NON-LINEAR APPARENT MASS OF THE SUPINE HUMAN BODY EXPOSED TO VERTICAL WHOLE-BODY VIBRATION

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Abstract

The vertical (i.e. *x*-axis) apparent mass and the cross-axis (foot-to-head, *z*-axis) apparent mass of the supine human body have been measured during random (0.25 to 20 Hz) vertical whole-body vibration at five magnitudes (0.125, 0.25, 0.5, 0.75 and 1.0 ms^{-2} r.m.s.). Twelve male subjects adopted a relaxed supine posture assumed to involve less trunk muscle activity than sitting or standing postures. A dominant primary resonance in the median normalised apparent mass resonance frequency decreased from 10.35 Hz to 7.32 Hz as the vibration magnitude increased from 0.125 to 1.0 ms^{-2} r.m.s. The non-linear response of the body was apparent in both the vertical (*x*-axis) and the horizontal (*z*-axis) directions.

1. Introduction

Biodynamic responses of the human body during whole-body vibration have been found to be non-linear: the resonance frequencies in frequency response functions (e.g., the apparent mass) decrease with increasing vibration magnitude. This non-linearity has been observed in the vertical and the fore-and-aft responses of the seated human body exposed to vertical whole-body vibration (e.g., Fairley and Griffin, 1989; Mansfield and Griffin, 2000; Mansfield and Griffin, 2002; Matsumoto and Griffin, 2002a; Nawayseh and Griffin, 2003), in the fore-and-aft and the vertical responses to the seated human body exposed to fore-and-aft whole-body vibration (Fairley and Griffin, 1990; Mansfield and Lundström, 1999; Holmlund and Lundström, 2001; Nawayseh and Griffin, 2005; Abdul Jalil, 2006), and in the vertical and the fore-and-aft responses of the standing human body exposed to vertical whole-body vibration (Matsumoto and Griffin, 1998; Subashi *et al.*, 2006).

To identify factors influencing the non-linearity, the effects of various steady-state sitting conditions have been studied, but the non-linearity has been found in all sitting postures investigated. Increased constant muscle tension at some locations of the body had no significant effect on the non-linearity (Mansfield and Griffin, 2002; Matsumoto and Griffin, 2002b). There are also insignificant changes in the non-linearity with different sitting contact pressures on the buttocks obtained by varying the footrest height for sitting subjects (Nawayseh and Griffin, 2003; Nawayseh and Griffin, 2005).

Electromyographic (EMG) measurements of trunk muscles show that muscle activity varies with vibration magnitude (Robertson and Griffin, 1989; Blüthner *et al.*, 2002). With some sitting conditions involving voluntary periodic upper-body movement, the non-linearity in the apparent mass resonance frequency was greatly reduced compared with a normal upright posture (Huang and Griffin, 2006). With voluntary movements, the resonance frequency was 4.7 Hz at 0.25 ms^{-2} r.m.s. and 4.6 Hz at 2.0

ms^{-2} r.m.s., whereas with a normal upright posture the resonance frequency was 5.5 Hz at 0.25 ms^{-2} r.m.s. and 4.4 Hz at 2.0 ms^{-2} r.m.s. The authors suggested that the reduction in the non-linearity might be due to a change in the involuntary phasic activity of the muscles stimulated by the whole-body vibration when the muscles are contracted voluntarily by the periodic upper-body movement. Alternatively, both the voluntary body movement and the associated muscular contraction may have altered the dynamic stiffness of the body by changes in the passive thixotropic behaviour of the tissues.

A relaxed supine position will involve less, or at least different, trunk muscle activity than sitting and standing. Measuring responses in a relaxed supine position may therefore allow analysis of the non-linearity with minimal muscle activity. The primary resonance frequency in the mechanical impedance of the supine human body during vertical excitation has been found in the vicinity of 6 Hz with both 2 to 20 Hz sinusoidal stimuli at 3.5 ms^{-2} r.m.s. (Vogt *et al.*, 1973) and 1 to 20 Hz sinusoidal stimuli at 2.1 ms^{-2} r.m.s. (Vogt *et al.*, 1978). With 0.69 ms^{-2} peak-to-peak sinusoidal vibration in the range 2 to 20 Hz, the resonance is reported to be around 5 Hz for transmissibility to the chest and 5 to 11 Hz for transmissibility to the abdomen of supine subjects (Liu *et al.*, 1996). With spacecraft crew in a semi-supine position, the primary resonance frequency of the mechanical impedance was observed between 7 and 11 Hz during 1 to 70 Hz sinusoidal vibration at 2.8 ms^{-2} r.m.s. (Vykukal, 1968). The variation in resonance frequency between these studies might be due to differences in the magnitudes of vibration, the supine postures, the measuring locations, the frequency resolutions, and inter-subject variability. Most of these studies were conducted with a single magnitude of vibration and some with an associated sustained acceleration.

