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ANALYSES OF BIODYNAMIC RESPONSES OF SEATED OCCUPANTS TO UNCORRELATED FORE-AFT AND VERTICAL WHOLE-BODY VIBRATION

Santosh Mandapuram[1], S. Rakheja[1], Pierre Marcotte[2], P.-É. Boileau[2]

[1]CONCAVE Research Centre, Concordia University, Montreal, Québec, CANADA
[2]Institut de recherche Robert-Sauvé en santé et en sécurité du travail, Montréal, Québec, CANADA

Corresponding author: S. Mandapuram, e-mail: santosh.mc@gmail.com

Abstract

The apparent mass and seat-to-head-transmissibility response functions of the seated human body were investigated under exposures to fore-aft (x), vertical (z), and combined fore-aft and vertical (x and z) axis whole-body vibration. The coupling effects of dual-axis vibration were investigated using two different frequency response function estimators based upon the cross- and auto-spectral densities of the response and excitation signals, denoted as H_1 and H_v estimators, respectively. The experiments were performed to measure the biodynamic responses to single and uncorrelated dual-axis vibration, and to study the effects of hands support, back support and vibration magnitude on the body interactions with the seatpan and the backrest, characterised in terms of apparent masses and the vibration transmitted to the head. The data were acquired with 9 subjects exposed to two different magnitudes of vibration applied along the individual x- and z- axis (0.25 and 0.4 m/s^2 rms), and along both the-axis (0.28 and 0.4 m/s^2 rms along each axis) in the 0.5 to 20 Hz frequency range. The two methods resulted in identical single-axis responses but considerably different dual-axis responses. The dual-axis responses derived from the H_v estimator revealed notable effects of dual-axis vibration, as they comprised both the direct and cross-axis responses observed under single axis vibration. Such effect, termed as the coupling effect, was not evident in the dual-axis responses derived using the commonly used H_1 estimator. The results also revealed significant effects of hands and back support conditions on the coupling effects and the measured responses. The back support constrained the upper body movements and thus showed relatively weaker coupling compared to that observed in the responses without the back support. The effect of hand support was also pronounced under the fore-aft vibration. The results suggest that a better understanding of the seated human body responses to uncorrelated multi-axis whole-body vibration could be developed using the power-spectral-density based H_v estimator.

Key words: Apparent mass, seat-to-heat-transmissibility, H_1 and H_v estimator, seated occupants, coupling, single and dual axis vibration, fore-aft and vertical vibration.

1.0 Introduction

The biodynamic responses of the seated occupants exposed to whole body vibration have been widely investigated in terms of apparent mass (APMS) or seat-to-head vibration transmissibility (STHT) under broad ranges of vibration and postural conditions [1-7]. The majority of these studies have focused on response analyses of seated body exposed to vertical (*z*) vibration, and relatively a few have investigated the responses to fore-aft (*x*) or lateral (*y*) vibration [1,3,7]. Furthermore, the reported studies, with the exception of a few recent studies, have been limited to single-axis vibration, where the response measurements are generally attained only in the direction of the applied vibration. A few studies have also investigated cross-axis STHT and APMS responses, and reported notable upper body movements along fore-aft axis under vertical vibration excitation and vice versa, suggesting coupled movements of the human body in the sagittal (*x*-*z*) plane [5-13]. The vibration environments of work vehicles comprise vibration along all the translational and rotational axes, while the applicability of reported single axis biodynamic responses to such vehicular environment has not yet been established. The characterization of biodynamic responses of seated human body to multi-axis vibration could yield better understanding of the human responses to more realistic vehicular vibration and contribute towards developments in multi-dimensional biodynamic models.

Only a few recent studies have measured the APMS responses of the seated occupants exposed to broad-band random translational vibration along the two- or three-axis [9,14-17]. The reported APMS responses to dual and three-axis vibration were generally quite comparable with those obtained under single-axis vibration. The peak APMS magnitudes and the corresponding frequencies measured under multi-axis vibration, however, were slightly lower than those observed in the single-axis responses. Mansfield and Maeda [9] further showed that the peak magnitudes of vertical APMS response to dual-axis vibration along *y*- and *z*- axis (*yz*) were lower than those under the *z*-axis vibration alone at frequencies below 6 Hz, although negligible coupling is observed in the responses in the *y*-*z* plane under individual axis vibration. This effect was also evident from the three-axis vibration (*xyz*) responses [15]. The observed differences could in-part be attributed to higher effective magnitudes of dual and three-axis vibration used in these studies compared to that of the single-axis vibration, which would lead to softening effect in the response [1,2,16]. Similar effect was also observed in the responses to combined *x*- and *z*-axes (*xz*) vibration reported by Qui and Griffin [17], which showed decreasing peak vertical APMS magnitude and the corresponding frequency under increasing *x*-axis vibration, and vice-verse. The lower resonant frequency under dual-axis vibration was clearly shown statistically which was also reported by Mansfield et al. [15] under three-axis vibration. A definite trend in the primary peak frequencies, however, was not evident from the reported data, which may in part be attributed to relatively poor frequency resolution used in the above studies, 0.25 Hz and 0.39 Hz [15,17]. The APMS responses to comparable effective magnitudes of single (*x* and *y*) and dual (*xy*) axis vibration revealed considerably smaller differences in the peak magnitude and the corresponding frequencies [16]. The data reported by Hinz et al. [14], however, suggested a few anomalies with regard to the number of vibration axis and the excitation magnitudes. The peak fore-aft APMS response magnitude to three-axis (*xyz*) vibration was observed to be higher than that due to the *x*-axis vibration alone under low excitation magnitudes. The peak magnitudes, however, were comparable under higher excitation magnitudes.

