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Biodynamic Responses of the Seated Human Body to Single-axis and Dual-axis Vibration

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Abstract: Occupational exposures to vibration always involve multi-axis vibration. Since human responses to vibration are highly nonlinear and cross-coupled, it is to be expected that excitation in one axis will alter response to vibration in another axis. The purpose of this study was to investigate nonlinearity in the apparent masses of subjects seated without a backrest and exposed to single-axis and dual-axis vertical and fore-and-aft excitation. The driving point apparent masses and cross-axis apparent masses in the two translational directions were measured with twelve subjects exposed to random vibration (0.2 to 20 Hz) in all 15 possible combinations of four vibration magnitudes (0, 0.25, 0.5, or 1.0 ms^{-2} r.m.s.) in the fore-and-aft and vertical directions. With single-axis excitation (either fore-and-aft or vertical), the median in-line apparent mass exhibited a nonlinear characteristic in which the body softened with increasing magnitude of vibration. With dual-axis excitation, at all magnitudes of vertical excitation the resonance frequency in the vertical apparent mass reduced as the magnitude of fore-and-aft vibration increased, and at all except the greatest magnitude of fore-and-aft excitation the resonance frequency in the fore-and-aft apparent mass reduced as the magnitude of vertical vibration increased. The coherency between the fore-and-aft acceleration and the fore-and-aft force was lowered by the addition of vertical excitation, and the coherency between the vertical acceleration and the vertical force was lowered by the addition of fore-and-aft excitation. The nonlinearity evident in both in-line apparent masses was also evident in the cross-axis apparent masses. It is concluded that with dual-axis excitation the fore-and-aft and vertical response of the seated human body is nonlinear, with resonance frequencies decreasing with increasing magnitude of vibration. Consequently, vibration in one axis (either fore-and-aft or vertical) affects the apparent mass of the body measured in the other axis (either vertical or fore-and-aft).

Key words: Apparent mass, Cross-axis apparent mass, Biodynamics, Dual-axis excitation

Introduction

Experimental studies of biodynamic responses of the seated human body to whole-body vibration have mostly investigated responses to single-axis excitation, especially vertical vibration. Many previous studies have found that the biodynamic responses of seated human body exposed to single-axis whole-body vibration exhibit a ‘softening’ phenomenon with increases in the magnitude of vibration[e.g., 1–7].

The resonance frequencies evident in the vertical apparent mass and transmissibilities to the heads, shoulders, and trunks of seated subjects were reported to be lower during exposure to vibration at 3.0 ms^{-2} r.m.s. than during exposure to 1.5 ms^{-2} r.m.s.[1]. Similarly, subjects exposed to four magnitudes of random vertical vibration were found to have apparent mass resonance frequencies that decreased progressively from about 6 Hz to 4 Hz as the magnitude increased from 0.25 to 2.0 ms^{-2} r.m.s.[2].

Reductions in the resonance frequency of the apparent mass (from 5.4 to 4.2 Hz) and corresponding reductions in resonance frequencies in the transmissibility to the lower abdomen have been reported with increases in the magnitude of random vibration from 0.25 to 2.5 ms^{-2} r.m.s.[3]. A similar nonlinear characteristic has been seen in the vertical apparent mass and transmissibilities to eight locations on the spine (the first, fifth and tenth thoracic vertebrae, the first, third and fifth lumbar vertebrae, and the pelvis)[4].

The nonlinear response to vertical excitation has been reported in many sitting postures. With nine postures, Mansfield and Griffin[5] found that the resonance frequencies in the vertical apparent mass and seat-to-pelvis pitch transmissibility decreased with increased vibration magnitude, with relatively small changes in apparent mass and transmissibility between postures. With four postures (feet hanging, and feet supported with minimum, average, and maximum thigh contact), Nawayseh and Griffin[6] found the characteristic nonlinear response in all postures, but to a lesser extent in the minimum thigh contact posture. Although changing the static posture has only small effects of the nonlinearity, it appears that some voluntary periodic movements of the body (back-abdomen bending) can reduce the nonlinearity[7].

Nonlinear biodynamic responses are not confined to vertical excitation but are also apparent during fore-and-aft and lateral

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excitation[e.g., 8–11].

A few studies have reported cross-axis responses of the seated body exposed to whole-body vibration. Kitazaki and Griffin[12] and Matsumoto and Griffin[13] reported appreciable movements of the body in the fore-and-aft direction during vertical excitation. Matsumoto and Griffin[14] measured the fore-and-aft cross-axis apparent mass (the complex ratio of the fore-and-aft force to the vertical acceleration) and found that it could be 40% of the static subject mass at some frequencies. The fore-and-aft and lateral cross-axis apparent mass has also been reported by Nawayseh and Griffin[6]. A similar cross-axis response has been found with fore-and-aft excitation: considerable vertical forces are caused by pure fore-and-aft oscillation of a seat[11].

Since human responses to vibration are cross-coupled and highly nonlinear in all axes, it is to be expected that excitation in one axis will alter the response of the body to vibration in another axis. Hinz *et al.*[15] investigated the apparent masses of subjects exposed to single-axis and tri-axial random vibration at three magnitudes and reported that the resonance frequencies in the apparent masses reduced with an increase in the number of vibration axes. In contrast, the apparent masses and cross-axis apparent masses of seated subjects exposed to single-axis vibration (fore-and-aft, lateral or vertical) and dual-axis vibration (fore-and-aft and lateral, fore-and-aft and vertical, and lateral and vertical) at one magnitude of vibration (0.4 ms^{-2} r.m.s.) were reported to be almost identical[16]. However, a similar study with tri-axial vibration at two magnitudes (0.4 and 0.8 ms^{-2} r.m.s.) found that the resonance frequency of the apparent mass reduced with increasing magnitude of vibration in directions orthogonal to that being measured[17].

This study was undertaken to investigate nonlinearity in the apparent masses of subjects seated without a backrest and exposed to single-axis and dual-axis fore-and-aft and vertical excitation. It was hypothesised that nonlinearity would be evident when using different magnitudes of single-axis excitation in either axis, and that nonlinearity would also be apparent when using a fixed magnitude of vibration in one axis and varying the magnitude of vibration in the other axis.

Method

Apparatus

A rigid seat was secured to the ISVR 6-axis motion simulator capable of ± 1 m vertical displacement, ± 0.5 m fore-and-aft and lateral displacement, ± 20 degrees of roll and pitch, and ± 10 degrees of yaw (Fig. 1). A force plate (Kistler 9281 B) consisting of four tri-axial quartz transducers at the four corners of a rectangular aluminium plate was secured to the supporting surface of the seat to measure forces in the vertical and fore-and-aft directions. Signals from the force platform were amplified using Kistler 5007 charge amplifiers. A tri-axial SIT-pad measured acceleration in fore-and-aft and vertical directions at the centre of the force platform.

Subjects and stimuli

Twelve male subjects, average age 28.1 yr (range 21 to 39 yr), weight 68.6 kg (range 49.5 to 90 kg), and stature 1.73 m (range 1.64 to1.80 m), participated in the study that was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton. Subjects sat in a normal relaxed upright posture with their hands on their laps and with average thigh contact (the supporting seat surface was 500 mm above the surface supporting the feet).

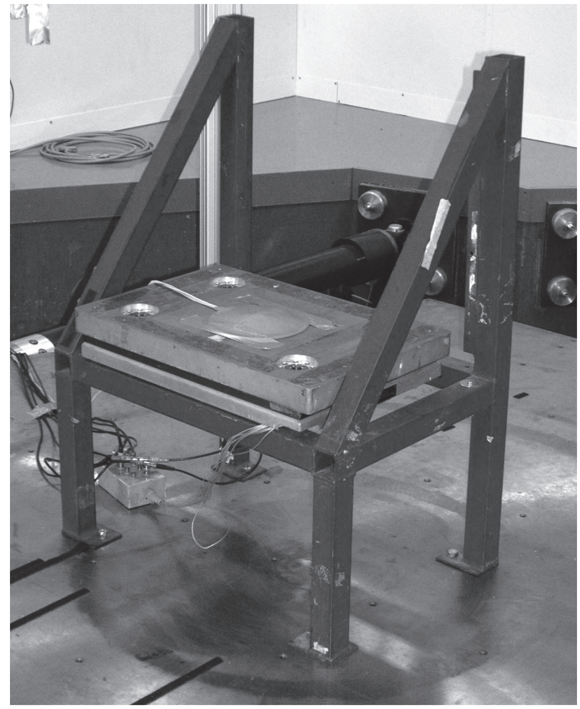

Fig. 1. Rigid seat fitted with force plate.