The study reported here was designed to investigate the non-linear biodynamic response of the relaxed supine human body during vertical whole-body vibration. It was hypothesized that, in a relaxed supine position, both vertical and horizontal cross-axis apparent mass resonance frequencies would decrease with increasing vibration magnitude.

2. Method

2.1 Apparatus

The supine support consisted of three parts: the back support, the leg rest and the headrest (Figure 1).

The back support was a horizontal flat rigid 660 mm by 660 mm by 10 mm aluminium plate with a high stiffness 3 mm thick laterally treaded rubber layer attached on the top. The complete back support was bolted rigidly to the upper surface of the force platform which monitored the vertical (*x*-axis of the supine subject) and horizontal (*z*-axis of the supine subject) forces exerted by the subject on the back support. The force platform was bolted rigidly to the vibrator platform. The horizontal distance between the edge of the back support and the edge of the leg rest was 50 mm (Figure 1).

Subject legs rested on a horizontal flat rigid aluminium leg rest with an 8 mm thick high stiffness rubber layer attached on the top. The height of the leg rest was adjustable to allow the lower legs to rest flat on the leg rest.

The headrest was a horizontal flat rigid wooden block with 75 mm thick car-seat foam attached to the upper surface. The top surface of the complete headrest was approximately 50 mm higher than the back support. The horizontal distance between the back support and headrest was adjustable by moving the headrest so that a subject's head could rest comfortably.

Vertical motions were reproduced on a 1-metre stroke electro-hydraulic vertical vibrator capable of accelerations up to ±10 ms^{-2} in the laboratory of the Human Factors Research Unit.

The vertical (x-axis) and the horizontal (z-axis) accelerations at the vibrator platform were measured using two identical Setra 141A ±2 g accelerometers fixed on the plane of vibrator platform below the back support and between the leg rest and the force platform (Figure 1). The vertical (x-axis) and the horizontal (z-axis) forces at the back support were measured using a Kistler 9281 B21 12-channel force platform. The four vertical (x-axis) force signals and the four horizontal (z-axis) force signals from the four corners of the platform were summed and conditioned using two Kistler 5001 charge amplifiers.

An *HVLab* v3.81 data acquisition and analysis system was used to generate test stimuli and acquire the vertical and horizontal accelerations and the vertical and horizontal forces from the transducers. The two acceleration signals and the two force signals were acquired at 200 samples per second via 67 Hz analogue anti-aliasing filters.
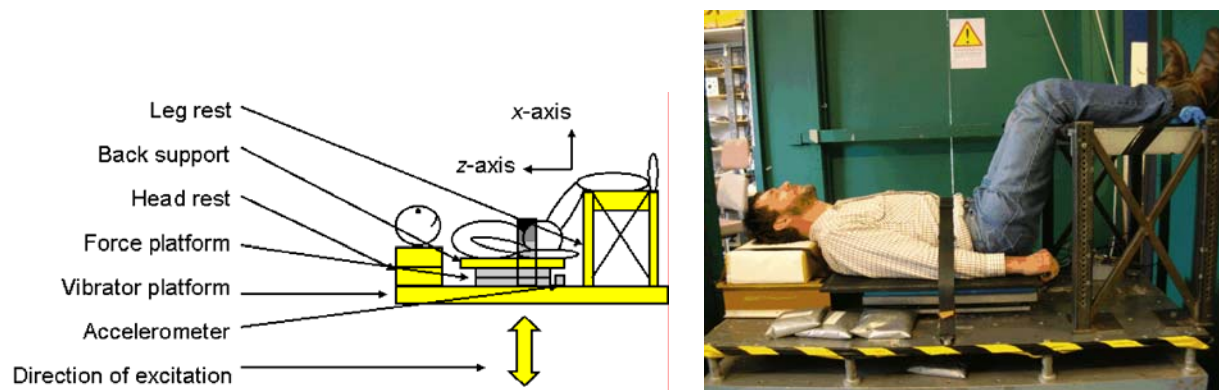

