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Fore-and-aft apparent mass of the back: Nonlinearity and variation with vertical location

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Abstract

The dynamic interaction between the human back and a backrest is complex: the forces at the back–backrest interface depend on the dynamic characteristics of both the back and the backrest, which vary with location over the backrest. This experimental study was designed to investigate the variation in the ratio of the force to acceleration (referred to as the apparent mass) at the back associated with variations in the vertical position and the magnitude of fore-and-aft vibration. Twelve male subjects were exposed to random fore-and-aft vibration in the frequency range 0.25–10 Hz at five vibration magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 m s^{-2} rms). The fore-and-aft forces were measured at five vertical locations (using a flat vertical contact area 120 mm in height) and with a flat vertical backrest covering the entire back. At all locations, but not for all subjects, three resonances were observed in the fore-and-aft apparent mass of the back. The first resonance around 1–2 Hz was most visible at the middle and lower back. A clearer, second resonance was exhibited between 4 and 5 Hz (in the upper back) and between 5 and 8 Hz (in the middle and lower back). A third resonance around 7 Hz was most apparent in the middle back. The forces at the back were highly dependent on the location: the lower back produced greater forces than the middle and the upper back. The apparent mass of the entire back showed three resonances at similar frequencies: around 2 Hz, between 4 and 6 Hz and between 7 and 8 Hz. The first and the third resonances were observed in most subjects, but not all. With the entire back, the forces were similar to those with the middle back. With variations in vibration magnitude, a nonlinearity in the apparent mass of the back was evident at all locations and with the entire back. It is concluded that biodynamic models of seated persons in contact with a backrest and excited by fore-and-aft vibration should allow for the effects of vibration magnitude and the location of excitation.

1. Introduction

When seated persons are exposed to whole-body vibration, forces are normally applied to the body by the supporting seat surface, the backrest and the footrest. The forces can be measured and used to calculate the mechanical impedance, or apparent mass, of the body at the seat and the backrest. The apparent mass

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provides information on the dynamic responses of the human body that can assist the development of biodynamic models and advance understanding of the coupling between the body and compliant seating.

There have been extensive studies of the apparent mass of seated persons in the vertical direction [1–4]. With vertical excitation, the human body shows a clear resonance at 4–5 Hz (e.g., [1]) that has been associated with a mode of the entire body [5,6], although variations in body posture or muscle tension can alter this resonance frequency [2,3]. Some studies have investigated the apparent mass of the seated body in horizontal directions (i.e. with fore-and-aft or lateral excitation) (e.g., [7–10]). Most measurements of the apparent mass of the body have been obtained with subjects seated on rigid seats without a backrest.

With both vertical and horizontal excitation, backrests will contribute to the dynamic forces applied to a seated person. With vertical vibration, a backrest may produce a shear force on the back, stiffening the upper body and increasing the resonance frequency [2,4]. With fore-and-aft vibration, a backrest may also restrict body movements: without a backrest, the fore-and-aft apparent masses of seated persons have been found to have resonances at 0.7 and 2.5 Hz, but with a backrest only one resonance was evident, around 3.5 Hz [7]. The authors of that study suggested that the increase in the resonance frequency with the backrest was due to stiffening of the upper body.

With seated subjects exposed to whole-body fore-and-aft vibration in a rigid seat, three resonances in apparent masses have been found from the forces and accelerations at a flat backrest: less than 2, 3–5 and 4–7 Hz [11]. The first and third resonances were clearer at low vibration magnitudes than at high magnitudes. In another study, a first resonance around 3 Hz was evident in the 'cross-axis' fore-and-aft apparent mass of the back when subjects were exposed to vertical vibration ('cross-axis' apparent mass is calculated from the force in a direction other than the direction of excitation and the acceleration in the direction of excitation). In the same study, all subjects showed a 'cross-axis' fore-and-aft resonance of the back between 5 and 10 Hz, with two peaks evident in this frequency range [4].

Without a backrest the apparent mass of the seated human body in the fore-and-aft direction is nonlinear with vibration magnitude: the resonance frequency of the second peak (i.e. around 2.5 Hz) decreasing with increasing vibration magnitude—but the vibration magnitude appears to have no effect on the first peak (i.e. around 0.7 Hz) [7]. A similar nonlinearity (i.e. a reduction in the frequency of the principal resonance frequency around 3–5 Hz with increasing vibration magnitude) has been reported by Holmlund and Lundström [9]. Nawayseh and Griffin [11] found that the fore-and-aft apparent mass of the back during fore-and-aft excitation of seated subjects was similarly nonlinear with vibration magnitude.

The fore-and-aft transmissibility of a seat backrest can vary with height above the seat surface [12]. It was suggested that this might partly be caused by variations in the dynamic stiffness of the backrest and partly by differences in the apparent mass of the back at different heights.

The present study was designed to investigate the forces at different locations on the back when subjects were exposed to whole-body fore-and-aft excitation. It was hypothesised that the apparent mass of the back would vary with location and that the apparent mass of the back would vary nonlinearly with vibration magnitude.

2. Method

2.1. Subjects

Twelve male subjects, with ages, weights, statures and seat-to-shoulder heights as shown in Table 1, participated in the study. The experiment was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. Prior to vibration exposure, each subject completed a health questionnaire and an exposure consent form.