The APMS responses to dual and three-axis vibration have been mostly characterized for body seated without a back support and hands in lap. The effect of a vertical back support on the APMS responses have been reported by Mansfield and Maeda [5,9] under combined dual and three-axis vibration, and by Mandapuram et al. [16] under dual-axis (*xy*) vibration. The effects of a back support on the measured responses were significant and similar to those observed under single axis vibration, while the peak APMS magnitudes were slightly lower under dual-axis vibration. The effects of hands support (hands in lap *vs* hands on steering wheel) have been reported in a single study under dual (*xy*) axis vibration, which suggested that hands support affects fore-aft APMS as well STHT responses considerably [16]. It has been suggested that STHT measure may exhibit greater emphasis of higher body modes associated with the lower inertia components of the seated body compared to the driving-point measure (APMS) [18]. The STHT responses to dual and three-axis translational vibration, however, have been reported in only two studies. Hinz et al. [19] performed comprehensive measurements of the translational and rotational STHT responses of the occupants seated without a back support and hands supported on a handle bar under single (*x*, *y*, *z*) and three (*xyz*) axis vibration. Another study reported the translational STHT responses of subjects seated with and without back and hands support under dual-axis (*xy*) vibration [16]. Both the studies showed definite differences between the single and multi-axis responses compared to those observed in the APMS responses, irrespective of the back and hands supports. This would suggest greater coupling effects of multi-axis vibration on the upper-body movements, which may not be entirely captured by the driving-point measures.

The observed differences between the responses to single and dual/three-axis vibration, however, were small compared to the magnitudes of the reported cross-axis STHT responses under single-axis vibration [6,7,19]. The comprehensive magnitudes of cross-axis STHT and APMS responses reported under single axis vibration suggest coupled motions of the seated body in the saggital plane, which would be expected to influence the responses to combined dual/ three-axis vibrations considerably [5-13]. Furthermore, the coupled motions of the upper body were clearly perceived by the subjects exposed to dual-axis vibration, and observed by the experimenter [16]. The reported small differences in the single and multi-axis responses thus raise an important concern on the method of characterization of the biodynamic responses to multi-axis vibration. The studies reporting the biodynamic responses to multi-axis vibration have invariably employed linear frequency response function (FRF), also known as the H_1 estimator, based on the cross-spectral density (CSD) of the response and the excitation variables. The CSD-based FRF considers correlated excitation and response data, and would not account for the contributions due to cross-axis responses under uncorrelated dual or three-axis orthogonal vibration [20] used in the reported studies [9,14-17].

The biodynamic responses to single-axis vibration have also been derived from the ratio of the power-spectral density (PSD) of the response and excitation, referred to as the PSD method [21]. It has been shown that both PSD and CSD methods yield very similar single-axis responses, while the PSD method does not provide the coherence and the phase relation, which is vital for deriving biodynamic models. Alternatively, Rocklin et al. [22] suggested an H_v estimator, which is similar to the PSD method but yields the necessary phase information. Under uncorrelated multi-axis vibration, the PSD method would consider the auto-spectra of the biodynamic response, including the contributions due to cross-axis responses to uncorrelated inputs. This method could thus help identify the possible coupling effects in the biodynamic responses to multi-axis vibration. Furthermore, the coupling effects of simultaneously applied multi-axis vibration may also depend on various factors such as the sitting posture including the hands and back support apart from the excitation magnitude. The sitting postures in vehicular environments generally involve both the hands as well as the back supports, which tend to alter the fore-aft, vertical and pitch motions of the upper body and may thus influence the biodynamic behaviour of the seated body, although only minimal efforts have been made to study their effects under multi-axis vibration. The influences of back and hands supports on both the STHT and APMS responses to coupled vertical and horizontal vibration have not yet been reported.

In this study, the STHT and APMS responses of the seated body exposed to single (*x* and *z*) and dual (xz) axis vibration are obtained using the H1 and Hv, frequency response estimators based on CSD and PSD of the measured response and excitation, respectively. The PSD method is expected to reveal contributions due to cross-axis responses and thus the coupling effects in the biodynamic responses under dual-axis vibration, which would be suppressed by the CSD method considering the uncorrelated nature of the dual-axis vibration. Furthermore, for the back supported posture, the APMS responses are characterized at the two driving-points formed by the buttock-pan and the upper-body-backrest interfaces together with the STHT responses.