Figure 1　　　Schematic diagram of the supine support showing the supine position and the axes of the force (z-axis and x-axis) and the acceleration (x-axis) transducers. A photographic representation of a test subject in the relaxed supine position for vertical whole-body vibration.

2.2 Stimuli

The random stimuli used in this study had an approximately flat constant-bandwidth acceleration power spectrum over the frequency range 0.25 to 20 Hz using 10-pole Butterworth band-pass filters. Each random stimulus lasted for 90 seconds and was tapered at the start and end with 0.5-second cosine tapers. Five unweighted accelerations at 0.125, 0.25, 0.5, 0.75, and 1.0 ms^{-2} r.m.s. were generated using five different random seeds.

Twelve subjects were randomly divided into six groups with two persons per group. With different groups, different random seeds were used to generate random stimuli. During the random motions, the order of presentation of the five random stimuli (five magnitudes) was balanced across the six subject groups.

2.3 Posture

During each test motion, subjects maintained a relaxed supine position with their lower legs lifted and resting on the horizontal leg rest so as to give maximum back contact with the back support (Figure 1). The horizontal distance between the bottom of buttocks and the near edge of the leg rest was 55 mm for all subjects. The height of the leg rest was adjustable so that the lower legs could rest horizontally. Subjects were instructed to totally relax with their eyes closed during each test motion. A loose safety belt passed around the subject abdomen and arms.

2.4 Subjects

Twelve male subjects, aged between 20 to 42 years, with median (minimum and maximum) stature 1.73 m (1.66 m and 1.80 m) and total body mass 66.4 kg (58.3 kg and 86.2 kg) participated in the study.

The experiment was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

2.5 Analysis

The vertical (x-axis) and horizontal (z-axis) forces measured at the supine back support were analysed relative to the vertical (x-axis) acceleration (Figure 1). Two frequency response functions – apparent mass (where the force was in-line with the acceleration in the vertical direction) and horizontal cross-axis apparent mass (where the horizontal force was perpendicular to the vertical acceleration in the sagittal plane, i.e. the z-axis) – were calculated using the cross-spectral density method:

$$M(f) = S_{af}(f) \,/\, S_{aa}(f) \tag{1}$$

where, $M(f)$ is the vertical apparent mass or the horizontal z-axis cross-axis apparent mass, in kg; $S_{af}(f)$ is the cross spectral density between the measured forces and the vertical excitation acceleration; $S_{aa}(f)$ is the power spectral density of the vertical excitation acceleration.

Before calculating the apparent mass, mass cancellation was carried out in the time domain to subtract the force caused by the masses above the force sensing elements (a total of 30.5 kg obtained dynamically in the frequency range 0.25 to 20 Hz). No mass cancellation was needed to calculate the horizontal cross-axis apparent mass as there was no motion in this direction.

The apparent masses at the five magnitudes were normalised by dividing by the apparent mass modulus measured at frequencies between 0.5 and 1.5 Hz, where the body was considered rigid. For motion at 0.125 ms^{-2} r.m.s. the normalisation was carried out at 1.37 Hz; for 0.25 ms^{-2} r.m.s. at 1.37 Hz; for 0.5 ms^{-2} r.m.s. at 0.59 Hz; for 0.75 ms^{-2} r.m.s. at 0.59 Hz; for 1.0 ms^{-2} r.m.s. at 0.39 Hz. The

median normalised apparent masses at the five magnitudes were then calculated. The horizontal z-axis cross-axis apparent masses at the five magnitudes were normalised by dividing by the vertical apparent mass modulus measured at the same frequencies as that of the vertical apparent mass at each magnitude. Then the median normalised z-axis cross-axis apparent masses were calculated.