2.2. Apparatus

2.2.1. Vibration generation

The experiment was performed using an electro-hydraulic vibrator in the Human Factors Research Unit at ISVR, University of Southampton, capable of producing a 1-m peak-to-peak horizontal displacement.

Table 1
Subject age, stature, weight and seat-to-shoulder height

	Age (yr)	Stature (m)	Body mass (kg)	Sitting shoulder-height (m) [13]
Minimum	20	1.64	50	0.58
Maximum	29	1.78	85	0.64
Median	23.8	1.72	67.7	0.62
Mean	23.5	1.71	66.9	0.60
Standard deviation	2.6	0.049	10.54	0.034

Table 2
Location of the wooden block on the force plate with the corresponding height, measured from the seat surface to the centre of the block at each location

Location	Vertical distance, measured from the centre of the block at each location to the seat surface (mm)
1	60
2	180
3	300
4	420
5	600
Entire back	Wooden block was removed so that the back was in contact with the force platform

The motion of the vibrator was measured using an Entran EGCSY-240D*-10 accelerometer mounted on the moving platform.

2.2.2. Seating and transducers

A rigid seat with a horizontal flat rigid seat-pan and a vertical flat rigid backrest was securely mounted on the vibrator platform. A force platform (Kistler 9421 A11) capable of measuring force in the fore-and-aft direction was secured on the rigid flat vertical backrest of the seat. The force plate (600 mm by 400 mm) consisted of four quartz force transducers. The signals from each of the force transducers were summed and conditioned using a Kistler 5007 charge amplifier. The acceleration of the backrest was measured using an Entran EGCSY-240D*-10 accelerometer positioned 350 mm above the horizontal seat surface.

A wooden block (600 mm $\times$ 120 mm $\times$ 50 mm) was placed between the force platform and the back at one of five different heights so as to measure the fore-and-aft force at the back at different heights above the seat surface. The block was securely attached to the surface of the force platform using clamps. The five areas were obtained by dividing the height of the force platform into five equal bands, with each band 120 mm in height. For measurements with the entire back in contact with the backrest, the wooden block was removed. Table 2 lists the vertical distance of each location, measured from the horizontal seat surface to the centre of the block at each location, including the condition in which there was contact with the entire back. The arrangement of the experimental equipment is shown in Fig. 1. The apparatus was rigid over the range of frequencies investigated in this study.

2.2.3. Subject posture

A loose safety belt was fastened around the subjects for safety but did not impinge on their movements. Subjects were asked to sit so as to make contact between their backs and the wooden block and maintain the same posture throughout the experiment. With the whole back in contact with the backrest, subjects were instructed to adopt an upright posture with the back leaning against the backrest.

With the wooden block at locations 1 and 2, there was a gap between the middle and upper back and the force plate of only 50 mm (i.e. the thickness of the wooden block). In a preliminary study, when a subject was

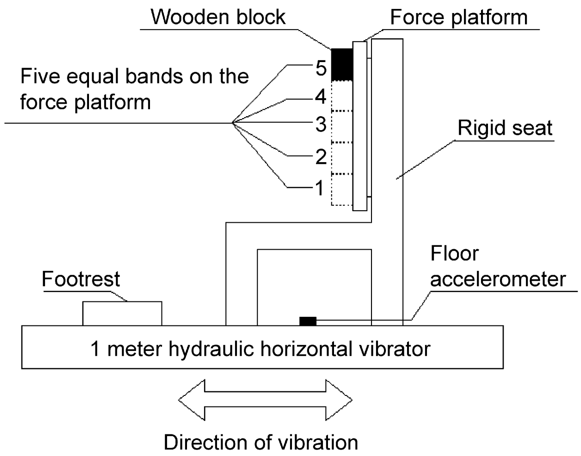

Fig. 1. Experimental set-up.

exposed to fore-and-aft vibration, the middle and upper back were observed to 'accidentally' touch the force plate when the wooden block was positioned at either location 1 or location 2. To prevent any effect on the force measurements at these locations, subjects were instructed to maintain the sitting posture and avoid the back touching the force plate directly.

The legs of subjects' rested on a horizontal footrest with the height of the footrest adjusted for each subject so as to make the upper and lower legs horizontal and vertical, respectively. The hands of subjects rested on their laps and held an emergency stop button.

2.2.4. *Signal generation*

A Gaussian random signal with a duration of 60 s and a nominally flat constant bandwidth acceleration spectrum over the frequency range of 0.25–10 Hz was generated using a *HVLab* version 3.81 Data Acquisition and Analysis system. At all locations, every subject was exposed to five vibration magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 $m\,s^{-2}$ rms) presented in an independent random order. All acceleration signals were conditioned and acquired directly into the *HVLab* Data Acquisition system at 512 samples per second via 170 Hz anti-aliasing filters.

2.3. *Analysis*

All acquired signals were normalised to remove any d.c. offset from the time histories using the *HVLab* data acquisition system before they were used to calculate the apparent mass at the back.

The ratios of the force to acceleration (referred to as the apparent mass) were calculated for five locations on the back using the cross-spectral density (CSD) method (see Section 4.1):

$$M_B(\omega) = \frac{F(\omega)}{a(\omega)} \tag{1}$$

where $M_B(\omega)$, is the apparent mass of the back, $F(\omega)$, is the CSD of the force and acceleration and $a(\omega)$ is the power spectral density of the input acceleration. The results are a complex function that is capable of giving modulus and phase. A resolution of 0.25 Hz was used, giving 60 degrees-of-freedom.