Subjects were exposed to random vibration with approximately flat constant-bandwidth acceleration spectra (0.2 to 20 Hz) in all 15 possible combinations of four magnitudes of fore-and-aft vibration (0, 0.25, 0.5, or 1.0 ms^{-2} r.m.s.) and four magnitudes of vertical vibration (0, 0.25, 0.5, or 1.0 ms^{-2} r.m.s.). All stimuli were of 120-s duration, with motions in the fore-and-aft and vertical directions uncorrelated with each other.

Data analysis

Forces and accelerations were acquired at 200 samples per second via anti-aliasing filters at 67 Hz. Prior to the calculation of the apparent mass, mass cancellation was performed in the time domain to remove the influence of the mass of the top plate from the measured force: in both axes, the acceleration time-history on the seat surface was multiplied by the mass of the force platform and then subtracted from the measured force. Signal processing was conducted with frequency resolution of 0.39 Hz.

With single-axis excitation, the in-line and cross-axis apparent masses were calculated using the single-input two-output model illustrated in Fig. 2. With a_x and a_z representing the fore-and-aft and vertical accelerations and f_x and f_z representing the fore-and-aft and vertical forces, the in-line apparent masses (M_{xx} and M_{zz}) and the cross-axis apparent masses (M_{xz} and M_{zx}) and associated coherencies, γ, were computed as:

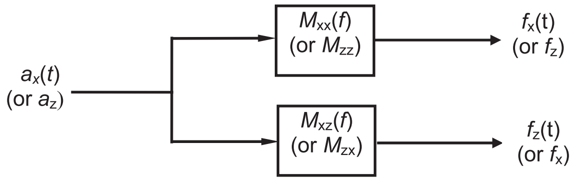

Fig. 2. Single-input and two-output model for computing in-line and cross-axis apparent masses with single-axis excitation.

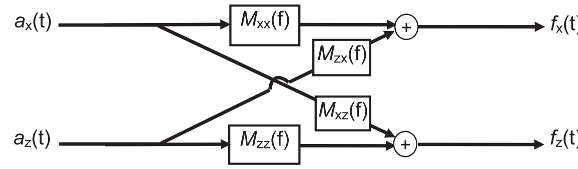

Fig. 3. Two-input and two-output model for computing in-line and cross-axis apparent masses with dual-axis excitation.

$$
\begin{aligned}
M_{xx} &= \frac{G_{a_x f_x}}{G_{a_x}}, & \gamma_{xx}^2 &= \frac{\left|G_{a_x f_x}\right|^2}{G_{a_x} G_{f_x}} \\
M_{zz} &= \frac{G_{a_z f_z}}{G_{a_z}}, & \gamma_{zz}^2 &= \frac{\left|G_{a_z f_z}\right|^2}{G_{a_z} G_{f_z}} \\
M_{xz} &= \frac{G_{a_x f_z}}{G_{a_x}}, & \gamma_{xz}^2 &= \frac{\left|G_{a_x f_z}\right|^2}{G_{a_x} G_{f_z}} \\
M_{zx} &= \frac{G_{a_z f_x}}{G_{a_z}}, & \gamma_{zx}^2 &= \frac{\left|G_{a_z f_x}\right|^2}{G_{a_z} G_{f_x}}
\end{aligned}
\tag{1}
$$

where:

G_{a_x} and G_{a_z} are the autospectra of a_x and a_z,
G_{f_x} and G_{f_z} are the autospectra of f_x and f_z,
$G_{a_x f_x}$ and $G_{a_z f_z}$ are the cross-spectra between a_x and f_x and between a_z and f_z, and
$G_{a_z f_x}$ and $G_{a_x f_z}$ are the cross-spectra between a_z and f_x and between a_x and f_z.

With dual-axis excitation, the in-line and cross-axis apparent masses were calculated using the two-input and two-output model illustrated in Fig. 3. Because the two input motions (a_x and a_z) were uncorrelated, the in-line and cross-axis apparent masses and associated coherencies can be computed using the same equations as in (1), with two additional equations to compute the multiple coherence functions showing how well the two acceleration inputs together linearly account for the two force outputs:

$$
\begin{aligned}
\gamma_{f_x}^2 &= \gamma_{xx}^2 + \gamma_{zx}^2 \\
\gamma_{f_z}^2 &= \gamma_{zz}^2 + \gamma_{xz}^2
\end{aligned}
\tag{2}
$$

Results

Fore-and-aft in-line apparent mass

Individual responses with single-axis and dual-axis excitation

Fore-and-aft in-line apparent masses of the 12 individual subjects and their median values are shown in Fig. 4 with single-axis fore-and-aft excitation at three magnitudes (in the top row) and with the addition of three magnitudes of vertical vibration (in the lower three rows). The median apparent mass over the 12 subjects is also shown.

The individual fore-and-aft apparent masses generally exhibit a primary peak between 2 Hz and 6 Hz, but with a tendency for the peak to reduce in frequency with increased fore-and-aft excitation or increased vertical excitation.

Median fore-and-aft apparent mass during single-axis excitation

With increasing magnitude of fore-and-aft excitation, there were significant reductions in the frequency of the principal resonance. There was also a consistent trend for the apparent mass at the resonance to reduce as the magnitude of vibration increased, although this did not reach statistical significance (first column in Fig. 5, Table 1). Clear evidence of nonlinearity was also apparent in significant reductions in the apparent mass at 1.2, 3.9, and 7.8 Hz as the magnitude of fore-and-aft vibration increased in the absence of vertical excitation (Table 2).

Median fore-and-aft apparent mass during dual-axis excitation

With dual-axis excitation, there is evidence of nonlinearity in the moduli, phases and coherency of the in-line fore-and-aft apparent mass as the magnitude of the fore-and-aft excitation or the magnitude of the vertical excitation changed (columns 2 to 4 in Fig. 5). As the magnitude of the vertical vibration increased, the nonlinearity evident with variation in the fore-and-aft excitation (e.g. reduced resonance frequency with increasing magnitude of fore-and-aft excitation) tended to reduce, but with statistically significant reductions in the resonance frequency with increasing magnitude of fore-and-aft excitation at all magnitudes of vertical excitation, except with the greatest magnitude of vertical excitation (a_z=1.0 ms^{-2} r.m.s.; Table 1). The apparent mass at resonance tended to decrease with increasing magnitude of fore-and-aft excitation at all magnitudes of vertical excitation, except when a_z=1.0 ms^{-2} r.m.s. where only a marginally significant reduction in the apparent mass at resonance was observed. Clear evidence of nonlinearity was also apparent in significant reductions in the apparent mass at 1.2, 3.9, and 7.8 Hz as the magnitude of the fore-and-aft excitation increased, except when a_z=1.0 ms^{-2} r.m.s. for 1.2 and 3.9 Hz (Table 2).

The coherency between the fore-and-aft acceleration and the fore-and-aft force was lowered by the addition of vertical excitation but raised by increasing the magnitude of the fore-and-aft excitation (Fig. 5).

Comparison of fore-and-aft apparent mass during single-axis and dual-axis excitation

The median fore-and-aft apparent mass of the 12 subjects during single-axis (fore-and-aft) excitation is compared with the median fore-and-aft apparent mass during dual-axis (fore-and-aft and vertical) excitation in Fig. 6. It may be seen that with the lowest magnitude of fore-and-aft excitation (a_x=0.25 ms^{-2} r.m.s.; column 1 in Fig. 6), the addition of vertical excitation resulted in a consistent change in the fore-