The cross spectral densities and the power spectral densities were both estimated via Welch's method at frequencies between 0.25 and 20 Hz. The frequency response functions for each of the 90-second continuous random signals used a fast Fourier transform (FFT) windowing length of 2048 samples, a hamming window with 100% overlap, a sampling rate of 200 samples per second and, therefore, a frequency resolution of 0.10 Hz.

To quantify the biodynamic non-linearity, the primary resonance frequencies of both individual and median normalised apparent masses are represented here by the frequency at which the modulus of the apparent mass was a maximum.

The horizontal z-axis cross-axis apparent mass 'peak frequency' was defined as the frequency at which the modulus of the cross-axis apparent mass had a maximum value within a limited frequency range where coherency was reasonably high (more than 0.7). The peak frequencies were considered to be a representation of the stiffness of some part of the body system similar to the resonance frequencies. This simplification was necessary as the z-axis cross-axis response of the body exhibited the behaviour of a multi-degree-of-freedom system with several peaks and troughs.

3. Results

3.1 Response in the vertical (x-axis) direction

The individual apparent masses and phases of 12 subjects with five vibration magnitudes of continuous random stimuli are shown in Figure 2. The median normalised apparent masses and phases of the group of 12 subjects are shown in Figures 3. The medians and ranges of individual apparent mass resonance frequencies are shown in Table 1.

Varying between subjects, the lowest coherency occurred with the lowest vibration magnitude (0.125 ms^{-2} r.m.s.) due to involuntary or voluntary subject movement (e.g. breathing and stretching), mainly at frequencies less than 1.0 to 2.0 Hz. The coherencies were generally in excess of 0.9 in the frequency range 0.5 to 20 Hz.

There was one dominant primary resonance frequency of the vertical apparent mass between 6.0 Hz and 12.0 Hz. A minor secondary resonance occurred in the frequency range 14.0 to 20.0 Hz, which was most distinct with subjects 1, 2, 6, 7, 8, 9, 10, and 12.

There was a significant effect of vibration magnitude on the apparent mass resonance frequencies ($p < 0.01$, Friedman two-way analysis of variance for k-sample cases). The resonance frequency decreased significantly with increasing vibration magnitude. There was a significant difference between each of the resonance frequencies at the five magnitudes ($p < 0.05$, Wilcoxon matched-pairs signed ranks test). There was no significant effect of vibration magnitude on the absolute difference between each two resonance frequencies with two adjacent vibration magnitudes (e.g., the difference

between the resonance frequencies with 0.25 and 0.5 ms^{-2} r.m.s. and the difference between the resonance frequencies with 0.75 and 1.0 ms^{-2} r.m.s. were not significantly different, p = 0.55, Friedman).

The median resonance frequencies of the apparent masses of the 12 subjects decreased from 9.72 Hz to 7.42 Hz as the vibration magnitude increased from 0.125 ms^{-2} r.m.s. to 1.0 ms^{-2} r.m.s. (Table 1).