2.0 Method

A rigid seat and a steering column were installed on a 6-DOF whole-body vibration simulator (IMV Corporation). A 600 × 400 mm^2 tri-axial force plate (Kistler 9281C) served as the pan of the seat at a height of 450 mm from the simulator platform. Another 450 mm force plate served as the vertical 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 formed at the seatpan and the backrest, along the *x*-, *y*- and *z*- axis. The platform vibration was measured by a three-axis accelerometer (Brüel and Kjaer 4506A) aligned with the translational axes of vibration. The head vibration was measured using a three-axis micro accelerometer mounted on a light-weight helmet strap [5]. Majority of the studies that reported STHT measures have used a bite-bar [6,7,19], which offers good coupling to the skull but the subjects generally find it uncomfortable, particularly when repetitive vibration measurements are involved, while a few have considered a helmet [23] and a light-weight head-band [18]. It has been suggested that the STHT measures obtained using a bite-bar may be influenced by the strength of the bite [18], while the large inertia of a helmet may affect the accuracy of the acceleration measured [24]. The different measurement methods, however, employ different measurement locations (e.g. mouth and scalp) and would thus be expected to yield important differences in the measured accelerations, particularly in the fore-aft acceleration owing to the pitch motions of the head.

Both the STHT and APMS responses were measured under individual fore-aft (*x*) and vertical (*z*) axis vibration, and combined vertical and fore-aft (*xz*) vibration. The experiment design included: (i) two different back support conditions (seated without a back support- NB; and with lower back against a vertical backrest- B0); (ii) two different hands positions (hands on steering wheel- HS; and hands on lap- HL); and (iii) two different levels of broad-band vibration with constant PSD in the 0.5-20 Hz frequency range applied along the individual *x*- and *z*- axis (0.25 and 0.4 m/s^2 rms un-weighted acceleration), and dual-axis (0.28 and 0.4 m/s^2 rms, un-weighted acceleration along each axis). The lower magnitude dual-axis vibration was synthesised to achieve overall rms acceleration of 0.4 m/s^2 (0.28 m/s^2 along each axis), comparable to that of the single axis vibration. This facilitated the study of the effects of dual-axis vibration under identical effective magnitudes of single and dual-axis vibration. The measurements performed with the seat loaded with a rigid mass of 60 kg revealed some degree of cross-talk in the simulator. A 0.4 m/s^2 vertical excitation revealed peak fore-aft vibration in the order of only 5% over the concerned frequency range (0.5-20 Hz). Figure 1 schematically illustrates the four sitting postures realised with two back (NB and B0) and two hands (HL and HS) positions . Each subject was advised to maintain a consistent backrest contact during vibration exposure, which was further monitored by examining the backrest force plate signal and magnitude of the low frequency backrest APMS (near 0.5 Hz).

The experiments employed a total of 9 healthy adult male subjects with average age 30.4 years (22-55), body mass 63.4 kg (57-69) and height 173.4 cm (162-179). The subjects had no prior history of back pain. Each subject was informed about the purpose of the study, experimental setup and usage of an 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. Each vibration exposure lasted for nearly 60 s and each subject was asked to put on a cotton lab coat to ensure uniform friction between the upper-body and the vertical back support. Each subject was asked to wear the head-accelerometer strap weighing around 220 grams and adjust its tension using the ratchet mechanism to ensure a tight but comfortable fit. The subject was asked to sit assuming the selected posture, as determined by the back and hands support conditions, comfortably with average thigh contact on the pan and lower legs oriented vertically with feet on the vibrating platform, as illustrated in Fig. 1. The feet support was adjusted vertically to provide the desired sitting posture for each subject. Prior to application of vibration, the head-band accelerometer orientation was visually monitored and appropriately adjusted by the experimenter to align the accelerometer with the chosen axis system. For this purpose, each seated subject was advised to aim at a fixed marker in the line of sight, while maintaining the desired posture. Experimenter ensured the tight fit of the head band so as to minimize the effects of hair and skin tissue. Wang et al [5] showed flat frequency response characteristics of the band, in the 0.5-20 Hz range measured on a skull-shaped rigid body when the band was sufficiently tight. The subject was subsequently advised to maintain the same head and neck posture by continually aiming at the fixed marker while being exposed to vibration. The order of the experiments was randomised and each experiment was repeated twice.