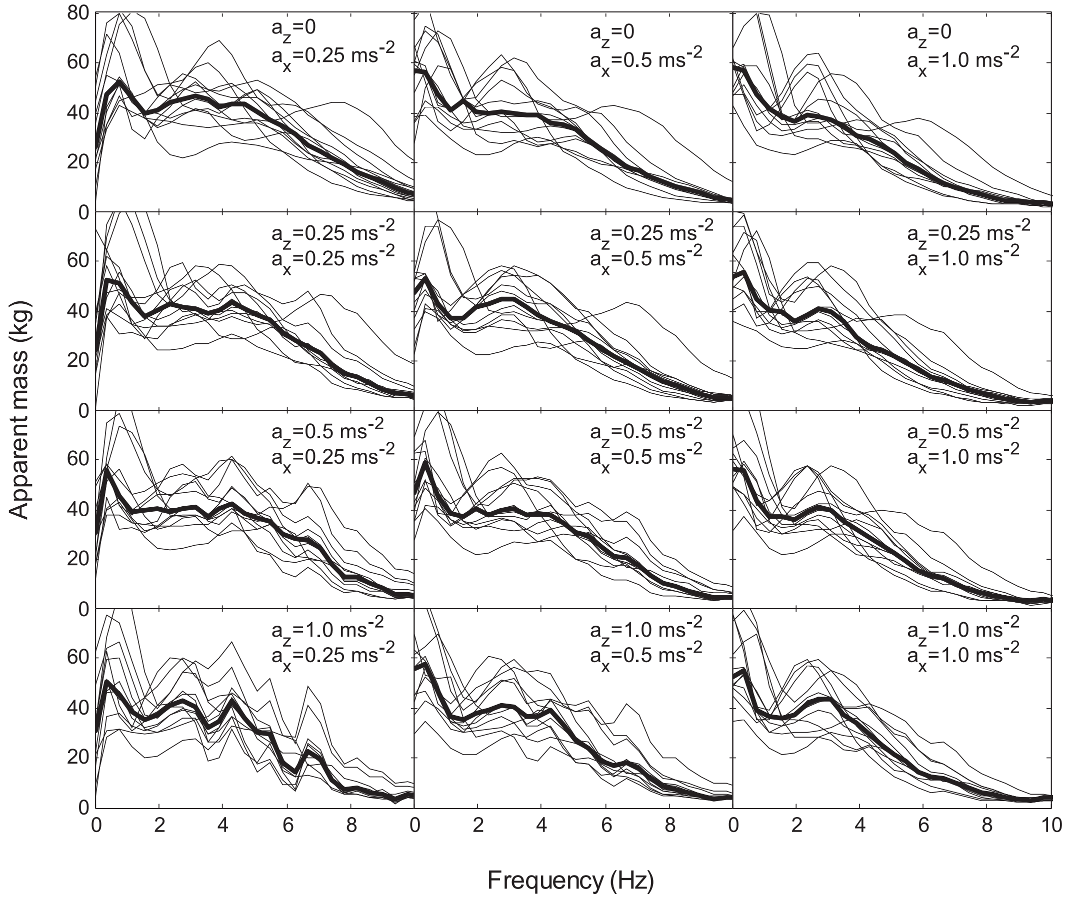

Fig. 4. In-line fore-and-aft apparent mass of 12 subjects and their median values with single-axis and dual-axis excitation.

and-aft apparent mass, similar to the softening characteristic seen in Fig. 5 when the magnitude of single-axis fore-and-aft excitation was increased. The effect is less apparent with the intermediate magnitude of fore-and-aft excitation (a_x=0.5 ms^{-2} r.m.s.; column 2 in Fig. 6) and almost non-existent at the greatest magnitude of fore-and-aft excitation (a_x=1.0 ms^{-2} r.m.s.; column 3 in Fig. 6). With the lowest magnitude of fore-and-aft excitation (a_x=0.25 ms^{-2} r.m.s. in column 1 of Fig. 6), the four apparent masses were significantly different at the tested frequencies of 1.2 and 7.8 Hz (p=0.007 and p<0.001, Friedman) but not at 2.0 and 3.9 Hz (p=0.063 and 0.117). With the intermediate magnitude of fore-and-aft excitation (a_x=0.5 ms^{-2} r.m.s. in column 2 of Fig. 6), the difference caused by the addition of vertical vibration was significant at 1.2, 2.0 and 7.8 Hz (p=0.04, 0.005 and 0.001, respectively), but not at 3.9 Hz (p=0.753). With the highest magnitude of fore-and-aft excitation (a_x=1.0 ms^{-2} r.m.s. in column 3 of Fig. 6), the differences were not significant at 1.2, 2.0 or 3.9 Hz, but were significant at 7.8 Hz (p=0.001).

Vertical in-line apparent mass

Individual responses with single-axis- and dual-axis excitation

The vertical in-line apparent masses of the 12 individual subjects are shown in Fig. 7 with single-axis vertical excitation at three magnitudes (in the far left column) and with the addition of three magnitudes of fore-and-aft vibration (in columns 2 to 4). The median apparent mass over the 12 subjects is also shown.

Over all combinations of single-axis and dual-axis excitation, the vertical in-line apparent mass has a primary peak in the range 4 to 8 Hz with most subjects exhibiting evidence of a second peak between 9 and 15 Hz.

Median vertical apparent mass during single-axis excitation

The moduli of the median vertical apparent masses show two distinct peaks: one in the range 4 to 8 Hz and another in the range 10 to 16 Hz (first column in Fig. 8, Table 3). With increasing magnitude of vertical excitation, there were significant reductions in the principal resonance frequency (p<0.001, Friedman) but no significant change in the apparent mass at resonance (p=0.368).

Median vertical apparent mass during dual-axis excitation

With dual-axis excitation, as the magnitude of fore-and-aft excitation increased, the nonlinearity in the vertical apparent mass associated with changes in the magnitude of vertical excitation became less apparent (columns 2 to 4 in Fig. 8 and Table 3).

The reduction of the resonance frequency with increasing magnitude of vertical vibration was statistically significant except with the greatest magnitude of fore-and-aft excitation (i.e. a_x=1.0 ms^{-2} r.m.s.). The apparent mass at resonance tended

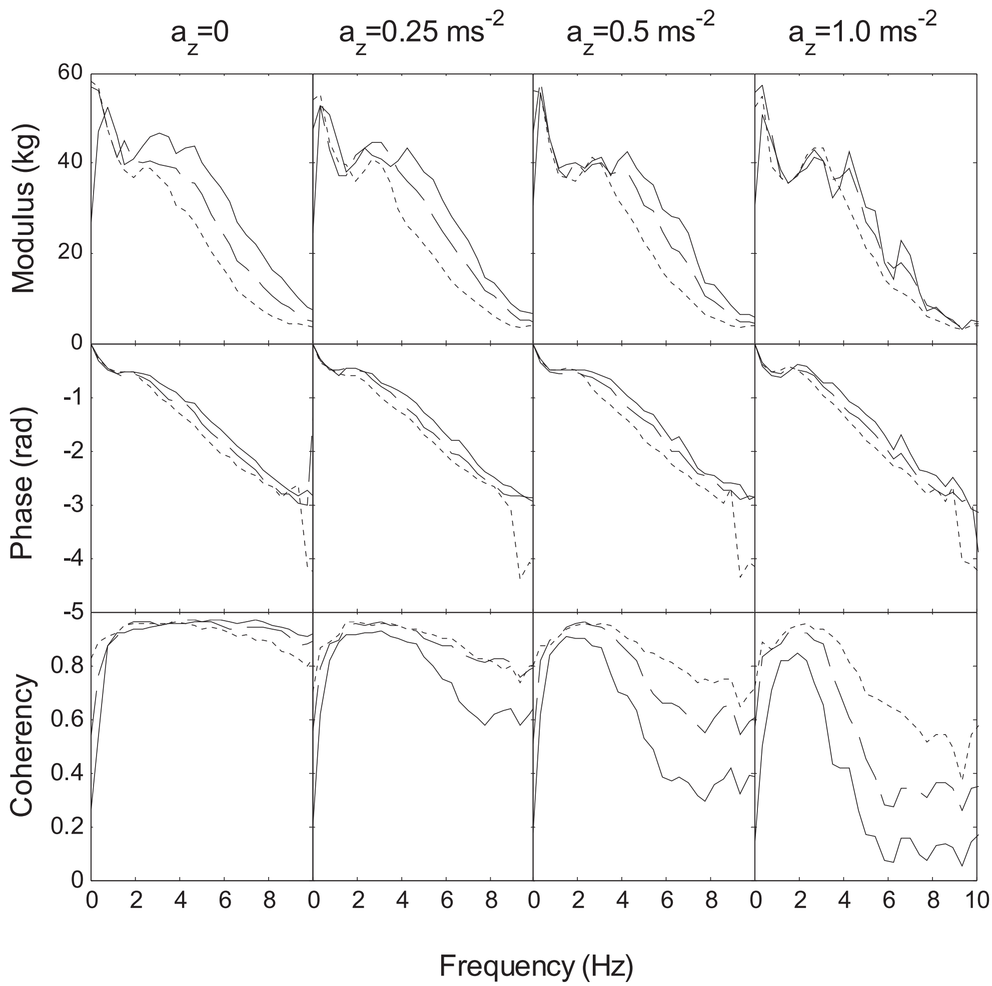

Fig. 5. Median in-line apparent mass of 12 subjects in the fore-and-aft direction with dual-axis excitation. —— a_x=0.25 ms^{-2} r.m.s.; — — — a_x=0.5 ms^{-2} r.m.s.; - - - - a_x=1.0 ms^{-2} r.m.s.