The resonance frequencies of median normalised apparent masses (Figure 3) of the group of 12 subjects were 10.35, 9.67, 8.01, 7.42, and 7.32 Hz with vibration magnitudes of 0.125, 0.25, 0.5, 0.75 and 1.0 ms^{-2} r.m.s., respectively.
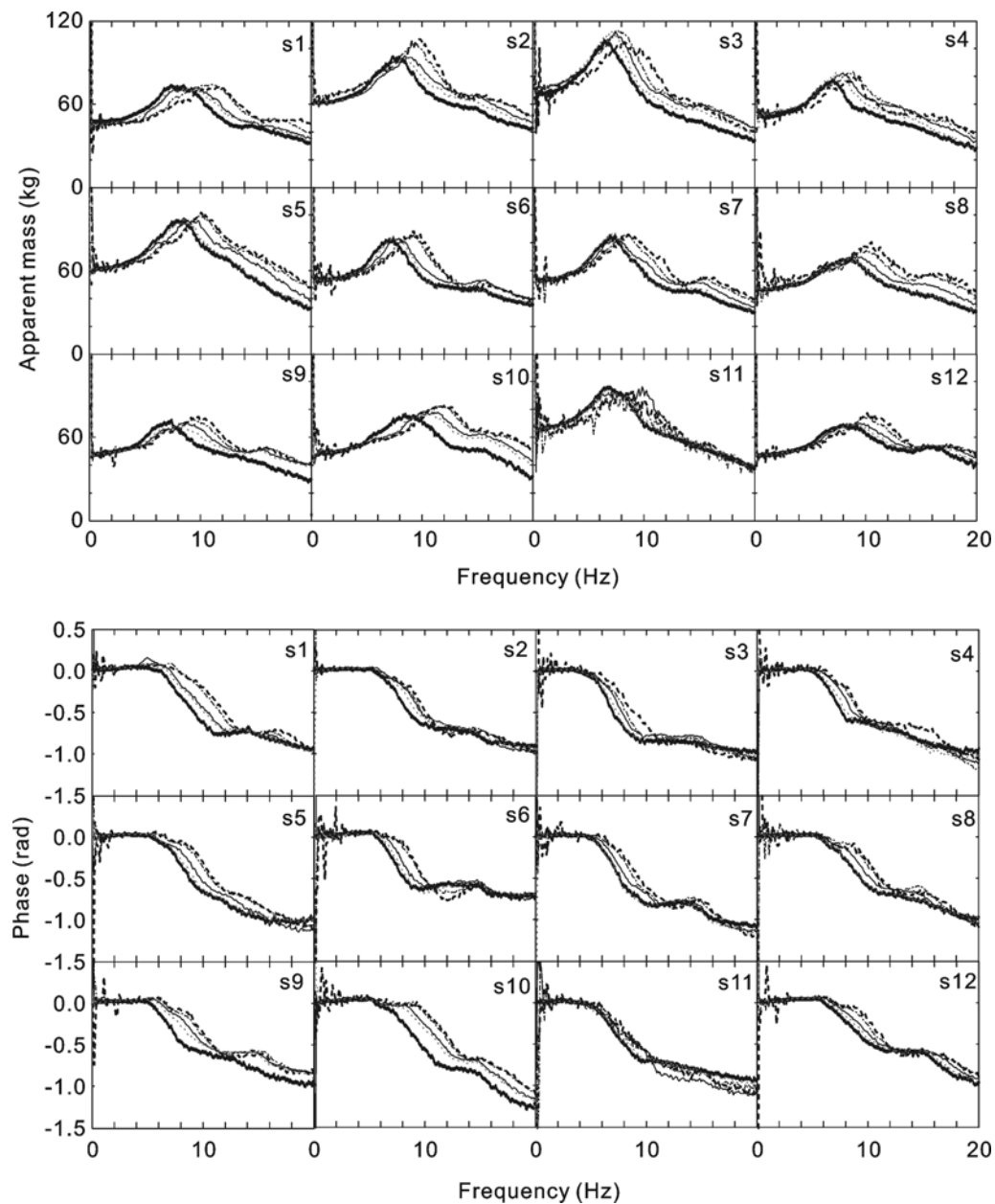

Figure 2 Individual apparent masses (upper) and phases (lower) of 12 subjects (S1 to S12) at five vibration magnitudes (- - - - - 0.125 ms^{-2} r.m.s.; _ ._ ._ ._ ._ 0.25 ms^{-2} r.m.s.; ——— 0.5 ms^{-2} r.m.s.; ········ 0.75 ms^{-2} r.m.s.; ▬▬▬ 1.0 ms^{-2} r.m.s.).
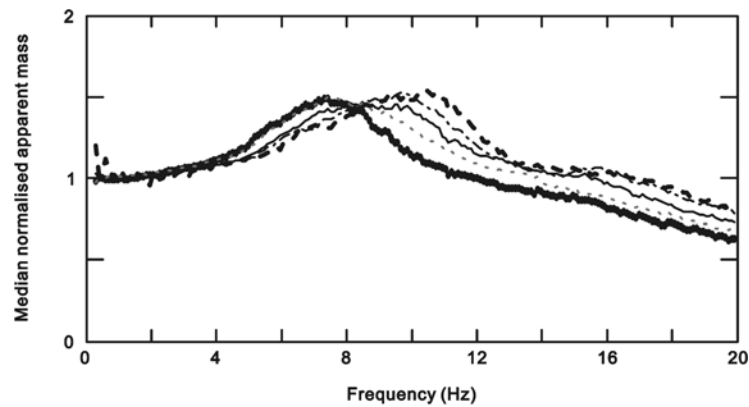
Figure 3 Median normalised apparent masses of the group of 12 subjects at five vibration magnitudes (- - - - 0.125 ms^{-2} r.m.s.; _._._._._ 0.25 ms^{-2} r.m.s.; ——— 0.5 ms^{-2} r.m.s.; .... 0.75 ms^{-2} r.m.s.; ——— 1.0 ms^{-2} r.m.s.).

