Biodynamic Response of the Seated Human Body to Single-axis and Dual-axis Vibration: Effect of Backrest and Non-linearity

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Abstract: The biodynamic responses to the human body give an understanding of why human responses to vibration (changes in health, comfort, and performance) vary with the frequency and direction of vibration. Studies have shown that biodynamic responses also vary with the magnitude of vibration and that the backrests of seats influence the transmission of vibration to the seated human body. There has been little study of the nonlinearity in the biodynamic responses of the body to dual-axis excitation and no study of the influence of backrests during dual-axis excitation. This study investigated the apparent mass and cross-axis apparent mass of the human body exposed to random vibration (0.2 to 20 Hz) in all 15 possible combinations of four magnitudes (0, 0.25, 0.5 and 1.0 ms^{-2} r.m.s.) of fore-and-aft vibration and the same four magnitudes of vertical vibration. Nonlinearity was evident, with the body softening with increasing magnitude of vibration when using a fixed magnitude of vibration in one direction and varying the magnitude of vibration in the other direction. The fore-and-aft apparent mass on the seat was greater without a backrest at the lower frequencies but greater with a backrest at the higher frequencies. The vertical apparent mass on the seat was decreased by the backrest at low frequencies. Cross-axis coupling was evident, with excitation in one axis producing a response in the other axis. It is concluded that the nonlinearity of the body evident during single-axis and multi-axis vibration, and the influence of backrests, should be taken into account when determining frequency weightings for predicting human responses to vibration and when optimising the dynamics of seating to minimise exposure to vibration.

Key words: Biodynamics, Dual-axis excitation, Backrest

Introduction

Musculoskeletal problems, including back pain, are common and affect most people at some stage in their life, but the cause of low back pain is often unclear. Epidemiological studies of persons occupationally exposed to driving have concluded that long-term exposure to whole-body vibration can be associated with increased risk of low back pain[1–3]. Many other factors, including body posture, are also thought to influence the risk of low back pain.

Seat backrests affect the posture of the body, including the curvature of the spine, and the curvature of the spine affects the transmission of vibration to the body. The risk of back pain may therefore be influenced by backrests due to their direct effects on sitting posture and their consequential effects on the transmission of vibration to

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the body[3]. However, there has been little systematic study of the influence of backrests on the biodynamic responses of the seated body or how backrest should be optimised to minimise the transmission of vibration to the body.

Drivers and passengers are exposed to whole-body multi-axis vibration of varying magnitude and frequency. The biodynamic responses of the seated human body have been studied extensively with single-axis vertical and single-axis horizontal vibration[e.g., 4–10] but there have been few studies of the driving-point apparent mass of the body with multi-axis excitation. No previous study has investigated systematically the biodynamic response of the body with backrest contact during dual-axis fore-and-aft and vertical excitation.

When seated without a backrest, the vertical apparent mass measured at the seat with single-axis vertical excitation exhibits a primary resonance at about 5 Hz, whereas the fore-and-aft apparent mass measured with single-axis fore-and-aft excitation shows resonances around 0.7 and 4 Hz[e.g., 5–6]. With excitation in two and three axes, the apparent mass at the seat when sitting without a backrest has been reported to differ from that with single-axis excitation[11]. In apparent contrast, the apparent masses and cross-axis apparent masses measured with some single-axis and dual-axis excitations (selected combinations of fore-and-aft, lateral, and vertical excitation) have been reported to be almost identical[12], although a later study with two magnitudes of single-axis and tri-axial excitation found that increasing the magnitude of vibration in directions orthogonal to the direction of excitation tends to reduce the resonance frequency[13].

Contact with a backrest changes the vertical apparent mass of the seated human body. With single-axis vertical excitation, a backrest tends to reduce the vertical apparent mass measured on the seat at frequencies less than the resonance frequency but increase the apparent mass at frequencies greater than the resonance frequency[5, 14]. An upright rigid backrest and an upright foam backrest reduce the vertical mass of the body supported on the seat surface, and reclining a backrest further reduces the proportion of subject mass supported on the seat surface, although with less reduction with a foam backrest[15]. The resonance frequency of the vertical apparent mass seems little affected by contact with either a vertical flat rigid backrest or a vertical foam backrest, but reclining a rigid backrest increased the resonance frequency and reclining a foam backrest decreased the resonance frequency[15].

Contact with a backrest also changes the fore-and-aft apparent mass of the seated body, with the dominant resonance in the fore-and-aft apparent mass measured at the seat changing from 0.7 Hz without a backrest to 4 Hz with a backrest[6, 16]. With single-axis fore-and-aft excitation the fore-and-aft forces at the backrest can be high, the apparent mass measured at the backrest exhibiting a first peak at a frequency less than 2 Hz and a second peak between 3 and 5 Hz[16]. There is no known study of fore-and-aft apparent mass at the backrest during dual-axis excitation.

The biodynamic responses of the body to vibration are coupled across axes: excitation in one axis results in a response in another axis. During vertical excitation there are appreciable movements of the body in the fore-and-aft direction[7, 8], causing the fore-and-aft cross-axis apparent mass to be about 40% of the subject static mass at some frequencies[17]. The fore-and-aft and lateral cross-axis apparent masses during vertical excitation with and without backrests have been reported by Nawayseh and Griffin[10, 14]. A similar cross-axis response results in considerable vertical forces during fore-and-aft excitation from a seat[16, 18]. With single-axis and dual-axis excitation, the fore-and-aft cross-axis apparent mass due to vertical excitation has been reported to be similar with and without a backrest.

The biodynamic responses of the seated human body are nonlinear, with a softening of the body as the magnitude of vibration increases. The resonance frequencies evident in the vertical and fore-and-aft apparent masses therefore decrease with increasing magnitude of single-axis excitation, both with and without backrest contact[5, 6, 10, 14, 16, 18]. There have been few studies of the influence of the nonlinearity on human responses to multi-axis excitation. The resonance frequency of the apparent mass measured at a seat without a backrest has been reported to reduce as the magnitudes of dual-axis and three-axis excitations increase[11]. In studies without a backrest, systematic variations in the magnitude of excitation in one axis have been found to affect the apparent mass of the body measured in the other axis: the resonance frequency in the vertical apparent mass reduced as the magnitude of fore-and-aft excitation increased, and the resonance frequency in the fore-and-aft apparent mass reduced as the magnitude of vertical excitation increased[19].

The health effects of whole-body vibration cannot be determined by experimental studies on human subjects so they are explored indirectly in studies of the biodynamic or subjective responses of the body to vibration. The risks arising from whole-body vibration are currently predicted using frequency weightings that reflect how human sensi-

tivity to vibration is assumed to vary with the frequency of vibration[20, 21]. The frequency-dependence of the body is influenced by the resonance frequencies of the body, but the variation in the resonance frequencies due to the nonlinearity of the body is not yet taken into account. Furthermore, the weightings in current standards tend to assume the frequency-dependence of the body that has been measured with single-axis vibration when sitting without a backrest yet the weightings are applied to evaluate exposures to multi-axis vibration when sitting with a backrest. The nonlinearity in the biodynamic responses of the body and the influence of backrests on the responses to the body also affect the dynamic coupling between the body and seating, but this is currently ignored when predicting and optimising the dynamic response of seating so as to minimise the transmission of vibration to the body.

This study systematically explored the nonlinearity in the apparent mass of the human body seated with a backrest, investigating the apparent mass at both the seat and the backrest during dual-axis (i.e. fore-and-aft and vertical) excitation. It was hypothesised that nonlinearity would be evident when using a fixed magnitude of vibration in one axis and varying the magnitude of vibration in the other axis. It was further hypothesised that during both single-axis excitation and dual-axis excitation, the fore-and-aft and vertical apparent masses on the seat would differ from those measured without a backrest.

