the APMS magnitude responses along the axis of applied vibration were generally lower in the vicinity of the resonant frequency, while the peak values of *CoV* in seatpan APMS magnitudes over the experimental conditions considered were in the of 21–40% range. The *CoV* of the seatpan APMS data obtained under dual axis vibration were consistently lower compared to those under single axis vibration. The observed ranges of *CoV* of the seatpan APMS magnitudes, however, were considerably lower than those reported[3]. The peak values of *CoV* of the backrest APMS data were in the range of 22–75% and significantly higher compared to those observed in the seatpan APMS data. This is attributable to variations in the upper body contact with the vertical backrest. Owing to the high variability and lower mean magnitudes, the *CoV* of the cross axis APMS magnitude responses were higher. The STHT responses revealed far greater variability in the data with peak values of *CoV* approaching 30% near resonances and even larger at higher frequencies, where the magnitudes are considerably small.

The coherence values for the direct APMS responses over the 0.5–20 Hz frequency range were generally about 1 and below 0.5 in case of the cross-axis fore-aft and lateral responses. Furthermore, the coherence values of the responses under single and dual axis vibration were observed to be similar. The fore-aft and lateral STHT responses of the subjects seated with NB and B0 posture revealed coherence in the order of 0.8 up to 5 Hz, while that of the cross-axis responses were 0.5 or below.

Owing to the relatively higher values of the coefficients of variation of the data, the mean data of the 9 subjects were considered to provide trend information on the effects of single- and dual-axis vibration, and hands and back supports. The mean magnitude and phase responses of direct and cross-axis components of the seatpan APMS and STHT under single-axis vibration, and total responses under dual-axis vibration were evaluated for each experimental condition. Although considerable magnitudes of cross-axis APMS and STHT were observed along the vertical axis under fore-aft vibration, the results are limited only to responses along the fore-aft and lateral axis. Both the APMS and STHT magnitudes were generally observed to be very small at frequencies above 10 Hz; the results are thus presented in the 0.5–10 Hz range with only a few exceptions. Furthermore, the results are presented for identical overall rms accelerations due to single and dual-axis vibration, namely 0.28 m/s^2 along each of the dual-axis vibration (overall magnitude = 0.4 m/s^2). The results attained from multi-factor ANOVA are presented in Tables 2 and 3 at selected frequencies in the 0.75–20 Hz range. The tables show the pair-wise comparisons of effects of hands support (HL vs HS) and the back support (NB vs B0), respectively, on

Table 2. Statistical significance (*p*-values) of hands support attained from ANOVA performed on the seatpan APMS and STHT magnitude responses to single-axis fore-aft and lateral vibration under different conditions

Factor	Hands support (HL *vs* HS)															
	Fore-aft								Lateral							
Freq (Hz)	NB				B0				NB				B0			
	0.25 m/s^2		0.4 m/s^2		0.25 m/s^2		0.4 m/s^2		0.25 m/s^2		0.4 m/s^2		0.25 m/s^2		0.4 m/s^2	
	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT
0.75	0.01	0.19	0.11	0.18	0.06	0.76	0.11	0.44	0.00	0.05	0.00	0.10	0.00	0.97	0.00	0.04
1	0.01	0.36	0.26	0.15	0.06	0.75	0.05	0.24	0.00	0.01	0.00	0.04	0.00	0.47	0.00	0.32
2	0.33	0.03	0.11	0.27	0.12	0.04	0.01	0.01	0.00	0.08	0.00	0.00	0.00	0.09	0.00	0.01
3	0.00	0.19	0.00	0.41	0.23	0.18	0.79	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00
4.5	0.00	0.02	0.00	0.01	0.04	0.01	0.02	0.00	0.01	0.82	0.04	0.96	0.02	0.66	0.01	0.05
6	0.03	0.00	0.04	0.40	0.00	0.01	0.00	0.01	0.01	0.67	0.00	0.67	0.01	0.49	0.00	0.16
8	0.01	0.00	0.02	0.00	0.03	0.59	0.09	0.79	0.13	0.07	0.02	0.19	0.05	0.53	0.00	0.28
10	0.03	0.00	0.05	0.01	0.19	0.24	0.02	0.25	0.03	0.34	0.00	0.12	0.06	0.36	0.00	0.22
12	0.01	0.00	0.02	0.00	0.28	0.73	0.26	0.90	0.00	0.83	0.00	0.13	0.03	0.63	0.00	0.36
14	0.91	0.18	0.91	0.00	0.57	0.44	0.75	0.58	0.00	0.02	0.00	0.08	0.03	0.66	0.00	0.32
16	0.09	0.41	0.31	0.06	0.72	0.71	0.81	0.63	0.00	0.20	0.00	0.33	0.02	0.19	0.00	0.06
18	0.09	0.09	0.36	0.10	0.70	0.51	0.55	0.46	0.00	0.36	0.00	0.44	0.01	0.21	0.00	0.05
20	0.08	0.83	0.44	0.35	0.66	0.48	0.51	0.31	0.00	0.21	0.00	0.51	0.01	0.06	0.00	0.20

back support: NB and B0; vibration magnitude: 0.25 and 0.4 m/s^2.

Table 3. Statistical significance (*p*-values) of back support attained from ANOVA performed on the seatpan APMS and STHT magnitude data under different conditions

Factor	Back support (NB *vs* B0)															
	Single axis								Dual axis							
Freq (Hz)	Fore-aft				Lateral				Fore-aft				Lateral			
	0.25 m/s^2		0.4 m/s^2		0.25 m/s^2		0.4 m/s^2		0.25 m/s^2		0.4 m/s^2		0.25 m/s^2		0.4 m/s^2	
	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT	APMS	STHT
0.75	0.80	0.18	0.01	0.31	0.09	0.00	0.01	0.00	0.03	0.03	0.01	0.11	0.01	0.11	0.00	0.01
1	0.08	0.01	0.00	0.68	0.24	0.01	0.01	0.00	0.00	0.03	0.00	0.48	0.00	0.12	0.00	0.02
2	0.00	0.93	0.00	0.93	0.07	0.83	0.16	0.16	0.00	0.10	0.00	0.07	0.03	0.68	0.03	0.41
3	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.92	0.00	0.77
4.5	0.00	0.38	0.00	0.27	0.00	0.88	0.00	0.12	0.00	0.02	0.00	0.15	0.00	0.93	0.00	0.60
6	0.00	0.80	0.00	0.76	0.00	0.09	0.00	0.02	0.00	0.48	0.00	0.00	0.00	0.02	0.00	0.02
8	0.00	0.28	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.06	0.00	0.00	0.00	0.01
10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.32
12	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.56	0.00	0.00	0.00	0.00	0.00	0.27	0.00	0.78
14	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.82	0.00	0.10
16	0.00	0.00	0.00	0.00	0.00	0.43	0.00	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	0.00	0.00	0.00	0.00	0.00	0.65	0.00	0.43	0.00	0.00	0.00	0.00	0.00	0.84	0.00	0.14
20	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.10	0.00	0.00	0.00	0.00	0.01	0.03	0.00	0.06

back support: NB and B0; hands support: HL and HS; vibration magnitude: 0.25 and 0.4 m/s^2; vibration direction: fore-aft and lateral; number of vibration axis: single and dual-axis.