Table 1. Variation in the principal resonance frequency and the apparent mass at resonance during fore-and-aft excitation (p-values from Friedman test)

		Single-axis excitation: fore-and-aft	Dual-axis excitation: fore-and-aft and vertical		
			a_z=0.25 ms^{-2}	a_z= 0.5 ms^{-2}	a_z=1.0 ms^{-2}
Median resonance frequency	a_x= 0.25 ms^{-2}	4.1 Hz	3.5 Hz	4.3 Hz	2.9 Hz
	a_x= 0.5 ms^{-2}	2.9 Hz	2.9 Hz	3.1 Hz	3.1 Hz
	a_x= 1.0 ms^{-2}	2.7 Hz	2.7 Hz	2.7 Hz	2.7 Hz
	Friedman	p=0.000	p=0.001	p=0.000	p=0.115
Median apparent mass at resonance	a_x= 0.25 ms^{-2}	50.4 kg	45.8 kg	49.3 kg	46.3 kg
	a_x= 0.5 ms^{-2}	41.6 kg	45.6 kg	41.5 kg	43.1 kg
	a_x= 1.0 ms^{-2}	38.7 kg	40.7 kg	41.1 kg	43.9 kg
	Friedman	p=0.097	p=0.035	p=0.009	p=0.05

to increase with increasing magnitude of vertical excitation, with the increase statistically significant other than in the presence of the greatest magnitude of fore-and-aft excitation (Table 3).

The coherency between the vertical acceleration and the vertical force was lowered by the addition of fore-and-aft excitation but raised by increasing the magnitude of the vertical excitation (Fig. 8).

Table 2. Effect of the magnitude of fore-and-aft excitation on fore-and-aft apparent mass at four frequencies with and without vertical excitation (*p*-values from Friedman test)

		Magnitude at fixed frequencies			
		1.2 Hz	2.0 Hz	3.9 Hz	7.8 Hz
Single axis excitation: fore-and-aft		0.017	0.368	0.009	0.000
Dual-axis excitation: fore-and-aft and vertical	a_z= 0.25 ms^{-2}	0.028	0.368	0.000	0.000
	a_z= 0. 5 ms^{-2}	0.050	0.779	0.001	0.000
	a_z=1.0 ms^{-2}	0.779	0.125	0.205	0.002

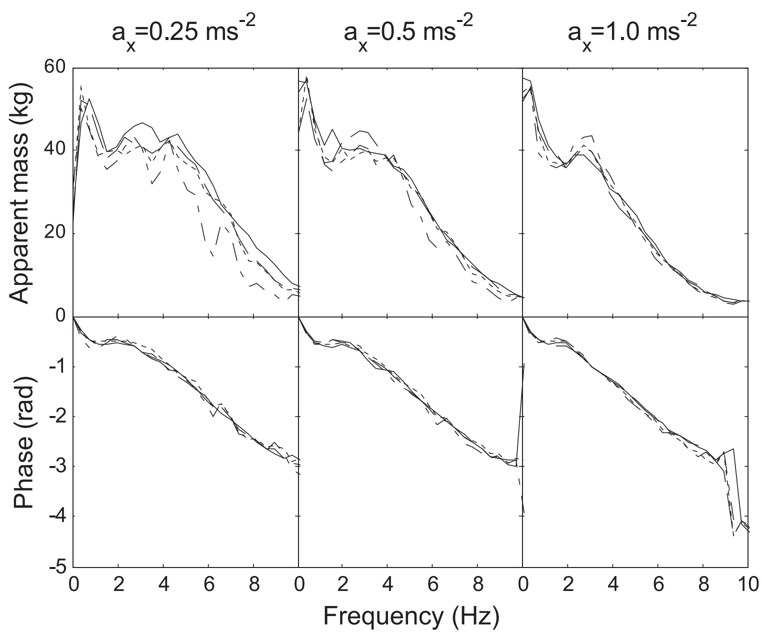

Fig. 6. Comparison of the median fore-and-aft apparent masses of 12 subjects under single-axis (fore-and-aft) excitation and dual-axis (fore-and-aft and vertical) excitation. —— a_z=0; — — — a_z=0.25 ms^{-2} r.m.s.; - - - - a_z=0.5 ms^{-2} r.m.s.; — - — - a_z=1.0 ms^{-2} r.m.s.

Comparison of vertical apparent mass during single-axis and dual-axis excitation

The median vertical apparent mass of the 12 subjects during single-axis vertical excitation is compared with the median vertical apparent mass during dual-axis (fore-and-aft and vertical) excitation in Fig. 9. With the lowest magnitude of vertical excitation (a_z=0.25 ms^{-2} r.m.s.; column 1 in Fig. 9), the addition of fore-and-aft excitation caused a consistent trend in the vertical apparent mass, similar to the softening characteristic seen in Fig. 8 when the magnitude of single-axis vertical excitation was increased. The effect is less but still apparent with the intermediate magnitude of vertical excitation (a_z=0.5 ms^{-2} r.m.s.; column 2 in Fig. 9) but barely apparent with the greatest magnitude of vertical excitation (a_z=1.0 ms^{-2} r.m.s.; column 3 in Fig. 9). For the two lowest magnitudes of vertical excitation (a_z=0.25 and 0.5 ms^{-2} r.m.s. in columns 1 and 2 of Fig. 9), the difference among the four apparent masses was significant at the tested frequencies of 3.9 and 7.8 Hz (p<0.001, Friedman) but not significant at 1.2 and 2.0 Hz. For the highest magnitude of vertical excitation (a_z=1.0 ms^{-2} r.m.s. in column 3 of Fig. 9) the difference was only significant at 3.9 Hz (p=0.004).

Fore-and-aft cross-axis apparent mass: fore-and-aft force due to vertical excitation

Fore-and-aft cross-axis apparent mass with single-axis vertical excitation

The fore-and-aft cross-axis apparent mass, computed from the complex ratio of the fore-and-aft force to the vertical acceleration excitation, showed a primary peak between 4 and 8 Hz (first column in Fig. 10). The median frequencies and the cross-axis apparent masses at this primary resonance were 6.3, 6.3 and 5.5 Hz and 17.5, 19.2 and 17.9 kg, respectively for three magnitudes (0.25, 0.5 and 1.0 ms^{-2} r.m.s.) of vertical excitation. With increasing magnitude of vertical excitation in the absence of fore-and-aft excitation, the frequency of the primary peak reduced significantly (p<0.001) and there were significant changes in the cross-axis apparent mass at the peak

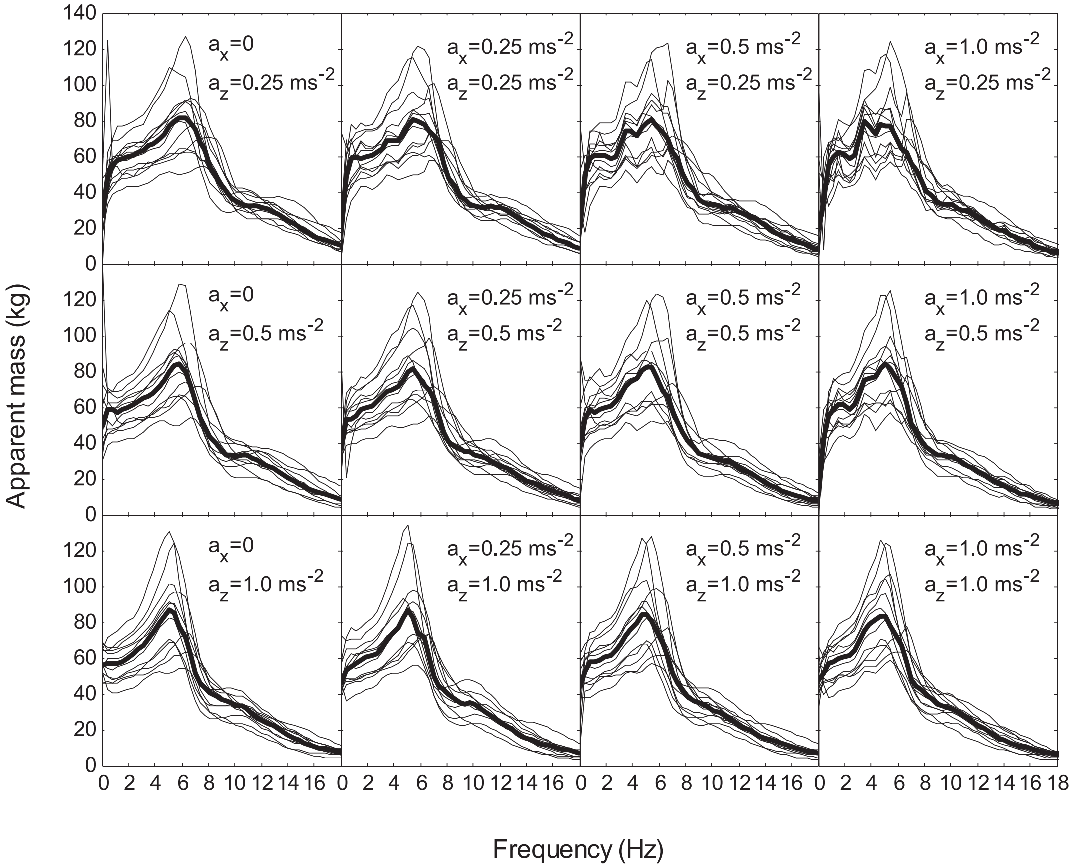

Fig. 7. In-line vertical apparent mass of 12 subjects and their median values with single-axis and dual-axis excitation.