Table 1 Medians and ranges of resonance frequencies of apparent masses of 12 subjects at five vibration magnitudes (0.125, 0.25, 0.5, 0.75 and 1.0 ms^{-2} r.m.s.).

	Resonance frequency (Hz)		
Magnitude	Minimum	Median	Maximum
0.125 ms^{-2} r.m.s.	7.13	9.72	12.01
0.25 ms^{-2} r.m.s.	7.52	9.28	11.33
0.5 ms^{-2} r.m.s.	7.42	8.74	11.43
0.75 ms^{-2} r.m.s.	6.45	8.50	10.84
1.0 ms^{-2} r.m.s.	6.45	7.42	8.50

3.3 Response in the horizontal (z-axis) cross-axis direction

The individual horizontal *z*-axis cross-axis apparent masses of the 12 subjects with the five magnitudes of continuous random vibration are shown in Figure 4. The median normalised cross-axis apparent masses of the group of 12 subjects are shown in Figures 5. The median and range of the individual peak frequencies are shown in Table 2.

Varying between subjects, the coherencies were lower than 0.5 with the lowest vibration magnitude (0.125 ms^{-2} r.m.s.) at frequencies less than 4.0 to 6.0 Hz. The coherencies were generally in excess of 0.7 in the frequency range from about 6 Hz to between 14 and 16 Hz.

There were three distinguishable peaks with each cross-axis apparent mass curve: the first below about 4.0 to 8.0 Hz, the second from around 4.0 and 8.0 Hz to around 12.0 Hz, the third between 14 and 16 Hz (Figures 4 and 5). The third peak was affected by the non-rigidity of the vibrator platform in the horizontal direction during the vertical excitation. The first two peaks were caused by the

biodynamic response of the human body which were of interest. The first peak had a low coherency (less than 0.3), so the second peak was used to obtain the horizontal z-axis cross-axis apparent mass peak frequency as described in Section 2.5. The magnitudes of the horizontal z-axis cross-axis apparent masses were less than 10% of the apparent masses in the vertical direction.

There was a significant effect of vibration magnitude on the horizontal z-axis cross-axis apparent mass peak frequencies ($p < 0.01$, Friedman). The peak frequency decreased significantly with increasing vibration magnitude from 0.125 to 0.75 ms^{-2} r.m.s. ($p < 0.05$, Wilcoxon). There was no significant difference in the peak frequencies between 0.75 and 1.0 ms^{-2} r.m.s. ($p = 0.14$, Wilcoxon). There was no significant difference in the absolute difference between the two peak frequencies with two adjacent vibration magnitudes (e.g., the difference between the peak frequencies with 0.25 and 0.5 ms^{-2} r.m.s. and the difference between the peak frequencies with 0.75 and 1.0 ms^{-2} r.m.s. were not significantly different, $p = 0.87$, Friedman).

The median peak frequencies of the cross-axis apparent masses of 12 subjects decreased from 8.89 Hz to 7.42 Hz as the vibration magnitude increased from 0.125 to 0.75 ms^{-2} r.m.s. (Table 2).