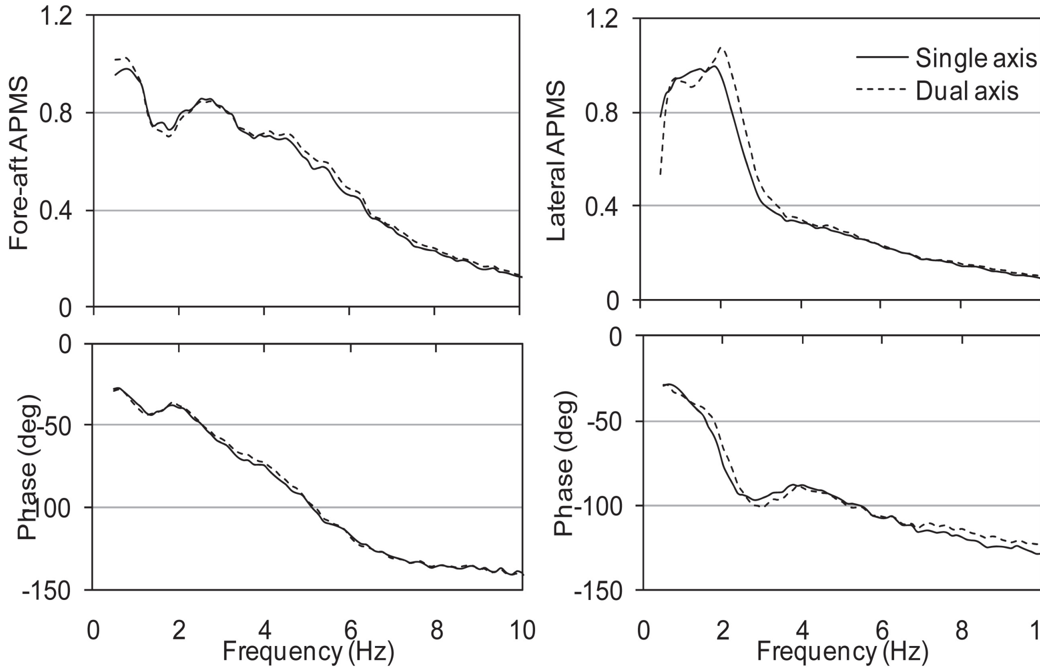


Fig. 4. Comparisons of mean APMS magnitude and phase responses to single- and dual-axis fore-aft and lateral vibration. (No back support; hands in lap; single axis: a_x=a_y=0.4 m/s^2; dual-axis: a_x=a_y=0.28 m/s^2).

both the APMS and STHT responses, while the interactions between the two were observed to be insignificant.

Apparent mass responses

Figure 4 illustrates comparisons of mean total fore-aft and lateral APMS magnitude and phase responses of subjects, seated with NB-HL posture, to single and dual-axis horizontal vibration. The APMS magnitudes along the axis of applied vibration are nearly 1.0 at low frequencies along the fore-aft axis but lower under lateral vibration. The lower values of lateral APMS are attributed to the selected normalization factor (Table 1). The direct fore-aft seatpan APMS magnitudes of occupants seated with NB-HL posture revealed peaks near 0.75, 2.5 and 4.13 Hz, which are similar to those reported[1, 3, 10]. The frequencies corresponding to the peak values of mean APMS obtained under different vibration and support conditions are summarised in Table 4, which may also referred to as the resonant frequencies. The direct lateral seatpan APMS responses reveal two distinct peaks near 0.88 and 1.88 Hz, which are also comparable to those reported[1, 3].

Figure 5 illustrates comparisons of the mean total fore-aft and lateral APMS magnitude and phase responses of subjects seated with B0-HL posture to single and dual-axis horizontal vibration. The fore-aft APMS responses of the occupants seated with back supported and hands in lap posture revealed peaks near 1.38 and 5 Hz. The observed low frequency peak was more distinct compared to that reported in the previous study[3]. The direct lateral seatpan APMS responses under single and dual axis vibration mostly revealed a single broad peak centered near 1.38 Hz. The lower magnitude vibration (0.25 m/s^2), however, revealed two peaks near 1 and 2 Hz (Table 4).

Figure 6 illustrates comparisons of the mean total fore-aft and lateral APMS magnitude and phase responses of the subjects seated with back support measured at the backrest to single and dual-axis horizontal vibration. The backrest APMS exhibits two peaks near 1.25 and around 4.5 Hz under fore-aft, and 0.88 and 2.25 Hz under lateral vibration, respectively. The mean cross-axis APMS magnitude responses, M_{xy} and M_{yx}, of subjects seated with NB-HL and B0-HL, and exposed to single axis horizontal vibration of magnitude of 0.4 m/s^2 are compared in Figs. 7(a) and 7(b), respectively. The cross-axis APMS magnitudes under single-axis vibration were significantly lower and the phase responses revealed excessive scatter in the data. Considering the wide scatter and relatively low coherence of the cross-axis data, the phase responses could not be considered reliable.

Seat-to-head-transmissibility responses

The mean fore-aft and lateral STHT magnitude and phase responses of subjects seated with NB-HL posture and exposed to identical overall magnitudes of single and dual-axis horizontal vibration are compared in Fig. 8. The fore-aft STHT magnitude responses revealed values nearly 1.5 to 2 at 0.5 Hz suggesting higher head motions of the seated body due to horizontal vibration. The mean fore-aft STHT responses revealed peak magnitudes near 1.38 and 2.8 Hz with peak magnitude approaching 2.7. The lateral STHT responses revealed peaks near 1.5 and 1.88 Hz with peak magnitude in the order of 2. The magnitude of the principle peak was slightly higher under dual axis vibration. These frequencies differ from those observed in the APMS responses (Table 4). The fore-aft and lateral STHT phase responses decrease with frequency and approach nearly 600° at 10Hz. The phase responses under single and dual-axis vibration, however, are nearly identical.