2.1 Data analysis

The seatpan and backrest forces, and the head and platform acceleration data were acquired in the PulseLabShop™ and analysed to derive the STHT and APMS responses of occupants seated with different back and hands support conditions, while exposed to single and dual-axis whole-body vibration (WBV). The analyses were performed using a band width of 100 Hz with a resolution (Δf) of 0.125 Hz. Inertial corrections of the measured APMS data were performed using the method described in [2]. The APMS response measured at the seatpan was considered as the total seated body APMS in the absence of a back support. In the presence of the upper-body contact with the back support, the total APMS was estimated from the sum of APMS responses measured at the seatpan and the backrest, such that [16]:

$$M_{sk,l}(f) = M_{pk,l}(f) \qquad \text{(without back support posture, NB)}$$
$$M_{sk,l}(f) = M_{pk,l}(f) + M_{bk,l}(f) \quad \text{(with back support posture-B0)} \qquad (1)$$

Where $M_{sk,l}(f)$ represents the total seated body APMS response, $M_{pk,l}(f)$ and $M_{bk,l}(f)$ represent the seat pan and backrest APMS responses, respectively, derived from the force response along axis k (k=x, z) due to acceleration input along axis l (l=x, z).

2.1.1 Analyses of biodynamic responses to multi-axis vibration

The biodynamic responses to single axis vibration have been derived using linear relationships between the excitation and the measured responses along the direct (axis of applied vibration) and the cross-axis. The seated occupant exposed to single axis vibration (x or z) can be considered as a single-input and multiple-output system as illustrated in Fig. 2, where q_{xx} and q_{zx} represent the direct and cross-axis forces or acceleration responses due to fore-aft vibration (a_x). Similarly, q_{zz} and q_{xz} represent the direct and cross-axis responses due to vertical axis (a_z) vibration. The direct and cross-axis biodynamic responses have been mostly derived from the linear frequency response function (FRF), also denoted as H_1 estimator, which involves the complex ratio of cross-spectral density (CSD) of the input and the measured response, and the auto-spectral density of the input. Under the single axis excitation along x or z-axis, the direct and cross-axis response functions are derived from [1,9,11]:

$$H_{kl}(f) = \frac{S_{a_l q_k}(f)}{S_{a_l}(f)}\ ;\ k=x,\ z \text{ and } l=x,\ z \qquad (2)$$

Where $H_{kl}(f)$ defines the direct (k=l) or cross-axis ($k \neq l$) complex biodynamic function under excitation along axis l (l = x, z) corresponding to excitation frequency f. $S_{a_l q_k}$ is the CSD of the response (q_k) measured along k (k=x, z) and input acceleration a_l (l = x, z), and S_{a_l} is the auto spectral density of the input acceleration.

The seated occupants' responses to simultaneous dual or three-axis vibrations, reported in recent studies, have invariably employed H_1 estimator. For dual-axis vibration along x and z axis, the biodynamic response functions along each axis are derived from:

$$H_k(f) = \frac{S_{a_k q_k}(f)}{S_{a_k}(f)}\ ;\ k=x,\ z \tag{3}$$

Where $H_k(f)$ defines the complex biodynamic function which relates the total measured response q_k along axis k ($k = x$, z) corresponding to excitation frequency f.

For coupled motions of the seated body in the sagittal plane, the total response q_k would comprise of components due to excitations along both the axes, a_x and a_z. Considering the uncorrelated nature of the excitations applied along the two axes, the biodynamic response function, derived using Eq (3), would ignore the contributions due to excitation along an axis other than the direct-axis. In particular, the total responses derived along x- and z- axis may suppress the contributions due to z- and x- axis vibration, respectively. This could be the reason for observing comparable APMS response magnitudes to single, dual or three-axis vibrations, reported in the recent studies [9,15]. These studies have shown that the APMS responses to dual and three-axis vibration exhibit slightly lower peak magnitude and the corresponding frequency compared to the single-axis responses. This in-part may be attributed to relatively higher effective magnitude of the multi-axis vibration compared to that of the single-axis vibration used in the studies.

The above is also evident from the cross-axis responses to dual and three-axis vibration that have been presented in two studies [17,19]. The cross-axis responses to dual (xz) axis vibration are derived from

$$H_{xz}(f) = \frac{S_{a_z q_x}(f)}{S_{a_z}(f)};\ \text{and}\ H_{zx}(f) = \frac{S_{a_x q_z}(f)}{S_{a_x}(f)} \tag{4}$$

Where $H_{xz}(f)$ is the cross axis response relating the total measured response q_x under dual axis vibration to excitation a_z alone, while H_{zx} relates the total response q_z under both axis of vibration to excitation a_x alone. The total responses q_x and q_z comprise the responses to direct (a_x and a_z, respectively) and the cross-axis (a_z and a_x, respectively) excitations, where the components due to the direct axis excitations are predominant. The reported cross axis responses evaluated using CSD (H_1) approach did not reveal significant magnitudes of APMS and STHT, which would be attributed to the uncorrelated nature of the dual and three-axis vibration employed in these studies.