The measured fore-and-aft forces at the back were influenced by the apparent mass of the subject, the mass of the force plate supported on the force transducer, the mass of the wooden block and also the masses of the clamps. Hence, a time domain method of mass cancellation was applied to subtract the masses 'above' the force plate (28.8 kg for the plate, 1.2 kg for the wooden block, 0.8 kg for the clamps) from the measured fore-and-aft apparent mass of the back at each location.

Statistical analysis of the data was performed using nonparametric tests: the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks test for related samples, and the Spearman test for correlations.

3. Results

3.1. Apparent mass of the back at five locations above the seat surface

Inter-subject variability was observed in the apparent masses of the backs of the 12 subjects at all five locations (Fig. 2). There was a tendency towards less variability at greater vibration magnitudes at all locations, and less variability at locations 4 and 5 at frequencies greater than 6 Hz at all vibration magnitudes.

There was a first peak in the apparent mass around 2 Hz in most individual data and at all locations—although most visible at the middle and the lower back (locations 1–3). A second, clearer, peak was present around 4–5 Hz at the upper back (locations 4–5), and at a higher frequency at the middle and the lower back (locations 1–3)—between 5 and 8 Hz. A third peak, around 7 Hz, appeared in the responses of a few subjects—clearer at locations 3 and 4 at 0.2, 0.4 and 0.8 $m\,s^{-2}$ rms.

The coherencies were generally high (more than 0.85) at all locations, except at frequencies less than 5 Hz at 0.1 $m\,s^{-2}$ rms and greater than 5 Hz at 1.6 $m\,s^{-2}$ rms at all locations (where coherencies were less than 0.85). This might have arisen from noise in the system at the lowest vibration magnitude and a tendency of the back to lose contact with the wooden block at the highest magnitude.

3.1.1. Effect of measurement location

An example of typical moduli and phases of the apparent mass at all locations for one subject is shown in Fig. 3. At 0.5 Hz, there were high forces at the lower back, with decreasing forces with increasing height above the seat surface. A first peak around 1–2 Hz is visible at all locations—more pronounced at the middle and the lower back (i.e. locations 1–3) with a frequency around 1 Hz and with a greater apparent mass at resonance than at the upper back (i.e. locations 4–5). A second peak is evident between 5 and 8 Hz—clearer at the middle and the lower back, but not very clear at the upper back at lower frequencies (between 4 and 5 Hz).

A trough in the apparent mass was observed between 2 and 4 Hz at the middle and the lower back. However, high forces were observed at the upper back at these frequencies, with a tendency to become a peak. Generally, forces at the lower back were greatest at frequencies less than 1.5 Hz and at frequencies greater than 5 Hz, whereas between 1.5 and 5 Hz the middle back produced greatest forces.

Clear differences with location above the seat surface can be seen in the individual apparent masses of the backs of the 12 subjects (Figs. 4 and 5). At low frequency (0.5 Hz), there was a significant difference in apparent mass at the different locations ($p<0.05$, Friedman). The forces at the lower back (locations 1 and 2) were greater than at the middle and the upper back (locations 3–5). There was also a significant difference in apparent mass over the five measurement locations at all vibration magnitudes and at each preferred $\frac{1}{3}$-octave centre frequency from 1 to 10 Hz ($p<0.05$, Friedman), except at 6.3 Hz (at 0.1 $m\,s^{-2}$ rms) and at 10 Hz (at 0.4 and 0.8 $m\,s^{-2}$ rms).

At 0.5 Hz, there was an increasing phase shift, by up to approximately 28° (0.5 radians), from the upper to the lower back at all vibration magnitudes (see Figs. 2, 3 and 5). The phase shift was observed in the results of all subjects, although the extent of the phase shift varied between subjects and vibration magnitudes.

3.1.2. Effect of vibration magnitude

The force at the back varied nonlinearly with vibration magnitude at all five locations (Figs. 6 and 7). The resonance frequencies and the apparent masses at resonance tended to decrease with increasing