Figure 9 illustrates comparisons of mean fore-aft and lateral STHT magnitude responses of subjects seated with B0-HL

Table 4. Frequencies (Hz) corresponding to important peak magnitudes observed in the mean APMS and STHT responses of seated occupants exposed to single axis horizontal vibration

Vibration & measurement axis	Posture	Magnitude	Seatpan				Back rest	
			HL		HS		HL	HS
			APMS	STHT	APMS	STHT	APMS	APMS
Fore-aft	NB	0.25 m/s^2	0.88 2.75 4.5	1.38 2.8	3.13 4.5	1.38 2.75	-	-
		0.40 m/s^2	0.75 2.5 4.13	1.38 2.8	2.75 4.5	1.38 2.75	-	-
	B0	0.25 m/s^2	1.25 4.5	1.8 3.13 9.88	1.38 5	1.8 3.75 9.5	1.25 4.3	1.38 4.38
		0.40 m/s^2	1.38 5	1.38 3 9.88	1.38 4.34	1.38 3.25 10.38	1.25 4–5	1.25 4–5
Lateral	NB	0.25 m/s^2	0.88 2	1.25 2.13	0.88 2.13	1.25 2 5.63	-	-
		0.40 m/s^2	0.88 1.88	1.5 1.88	1 1.88	1.25 1.88	-	-
	B0	0.25 m/s^2	1 2	1.25 1.88	1 2.38	1.25 2	0.88 2.25	0.75 2.38
		0.40 m/s^2	1.38	1.13	1.5 1.88	1.5	1 2	<0.5† 2.38

†peak occurring at a frequency below 0.5 Hz.

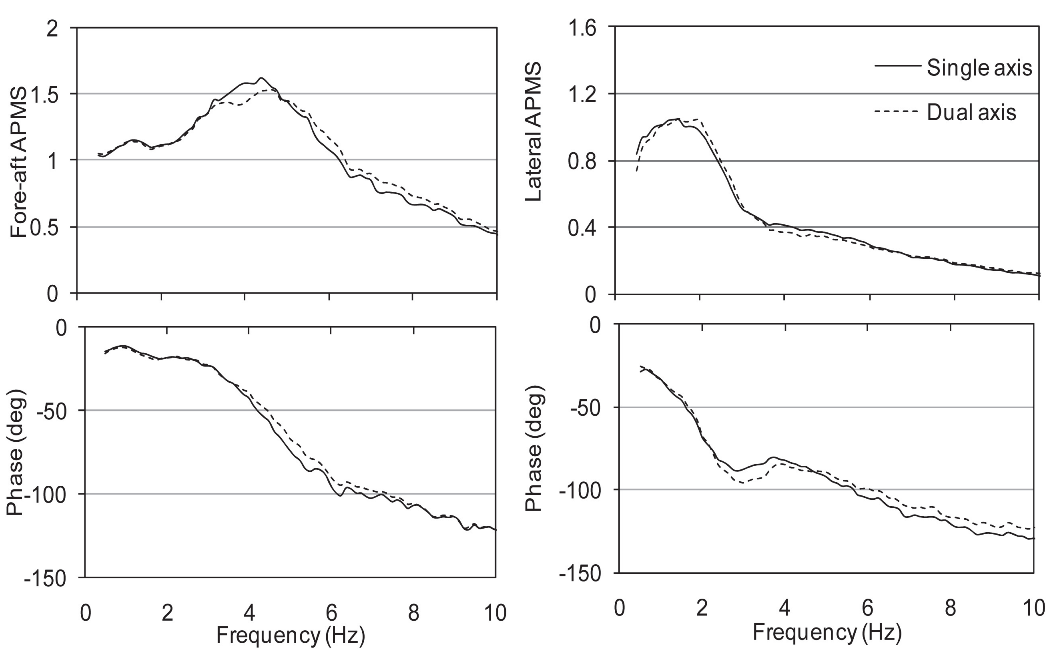


Fig. 5. Comparisons of mean APMS magnitude and phase responses to single- and dual-axis fore-aft and lateral vibrations. (Back support; hands in lap; single axis: a_x=a_y=0.4 m/s^2; dual-axis: a_x=a_y=0.28 m/s^2).

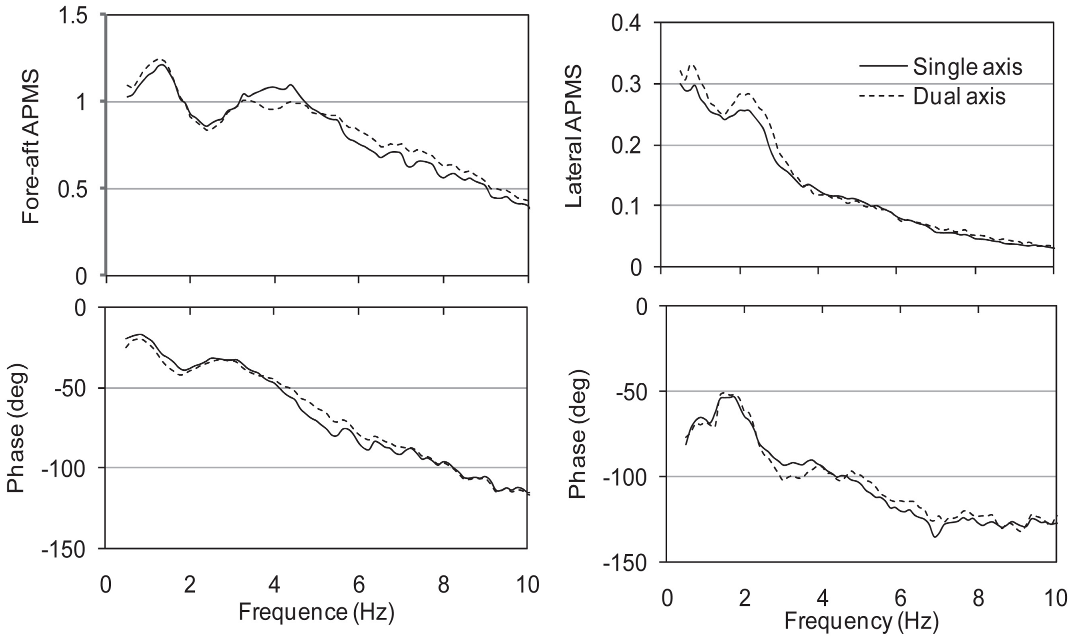


Fig. 6. Comparisons of mean backrest APMS magnitude and phase responses to single- and dual-axis fore-aft and lateral vibrations. (Hands in lap; single axis: a_x=a_y=0.4 m/s^2; dual-axis: a_x=a_y=0.28 m/s^2).

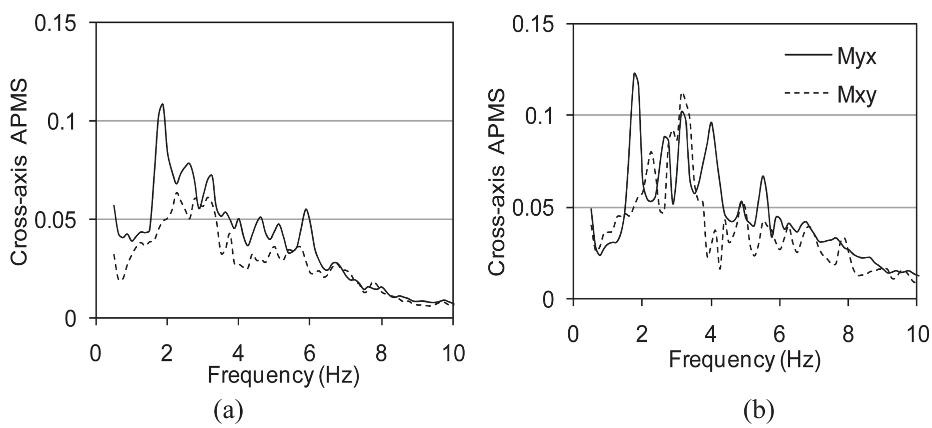


Fig. 7. Comparisons of mean cross-axis APMS responses obtained at the seatpan along fore-aft (M_{xy}) and lateral (M_{yx}) axis. (Single axis vibration: a_x=a_y=0.4 m/s^2: (a) No back support; (b) Back support).