Method

Apparatus

The study was carried out using a 6-axis motion simulator in the ISVR at the University of Southampton. The simulator is capable of translational displacements of ± 0.5 m in the vertical direction and ± 0.25 m in the fore-and-aft and lateral directions, and rotational displacements of ± 20 degrees in roll and pitch motion and ± 10 degrees in yaw. A rigid seat with rigid vertical backrest was secured to the motion simulator (Fig. 1). A force platform (Kistler 9281 B) with tri-axial force transducers located at the four corners of a force plate was secured to the seat surface to measure fore-and-aft and vertical forces, and a second force platform (Kistler 9421 A11) with single-axis force transducers at the four corners of a force plate was fixed to the backrest to measure fore-and-aft force at the backrest. Signals from the force platforms were amplified using Kistler 5007 charge amplifiers. A tri-axial SIT-pad was used to measure fore-and-aft and vertical accelerations at the seat surface. A single-axis SIT-pad was attached to the
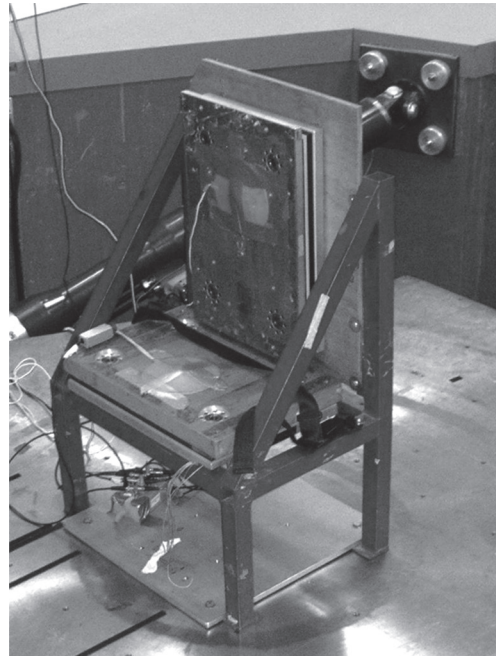

Fig. 1.   Rigid seat with backrest fitted with force plates and SIT-pads.

backrest 410 mm above the seat surface to measure fore-and-aft acceleration at the back.

Subjects and stimuli

Twelve male subjects with average weight 68.6 kg (range: 49.5 to 90 kg) and average age 28.1 yr (range: 21 to 39 yr) 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 were asked to sit in a normal relaxed upright posture against the backrest with their hands on their laps and with average thigh contact with the seat (the supporting seat surface was 500 mm above the surface supporting the feet).

In both the fore-and-aft and the vertical direction, the stimuli were 120-s periods of random vibration with flat constant bandwidth acceleration spectra over the frequency range 0.2 to 20 Hz. The stimuli were presented in all 15 possible combinations of four magnitudes (0, 0.25, 0.5, and 1.0 ms^{-2} r.m.s.) of fore-and-aft vibration and four magnitudes (0, 0.25, 0.5 and 1.0 ms^{-2} r.m.s.) of vertical vibration. Although the same spectra were used in the fore-and-aft and vertical directions, the random waveforms were generated independently so that the fore-and-aft vibration was not correlated with the vertical vibration.

Data analysis

With single-axis excitation, the in-line and cross-axis apparent masses were calculated using a single-input single-output model. With a_{sx} and a_{sz} representing the fore-and-aft and vertical accelerations and f_{sx} and f_{sz} representing the fore-and-aft and vertical forces on the seat, the in-line apparent masses (M_{xx}^s and M_{zz}^s) and the cross-axis apparent masses (M_{xz}^s and M_{zx}^s) on the seat and associated coherencies ($_s\gamma_{xx}^2, {}_s\gamma_{zz}^2, {}_s\gamma_{xz}^2, {}_s\gamma_{zx}^2$) were computed as:

$$M_{xx}^s = \frac{G_{a_{sx}f_{sx}}}{G_{a_{sx}}}, \qquad _s\gamma_{xx}^2 = \frac{\left|G_{a_{sx}f_{sx}}\right|^2}{G_{a_{sx}}G_{f_{sx}}}$$

$$M_{zz}^s = \frac{G_{a_{sz}f_{sz}}}{G_{a_{sz}}}, \qquad _s\gamma_{zz}^2 = \frac{\left|G_{a_{sz}f_{sz}}\right|^2}{G_{a_{sz}}G_{f_{sz}}}$$

$$M_{xz}^s = \frac{G_{a_{sx}f_{sz}}}{G_{a_{sx}}}, \qquad _s\gamma_{xz}^2 = \frac{\left|G_{a_{sx}f_{sz}}\right|^2}{G_{a_{sx}}G_{f_{sz}}} \qquad (1)$$

$$M_{zx}^s = \frac{G_{a_{sz}f_{sx}}}{G_{a_{sz}}}, \qquad _s\gamma_{zx}^2 = \frac{\left|G_{a_{sz}f_{sx}}\right|^2}{G_{a_{sz}}G_{f_{sx}}}$$

where:

$G_{a_{sx}}$ and $G_{a_{sz}}$ are the autospectra of a_{sx} and a_{sz},

$G_{f_{sx}}$ and $G_{f_{sz}}$ are the autospectra of f_{sx} and f_{sz},

$G_{a_{sx}f_{sx}}$ and $G_{a_{sz}f_{sz}}$ are the cross-spectra between a_{sx} and f_{sx} and between a_{sz} and f_{sz}, and

$G_{a_{sx}f_{sz}}$ and $G_{a_{sz}f_{sx}}$ are the cross-spectra between a_{sx} and f_{sz} and between a_{sz} and f_{sx}.

Similarly, the fore-and-aft apparent masses (M_{xx}^b) on the backrest and associated coherencies, $_b\gamma_{xx}^2$, were computed as:

$$M_{xx}^b = \frac{G_{a_{bx}f_{bx}}}{G_{a_{bx}}}, \qquad _b\gamma_{xx}^2 = \frac{\left|G_{a_{bx}f_{bx}}\right|^2}{G_{a_{bx}}G_{f_{bx}}} \qquad (2)$$

with

$G_{a_{bx}}$ are the autospectra of the fore-and-aft acceleration a_{bx} at the backrest,

$G_{f_{bx}}$ are the autospectra of the fore-and-aft force f_{bx} at the backrest, and

$G_{a_{bx}f_{bx}}$ are the cross-spectra between a_{bx} and f_{bx}.

With dual-axis excitation, the force measured in a particular axis is induced not only from the excitation in that axis but also from the excitation in the other direction. The in-line and cross-axis apparent masses should generally be calculated using a two-input and one-output model. Assuming the force being measured is the fore-and-aft force on the seat, f_{sx}, the fore-and-aft in-line apparent mass and fore-and-aft cross-axis apparent mass on the seat could be computed via a two-input and one-output model as:

$$M_{xx}^s(f) = \frac{G_{a_{sx}f_{sx}}\left(1 - \dfrac{G_{a_{sx}a_{sz}}G_{a_{sz}f_{sx}}}{G_{a_{sz}a_{sz}}G_{a_{sx}f_{sx}}}\right)}{G_{a_{sx}a_{sx}}(1-\gamma^2)}$$

$$(3)$$

$$M_{zx}^s(f) = \frac{G_{a_{sz}f_{sx}}\left(1 - \dfrac{G_{a_{sz}a_{sx}}G_{a_{sx}f_{sx}}}{G_{a_{sx}a_{sx}}G_{a_{sz}f_{sx}}}\right)}{G_{a_{sz}a_{sz}}(1-\gamma^2)}$$

with

$$\gamma^2 = \frac{\left|G_{a_{sx}a_{sz}}\right|^2}{G_{a_{sx}a_{sx}}G_{a_{sz}a_{sz}}}$$

Since the fore-and-aft and vertical excitations used in the study were independent (i.e., $\gamma^2 = 0$ and $G_{a_{sx}a_{sz}} = G_{a_{sz}a_{sx}} = 0$), the above apparent masses can be simplified as:

$$M_{xx}^s(f) = \frac{G_{a_{sx}f_{sx}}}{G_{a_{sx}a_{sx}}}$$

$$(4)$$

$$M_{zx}^s(f) = \frac{G_{a_{sz}f_{sx}}}{G_{a_{sz}a_{sz}}}$$

These are the same formula used to compute fore-and-aft in-line apparent mass and fore-and-aft cross-axis apparent mass with single-axis excitation in Equation (1). Similarly, the vertical in-line apparent mass and vertical cross-axis apparent mass with the dual-axis excitation can be computed using Equation (1). The fore-and-aft apparent mass measured at the backrest with dual-axis excitation can be calculated with Equation (2).