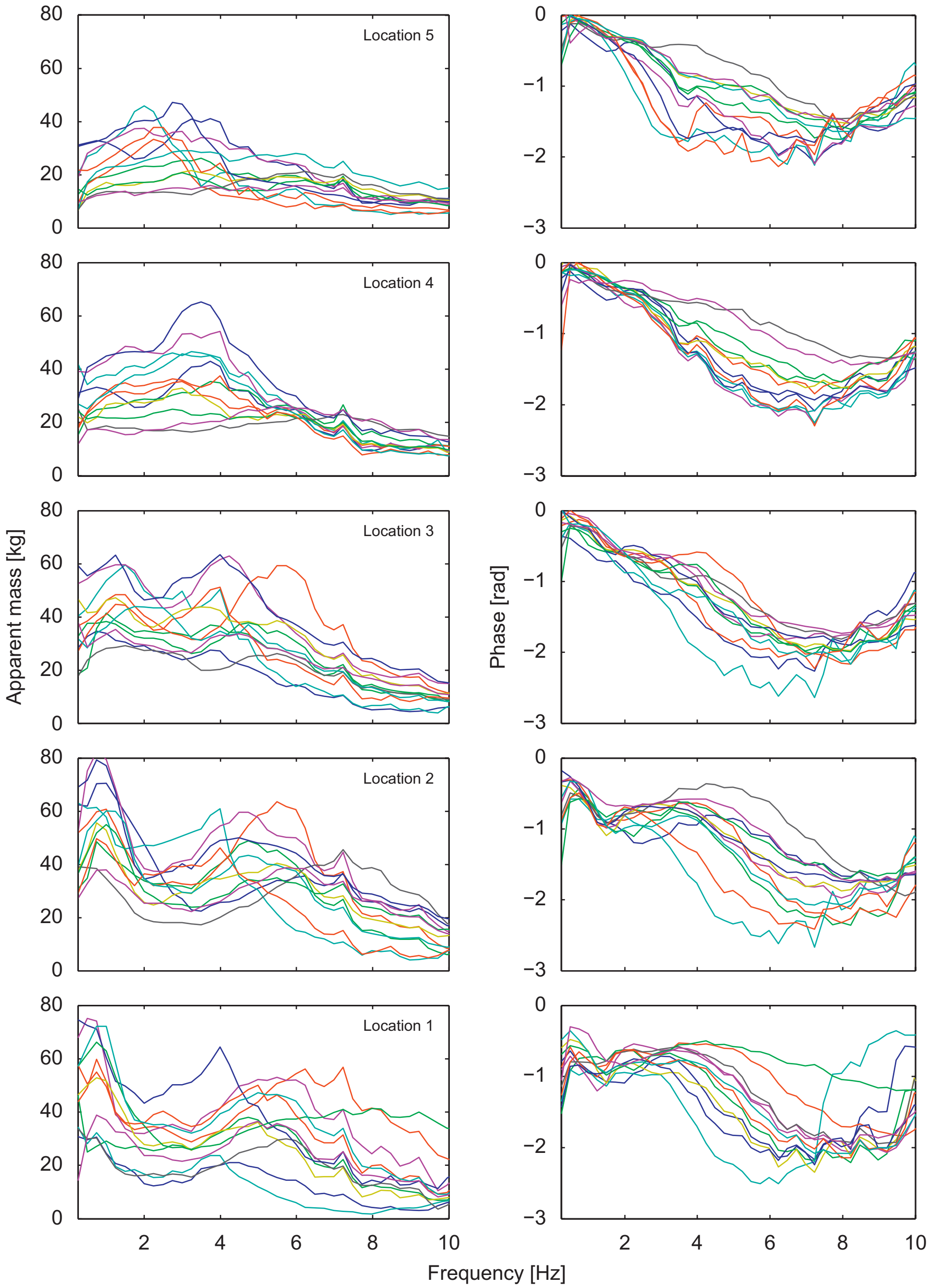

Fig. 2. Inter-subject variability in the apparent masses and phases of the backs of 12 subjects at different heights above the seat surface at a vibration magnitude of 0.8 $m s^{-2}$ rms.

vibration magnitude at all locations. At each location and at each preferred 1/3-octave centre frequency, from 1 to 10 Hz, the statistical significances of the variations in the modulus of the apparent masses were investigated. The apparent mass at the lower and upper back (locations 1 and 5) varied nonlinearly with vibration magnitude at frequencies greater than 5 and 1.25 Hz, respectively ($p<0.05$, Friedman). The apparent mass around the middle back (locations 2–4) varied nonlinearly at frequencies greater than 2.5 Hz ($p<0.05$).