posture and exposed to single and dual-axis horizontal vibration. The fore-aft responses revealed peaks near 1.38, 3 and 10 Hz (Table 4), with a high magnitude narrow band peak near 1.38 Hz with magnitude in the order of 2.5, which is significantly different from the broad peak observed near 3 Hz with NB posture (Fig. 8). Furthermore, the fore-aft STHT responses exhibit patterns that are considerably different from the APMS. The lateral STHT response revealed higher resonant magnitudes under dual axis vibration, where the peaks occur near 1.13 Hz and 1.2 Hz under single and dual axis vibration, respectively. The lateral STHT response to lower lateral vibration (0.25 m/s^2), however, revealed two peaks near 1.25 and 1.88 Hz (results not shown), which were comparable under those observed under dual axis vibration, as seen in Fig. 9. These two peaks converged to a single peak near 1.13 Hz under the higher magnitude lateral vibration. The cross-axis fore-aft and lateral STHT magnitude responses were observed to be insignificant, generally below 0.2, irrespective of the experimental conditions. These results are thus not presented.

Effect of hands position

Figure 10 illustrates comparisons of mean fore-aft and lateral APMS responses of the subjects seated with HL and HS condition under dual-axis vibration and NB posture. The results show that the HS condition yields higher fore-aft and lateral APMS magnitudes compared with those attained with

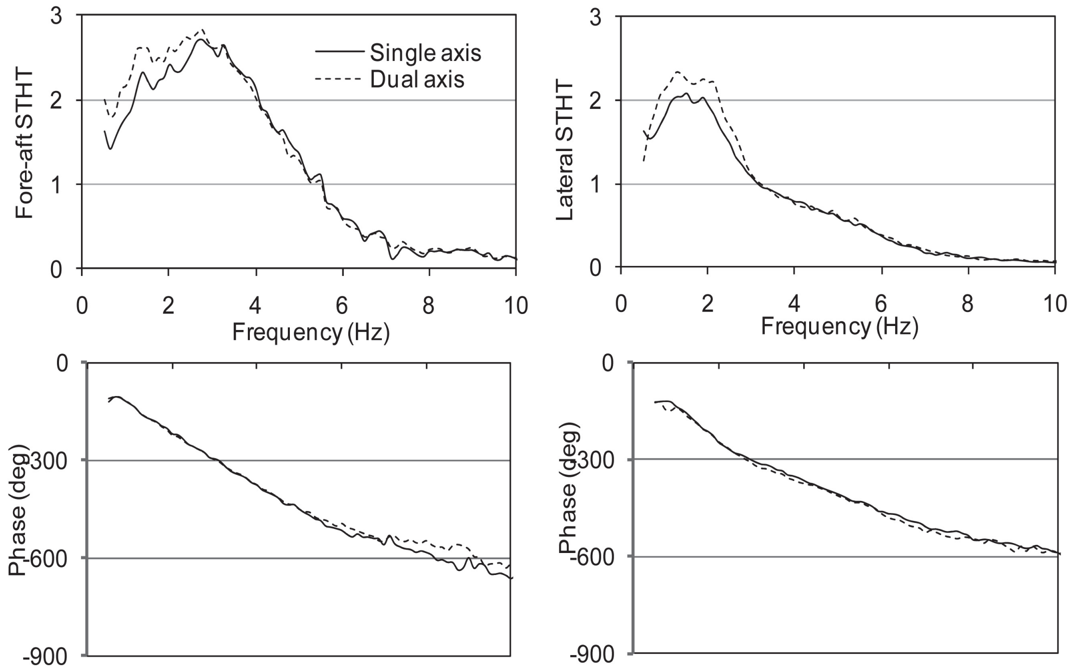


Fig. 8. Comparisons of mean STHT magnitude and phase responses to single and dual-axis fore-aft and lateral vibrations. (No back support; hands in lap; single axis: a_x=a_y=0.4 m/s^2; dual-axis: a_x=a_y=0.28 m/s^2).

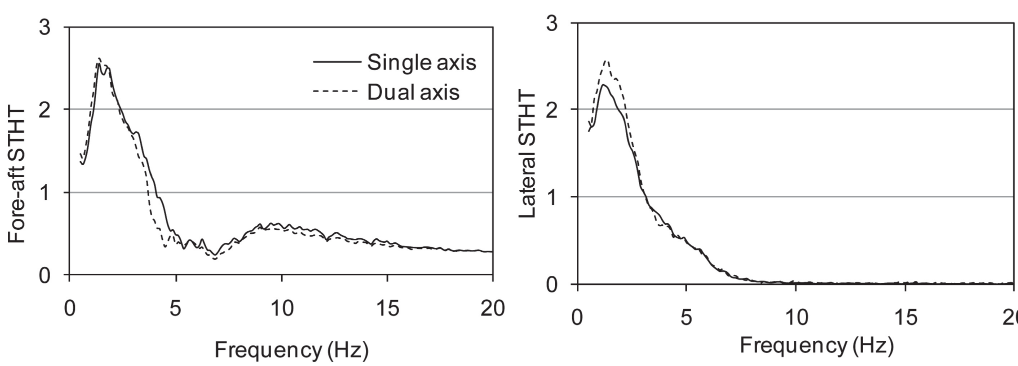


Fig. 9. Comparisons of mean STHT magnitude responses to single and dual-axis fore-aft and lateral vibrations. (Back support; hands in lap; single axis: a_x=a_y=0.4 m/s^2; dual-axis: a_x=a_y=0.28 m/s^2).

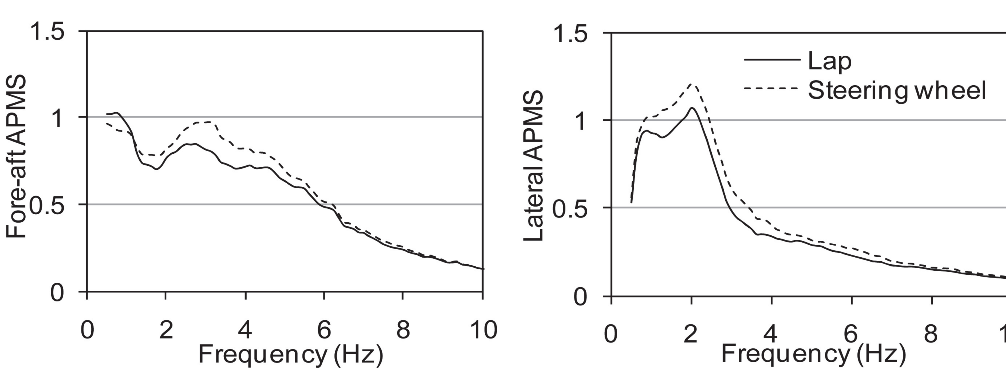


Fig. 10. Comparisons of mean seatpan APMS responses of occupants seated with hands in lap and hands on steering wheel. (No back support; dual-axis: a_x=a_y=0.28 m/s^2).