(p=0.006).

Fore-and-aft cross-axis apparent mass with dual-axis vertical and fore-and-aft excitation

With dual-axis excitation, the median fore-and-aft cross-axis apparent mass exhibited a primary peak around 5 to 8 Hz when the magnitude of fore-and-aft vibration was low, but the peaks are less clear with higher magnitudes of fore-and-aft excitation.

The addition of fore-and-aft excitation reduced the coherency between the vertical acceleration and the fore-and-aft force (Fig. 10). With a constant magnitude of fore-and-aft excitation, the coherency between the vertical acceleration and the fore-and-aft force increased with increasing magnitude of the vertical excitation.

Vertical cross-axis apparent mass: vertical force due to fore-and-aft excitation

Vertical cross-axis apparent mass with single-axis fore-and-aft excitation

The vertical cross-axis apparent mass computed from the complex ratio of the vertical force to the fore-and-aft acceleration, showed two distinct peaks: one at around 1 Hz (visible for eleven subjects) and the other in the range 3 to 8 Hz (visible for all twelve subjects) (first column in Fig. 11). The median frequencies and the cross-axis apparent masses at the second peak obtained from 12 subjects were 5.9, 5.7 and 3.9 Hz and 22.9, 19.9 and 17.4 kg respectively for three magnitudes (0.25, 0.5, and 1.0 ms^{-2} r.m.s.) of fore-and-aft excitation. With increasing magnitude of fore-and-aft excitation, there were significant reductions in the frequency of the second peak (p=0.004) and the associated cross-axis apparent mass (p=0.009)

Vertical cross-axis apparent mass with dual-axis fore-and-aft and vertical excitation

With dual-axis excitation, the peaks in the vertical cross-axis apparent mass appeared less clear than with single-axis fore-and-aft excitation. The additional vertical excitation reduced the coherency between the fore-and-aft acceleration and the vertical force (Fig. 11). With a constant magnitude of vertical excitation, the coherency between the fore-and-aft acceleration and the vertical force increased with increasing magnitude of fore-and-aft excitation.

Discussion

Fore-and-aft in-line apparent mass

Single-axis excitation

With solely fore-and-aft excitation, the fore-and-aft apparent mass showed a first peak around 1 Hz and a principal peak between 2 and 6 Hz, with a small number of subjects showing an extra peak between 1 and 6 Hz, similar to previous studies. Fairley and Griffin[8] reported one mode at about 0.7 Hz and another in the region of 1.5 to 3 Hz. Investigating

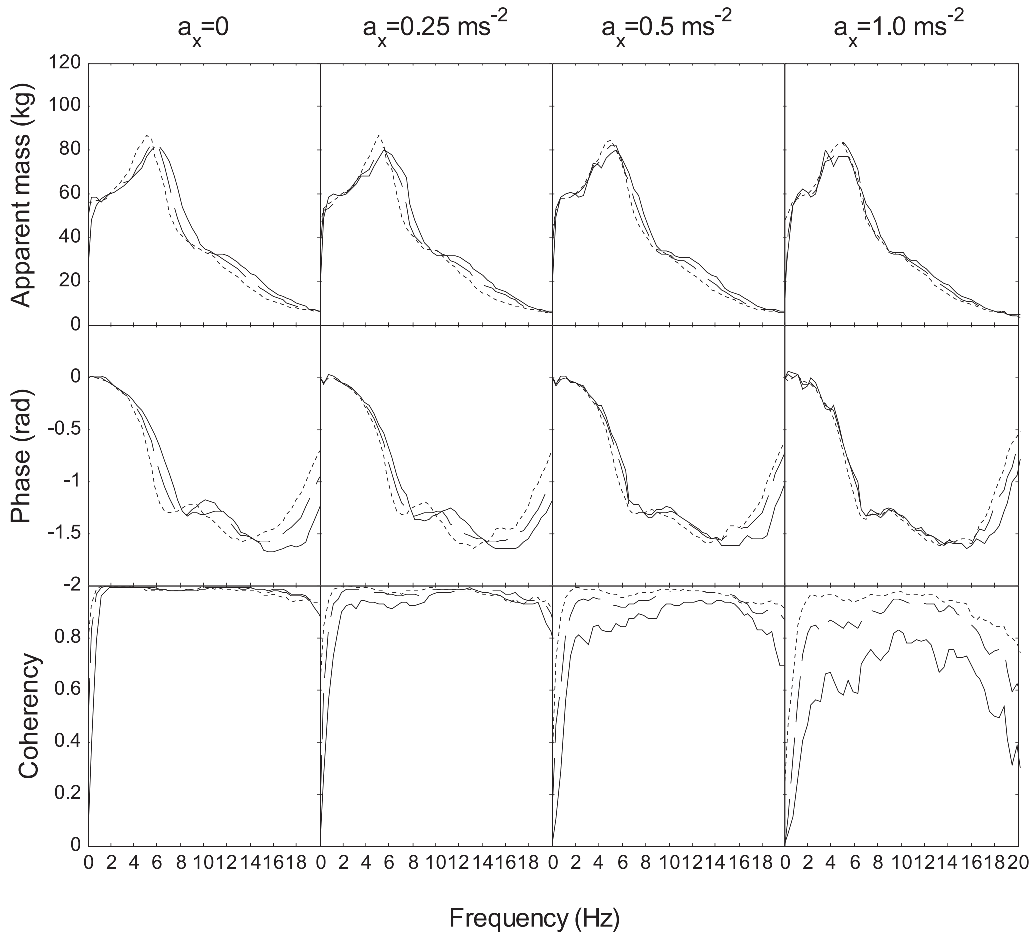

Fig. 8. Median in-line apparent mass of 12 subjects in the vertical direction with single-axis and dual-axis excitation. —— a_z=0.25 ms^{-2} r.m.s.; — — — a_z=0.5 ms^{-2} r.m.s.; - - - - a_z=1.0 ms^{-2} r.m.s.

Table 3. Variation in the principal resonance frequency and the apparent mass at resonance during vertical excitation (*p*-values from Friedman test)

			Single-axis excitation: vertical	Dual-axis excitation: fore-and-aft and vertical		
				a_x=0.25 ms^{-2}	a_x= 0.5 ms^{-2}	a_x=1.0 ms^{-2}
Principal resonance	Median frequency	a_z= 0.25 ms^{-2}	6.3 Hz	5. 7 Hz	5. 7 Hz	5.3 Hz
		a_z=0.5 ms^{-2}	5.9 Hz	5. 7 Hz	5.5 Hz	5.5 Hz
		a_z=1.0 ms^{-2}	5.3 Hz	5.3 Hz	5.1 Hz	5.1 Hz
		Friedman	p=0.001	p=0.000	p=0.001	p=0.558
	Median magnitude	a_z=0.25 ms^{-2}	82.2 kg	80.2 kg	81.2 kg	82.3 kg
		a_z=0.5 ms^{-2}	83.8 kg	82.2 kg	83.4 kg	85.7 kg
		a_z=1.0 ms^{-2}	86.7 kg	86.9 kg	85.6 kg	84.7 kg
		Friedman	p=0.368	p=0.039	p=0.028	p=0.338

frequencies greater than 1 Hz, Holmlund and Lundström[9] observed a single mode between 2 and 5 Hz while Mansfield and Lundström[10] reported modes around 3 Hz and 5 Hz. Nawayseh and Griffin[11] found three modes at frequencies less than 5 Hz (around 1 Hz, between 1 and 3 Hz, and between 3 and 5 Hz). Hinz *et al.*[15] reported a first peak around 1 Hz and a second, the maximum peak, around 3 Hz, but they also found additional peaks for some subjects, mainly with the lowest magnitude of vibration. In the present study, as the magnitude of fore-and-aft vibration increased from 0.25