Forces and accelerations were acquired at 200 samples per second via anti-aliasing filters set 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 a frequency resolution of 0.39 Hz.

Results

Fore-and-aft apparent mass at the seat

The fore-and-aft in-line apparent masses measured on the seat with backrest contact with single-axis fore-and-aft excitation and with dual-axis fore-and-aft and vertical excitation vary between subjects, but always with a principal resonance in the range of 3 to 6 Hz.
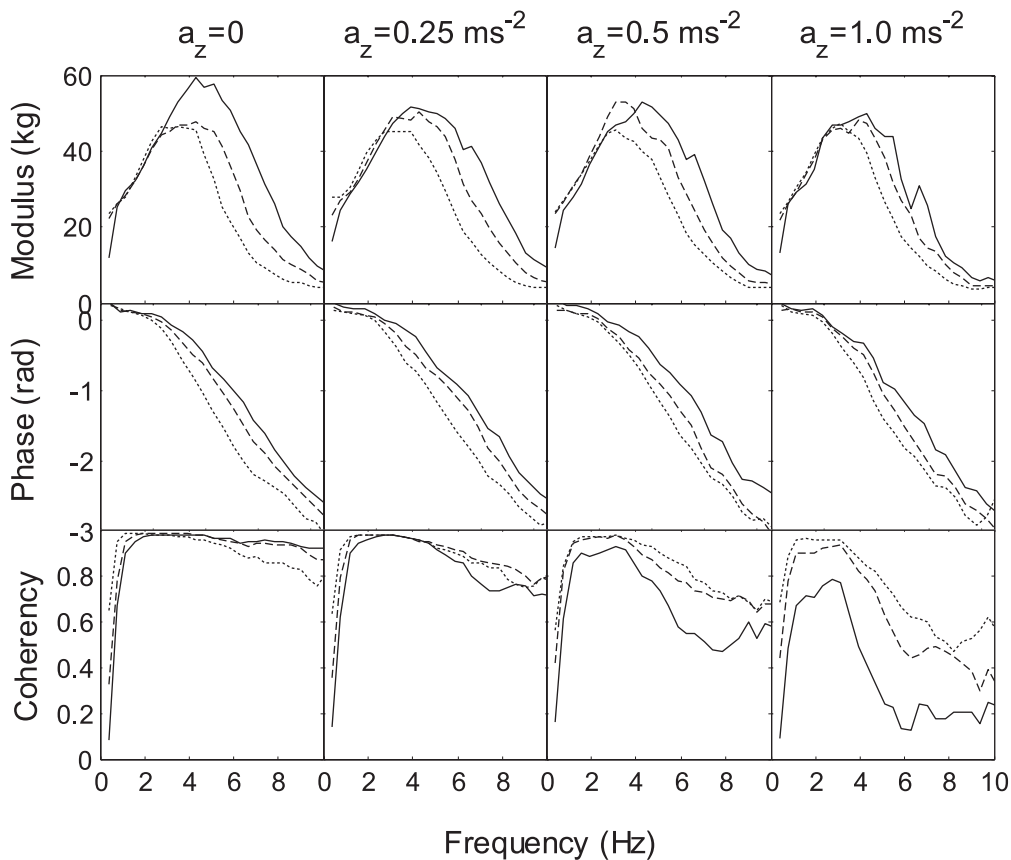
Fig. 2. Median in-line apparent masses of 12 subjects in the fore-and-aft direction with dual-axis excitation.
——— a_x = 0.25 ms^{-2} r.m.s.; – – – a_x = 0.5 ms^{-2} r.m.s.; ········ a_x = 1.0 ms^{-2} r.m.s.

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 in the median fore-and-aft apparent mass (p=0.002, Friedman, column 1 of Fig. 2; Table 1). There was also a trend for the apparent mass at the resonance to reduce as the magnitude of vibration increased (p<0.001).

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

With the addition of vertical vibration, so as to produce dual-axis excitation, a similar nonlinearity was evident in the moduli and phases of the fore-and-aft apparent mass on the seat as the magnitude of either the fore-and-aft excitation or the magnitude of the vertical excitation increased (columns 2 to 4 in Fig. 2). As the magnitude of fore-and-aft excitation increased, there were statistically significant reductions in the resonance frequency at all magnitudes of vertical excitation (Table 1) and the apparent mass at

resonance also tended to decrease.

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. 2).

Vertical apparent mass on the seat

The vertical in-line apparent masses measured at the seat with backrest contact from the 12 subjects exposed to single-axis vertical excitation and dual-axis vertical and fore-and-aft excitation exhibit a principal resonance in the range 4 to 8 Hz and a second peak may be seen between 9 and 15 Hz in the responses of most subjects.

Median vertical apparent mass during single-axis excitation

With increasing magnitude of vertical excitation, there were significant reductions in the principal resonance frequency (p=0.032, Friedman; first column in Fig. 3 and Table 1) and in the apparent mass at this resonance (p=0.027).

Table 1. Variation in the principal resonance frequency and the associated modulus of the fore-and-aft and vertical apparent masses at the seat during single-axis and dual-axis excitation, and the effect of the magnitude of fore-and-aft excitation on the fore-and-aft apparent mass at the backrest at four frequencies with and without vertical excitation

Fore-and-aft apparent mass at the seat

	Single-axis fore-and-aft excitation: $a_z = 0$	Dual-axis fore-and-aft and vertical excitation		
		$a_z = 0.25$ ms^{-2}	$a_z = 0.5$ ms^{-2}	$a_z = 1.0$ ms^{-2}
$a_x = 0.25$ ms^{-2}	4.9 Hz	4.3 Hz	4.5 Hz	4.3 Hz
$a_x = 0.5$ ms^{-2}	4.3 Hz	3.9 Hz	3.9 Hz	4.3 Hz
$a_x = 1.0$ ms^{-2}	3.5 Hz	3.1 Hz	3.1 Hz	3.1 Hz
Friedman	$p=0.002$	$p=0.002$	$p=0.000$	$p=0.01$
$a_x = 0.25$ ms^{-2}	60.4 kg	53.6 kg	55.4 kg	50.8 kg
$a_x = 0.5$ ms^{-2}	47.5 kg	53.4 kg	53.7 kg	50.6 kg
$a_x = 1.0$ ms^{-2}	47.3 kg	47.5 kg	47.2 kg	48.2 kg
Friedman	$p=0.000$	$p=0.002$	$p=0.000$	$p=0.002$

Vertical apparent mass at the seat

	Single-axis vertical excitation $a_x = 0$	Dual-axis excitation: vertical and fore-and-aft		
		$a_x = 0.25$ ms^{-2}	$a_x = 0.5$ ms^{-2}	$a_x = 1.0$ ms^{-2}
$a_z = 0.25$ ms^{-2}	5.9 Hz	6.3 Hz	6.3 Hz	5.1 Hz
$a_z = 0.5$ ms^{-2}	5.9 Hz	5. 5 Hz	5.7 Hz	5.1 Hz
$a_z = 1.0$ ms^{-2}	5.3 Hz	5.1 Hz	5.3 Hz	5.1 Hz
Friedman	$p=0.032$	$p=0.001$	$p=0.049$	$p=0.093$
$a_z = 0.25$ ms^{-2}	81.6 kg	79.7 kg	81.7 kg	82.3 kg
$a_z = 0.5$ ms^{-2}	79.2 kg	78.2 kg	79.3 kg	79.9 kg
$a_z = 1.0$ ms^{-2}	75.9 kg	79.3 kg	80.7 kg	80.7 kg
Friedman	$p=0.027$	$p=0.039$	$p=0.046$	$p=0.174$

Fore-and-aft apparent mass at the backrest

Test frequency	Single axis fore-and-aft excitation: $a_z = 0$	Dual-axis fore-and-aft and vertical excitation		
		$a_z = 0.25$ ms^{-2}	$a_z = 0.5$ ms^{-2}	$a_z = 1.0$ ms^{-2}
0.8 Hz	0.717	0.472	0.105	0.779
3.1 Hz	0.174	0.920	0.046	0.264
5.1 Hz	0.006	0.000	0.009	0.001
7.0 Hz	0.000	0.002	0.000	0.039

p-values from Friedman test.