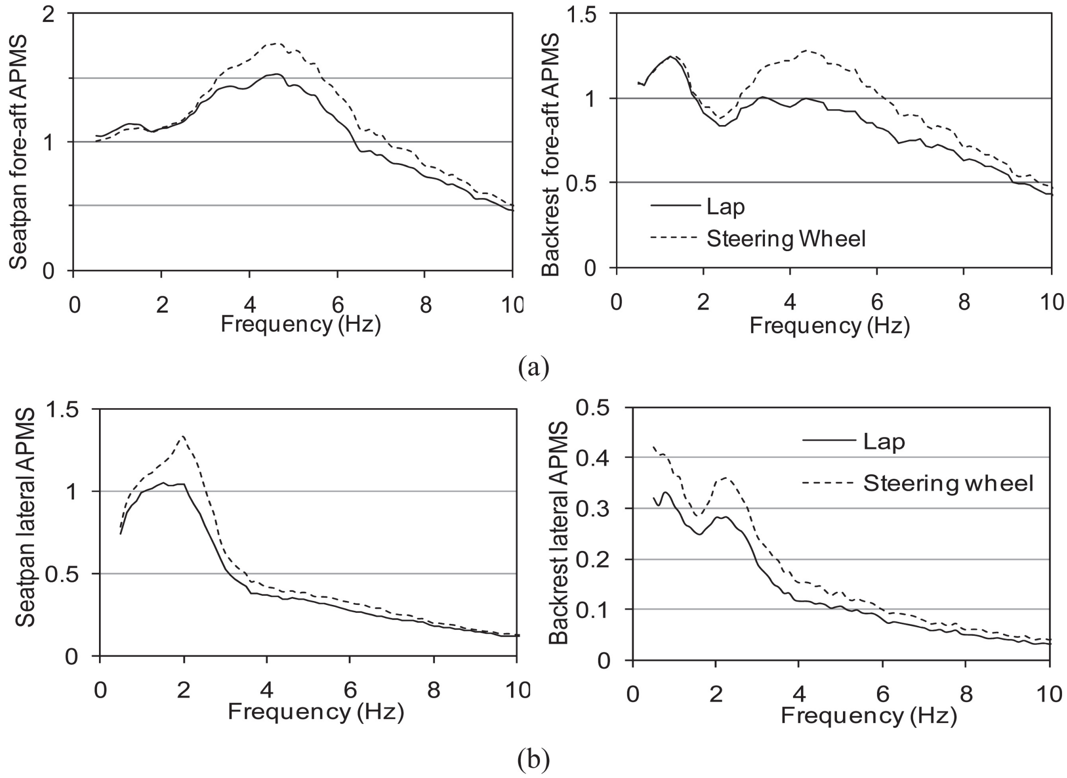


Fig. 11. Comparisons of mean total and backrest APMS responses of occupants seated with hands in lap and hands on steering wheel to: (a) fore-aft; and (b) lateral vibration. (Back support; dual-axis vibration: a_x=a_y=0.28 m/s^2).

HL condition in the 1–8 Hz range. The results also show comparable responses at low frequencies confirming the validity of the normalisation factors (87.8% and 77.8% of body mass for HL and HS conditions, as seen in Table 1). The primary peak observed in the fore-aft APMS responses with the HL condition was not observed in the response with HS condition. This was more distinctly observed from the single-axis responses (results not shown). The second and third peaks in the fore-aft APMS, however, occurred in comparable frequency bands for both hands positions (Table 4).

Figure 11 illustrates comparisons of mean total and backrest APMS responses obtained with HL and HS conditions under dual-axis vibration with B0 posture. The responses with B0 posture reveal considerably higher magnitudes with hands on steering wheel compared to those with HL condition under both fore-aft and lateral vibration, particularly in the vicinity of the resonance. The total APMS responses under fore-aft vibration revealed slightly lower magnitudes at low frequencies up to 1.6 Hz, while no effect of the hands support was observed in 1.8–2.4 Hz frequency range. The HS condition, however, yields higher magnitudes at frequencies above 2.4 Hz. The backrest APMS responses under fore-aft vibration also revealed strong effects of hands support at frequencies about 1.8 Hz, as illustrated Fig. 11(a). The peaks observed in the fore-aft backrest responses with hands in lap and on steering wheel occurred at nearly identical frequencies (Table 4). The total and backrest APMS responses under lateral vibration with HS are also considerably higher compared to the HL position.

Figure 12 illustrates comparisons of mean STHT responses of the subjects seated with HL and HS conditions, with NB and B0 postures under dual axis vibration. The fore-aft STHT responses revealed only minimal effect of the hands support with NB posture, while a considerable effect was observed in the lateral STHT responses, particularly in the vicinity of the resonance. Although the upper body motion is known to be restrained by the hands support, particularly under fore-aft vibration, only a small effect was observed on the vibration transmitted to the head. The results attained from ANOVA also revealed insignificant effect (p>0.05) of the hands support on the fore-aft STHT response, while a significant effect (p<0.05) on the lateral STHT data was evident in the vicinity of the resonance (Table 2). The fore-aft and lateral STHT responses revealed considerable effect of the hands support with B0 posture, as seen in Fig. 12(b). The fore-aft STHT responses with hands and back supported posture revealed higher magnitudes in the 1.5 to 6.5 Hz range but minimal effect at frequencies below 1.5 Hz and relatively lower magnitudes in the 6.7 to 10.3 Hz range. The fore-aft STHT response with B0 posture showed trends that are quite different from the corresponding APMS; while the peak STHT occurred near 1.38 Hz, the peak APMS is observed near 4.3 Hz. The lateral APMS and STHT, however, show comparable trends in frequencies corresponding to peak responses and the hands support effect. Furthermore, statistically significant effect (p<0.05) of the hands support was observed on both the fore-aft and lateral STHT responses (Table 2). The higher magnitudes of lateral STHT responses were observed in