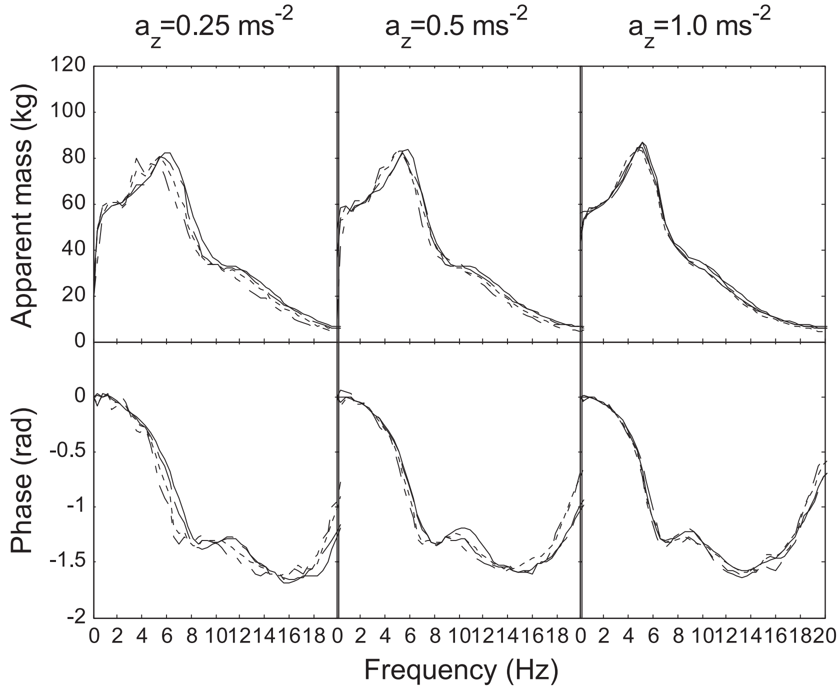

Fig. 9. Comparison of the median vertical apparent masses of 12 subjects under single-axis (vertical) excitation and dual-axis (vertical and fore-and-aft) excitation. —— a_x=0; — — — a_x=0.25 ms^{-2} r.m.s.; - - - - a_x=0.5 ms^{-2} r.m.s.; — - — - a_x=1.0 ms^{-2} r.m.s.

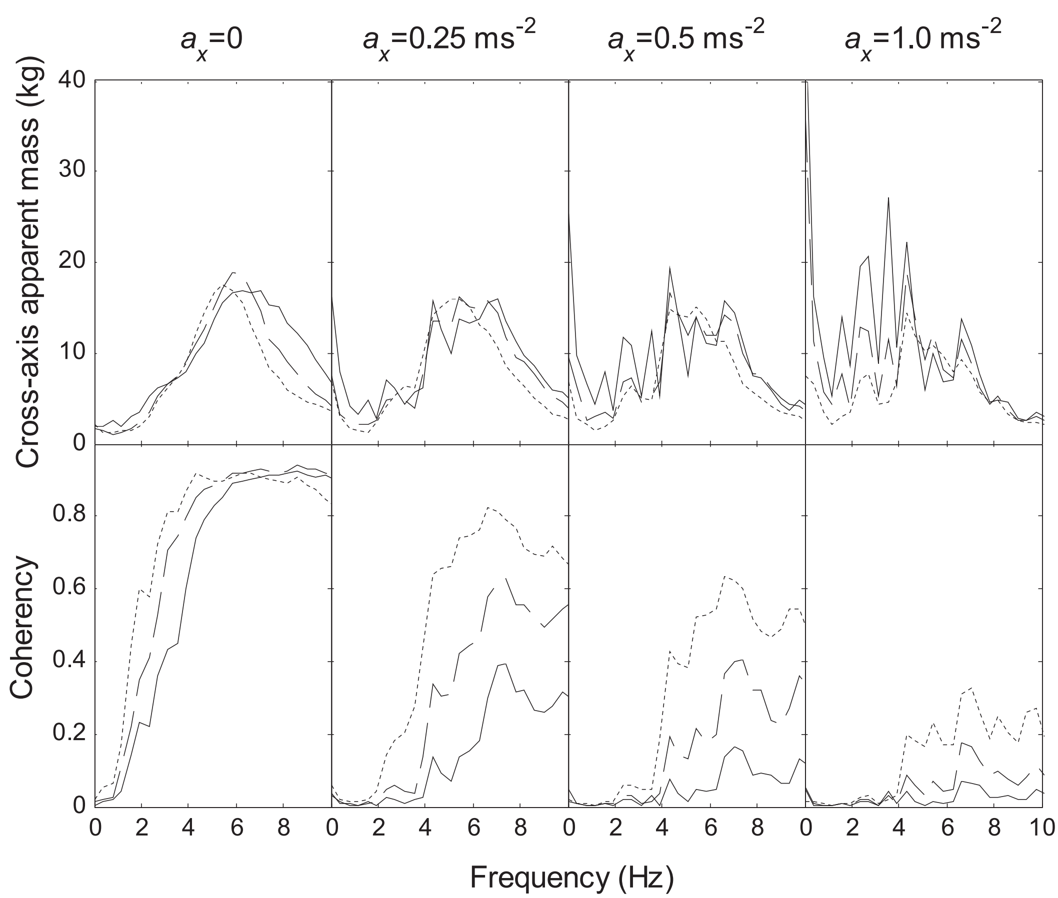

Fig. 10. Median fore-and-aft cross-axis apparent mass of 12 subjects (fore-and-aft force during vertical vibration) with single-axis and dual-axis excitation. —— a_z=0.25 ms^{-2} r.m.s.; — — — a_z=0.5 ms^{-2} r.m.s.; - - - - a_z=1.0 ms^{-2} r.m.s.

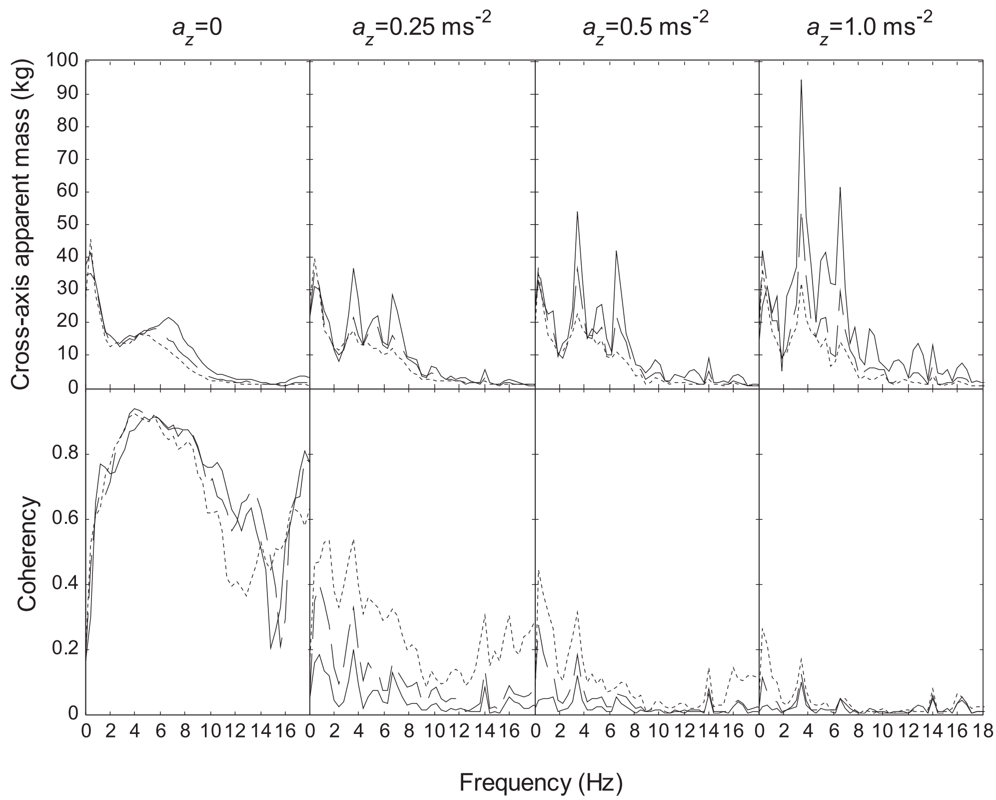

Fig. 11. Median vertical cross-axis apparent mass of 12 subjects (vertical force during fore-and-aft vibration) with single-axis and dual-axis excitation. —— a_x=0.25 ms^{-2} r.m.s.; — — — a_x=0.5 ms^{-2} r.m.s.; - - - - a_x=1.0 ms^{-2} r.m.s.

to 1.0 ms^{-2} r.m.s., the median frequency of the principal resonance reduced from 4.1 Hz to 2.7 Hz, consistent with the nonlinear response seen in previous studies.