Similarly, the reported coherence functions (γ^2) of the responses to dual or three-axis vibrations are derived as a function of the CSD, $S_{a_k q_k}(f)$:

$$\gamma^2 = \frac{\left|S_{a_k q_k}(f)\right|^2}{S_{a_k}(f)\, S_{q_k}(f)};\ k = x,\ z \tag{5}$$

Where $S_{a_k q_k}(f)$ considers the correlated input (a_k)–ouput (q_k) component only of the actual total response to dual-axis vibration. $S_{q_k}(f)$, however, is auto-spectral density of the total response measured along axis k to dual axis vibration. The presence of coupling in the x-z plane would lead to relatively larger values of $S_{q_k}(f)$ and thus lower coherence values of the response. This is also evident in the reported coherence values under dual and three-axis vibration [17,19]. It has been suggested that the coherencies of the responses along the axis of vibration can be derived from the sum of the coherencies of the direct and cross-axis responses [17].

The studies reporting either APMS or STHT responses to dual or three-axis vibrations have therefore not revealed substantial effects of dual or three axis vibrations. The expected coupling in the fore-aft and vertical responses to simultaneous dual or three-axis vibration could not be clearly observed in the reported responses [9,10-13,19], although many studies reporting biodynamic responses to vertical vibration have clearly illustrated coupled sagittal plane motions of the body [10,11].

2.1.2 PSD method of analysis

The modulus of the biodynamic response to single-axis vibration can also be derived by relating the PSD values of response and excitation variables assuming that the output response is due to input alone, such that [21]:

$$H_k(f) = \sqrt{\frac{S_{q_k}(f)}{S_{a_k}(f)}} \qquad (k = x, z) \qquad (6)$$

Where $H_k(f)$ is the response function, and $S_{q_k}(f)$ and $S_{a_k}(f)$ are the PSDs of the biodynamic response and excitation along axis k, respectively. The output, however, may include the contributions due to noise present in both the input and output signals [20]. A few reported studies have shown that the APMS responses derived using the PSD method is similar to that obtained from the CSD-based H_1 estimator, suggesting that the contributions of the signal noise are relatively small [10-13]. Under uncorrelated multi-axis vibration, $S_{q_k}(f)$ would represent the PSD of the total response to multi-axis excitations. The PSD method may thus be considered better suited for the analysis of biodynamic responses to uncorrelated multi-axis vibration. This approach, however, does not yield the phase information, which is vital for deriving biodynamic models of the seated body exposed to vibration.

2.1.3 H_v Estimator

Rocklin et al.[22] suggested an alternate FRF estimator for the modal extractions of responses of the multiple-input multiple-output (MIMO) systems. The estimator, denoted as H_v, is derived from:

$$H_k(f) = \frac{S_{a_k q_k}(f)}{\left|S_{q_k a_k}(f)\right|} \sqrt{\frac{S_{q_k}(f)}{S_{a_k}(f)}} \qquad (k = x, z) \qquad (7)$$

In the above equation, H_k defines the frequency response along axis k (k=x, z), while $S_{q_k}(f)$ is the auto-spectra of the total response measured along k under multi-axis vibration. It has also been suggested that this estimator is better suited in the presence of input and output noises. Under single-axis vibration, the magnitude of the FRF derived from the H_v method reduces to that obtained from the PSD method, as seen in Eq (6). Unlike the PSD method, the H_v estimator also yields the phase information of the signals, which would be identical to that obtained from the H_1 method. In this study, the measured data were analysed to evaluate the APMS and STHT functions using the two frequency response estimators, namely the H_1 and H_v methods. The resulting responses are compared to illustrate the validity of the H_v method for analyses of biodynamic responses to uncorrelated dual-axis excitations.

2.2 Normalisation factors

Owing to the significant effect of the seated body mass on the measured APMS responses, the single-axis responses have been generally normalized with respect to the static seated body mass or the APMS magnitude at a very low frequency such as 0.5 Hz [2,4]. Hinz et al. [14] applied the static seated mass as a normalization factor for the APMS responses measured along *x*-, *y*-and *z*-axis to three-axis vibration. The static seated mass, however, tends to differ with the sitting posture, particularly when a back support is used [4]. Alternatively, the available anthropometric data have been applied to determine the seated body mass supported by both the seatpan and the back support [16].

In this study, the normalisation factors for the direct and cross-axis vertical seatpan APMS responses have been obtained from the static body mass measured below the entire seat reported in [4]. The fore-aft APMS data were normalized by considering the proportions of the body mass supported by the seatpan and the backrest along each axis, which were determined from the human anthropometric data [3,25]. Table 1 summarizes the proportions of body weights supported by the seatpan and the back support corresponding to each axis for the 4 postural conditions considered in the study, namely NB-HL, NB-HS, B0-HL and B0-HS.