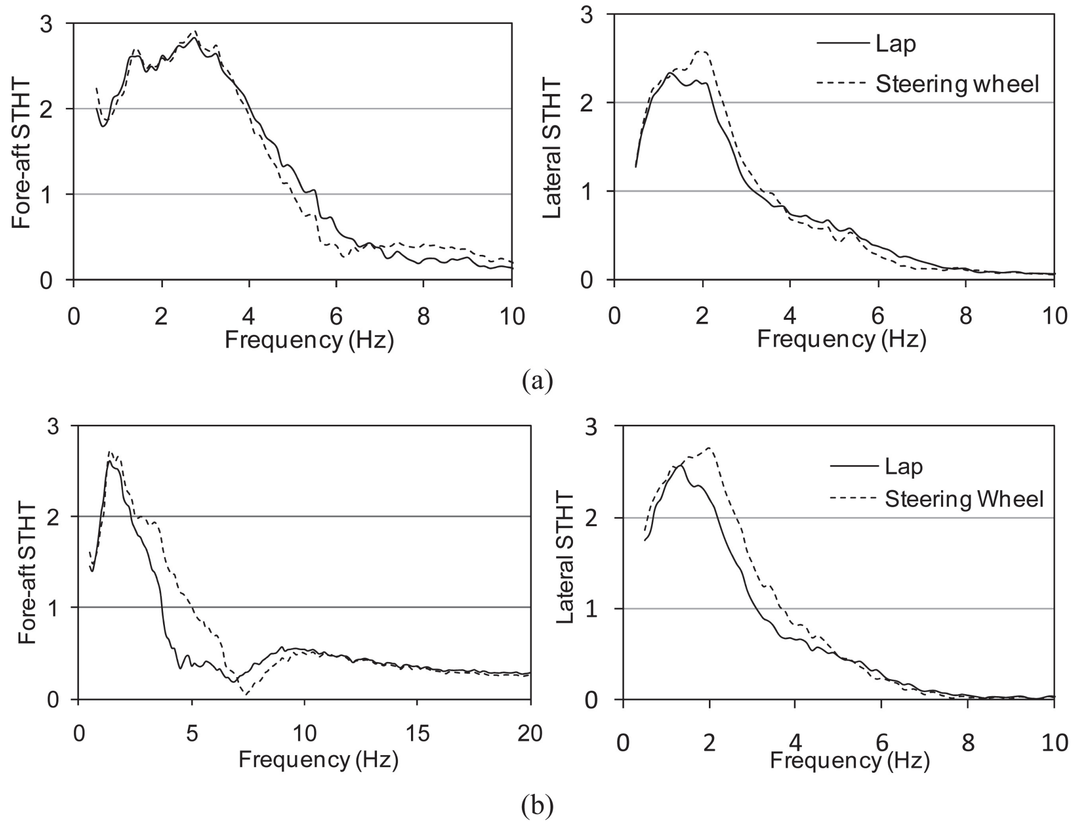


Fig. 12. Comparisons of mean STHT responses of the occupants seated with hands in lap and hands on steering wheel. (Dual-axis: a_x=a_y=0.28 m/s^2: (a) No back support and (b) Back support).

1.2 to 5.2 Hz frequency range with hands and back supported posture. The significant hands support effect was observed particularly in the vicinity of the resonance, in both the mean data (p<0.05), as shown in Table 2.

Effect of back support

Figure 13 illustrates comparisons of mean responses obtained with NB and B0 postures under dual-axis vibration. The APMS and STHT responses are presented for both HL and HS conditions, along fore-aft and lateral axis. The fore-aft APMS magnitudes near 0.5 Hz frequency were nearly unity, validating the considered normalisation factors (Table 1). The addition of the vertical back support resulted in the shift in the primary resonance to a higher frequency, while the dominant magnitude peak occurred in the 4–5 Hz range (Table 4) with normalised magnitude peak approaching 1.7 under HS condition. Although a back support is believed to suppress the pitch motion of the upper body to an extent, the back support resulted in higher magnitudes of vibration transmissibility and fore-aft APMS responses, which could be attributed to additional vibration from the backrest and greater contact with the back support. The statistical significance (p<0.05) of the back support under fore-aft vibration was observed in the entire frequency range (Table 3). However, relatively smaller but significant effect of the back support was also observed in the lateral APMS responses, which can be attributed to the tendency of the upper body to slide against the backrest surface and therefore offer less resistance to the upper body sway motion. Furthermore, the statistical significance (p<0.05) of the back support in view of the APMS is also evident from the ANOVA results attained considering two hands support conditions for each back support under single- as well as dual-axis vibration (Table 3).

The fore-aft APMS responses obtained at the backrest revealed significant dynamic interactions of the upper body with the back support, as evident in Fig. 6. Unlike the trends observed in APMS responses with the B0 posture, the STHT responses along fore-aft show significantly lower magnitudes in 1.5 to 6.5 Hz frequency range, and a secondary peak near 9.88 Hz, as illustrated in Fig. 13(b). The higher fore-aft STHT response observed with NB posture in the 1.5 to 6.5 Hz range could be attributed to the pitch motion of the upper body which is partly restrained with the back support. The significant effects of the back support on the STHT responses are also evident in terms of the resonant frequencies (Table 4) and results attained from ANOVA (Table 3). However, the effect of back support was small on the lateral STHT responses. Mean APMS and STHT responses of occupants seated with NB-HL and B0-HL postures under dual-axis horizontal vibration are further compared in Fig. 14, which show significantly different trends in the two measures in terms of magnitudes and the corresponding frequencies, particularly along the fore-aft axis. The lateral-axis responses, however, exhibit comparable frequencies but differ considerably in peak magnitudes.