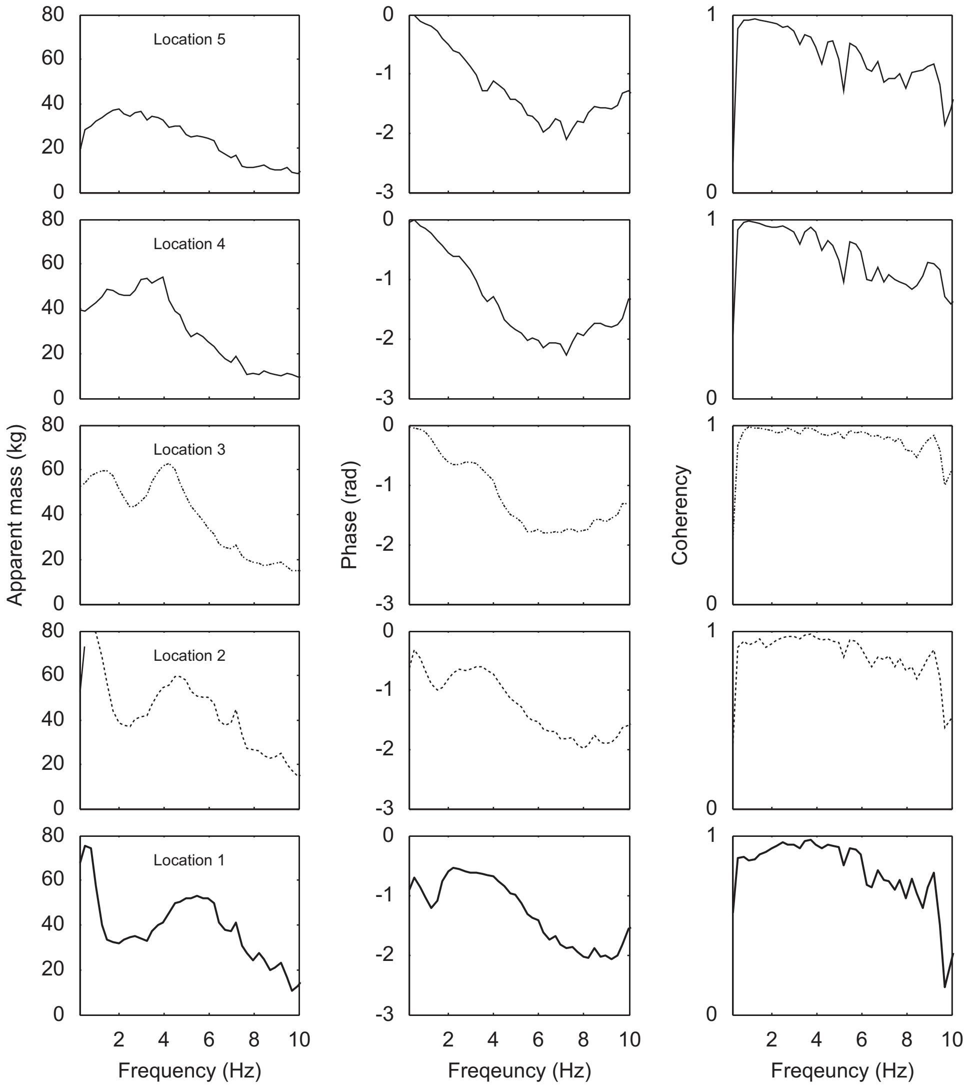

Fig. 3. Example of typical apparent mass moduli, phases and coherencies measured at the back of one subject (subject 5) with a magnitude of $0.8\,\mathrm{m\,s^{-2}}$ r.m.s.

3.2. Apparent mass of the entire back

The large subject variability in the fore-and-aft apparent masses of the back at the five locations was also present in the fore-and-aft apparent masses of the entire backs of ten subjects (Fig. 8). (Note: the results of subjects 1 and 2 were excluded due to an experimental problem).

A first peak in the apparent mass around 2 Hz was observed in most of the ten subjects. A second, more pronounced peak was observed between 4 and 6 Hz. A third, less profound peak, was noticed in some of the individual responses between 7 and 8 Hz.

There were positive correlations between total body mass and the modulus of the apparent mass of the entire back at low frequency (0.5 Hz) ($p<0.05$, Spearman). Body stature and the seat-to-shoulder height were not significantly correlated with the apparent mass of the entire back at 0.5 Hz ($p>0.05$). The frequency of the first peak of the apparent mass of the entire back (around 2 Hz) was positively correlated with total body mass at all vibration magnitudes ($p<0.05$), except at $1.6\,\mathrm{m\,s^{-2}}$ rms, but there were no significant correlations

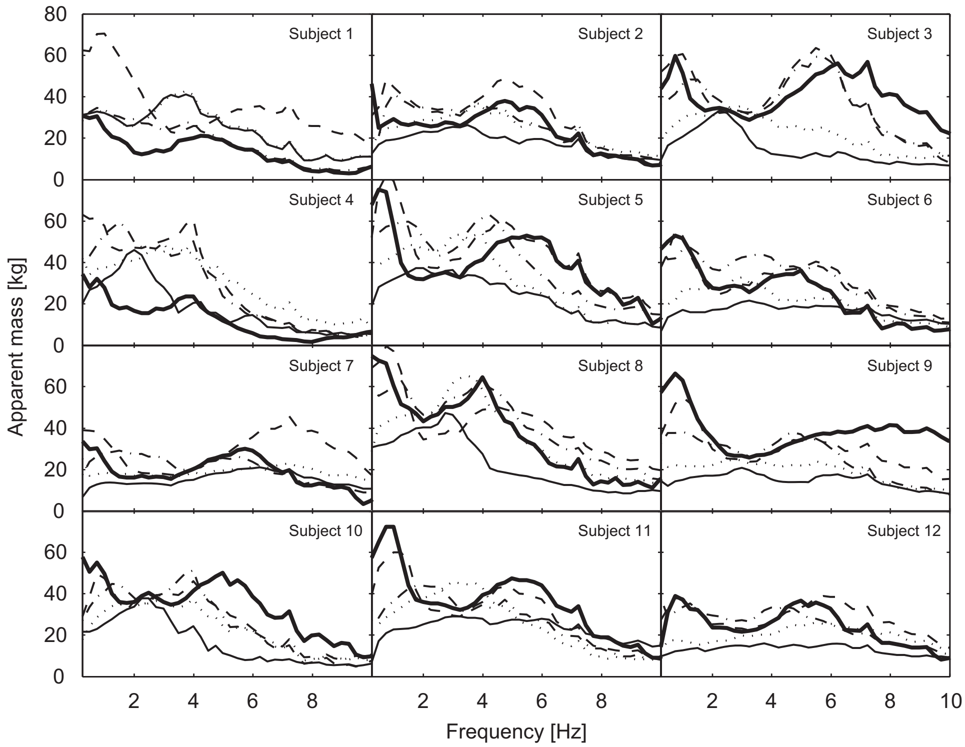

Fig. 4. The effect of measurement location on the moduli of the apparent masses measured at the backs of twelve subjects at a vibration magnitude of 0.8 $m\,s^{-2}$ r.m.s.: location 1 (▬▬▬), location 2 (– – – –), location 3 (–· –· –· –), location 4 (············) and location 5 (———).