Median vertical apparent mass during dual-axis excitation

With the addition of fore-and-aft vibration, so as to produce dual-axis excitation, a similar nonlinearity was evident in the moduli and phases of the vertical apparent mass on the seat as the magnitude of the vertical excitation increased. However, the nonlinearity became less as the magnitude of the additional fore-and-aft excitation increased (columns 2 to 4 in Fig. 3). The reduction in the resonance frequency with increasing magnitude of vertical excitation was statistically significant with the two lowest magnitudes of fore-and-aft excitation ($p=0.001$, and

$p=0.049$, respectively; Table 1), but not significant with the greatest magnitude of fore-and-aft excitation ($p=0.093$). With a constant magnitude of the additional fore-and-aft excitation, there was no clear trend in the modulus of the apparent mass at resonance as the magnitude of vertical excitation increased. However, with the two lowest magnitudes of the additional fore-and-aft excitation the changes in the modulus of the apparent masses at resonance were statistically significant ($p=0.039$ and $p=0.046$, respectively). There was no significant change in the apparent mass at resonance as the magnitude of the vertical excita-
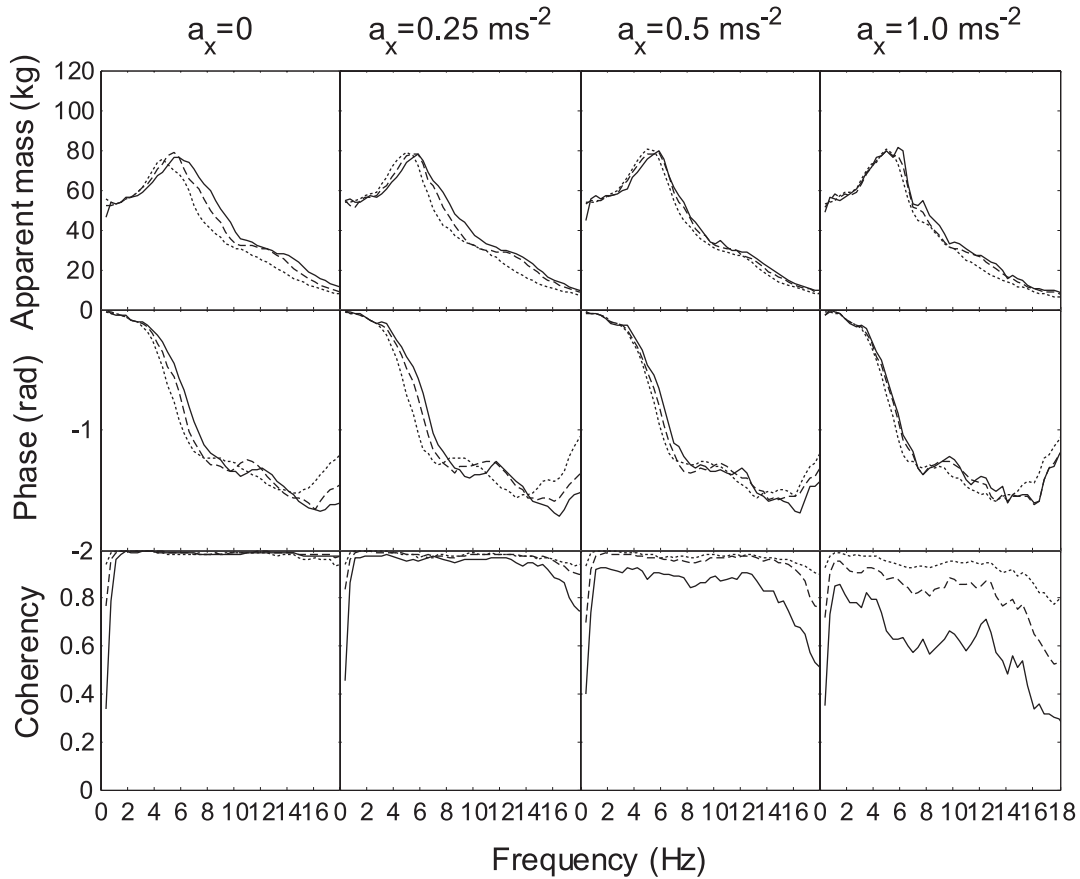
Fig. 3. **Median in-line apparent masses of 12 subjects in the vertical direction with single-axis and dual-axis excitation.**

—— $a_z = 0.25$ ms^{-2} r.m.s.; – – – $a_z = 0.5$ ms^{-2} r.m.s.; ········ $a_z = 1.0$ ms^{-2} r.m.s.

tion increased with the greatest magnitude of fore-and-aft excitation (p=0.174).

The coherency between the vertical acceleration and the vertical force on the seat was lowered by the addition of fore-and-aft excitation but raised by increasing the magnitude of the vertical excitation (Fig. 3).

Fore-and-aft apparent mass at the backrest

The fore-and-aft in-line apparent masses measured at the backrest with single-axis fore-and-aft excitation and with dual-axis fore-and-aft and vertical excitation vary among subjects but two resonances are often seen: one at a frequency less than 2 Hz and the other in the range of 3 to 6 Hz.

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

Although two resonances may be apparent in the median fore-and-aft apparent mass at the back with the lowest and

intermediate magnitudes (a_x=0.25 and 0.5 ms^{-2} r.m.s.) only one resonance is evident at the greatest magnitude of fore-and-aft vibration (a_x=1.0 ms^{-2} r.m.s.) (the first column in Fig. 4). There is nonlinearity with significant reductions in the fore-and-aft apparent mass at the back at 5.1 and 7.0 Hz but not at 0.8 and 3.1 Hz as the magnitude of fore-and-aft vibration increased in the absence of vertical excitation (Table 1).

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

With the addition of vertical vibration, so as to produce dual-axis excitation, a similar nonlinearity was evident in the moduli and phases of the fore-and-aft apparent mass at the backrest as the magnitude of either the fore-aft excitation or the magnitude of vertical excitation increased (columns 2 to 4 in Fig. 4). As the magnitude of fore-and-aft excitation increased, there were statistically significant reductions in the apparent mass at 5.1 and 7.0 Hz, with
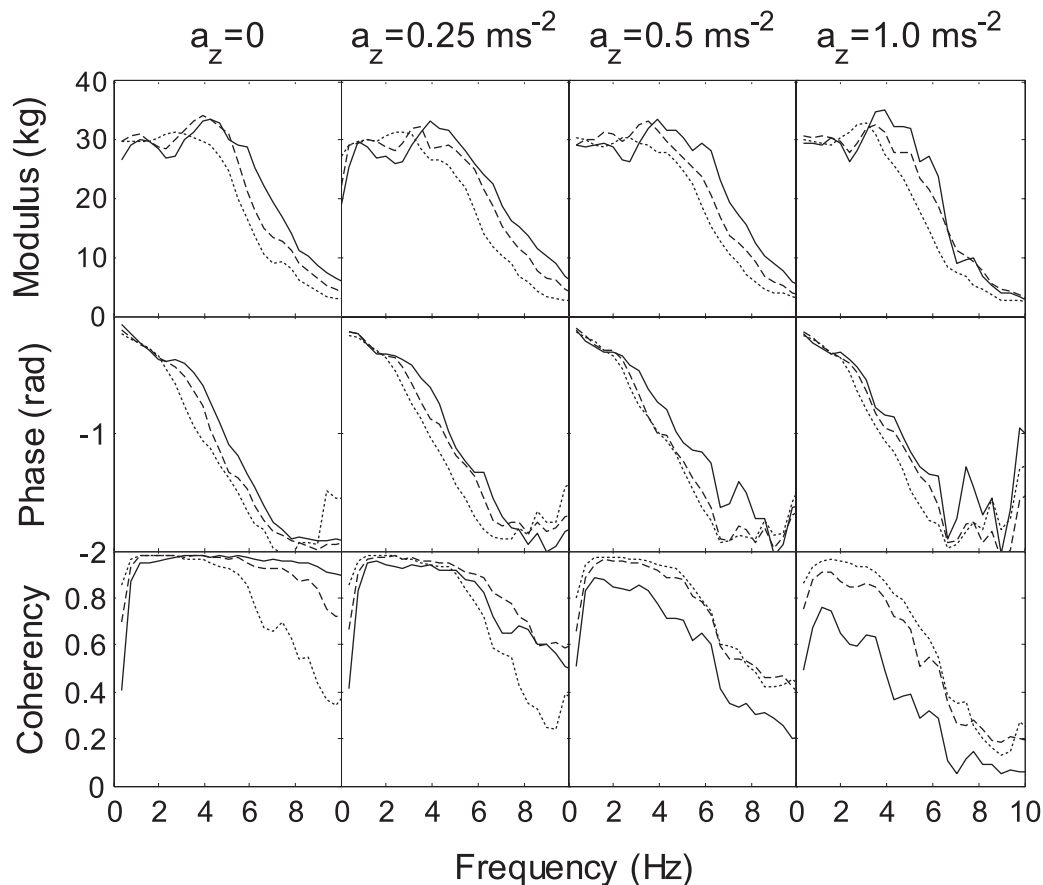
Fig. 4.   Median in-line apparent masses at the backrest for 12 subjects in the fore-and-aft direction with single-axis and dual-axis excitation.