The peak frequencies of the median normalised cross-axis apparent masses of the group of 12 subjects were 8.40, 7.91, 7.52, 7.42, and 7.42 Hz with vibration magnitude of 0.125, 0.25, 0.5, 0.75, and 1.0 ms^{-2} r.m.s., respectively (Figure 5).
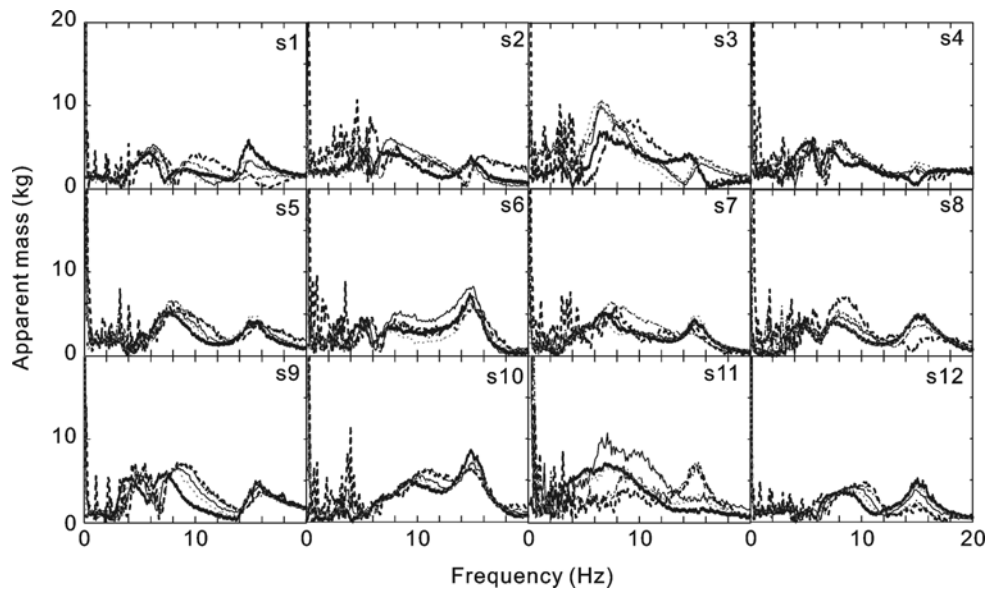

Figure 4   Individual horizontal z-cross-axis apparent masses of 12 subjects (S1 to S12) at five vibration magnitudes (- - - - - 0.125 ms^{-2} r.m.s.; _ ._ ._ ._ ._ 0.25 ms^{-2} r.m.s.; ——— 0.5 ms^{-2} r.m.s.; .... 0.75 ms^{-2} r.m.s.; ▬▬▬ 1.0 ms^{-2} r.m.s.).
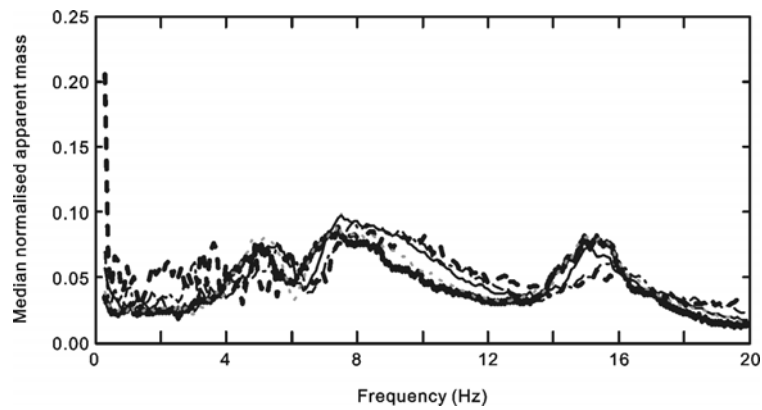
Figure 5 Median normalised horizontal *z*-axis cross-axis apparent masses of the group of 12 subjects at five vibration magnitudes (**- - - - -** 0.125 ms^{-2} r.m.s.; _._._._._ 0.25 ms^{-2} r.m.s.; ——— 0.5 ms^{-2} r.m.s.; **………** 0.75 ms^{-2} r.m.s.; ——— 1.0 ms^{-2} r.m.s.).

Table 2 Medians and ranges of peak frequencies of horizontal *z*-axis cross-axis apparent masses of 12 subjects at five vibration magnitudes (0.125, 0.25, 0.5, 0.75, and 1.0 ms^{-2} r.m.s.).