Dual-axis excitation

There is no directly comparable study of the effect of vibration magnitude on apparent mass with dual-axis (fore-and-aft and vertical) excitation, but Hinz *et al*.[15] measured the apparent mass of seated men exposed to dual-axis fore-and-aft and lateral excitation and three-axis (fore-and-aft, lateral and vertical) excitation at various magnitudes. They found that the peak frequencies of the apparent mass reduced with increasing magnitude of single-axis, dual-axis, and three-axis excitation. Similar findings were obtained with dual-axis excitation in the present study: nonlinearity was evident in the in-line fore-and-aft apparent mass with changes in the magnitude of either the fore-and-aft excitation or the vertical excitation, although as the magnitude of the vertical excitation increased the nonlinearity evident with variations in the fore-and-aft excitation reduced. The findings are consistent with fore-and-aft and vertical excitation influencing the same mode of vibration.

Vertical in-line apparent mass

Single-axis excitation

The vertical in-line apparent mass of all subjects had a primary peak in the range 4 to 8 Hz and the majority of subjects showed a second peak between 8 and 13 Hz, consistent with previous findings[e.g., 6, 15]. To understand the mechanism in which the resonance of the body occurs, Mansfield and Griffin[3] measured both apparent mass and transmissibility during vertical excitation and found that vertical motion of the lumbar spine and pelvis showed resonances at about 4 Hz and between 8 and 10 Hz. Matsumoto and Griffin[13] investigated movement of the upper-body of seated subjects exposed to vertical whole-body vibration at the principal resonance frequency and concluded that more than one vibration mode may contribute to the principal resonance in the apparent mass observed at about 5 Hz. A bending mode of the spine, a rocking mode of the thoracic spine, a mode involving axial and shear deformation of the tissue beneath the pelvis, and a pitch mode of pelvis may be coupled with each other due to the heavy damping of the human body.

As the magnitude of the vertical excitation increased from 0.25 to 1.0 ms^{-2} r.m.s., the principal resonance frequency reduced from 6.3 Hz to 5.3 Hz, showing a nonlinearity consistent with previous studies[e.g. 1–3, 6, 13].

Correlations were determined to investigate whether resonance frequencies in the vertical in-line apparent mass were associated with resonance frequencies in the fore-and-aft in-line apparent mass. As expected, for none of the nine combinations of fore-and-aft and vertical vibration magnitude was there a significant correlation (p>0.315; Spearman).

Dual-axis excitation

Hinz *et al*.[15] reported a shift in the peak frequencies of the vertical apparent mass caused by the addition of combined fore-and-aft and lateral excitation, similar results to the current study where the addition of fore-and-aft excitation reduced the principal resonance frequency of the vertical in-line apparent mass (Table 3). Similar to the effect of vertical excitation on the fore-and-aft in-line apparent mass, as the magnitude of fore-and-aft excitation increased the nonlinearity in the vertical apparent mass associated with changes in the magnitude of vertical excitation became less apparent.

Fore-and-aft cross-axis apparent mass

Single-axis vertical excitation resulted in both vertical and fore-and-aft forces on the seat. Similar to Nawayseh and Griffin[6], a primary resonance between 4 and 8 Hz was found in the median fore-and-aft cross-axis apparent mass during vertical excitation. The frequency of the peak in the fore-and-aft cross-axis apparent mass appeared similar to the resonance frequency evident in the in-line vertical apparent mass and decreased with increasing magnitude of vertical excitation, similar to the nonlinearity in the vertical in-line apparent mass and consistent with findings of Nawayseh and Griffin[6]. In the present data there were significant correlation between the resonance frequencies of the fore-and-aft cross-axis apparent mass and the resonance frequencies of the vertical in-line apparent mass with all three magnitudes of vertical excitation (Fig. 12, left column).

Vertical cross-axis apparent mass

Nawayseh and Griffin[11] measured the vertical cross-axis apparent mass during single-axis fore-and-aft excitation with an average thigh contact posture similar to that employed in the present study and found that most of twelve subjects showed modes with frequencies around 1 and around 3 Hz, with a few showing a mode at a higher frequency. In the present study, two modes were observed: around 1 Hz and between 3 and 8 Hz. Similar to the findings of Nawayseh and Griffin, the magnitude of the vertical cross-axis apparent

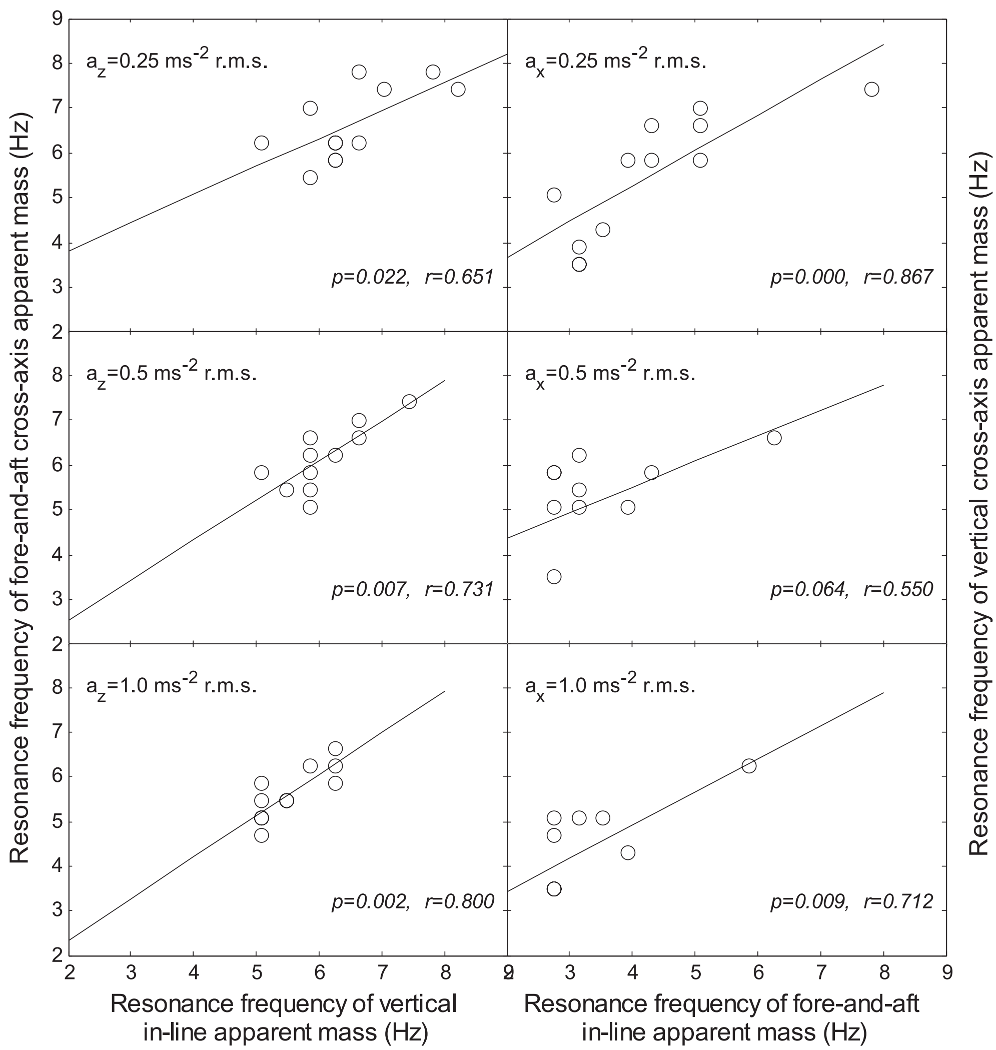

Fig. 12. Correlation of resonance frequencies between the vertical apparent mass and the fore-and-aft cross-axis apparent mass (left column) and between the fore-and-aft apparent mass and the vertical cross-axis apparent mass (right column) with single-axis excitation. Correlation coefficients *r* and *p*-values were obtained using Spearman rank correlation.