—— $a_x = 0.25$ ms^{-2} r.m.s.; – – – $a_x = 0.5$ ms^{-2} r.m.s.; ········ $a_x = 1.0$ ms^{-2} r.m.s.

all magnitudes of the additional vertical excitation (Table 1). The fore-and-aft apparent mass was not significantly changed at 0.8 or 3.1 Hz, except at 3.1 Hz with the intermediate magnitude of vertical excitation (p=0.046).

The coherency between the fore-and-aft acceleration and the fore-and-aft force at the backrest was lowered by the addition of vertical excitation but raised by increasing the magnitude of the fore-and-aft excitation (Fig. 4).

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

There were considerable fore-and-aft forces on the seat during single-axis vertical excitation. The median fore-and-aft cross-axis apparent mass of the 12 subjects exhibited a primary peak (first column of Fig. 5) at a frequency that reduced significantly (7.0, 6.3 and 5.5 Hz; p<0.001, Friedman) as the magnitude of vertical excitation increased (0.25, 0.5 and 1.0 ms^{-2} r.m.s.).

With dual-axis vertical and fore-and-aft excitation, the

median apparent masses of the 12 subjects computed from the complex ratio of the fore-and-aft force to the vertical acceleration excitation are also shown in Fig. 5 (columns 2 to 4) and the characteristics appear less clear. The addition of fore-and-aft excitation reduced the coherency between the fore-and-aft force and the vertical acceleration on the seat, whereas with a constant magnitude of fore-and-aft excitation, increasing the magnitude of the vertical excitation increased the coherency.

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

The median vertical cross-axis apparent mass of the 12 subjects during single-axis fore-and-aft excitation (first column of Fig. 6) exhibited a primary peak (between 4 and 7 Hz) with a frequency (6.5, 5.7 and 5.1 Hz) that reduced with increasing magnitude of fore-and-aft excitation (0.25, 0.5 and 1.0 ms^{-2} r.m.s.; p<0.014).

With dual-axis fore-and-aft and vertical excitation, the
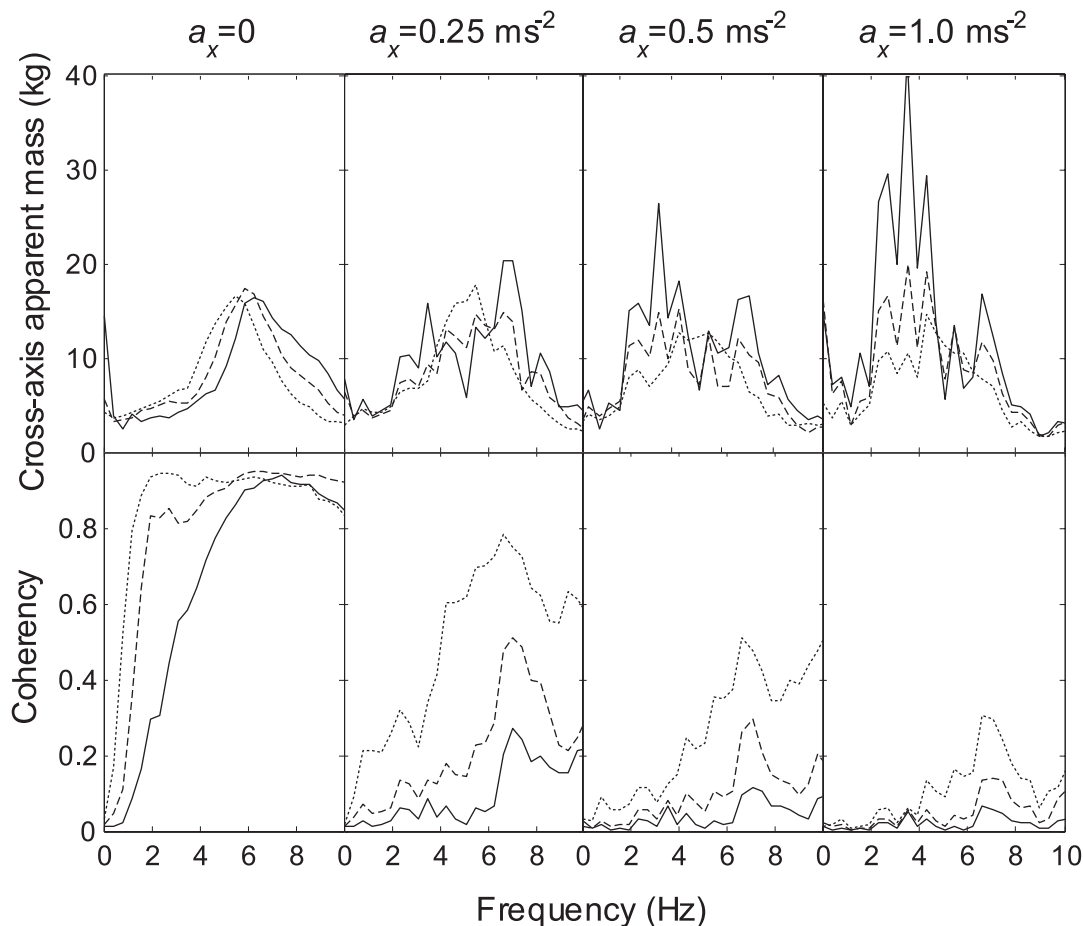
Fig. 5. Median fore-and-aft cross-axis apparent masses for 12 subjects (fore-and-aft force during vertical vibration) with single-axis and dual-axis excitation.
—— $a_z = 0.25$ ms^{-2} r.m.s.; – – – $a_z = 0.5$ ms^{-2} r.m.s.; ········ $a_z = 1.0$ ms^{-2} r.m.s.

characteristics of the median apparent masses computed from the complex ratio of the vertical force to the fore-and-aft excitation from the 12 subjects (columns 2 to 4 of Fig. 6) became less clear. The additional vertical excitation reduced the coherency between the fore-and-aft acceleration and the vertical force. With a constant magnitude of vertical excitation, the coherency increased with increasing magnitude of fore-and-aft excitation.

Discussion

Fore-and-aft apparent mass on the seat and effect of backrest contact

The primary peak in the fore-and-aft apparent mass on the seat with backrest around 2 to 6 Hz is consistent with previous measurements during single-axis fore-and-aft excitation[e.g., 16]. The reduction in the resonance frequency and the associated apparent mass with increasing magni-

tude of fore-and-aft excitation is also consistent with previous findings[e.g., 16].