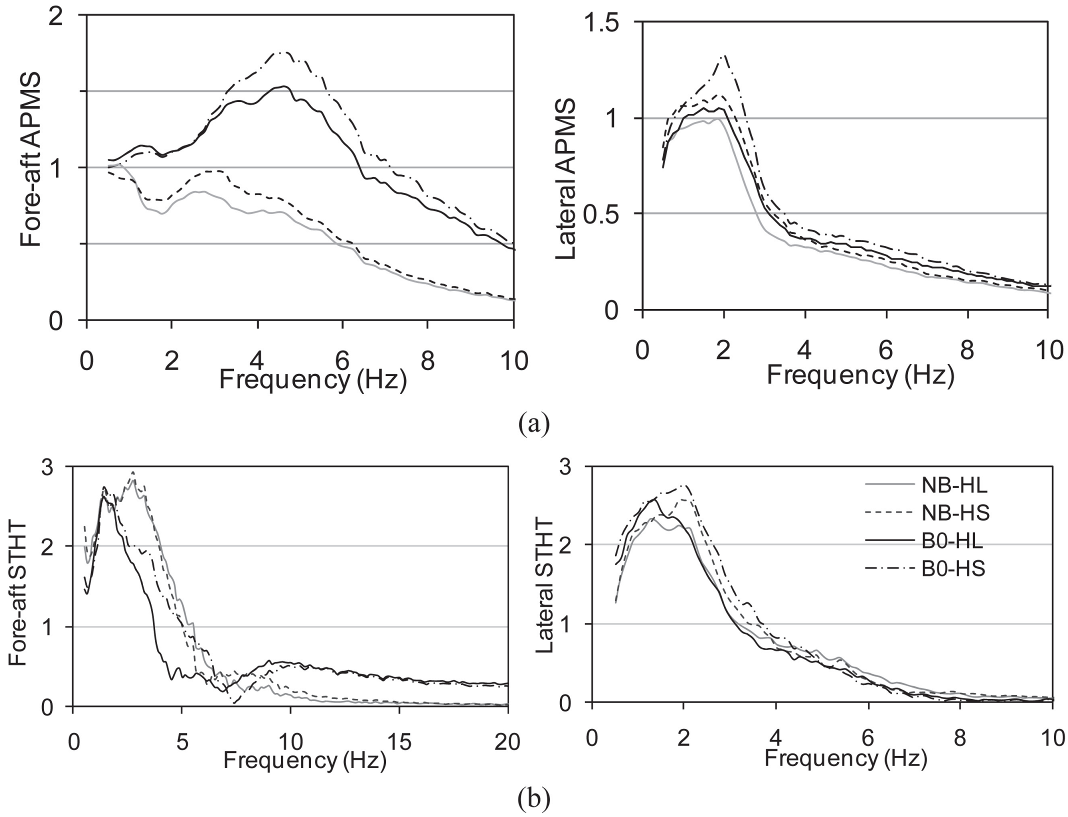


Fig. 13. Comparisons of mean (a) total APMS and (b) STHT responses of occupants seated with back unsupported (NB) and supported (B0), and hands in lap (HL) and hands on steering wheel (HS) under dual axis vibration (a_x=a_y=0.28 m/s^2).

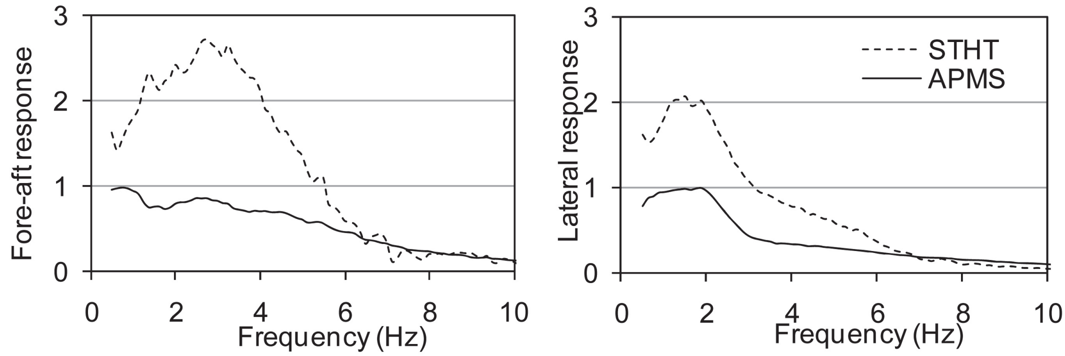
Effect of excitation magnitude

The mean APMS responses generally revealed slightly lower peak magnitudes and corresponding frequencies with increase in the vibration magnitude from 0.25 to 0.4 m/s^2 (Table 4). The lower frequencies under higher magnitude of vibration were attributed to the softening effect of the human body[1–4]. The STHT responses revealed relatively lower magnitudes but comparable resonant frequencies with increase in the magnitude of vibration (Table 4). The results attained from ANOVA with vibration magnitude as the independent variable and considering both hands and back support conditions showed that the effect of vibration magnitude is significant (p<0.05) on both the APMS and STHT responses, particularly in the vicinity of the resonance frequencies.

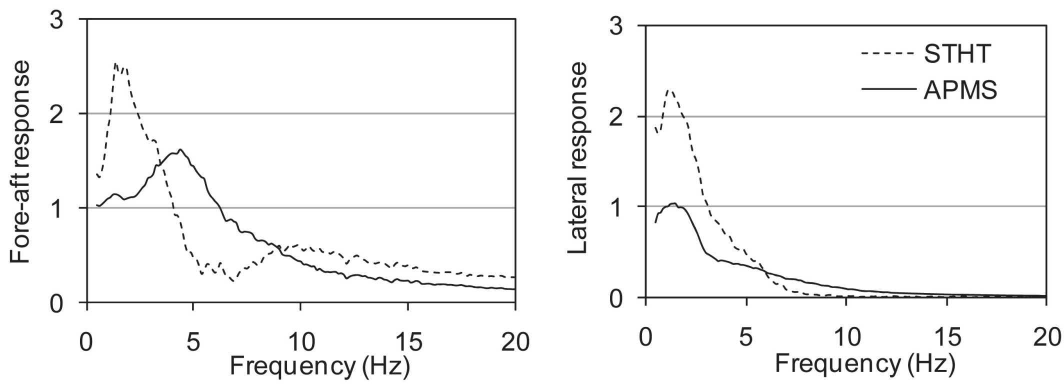
Discussions

The fore-aft APMS measures of the seated body with a back support necessitate careful consideration of the location of the force measurement. The measurement of biodynamic force directly at the buttock-seat interface does not account for the upper body interactions with the backrest and thus yields considerably lower magnitude. The total seat APMS, however, can be estimated from the sum of seatpan and backrest responses, using Eq. (9), when the seatpan AMPS is derived from the force measured directly at the seatpan. The results show that the biodynamic responses of the seated body exposed to single and dual-axis horizontal vibration are strongly influenced by the motion constraints caused by the hands and back support conditions. Sitting with partial back support and hands on a steering wheel, representative of a typical vehicle driving posture, yields considerably higher peak magnitudes of APMS responses and corresponding frequencies compared to those attained with a posture involving no back and hands supports (Figs. 11 and 13). The hands support help maintain a stable sitting posture under horizontal vibration, although it may serve as an additional source of vibration. Sitting with hands support yields higher magnitude of fore-aft APMS at frequencies above 2.4 Hz for the back supported posture, while the effect on fore-aft STHT was insignificant (p>0.05). The lateral APMS response with hands supports tends to be higher at frequencies above 2 Hz compared to that with hands in lap for the back supported posture.

The hands support also affects the lateral STHT significantly (p<0.05), particularly with the back supported condition. The effect of hands support appeared to be relatively smaller when sitting with a back support, which suggests coupled effects of both the supports. The use of a back support significantly alters the biodynamic responses of the seated body, particularly along the fore-aft axis. This is attributable to the constraint due to the backrest support. The effect of back support on the fore-aft responses was observed to most significant in the entire frequency range (p<0.05). The effect was also significant on lateral APMS response, although relatively



(a)



(b)

Fig. 14. Comparison of normalized total APMS and STHT measures of occupants seated with hands in lap and exposed to dual-axis vibration (a_x=a_y=0.28 m/s^2). (a) No back support and (b) Back support).

small, which is again attributable to the motion resistance offered by the back support. The use of a hands support also helps maintain greater and uniform contact of the upper body with the backrest. Relatively higher magnitudes of the lateral seatpan and backrest APMS with the hands support can be attributed to greater contact of the upper body with the backrest and thereby larger friction force. The higher magnitudes of the STHT responses observed with HS posture can be attributed to the greater contact with the backrest and thus increase in the vibration transmitted from the backrest.