Cross-axis peak frequency (Hz)			
Magnitude	Minimum	Median	Maximum
0.125 ms^{-2} r.m.s.	7.81	8.89	11.04
0.25 ms^{-2} r.m.s.	6.64	8.26	10.74
0.5 ms^{-2} r.m.s.	6.54	8.01	9.86
0.75 ms^{-2} r.m.s.	6.35	7.47	9.86
1.0 ms^{-2} r.m.s.	6.45	7.42	9.28

4. Discussion

4.1 Response in the vertical (x-axis) direction

The vertical in-line apparent masses at five magnitudes show that the supine body is significantly non-linear: the resonance frequencies decreased with increasing vibration magnitude. The relaxed supine position was assumed to involve less muscular-postural control of the body than the sitting conditions used in most previous studies of the non-linearity of the body. The effect of the muscular activity on the biodynamic non-linearity of the body may therefore be assumed to be small. The consistent non-linear response here may suggest that the non-linearity is not caused by active control of muscles but some passive property of the body (e.g., thixotropy) or, alternatively, some involuntary reflex response of the body.

Involvement of muscle activity implies that muscles are activated either by voluntary control or reflex responses (i.e. involuntary muscle response to excitation). Involvement of a passive thixotropic

characteristic implies that the dynamic stiffness of muscles or other body components undergo a reduction as a result of perturbation, with a recovery after a certain period of stillness (Lakie, 1986). Fairley and Griffin (1989) speculated that the non-linear loosening effect of the musculo-skeletal structure had a similar mechanism to the thixotropic property of relaxed human muscles. However, there was no experimental data to support this hypothesis. The current study shows that the non-linearity is present not only in postures where there is muscular control but also in postures with minimal muscular activity. Previous studies with upright sitting and standing postures have found that variations in posture so as to vary the muscular tension have little effect on the non-linearity. This tends to support the hypothesis that thixotropy is the cause of the non-linearity.

Compared to a normal no-backrest upright sitting condition, the supine position increased the equivalent dynamic stiffness of the body (indicated by the increased resonance frequency) at all vibration magnitudes, and also increased the damping reflected in a lower magnitude of the apparent mass at resonance. In the present study, the median normalised apparent masses (and resonance frequencies) of the 12 supine subjects at resonance were 1.54 (10.35 Hz), 1.52 (9.67 Hz), 1.47 (8.01 Hz), 1.50 (7.42 Hz) and 1.49 (7.32 Hz) with vibration magnitudes of 0.125, 0.25, 0.5, 0.75 and 1.0 ms^{-2} r.m.s., respectively. While the median normalised apparent masses (and resonance frequencies) of 12 upright sitting subjects at resonance were 1.80 (5.27 Hz), and 1.84 (4.20 Hz) at 0.25 and 2.0 ms^{-2} r.m.s. respectively (Huang and Griffin 2005). This may indicate an increase in stiffness and damping when changing from an upright sitting posture to the supine posture. An increase in stiffness and damping has been found when an upright sitting subject makes contact with a backrest or a backrest is reclined (Toward, 2003). The author explained that if the body can be represented as a multi degree of freedom system, the additional stiffness and damping could come from additional constraint from the backrest. A similar explanation could be applied to the present results where the supine back support introduced more constraint than an upright backrest when seated.

4.2 Response in the horizontal (z-axis) cross-axis direction

The horizontal z-axis cross-axis apparent masses at five magnitudes show that the supine body is significantly non-linear: the peak frequency decreased with increasing vibration magnitude. The cross-axis response was caused by the shear deformation in the horizontal direction due to imbalanced moment along the z-axis relative to the centre of pressure of the supine body in the z-axis. The two possible explanations of the non-linearity in the vertical direction – passive thixotropy and involuntary reflex responses of muscles – are associated with axial deformation in the direction of excitation. The presence of non-linearity in the cross-axis direction may suggest that thixotropy or reflex responses occur with shear deformation in the horizontal cross-axis. Shear deformation in the horizontal, z-axis, could be due to either the tissues between the spinal column and the back support, or the movement of tissues and organs within the skeletal structure.

The non-linear cross-axis response in the mid-sagittal plane in the present study is similar to that with a normal upright sitting posture with no backrest (Nawayseh and Griffin 2003). However, the horizontal cross-axis response in the supine position is much less than with an upright sitting posture, due to less body movement in the cross-axis direction.

5. Conclusions

During vertical whole-body vibration, the biodynamic response of the relaxed supine body is non-linear, both in the vertical direction and in the horizontal *z*-axis cross-axis direction.

Compared with apparent masses measured with upright sitting and standing postures, the supine posture exhibited a stiffer biodynamic system with less horizontal cross-axis response.

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