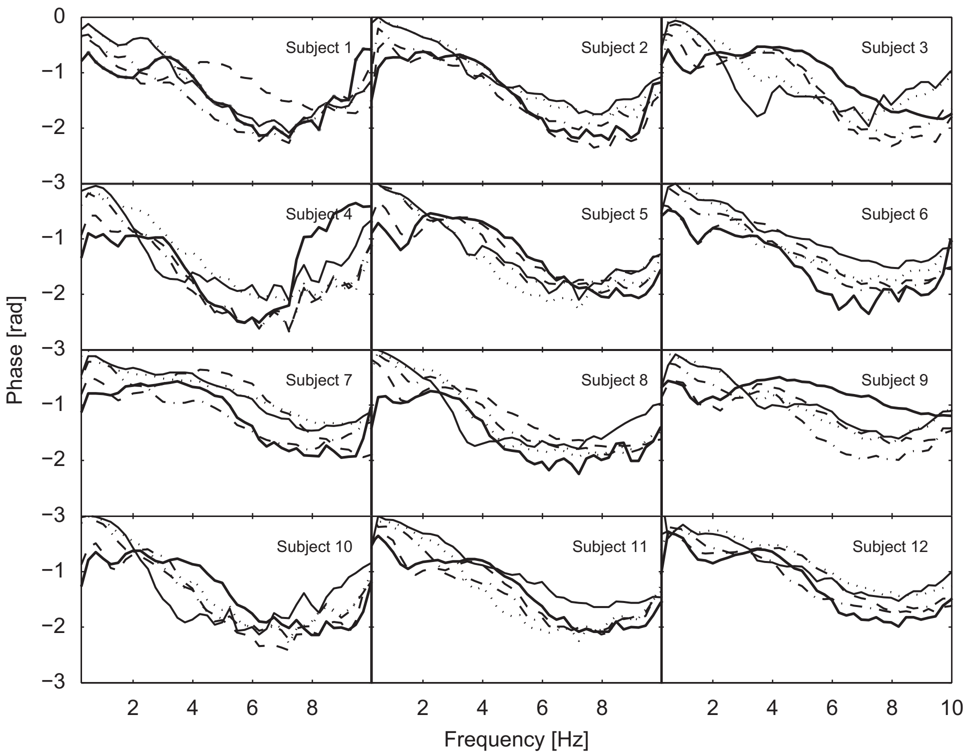

Fig. 5. The effect of measurement location on the phases of the apparent masses measured at the backs of twelve subjects at a vibration magnitude of 0.8 $m\,s^{-2}$ r.m.s.: location 1 (————), location 2 (– – – –), location 3 (–· –· –· –), location 4 (············) and location 5 (▬▬▬).

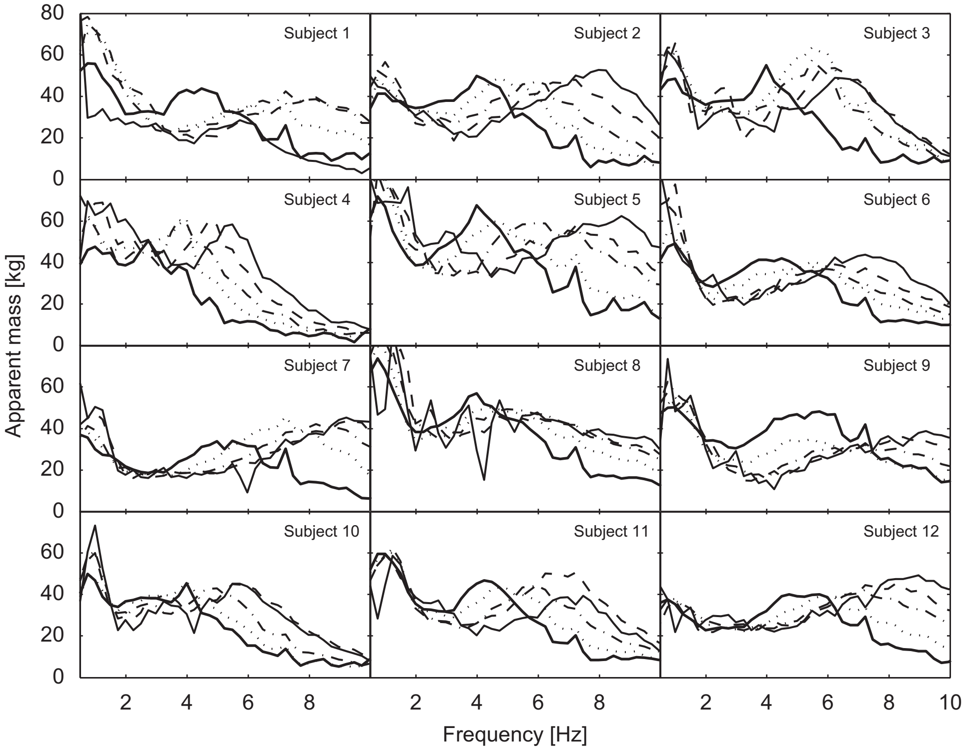

Fig. 6. Effect of vibration magnitude on the fore-and-aft apparent masses measured at the backs of twelve subjects at location 3: 0.1 $m s^{-2}$ r.m.s. (———), 0.2 $m s^{-2}$ r.m.s. (– – – –), 0.4 $m s^{-2}$ r.m.s. (–· –· –· –), 0.8 $m s^{-2}$ r.m.s. (··········) and 1.6 $m s^{-2}$ r.m.s. (▬▬▬).

between the second and third peak and total body mass ($p > 0.05$). The statures and seat-to-shoulder heights of the subjects were also uncorrelated with the apparent mass of the second and third peaks ($p > 0.05$).