3.0 Results

The measured data were analyzed to determine the STHT and APMS responses of each subject to single and dual-axis vibration using the H_1 and H_v FRF estimators. The direct and cross-axis STHT and APMS magnitude responses to single axis vibration derived using both the estimators were observed to be nearly identical for all the subjects considered in the study. As an example, Fig. 3 illustrates comparisons of the direct and cross-axis STHT magnitude responses of one subject to individual *x*- and *z*-axis vibration, derived from the H_1 and H_v methods. The results are presented for the back unsupported and hands in lap (NB-HL) posture and 0.4 m/s^2 excitation along each axis. Both the methods also resulted in nearly identical phase response (results not shown). In order to avoid the effects of averaging and the inter-subject variability, the results attained from H_1 and H_v estimators for single as well as dual-axis vibration were compared using the individual subjects' responses. As examples, Figs. 4 and 5 compare the fore-aft and vertical STHT and APMS responses to dual-axis vibration of two different subjects (denoted as S1 and S2), seated with back support and hands in lap posture (B0-HL). The figures also illustrate the direct and cross-axis responses of the same subjects to single axis vibration derived using the H_1 estimator. The responses under identical effective magnitudes of single (0.4 m/s^2) and dual (0.28 m/s^2 along each axis) are considered to study the effects of dual-axis vibration. Similar trends were observed in the results attained with all the subjects, although considerable inter-subject variability was evident.

Owing to the considerable scatter among the individual data acquired for each test condition, the mean data of the 9 subjects were obtained to study the differences due to the method of analysis (H_1 *vs* H_v), dual-axis vibration, contributory factors such as hands and back support, and the vibration magnitude. The results are limited to magnitude responses only while both the H_1 and H_v estimators resulted in very similar STHT and APMS phase responses. Figures 6 and 7 illustrate the mean STHT and APMS magnitude responses of the subjects seated without and with the vertical back support, respectively, and hands in lap posture to dual (*xz*) axis vibration derived using the H_1 and H_v estimators. Figures also show the mean direct and cross-axis responses obtained under single (*x* or *z*) axis vibration derived using the H_1 estimator.

The pair-wise comparison was performed to determine the statistical significance of the method of analysis at some of the excitation frequencies (Table 2), using the data corresponding to two levels each of the hands supports and the excitation magnitudes. The effect of method of analyses (H_1 and H_v) was observed to be significant ($p<0.01$) in the fore-aft STHT responses in the 4-10 Hz frequency range, irrespective of the back support condition. The effect on the vertical STHT, however, was significant at frequencies below 4 Hz for both with and without back supported postures, and additionally at frequencies above 5 Hz with the back supported posture. The fore-aft APMS responses of subjects seated without a back support posture derived using both the estimators were observed to be nearly identical ($p>0.2$) in the entire frequency range, while the difference in the vertical APMS response was significant at frequencies below 4 Hz ($p<0.01$). Addition of a vertical back yields higher magnitudes of fore-aft APMS in most of the frequency range above 4-5 Hz and vertical APMS at frequencies below 4 Hz and in the 5.5-7.5 Hz range (Fig. 6) compared to those observed with the unsupported back posture. The frequencies corresponding to peak STHT and APMS magnitude responses to single and dual-axis vibration are shown in Table 3.

The coupling effects in the responses evaluated from H_1 and H_v estimators are further studied through pair-wise comparisons of the STHT and APMS responses to single and dual-axis vibration for each back support condition (Table 4). The results suggest that the differences between the STHT responses to single and dual-axis vibration are generally more significant in a wider frequency range when H_v estimator is used, compared to the H_1 estimator.

The mean biodynamic responses, derived using H_v estimator are subsequently considered to further analyse the effects the posture and magnitudes of dual-axis vibration. Figure 8 compares the mean fore-aft STHT and APMS responses obtained with hands in lap (HL) and on the steering wheel (HS) for both the unsupported and supported back conditions (NB and B0). The figure shows the total fore-aft APMS measured at the seatpan, while those measured at the backrest for hands in lap and on the support (HL and HS) conditions are compared in Fig. 9 for effective vibration magnitude of 0.4 m/s^2. The hands support yields higher APMS magnitude in the 1.5-4.0 Hz frequency range for the unsupported back (NB) posture ($p<0.01$) but considerably lower magnitude near the primary resonance of 0.7 Hz, compared to the hands in lap condition.

For the supported back (B0) posture, higher APMS magnitude is obtained in the 4-7.5 Hz range when the hands are supported ($p<0.01$). Similar differences are also evident from the upper-body APMS measured at the back support (Fig. 9), which clearly show the significant effect of the hands support ($p<0.01$, as seen in Table 5). The results in Fig. 9 also show near unity low frequency APMS magnitude that corresponds to 67.8% of total body mass as evident from the normalization factors presented in Table 1. The low frequency back APMS magnitudes for individual subjects also revealed similar values, which further confirmed the consistency of the backrest contact during vibration exposure. The pair-wise comparisons of the measured dual-axis responses revealed insignificant effect of the hands support on the vertical STHT and the APMS measured at the seatpan ($p>0.05$), in majority of the frequency range, irrespective of the back support condition (Table 5). The vertical APMS measured at the backrest, however, revealed significant effect of hands support in the 4-5.5 and 7.5-10 Hz frequency ranges ($p<0.01$), although the APMS magnitudes were very small.