The only other study to have measured the fore-and-aft apparent mass with a backrest during dual-axis fore-and-aft and vertical excitation found the apparent mass was similar with single-axis and dual-axis excitation, although the resonance frequencies tended to be lower with dual-axis excitation[12]. Only one magnitude of vibration was studied (0.4 ms^{-2} r.m.s.) so the effect of vibration magnitude on the apparent mass was not determined. In the present study, although the fore-and-aft apparent mass is similar with single-axis and dual-axis excitation (Fig. 2), there is clear evidence of nonlinearity associated with changes in the magnitude of either the fore-and-aft or the vertical excitation. The resonance frequency in the fore-and-aft apparent mass, and the apparent mass at resonance, decreased with increasing magnitude of fore-and-aft excitation at all magnitudes of the additional vertical
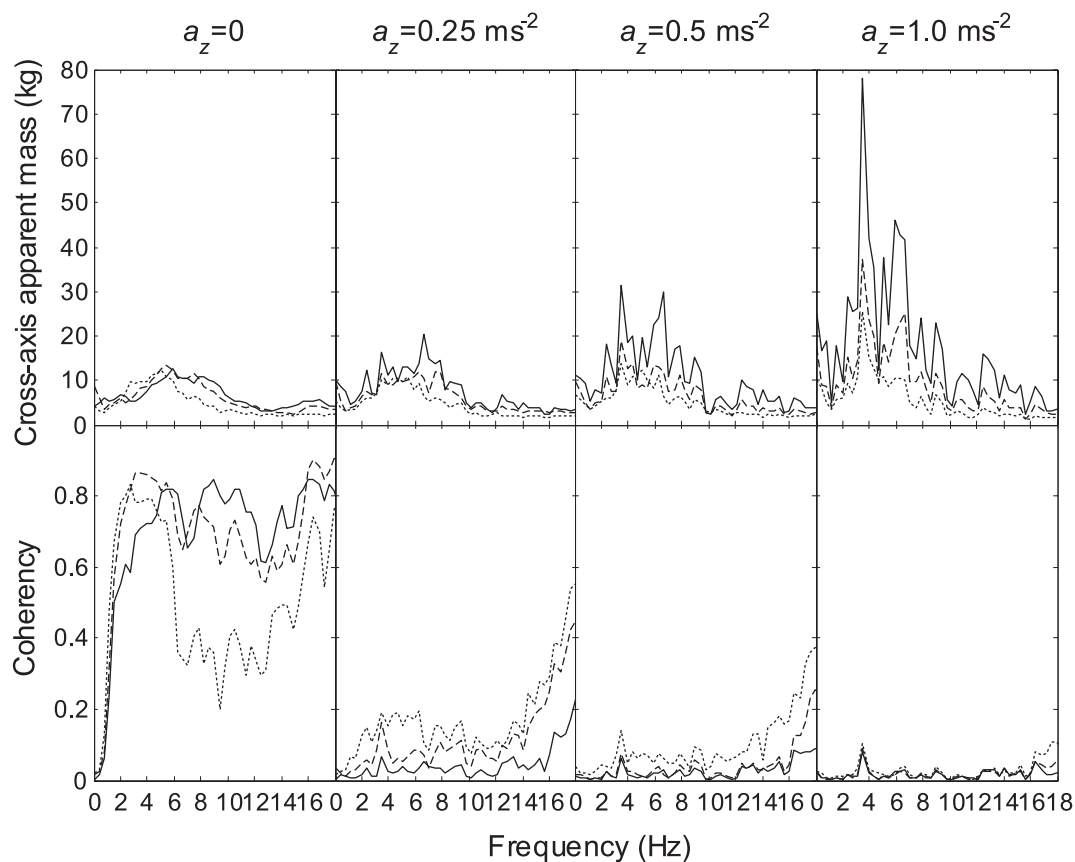
Fig. 6.   Median vertical cross-axis apparent masses of 12 subjects (vertical force during fore-and aft vibration) with single-axis and dual-axis excitation.
—— $a_x = 0.25$ ms^{-2} r.m.s.; $- - -$ $a_x = 0.5$ ms^{-2} r.m.s.; ······· $a_x = 1.0$ ms^{-2} r.m.s.

excitation (Table 1). This body softening phenomenon was also observed when the magnitude of fore-and-aft excitation was constant and the magnitude of vertical excitation increased, although less apparent than when increasing the magnitude of fore-and-aft excitation. The resonance frequency of a seat is usually set away from, and ideally at lower frequency than, the resonance frequency of the human body so as to minimise the severity of vibration transmitted to the body. The resonance frequency of the fore-and-aft apparent mass decreased by 1.4 Hz (from 4.9 Hz to 3.5 Hz with single-axis fore-and-aft excitation) when the vibration magnitude increased from 0.25 to 1.0 ms^{-2} r.m.s. – a large change that could be of importance when optimising seat dynamics. Ignorance of this effect could result in a seat amplifying rather than attenuating vibration, with increased risk to human health.

There were significant reductions in the fore-and-aft apparent mass as the magnitude of the additional vertical excitation increased, consistent with a previous study in which the apparent mass at resonance was found to be less

with dual-axis excitation than with single-axis fore-and-aft excitation[12].

The fore-and-aft apparent masses measured on the seat in the present study with backrest can be compared with those measured using the same 12 subjects on the same seat without backrest[19]. The fore-and-aft apparent mass on the seat was greater without the backrest at the lower frequencies but greater with the backrest at the higher frequencies (far left column of Fig. 7), consistent with previous studies[6, 19]. With single-axis fore-and-aft excitation, the differences were highly significant at two example frequencies (0.78 and 3.91 Hz; $p<0.004$; Wilcoxon) for all three magnitudes of the fore-and-aft excitation. With dual-axis fore-and-aft and vertical excitation there was a similar effect of the backrest on the fore-and-aft apparent mass with similar significant differences at the same frequencies for all three magnitudes of vertical excitation (columns 2–4 of Fig. 7). The high fore-and-aft force on the seat at low frequencies without the backrest may arise from pitch motion of the upper-body and the pelvis with
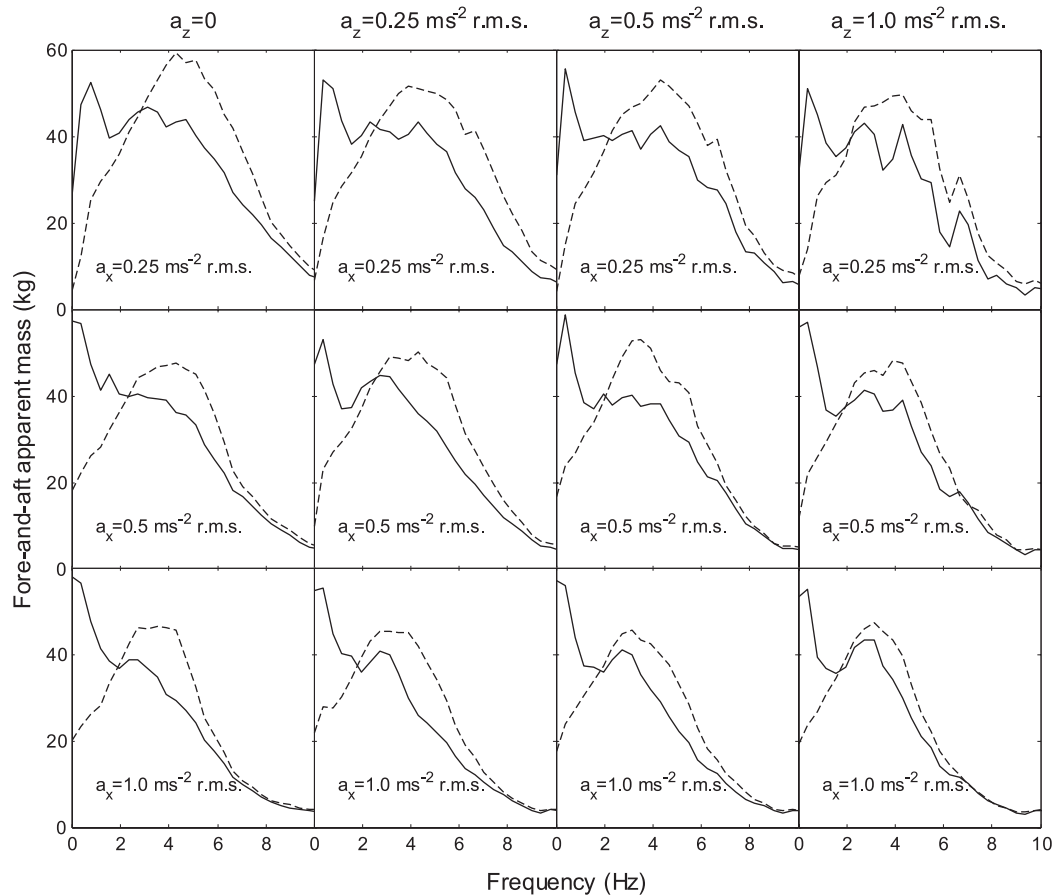
Fig. 7. Fore-and-aft apparent masses.
—— without backrest; – – – with backrest; data without backrest from Qiu and Griffin, 2010[19].

axial and shear deformation of tissue beneath the pelvis. It would seem desirable that a seat backrest restrains this body movement at low frequencies while minimising the transmission of vibration to the body at high frequencies.