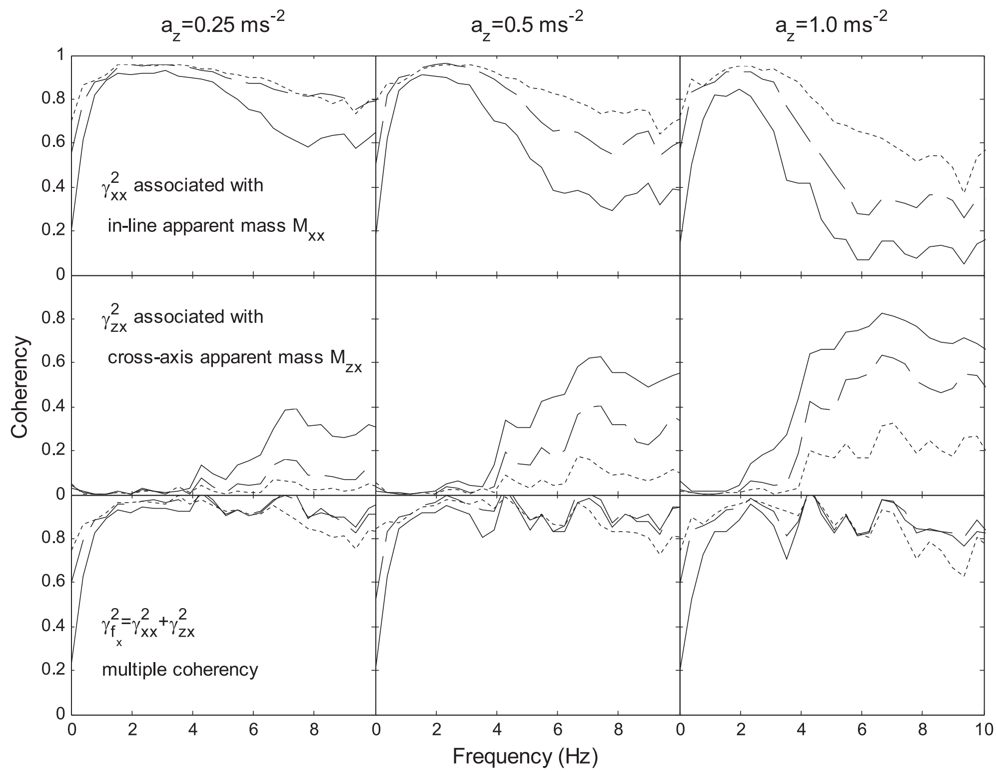

Fig. 13. Coherencies associated with the median fore-and-aft in-line apparent mass and the median fore-and-aft cross-axis apparent mass and multiple coherency. —— a_x=0.25 ms^{-2} r.m.s.; — — — a_x=0.5 ms^{-2} r.m.s.; - - - - a_x=1.0 ms^{-2} r.m.s.

mass tended to decrease with increasing magnitude of fore-and-aft excitation. With increasing magnitude of fore-and-aft excitation, the resonance frequency between 3 and 8 Hz reduced and the cross-axis apparent mass at the resonance reduced. There were significant correlations between the resonance frequencies of the vertical cross-axis apparent mass and the resonance frequencies of the fore-and-aft in-line apparent mass, except one magnitude of fore-and-aft excitation where the correlation was marginally nonsignificant (Fig. 12, right column).

Coherence and multiple coherence

With dual-axis excitation, the body can be treated as a two-input system (fore-and-aft and vertical acceleration) with one-output (either fore-and-aft or vertical force on the seat) as shown in Fig. 3. Since the two inputs were uncorrelated, if the system was linear, the sum of the coherency between, for example, the fore-and-aft acceleration and the fore-and-aft force and the coherency between the vertical acceleration and the fore-and-aft force would be unity (i.e. $\gamma^2_{f_x}=\gamma^2_{xx}+\gamma^2_{zx}$), as shown in Equation (2). Any discrepancy between the multiple coherency and unity is caused by unmeasured noise or the two inputs not being completely uncorrelated.

The coherency between fore-and-aft acceleration and fore-and-aft force was lowered by the addition of vertical excitation but raised by increasing the fore-and-aft excitation (Fig. 5). This is because the fore-and-aft force was not wholly caused by the fore-and-aft acceleration excitation but also linearly related to the vertical acceleration excitation. The multiple coherency (sum of the two coherencies) was close to unity (Fig. 13).

The coherency between vertical acceleration and vertical force was lowered by the addition of fore-and-aft excitation but raised by increasing the magnitude of the vertical excitation (Fig. 7), because the vertical force was not wholly caused by the vertical acceleration excitation, but also linearly related to the fore-and-aft acceleration excitation. Again, the multiple coherency (sum of the two coherencies) was close to unity (Fig. 14).

Conclusions

With single-axis vibration excitation (either fore-and-aft or vertical), the apparent mass of a seated human body exhibits a nonlinear characteristic in which the body softens with increasing magnitude of vibration.

With dual-axis excitation (combined fore-and-aft and vertical vibration), the vibration in one axis affects the apparent mass of the body measured in the other axis. The resonance frequency in the vertical apparent mass is reduced as the magnitude of fore-and-aft excitation increases, and the resonance frequency in the fore-and-aft apparent mass is reduced as the magnitude of vertical vibration increases.

Biodynamic responses to dual-axis excitation differ from those to single-axis excitation. The modelling of nonlinear human responses to multi-axis occupational vibration environments requires biodynamic data applicable to the multi-axis excitation.

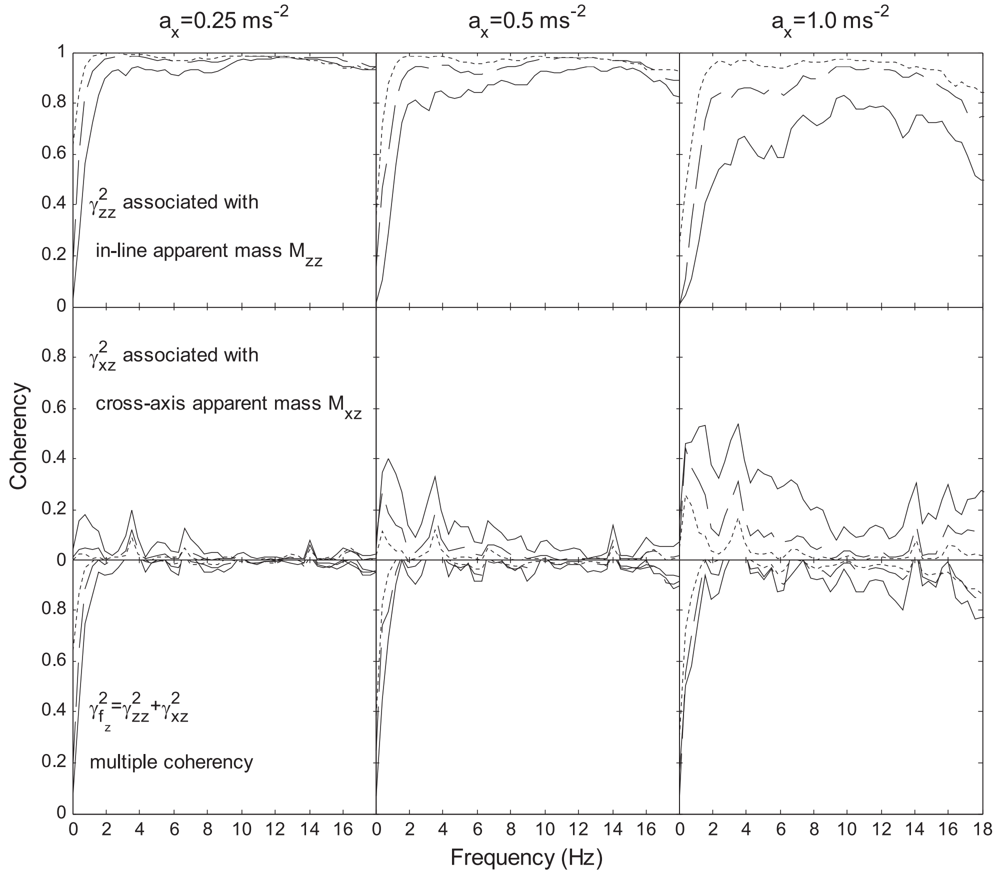

Fig. 14. Coherencies associated with the median vertical in-line apparent mass and the median vertical cross-axis apparent mass and multiple coherency. —— a_z=0.25 ms^{-2} r.m.s.; — — — a_z=0.5 ms^{-2} r.m.s.; - - - - a_z=1.0 ms^{-2} r.m.s.

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