Figure 10 illustrates comparisons of mean STHT and APMS responses obtained with unsupported and supported back (NB and B0) conditions, with hands in lap under single and dual (*xz*) axis vibration. The dual-axis response magnitudes, evaluated from the H_v estimator, are in general are higher than those due to single axis vibration. The mean fore-aft STHT response with the back supported (B0) posture is considerably lower than that with the unsupported back (NB) posture at frequencies up to 6.5 Hz. The same trend is also evident in the fore-aft STHT response. At frequencies above 6.5 Hz, the back supported (B0) posture yields higher fore-aft STHT magnitude, compared to the unsupported back (NB) posture. This could be attributed to contributions of pitch motion of the upper body, which is constrained by the backrest. The back supported (B0) posture, however, yields substantially higher magnitudes of fore-aft APMS responses in nearly entire frequency range.

An increase in the single axis vibration magnitude from 0.25 to 0.4 m/s^2 yields lower direct-axis fore-aft STHT response at frequencies below 5 Hz but lower cross-axis STHT response in the 5-10 Hz range, as seen in Fig 11. The similar trends are also observed in the direct and cross-axis vertical STHT responses in the 5-10 Hz and 3-10 Hz ranges, respectively. The effect of magnitude of dual-axis vibration is more significant on the STHT responses (Fig. 12) compared to the APMS for the back unsupported and supported (NB and B0) postures.

4.0 Discussions

The STHT and APMS responses to single axis vibration derived from both H_1 and H_v estimators were observed to be similar while those under dual-axis vibration differed. The comparisons of results obtained from the H_1 and H_v estimators (Figure 4 and 5) show that the dual-axis STHT and APMS responses derived using H_1 estimator are comparable to those obtained under single axis vibration, as observed in the reported studies [9,14-17]. This is attributed to the uncorrelated nature of the dual-axis excitations, as described in section 2.1. Small differences observed in the single and dual-axis responses are most likely due to small correlation between the fore-aft and vertical vibration (dual-axis) caused by the cross-talk among the different actuators in the multi-axis vibration generator.

The results clearly show that the H_v estimator accounts for the contributions due to the cross-axis responses, while the H_1 estimator does not clearly show such contributions under uncorrelated dual-axis vibration. The magnitudes of STHT and APMS dual-axis responses determined from the H_v estimator are thus generally higher than the responses to single axis vibration. The fore-aft STHT responses of all the subjects under dual-axis vibration, estimated using H_v, exhibit an additional peak in the 5-6 Hz range associated with the vertical mode resonance that is clearly evident from the cross-axis fore-aft response (H_{xz}) under single axis vertical vibration, as seen in Figs. 4 and 5. This suggests the notable contribution of the cross-axis response and thus the coupling effects of dual-axis vibration, which is not evident from the fore-aft STHT response evaluated using the H_1 estimator. Similarly, the magnitude of dual-axis vertical STHT response derived using the H_v estimator revealed additional peak near 2 Hz, which is also evident from the cross-axis vertical response (H_{zx}) under single axis fore-aft vibration. Furthermore, the peak magnitudes estimated from H_v in the 5-6 Hz range are substantially higher than those estimated from the H_1 estimator, which is also attributed to contributions due to the cross-axis responses shown in Figs. 4 and 5. These results further confirm the coupling effects of dual-axis vibration that are evident only in the responses derived from the H_v estimator.

The APMS responses to dual-axis vibration derived from H_v, tend to differ from those obtained from H_1. The differences were, however, smaller compared to those observed in the STHT responses. These small differences can partly be attributed to relatively lower magnitudes of the cross-axis APMS responses to individual axis vibration compared to those in STHT responses, as seen in Figs. 6 and 7. Owing to its definition, the APMS predominantly relies on the dynamic interactions of the lower body (buttocks, thighs, pelvis) with the seatpan, where the cross-axis motion would be considerably small. Thus the dual-axis coupling effects in the seatpan APMS responses are expected to be relatively small.

4.1 Effects of supports

The seated body supports (back and hands supports) tend to alter the upper body movements and thus the biodynamic responses. In particular, sitting with a back support yields greater interactions of the upper body and the backrest along the fore-aft direction, and thereby affects both the fore-aft STHT and APMS responses substantially [1,3,16]. A back support also tends to limit the coupling in the sagittal plane motions of the seated body, which yields relatively lower magnitudes of cross-axis vertical STHT and APMS responses to fore-aft vibration at frequencies below 5 Hz, as seen in Figs. 6 and 7. The magnitudes of these cross-axis responses, however, tend to be considerably higher at frequencies above 5.5 Hz, which can be attributed to the fact that backrest serves as an additional source of fore-aft vibration to the upper body. The cross-axis vertical responses contribute to the coupling effect of dual-axis vibration and yield higher magnitudes of the vertical biodynamic responses in the presence of a back support compared to those with the unsupported back, particularly at frequencies above 5.5 Hz (Fig. 10).