Sitting with the B0 posture yields greater interactions of the upper body with the back support, while the back support serves as an additional source of vibration. Such interactions were observed to be greatly significant under single-axis fore-aft vibration, however, minimal under lateral vibration[1, 3, 8)]. These interactions are also known to effect the vibration transmitted to the head particularly under fore-aft vibration[14)]. Furthermore, the fore-aft seatpan APMS responses of seated occupants with B0 posture are strongly coupled with those at the back support[3, 8)]. The lateral backrest APMS responses exhibit significantly lower values in the 0.3 to 0.4 range suggesting relatively smaller dynamic interactions of the upper body with the backrest, which is limited to sliding only. The lower magnitude at low frequencies could also be attributed to the selected normalisation factors, and suggests the need for identification of appropriate normalisation factors based on human anthropometry.

It has been shown that the STHT and APMS responses to vertical vibration exhibit comparable trends in terms of the resonant frequencies and peak magnitudes[15)]. The fore-aft and lateral STHT responses, however, exhibit patterns that are considerably different from the APMS (Fig. 14), irrespective of the back support condition. This suggests that the upper body modes contributing to the STHT response differ from the modes contributing to the body-seatpan interactions under horizontal vibration. The STHT magnitude responses obtained in this study were significantly greater compared to those reported[14)], which is partly due to differences in the measurement location and method. The STHT response in the reported study was measured at the mouth level using a bite-bar, while the present study measured the STHT at the skull near the coronel suture. It is believed that the pitch and roll rotations of the head and neck contributed to greater fore-aft and lateral responses at the head.

The APMS and STHT magnitude as well as phase responses to simultaneously applied dual-axis horizontal vibration were generally very close to those attained under singleaxis vibration, suggesting a weaker coupling between the fore-aft and lateral axis responses. These observations are consistent with those reported in terms of APMS[5, 6)]. These studies, however, presented comparisons of single and dual-axis responses under different magnitudes of vibration. Mansfield and Maeda[6)] and Hinz *et al.*[5)] compared the APMS responses to single- and multiple-axis vibration under identical magnitudes of vibra-

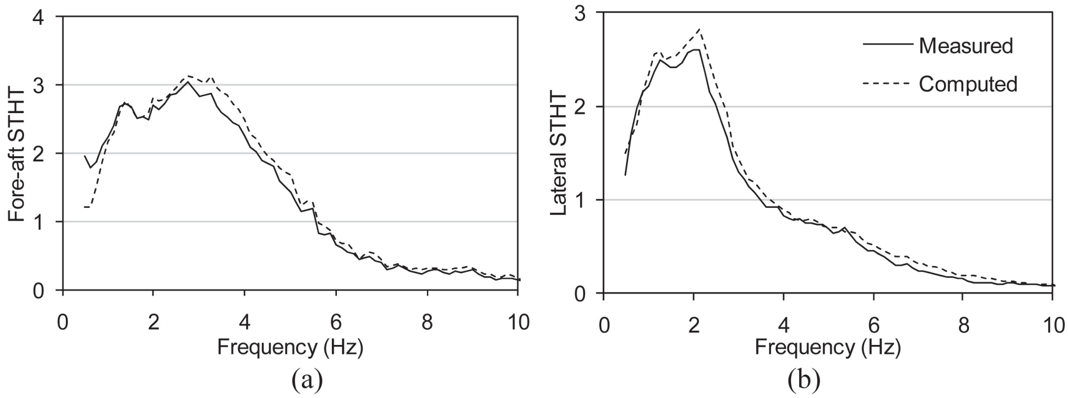


Fig. 15. Comparisons of estimated and measured fore-aft and lateral STHT responses to dual-axis vibration. (a) fore-aft; and (b) lateral (No back support; a_x=a_y=0.28 m/s^2).

tion along each axis, which would result in higher effective vibration magnitude of the multi-axis vibration. The dual and three-axis responses suggested lower peak APMS magnitudes and the corresponding frequencies compared to the single-axis responses, which could in-part be attributed to higher effective magnitude of multi-axis vibration. However, the magnitudes of the direct-axis lateral and fore-aft STHT responses to single axis vibration were lower than those to the dual axis vibration magnitudes at frequencies below 3 Hz (Fig. 8).

Experimental studies involving biodynamic responses of the seated human exposed to vertical vibration have reported considerable saggital plane motion of the upper body suggesting the coupled vertical and fore-aft motions[7, 8, 10, 13, 14]. This is also evident from the magnitudes of the cross-axis APMS and STHT responses under either vertical or fore-aft vibration. The APMS and STHT responses measured under the considered experimental conditions, however, revealed only minimal effect of dual axis vibration, suggesting negligible or weak coupling between the fore-aft and lateral axis responses. This is further supported by the results attained from ANOVA, which revealed insignificant differences in the single- and dual-axis responses (p>0.05) in most of the frequency range, for all the test conditions considered. Significant differences, however, were obtained between the lateral STHT responses to single and dual-axis vibration (p<0.01) in the vicinity of the resonance frequencies, which are also evident in Figs. 8 and 9.

The small magnitudes of the cross-axis APMS and STHT responses under all conditions of the experiments further indicate weak coupling in the responses to dual-axis horizontal vibration (Fig. 7). The total APMS and STHT responses to dual-axis WBV were further estimated considering the single-axis direct and cross-axis responses based on the principle of superposition described in Eqs (16) to (19), for each experimental condition. The analyses were performed on the single axis data acquired with each subject. The mean of the estimated total responses were then compared with the mean measured data under dual-axis vibration to illustrate the validity of the superposition. The comparisons generally revealed either comparable or slightly higher estimated responses compared to the measured dual-axis responses. As an example, Fig. 15 illustrates a comparison of the estimated and measured fore-aft and lateral STHT responses of the occupants seated with NB and HL condition to dual axis WBV. The results show only small differences between the estimated and measured responses. The validity of the linear superposition theory, however, could not be concluded considering very small magnitudes of the cross-axis components under horizontal vibration, small differences in the single and dual-axis responses and consideration of identical magnitudes of x- and y- axis excitation in the present study.

Unlike the biodynamic responses to vertical vibration, the APMS and vibration transmissibility measures under fore-aft vibration show considerably different trends in terms of magnitudes and resonance frequencies. The differences observed in the fore-aft and lateral responses may in-part be attributed to greater flexibility of the upper body in the sagittal-plane (x-z) compared to the coronal plane (y-z). Moreover, the seat-to-head vibration transmissibility responses encompass the translational and rotational motions of the head and upper body compared to the APMS responses, which reflect the dynamic interaction of the seated occupant with the seat at the driving-points: seatpan and the backrest. It has been suggested that the vibration modes associated with the upper body and head-neck, and other low-inertia body segments may not be adequately reflected in the driving-point measures[15]. This could be observed from the higher frequency peak in the fore-aft STHT response near 9.88 Hz, which is not evident in the APMS in Fig. 14(b). Both the biodynamic measures are thus suggested to fully characterise the seated occupants responses to horizontal vibration and to identify reliable target functions for defining the biodynamic models and frequency weightings.

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