Vertical apparent mass on the seat and effect of backrest contact

The principal resonance frequency in the vertical apparent mass on the seat during single-axis vertical excitation with the backrest was reduced from 5.9 to 4.7 Hz as the magnitude of the vertical excitation increased from 0.25 to 1.0 ms^{-2} r.m.s., showing a nonlinearity consistent with previous studies[e.g., 5, 14].

Using one magnitude of excitation, a similar vertical apparent mass has been reported with single-axis vertical excitation and dual-axis vertical and fore-and-aft excitation[12]. The present study shows that the expected nonlinearity in the vertical apparent mass depends on the magnitude of the fore-and-aft excitation. With a low magnitude of fore-and-aft excitation (a_x=0.25 ms^{-2}

r.m.s., Fig. 3 and Table 1), increasing the magnitude of vertical excitation reduced the resonance frequency of the vertical apparent mass. The effect of the magnitude of vertical excitation was only marginally significant with the intermediate magnitude of fore-and-aft excitation (a_x=0.5 ms^{-2} r.m.s.), and was less or insignificant at the greatest magnitude of fore-and-aft excitation (a_x=1.0 ms^{-2} r.m.s.). At a constant magnitude of vertical excitation, varying the magnitude of fore-and-aft excitation changed the vertical apparent mass at all three magnitudes of vertical excitation (Table 1).

The vertical apparent mass on the seat was changed by the addition of fore-and-aft excitation, although not at all frequencies and the effect was less apparent at the greatest magnitude of vertical excitation. A previous study reported no significant difference in the apparent mass at resonance with single-axis (vertical) and dual-axis (fore-and-aft and vertical) excitation[12].

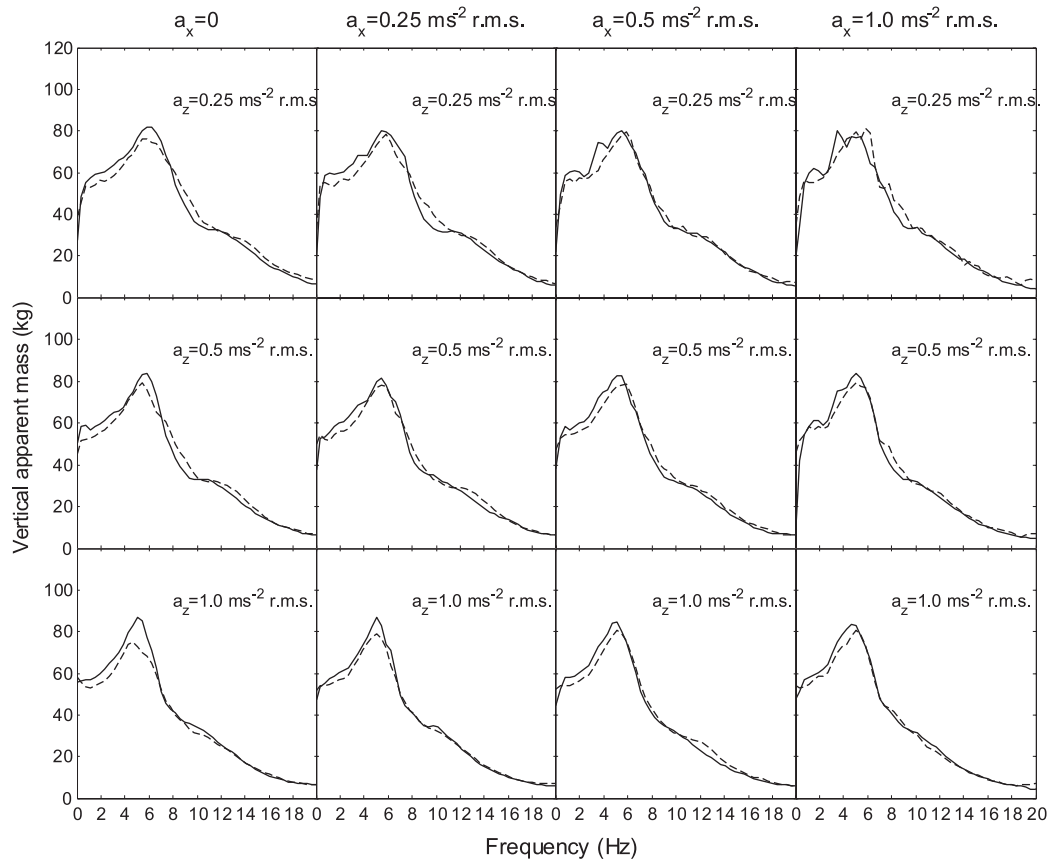The vertical apparent masses measured on the seat in the present study with backrest can be compared with those

Fig. 8.   Vertical apparent masses.
—— without backrest; – – – with backrest; data without backrest from Qiu and Griffin, 2010[19].

measured using the same 12 subjects on the same seat without backrest[19] (Fig. 8). With low magnitudes of single-axis vertical excitation, the backrest tended to slightly decrease the vertical apparent mass on the seat at the lower frequencies and slightly increase the vertical apparent mass on the seat at frequencies greater than the resonance frequency, as previously reported[5, 14]. With dual-axis vertical and fore-and-aft excitation, the effect of the backrest on the vertical apparent mass on the seat seems similar to that with single-axis vertical excitation. At an example frequency less than the resonance frequency (i.e. 2.73 Hz), the reduction in the vertical apparent mass on the seat was statistically significant for all 12 cases shown in Fig. 8 ($p<0.019$, Wilcoxon), except for the three cases involving the highest magnitude of fore-and-aft or vertical excitation (i.e., $a_x=1.0$ ms^{-2} r.m.s. with $a_z=0.25$ ms^{-2} r.m.s.; $a_x=0.25$ ms^{-2} r.m.s. with $a_z=1.0$ ms^{-2} r.m.s.; $a_x=1.0$ ms^{-2} r.m.s. with $a_z=1.0$ ms^{-2} r.m.s.), where the reduction was marginally insignificant ($p=0.06$, 0.06 and 0.07, respectively). At an example frequency greater than the resonance frequency (i.e. 8.2 Hz), there were no statistically significant diffe-

rences.