While the important effects of a back support on the biodynamic responses are evident under both single and dual-axis vibration (p<0.05), the contributions due to the cross-axis responses and thus the coupling effect is more clearly evident from the dual-axis responses obtained using H_v. The dual-axis vertical STHT responses revealed additional peak near 2 Hz, which is evident in the cross-axis responses (Figs. 6 and 7). This response peak is not clearly evident in the dual axis vertical responses obtained from the H_1 estimator. The effect of the back support is also evident in the cross-axis fore-aft APMS and STHT responses to vertical vibration, which yields relatively higher magnitudes at frequencies above 4.37 Hz and 7 Hz, respectively, which is due to contributions of the cross-axis response component and additional vibration through the back support. . The fore-aft seatpan APMS is substantially greater in the entire frequency range, as it has been reported under single-axis fore-aft vibration [1,3]. The pair-wise comparisons of the measured dual-axis responses also revealed significant (p<0.01) effect of the back support on the fore-aft APMS in the entire frequency range, while the effect on the STHT responses is significant at frequencies below 5 and above 9 Hz (Table 6). The effect of back support on the vertical STHT and APMS responses are also significant below 5 Hz and at frequencies above 9 Hz, with only a few exceptions.

Apart from the back support, the hands support could also serve as an important constraint that may enhance the upper-body-backrest interactions while limiting the upper body pitch. The results show higher magnitudes of the backrest APMS with hands on steering wheel (HS) compared to that with hands in lap (HL) condition, in the 2-8 Hz frequency range (Fig. 9). Similar trend was also observed in the fore-aft seatpan APMS; the hands support yielded higher magnitudes in the 2.3-8 Hz frequency range for the supported back posture, while the magnitudes are lower near 1 Hz and higher in the 1.25-4.3 Hz frequency range for the unsupported back posture. The significant effect of the hands support on the backrest and seatpan fore-aft APMS responses (p<0.01) is also evident at different frequencies in Table 5.

Unlike the seatpan fore-aft APMS response, the fore-aft STHT magnitudes for the unsupported back (NB) posture in the 4.5-5 Hz range tend to be only slightly lower with the hands support (Fig. 8). This may be attributed to two factors: (i) a hands supported posture tends to limit upper-body pitch motion; and (ii) the presence of a back support could serve as an additional source of vibration to the upper body. However, the vertical biodynamic responses show relatively small effects of the hands support as reported in [4].

4.2 Vibration magnitude effect

An increase in the single axis vibration magnitude from 0.25 to 0.4 m/s^2 has shown nonlinear effects of vibration magnitude on the direct and cross-axis fore-aft and vertical STHT responses (Fig. 11), similar to those reported in the single and dual-axis fore-aft and vertical APMS responses to dual-axis vibration [1-3,5,17,19]. The studies reporting the biodynamic responses to single-axis vibration have shown notable effects of vibration magnitude on the APMS and STHT responses, which is substantial under the fore-aft vibration but relatively small under vertical vibration. Such effect was attributed to the subjects tendencies to stiffen under greater upper body motion caused by higher fore-aft vibration magnitudes, and to shift greater portion of the weight towards the legs to realize a more stable sitting posture [1-3,5,11].

The effect of magnitude of dual-axis vibration, however, is far more significant on the STHT responses (Fig. 12) compared to the APMS for both the back unsupported and supported (NB and B0) postures. This is attributable to greater contributions of the upper body movement to the STHT response, particularly in the fore-aft axis, as seen in Fig 12 (a), for the unsupported back condition. The effect on vertical STHT, however, is relatively small as observed in the single axis response but statistically significant near 2.5 Hz and in the 6-7.5 Hz range. Further, the magnitude effect on the fore-aft response is relatively smaller for the supported back condition, as seen in Fig 12 (b), due to partly constrained upper body movements. The higher vibration magnitude yields considerably lower peak magnitude of the fore-aft STHT, while the widely reported softening effect is not clearly evident. The relatively smaller effects of vibration magnitude are most likely attributed to small difference in the selected vibration magnitudes in the study (0.4 and 0.58 m/s^2).

5.0 Conclusions

The dual-axis responses derived using H_v estimator differ considerably from those derived using the commonly used H_1 frequency response function estimator. The differences were related to the contributions of the corresponding cross-axis responses, which were observed under single-axis vibration. Such contributions of the cross-axis responses were not evident in the dual-axis responses derived from the H_1 estimator, which was attributed to uncorrelated nature of the dual-axis excitation. It is thus suggested that H_v estimator be employed for characterization of biodynamic responses of the seated body to uncorrelated dual- or multi-axis vibration. Evidence of the contributions of the cross-axis responses in the fore-aft and vertical biodynamic responses derived using H_v estimator illustrated greater coupling in the responses to uncorrelated dual-axis vibration, compared to the H_1 estimator. The results also revealed that addition of the back and hands supports results in higher fore-aft APMS responses compared to unsupported hands and back postures, which can be attributed to the constrained upper body movements and imposed backrest vibration to the seated body. However, the supported postures resulted in restrained upper-body movements and thus revealed lower coupling, compared to those with back unsupported posture under dual-axis vibration.

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