Fore-and-aft apparent mass at the backrest

Three peaks in fore-and-aft apparent mass measured on a backrest have been noticed previously during single-axis fore-and-aft excitation[16]. The first two peaks (one at a frequency less than 2 Hz and the other between 3 and 5 Hz) were present in almost all subjects, but a third peak in the range 4 to 7 Hz appeared in the responses of only a few subjects. In the present study, there were two clear peaks (one at a frequency less than 2 Hz and the other in the range of 3 to 6 Hz). It has previously been suggested the first peak between 1 and 2 Hz might be associated with a pitching mode of the body[16, 22–24]. In the present study it was found that with increasing magnitude of fore-and-aft excitation there were significant reductions in the fore-and-aft apparent mass at the back at high frequencies, with no significant change in the apparent mass at lower frequencies (Table 1). The pitching mode of the body evident at low frequencies without a backrest may have been restrained by the backrest.
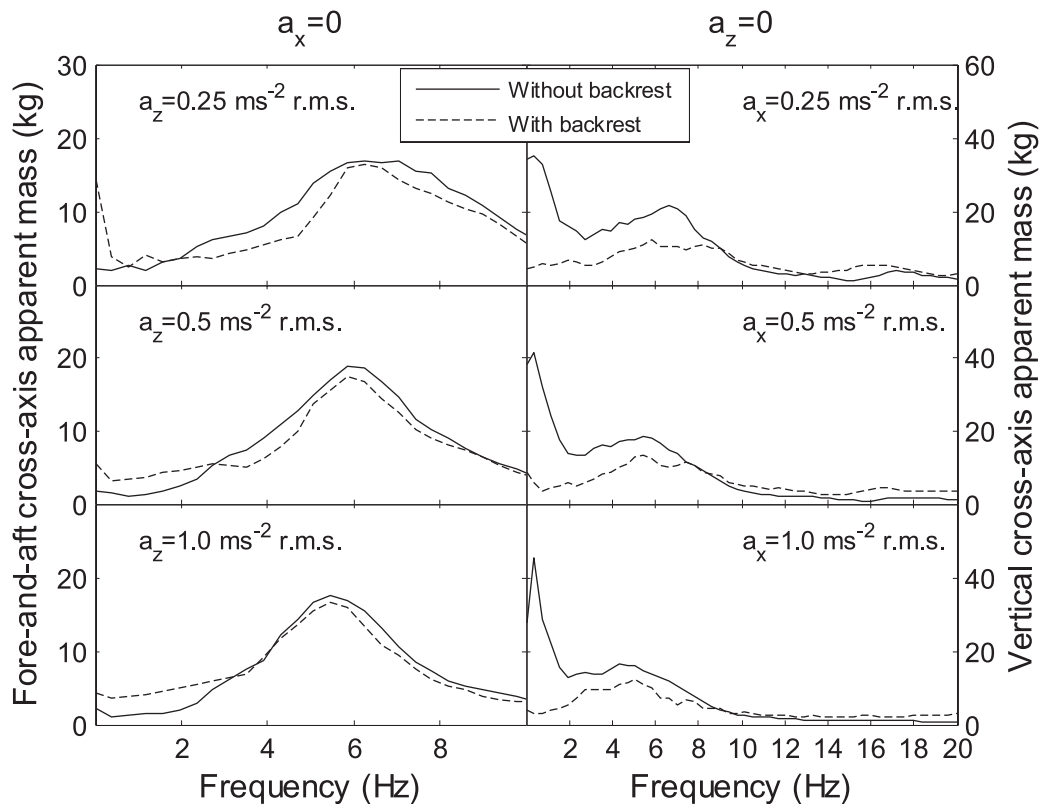
Fig. 9. Comparison of fore-and-aft cross-axis apparent masses (fore-and-aft force due to vertical excitation) and vertical cross-axis apparent masses (vertical force due to fore-and-aft excitation) during single-axis excitation with and without backrest contact.
—— without backrest; – – – with backrest; data without backrest from Qiu and Griffin, 2010[19].

There are no known previous studies of fore-and-aft apparent mass at the back with dual-axis fore-and-aft and vertical excitation. The fore-and-aft apparent mass at the back with dual-axis excitation in the present study had a similar characteristic to that obtained with single-axis fore-and-aft excitation. Nonlinearity was evident in the moduli and phases of the fore-and-aft apparent mass at the back as the magnitude of either the fore-and-aft or the vertical excitation changed. With a fixed magnitude of vertical excitation, the fore-and-aft apparent mass at the back reduced at high frequencies as the magnitude of fore-and-aft excitation increased (Table 1).

Fore-and-aft cross-axis apparent mass on the seat

The fore-and-aft cross-axis apparent mass on the seat measured with and without backrest during single-axis vertical excitation is compared in the left column of Fig. 9. With both conditions, the primary resonance was between 4 and 8 Hz, similar to Nawayseh and Griffin[10, 14]. Differences between the fore-and-aft cross-axis apparent masses with and without backrest were tested at 0.78, 1.95,

3.91 and 7.81 Hz (Wilcoxon matched-pairs signed ranks tests). There were significant differences between the fore-and-aft cross-axis apparent masses with and without backrest at 3.91 Hz (for $a_z = 0.25$ ms^{-2} r.m.s., $p=0.05$), at 0.78, 1.95, and 3.91 Hz (for $a_z = 0.5$ ms^{-2} r.m.s., $p=0.004$, 0.019 and 0.023, respectively) and at 0.78 and 1.91 Hz (for $a_z = 1.0$ ms^{-2} r.m.s., $p=0.005$ and 0.005). The reduction in the principal resonance frequency of the fore-and-aft cross-axis apparent mass with increasing magnitude of vertical excitation that is evident in Fig. 5 was statistically significant with the backrest.

Investigations of the movement of the upper-bodies of seated subjects exposed to vertical whole-body vibration at the principal resonance frequency have suggested more than one vibration mode may contribute to the principal resonance in the apparent mass around 5 Hz[8]. It was suggested that 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 the pelvis may be coupled with each other due to the heavy damping of the human body. Without a back-

rest, the principal resonance frequencies in the fore-and-aft cross-axis apparent masses of the subjects were found to be correlated with the resonance frequencies in their vertical in-line apparent masses at all three magnitudes of vertical excitation[19].

In the present study with backrest contact, the principal resonance frequencies in the fore-and-aft cross-axis apparent mass on the seat and the vertical in-line apparent mass on the seat were not significantly correlated at low magnitudes of vertical excitation (p=0.991 and 0.178 for a_z=0.25 and 0.5 ms^{-2} r.m.s., Spearman) but were highly correlated at the highest magnitude (a_z=1.0 ms^{-2} r.m.s.; p=0.002). This may imply the dominant modes of vibration changed with vibration magnitude and that some factors can influence the principal resonance in the fore-and-aft cross-axis apparent mass without having a corresponding influence on the principal resonance in the vertical in-line apparent mass. The backrest tended to restrain the bending mode of the spine and the pitch mode of the pelvis so as to reduce the fore-and-aft forces on the seat and change the way the body responded to vertical excitation. More research would be required to understanding of the mechanisms associated with the influences of backrests on how the seated human body responds to vertical excitation.

Vertical cross-axis apparent mass on the seat

The vertical cross-axis apparent mass on the seat measured with and without backrest during single-axis fore-and-aft excitation is compared in the right column of Fig. 9. Without backrest contact, there were two modes (around 1 Hz and between 3 and 8 Hz), but with backrest contact the peak at the lower frequency disappeared. This finding is similar to that reported by Mansfield and Maeda[12] who without using a backrest observed elevated vertical cross-axis apparent mass at frequencies below the peak frequency at 3 Hz during single-axis and dual-axis excitation. Similar to previous findings[16, 18, 19], non-linearity was evident in the vertical cross-axis apparent masses with a backrest: the frequency of the principal resonance with backrest contact decreased significantly with increasing magnitude of fore-and-aft excitation. The difference between the vertical cross-axis apparent mass measured with and without a backrest was tested at four frequencies (0.78, 1.95, 3.91, and 7.81 Hz) (Wilcoxon matched-pairs signed ranks tests). There were significant differences between the vertical cross-axis apparent masses with and without backrest for all three magnitudes of single-axis fore-and-aft excitation at all frequencies tested (p<0.012), except for 7.81 Hz.

Without the backrest there were significant correlations between the frequency of the second peak in the vertical cross-axis apparent mass and the frequency of the resonance in the fore-and-aft in-line apparent mass, except for one magnitude of fore-and-aft excitation where the correlation was marginally non-significant[19]. With the backrest, similar to the fore-and-aft cross-axis apparent mass, the correlation between the resonance frequencies in the vertical cross-axis apparent mass and the fore-and-aft in-line apparent mass was not significant at low magnitudes (p=1.0 and 0.16 with a_x = 0.25, and 0.5, respectively) but only marginally insignificant at the highest magnitude (p= 0.08 at a_x = 1.0 ms^{-2} r.m.s.).

Conclusions

The human body has a nonlinear response to whole-body vibration: a softening response as the magnitude of vibration increases. The nonlinearity is apparent when the body is excited at varying magnitudes of single-axis vibration and when the body is excited by a fixed magnitude of vibration in one axis and varying magnitudes of vibration in another axis.

The presence of a backrest changes the biodynamic response of the seated body, especially during fore-and-aft excitation.

The nonlinearity of the body evident during single-axis vibration and multi-axis vibration, and the influence of backrests, should be taken into account when determining frequency weightings for human responses to vibration and when optimising the dynamics of seating.

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