3.2.1. Effect of vibration magnitude

With an increase in vibration magnitude, there were reductions in the modulus of the apparent mass and increases in the phase lag measured with the entire back. The changes were statistically significant at frequencies greater than 5 Hz ($p < 0.05$, Friedman; Fig. 9).

3.3. Comparing five locations with the entire back

The median apparent mass of the back at each location for ten subjects was compared with the median apparent mass of the entire back for the same ten subjects (Fig. 10). At frequencies less than 2 Hz, the forces of the entire back were 30% greater than those of the upper back and 10% greater than those of the middle back. The forces of the back near the shoulder area (location 5) were about half those of the entire back. The forces at the lower back were 40% greater than those of the entire back. At frequencies greater than 2 Hz, the forces of the entire back were greater than at any of the five locations on the back. The forces at the back near the shoulder area were the least—50% less than the entire back. Generally, at frequencies below 7 Hz, the forces of the entire back showed similar trends to those of the middle back, but the former produced greatest force. At frequencies greater than 7 Hz, the response of the entire back was closest to the response at location 2 (the lower back).

4. Discussion

For simplicity, it has been assumed that vibration at the horizontal supporting surface of the seat (at the ischial tuberosities) had little effect on force at the back–backrest interface. This would be true if motion of the

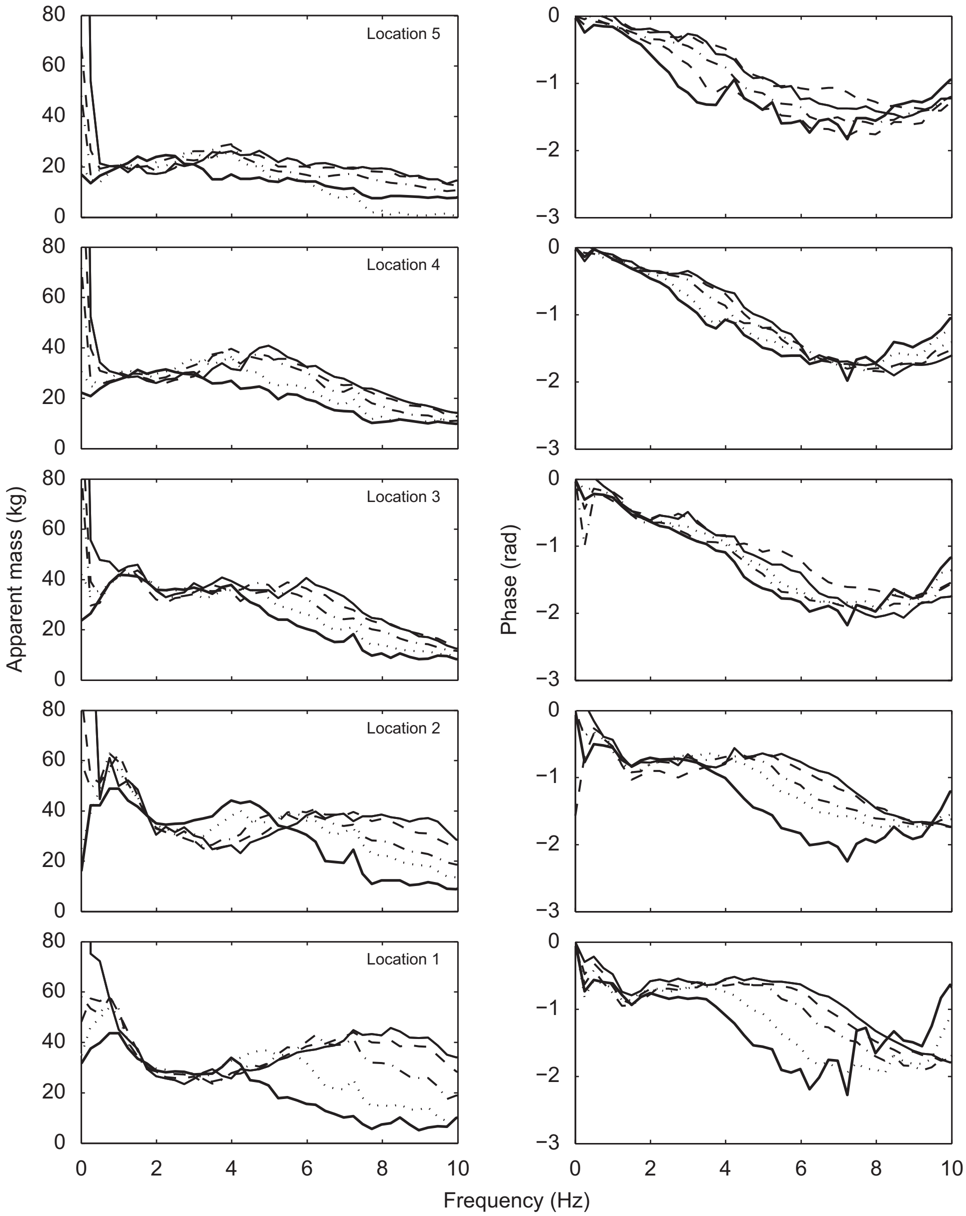

Fig. 7. Effect of vibration magnitude on the median moduli and phases of the fore-and-aft apparent masses of the back at each of five locations: 0.1 m s^{-2} r.m.s. (————), 0.2 m s^{-2} r.m.s. (– – – –), 0.4 m s^{-2} r.m.s. (–· –· –· –), 0.8 m s^{-2} r.m.s. (··········) and 1.6 m s^{-2} r.m.s. (▬▬▬).

pelvis was entirely de-coupled from motion of the spine and upper body, which is certainly not the case. In practice, in the conditions of this experiment and when seated in a car, the dynamic forces at the back will arise partially from vibration of the backrest and partially from vibration at the ischial tuberosities. In a car seat, the relative contribution from the two inputs will probably vary as the phase between vibration at the ischial tuberosities and the back varies, mainly due to compliance of the backrest. In the present study, the seat was rigid, so the vibration at the ischial tuberosities was identical with that at the backrest and their relative contributions cannot be separated.

In previous studies, sitting posture has been found to affect the apparent mass of the body measured on the seat with vertical excitation, with increasing apparent mass on the seat between 4 and 8 Hz and increasing

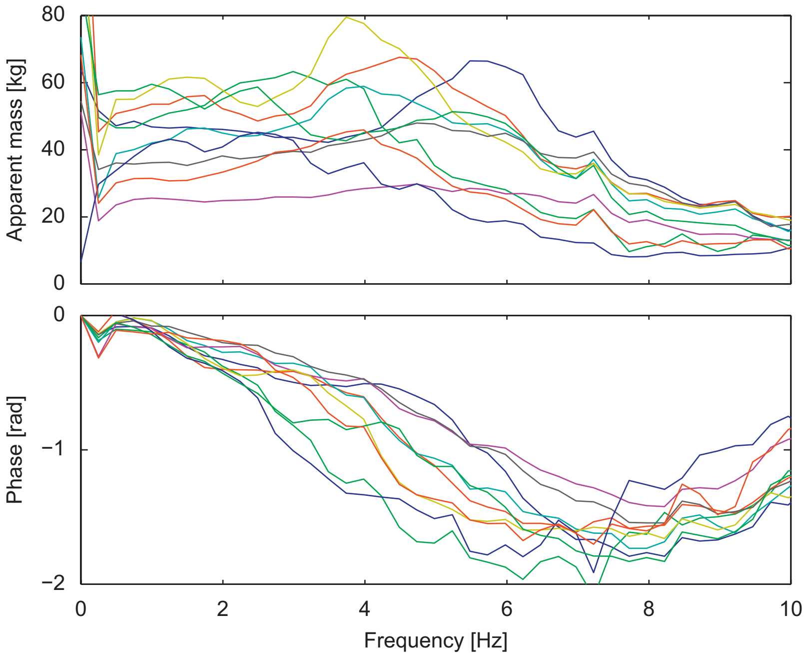

Fig. 8. Inter-subject variability in the moduli and phases of the apparent mass of the entire back of ten subjects at 0.8 m s^{-2} r.m.s.

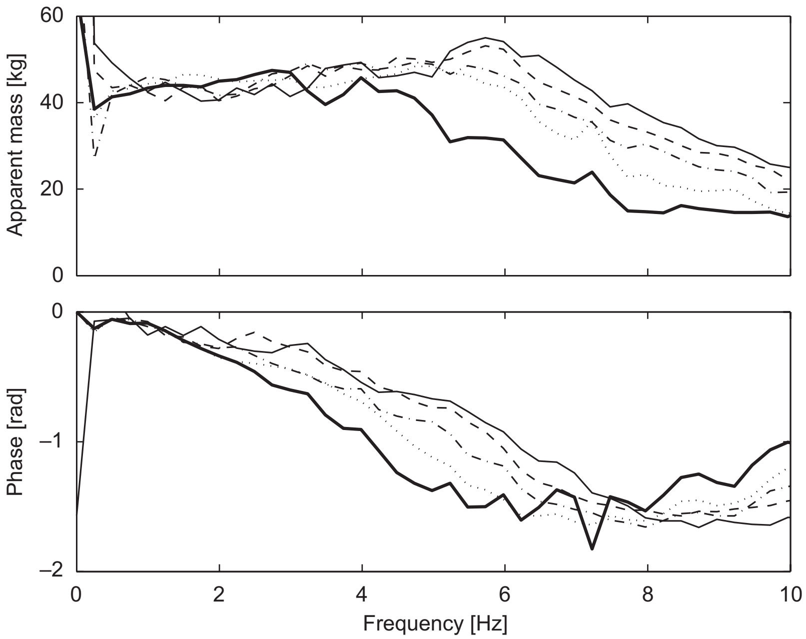

Fig. 9. Effect of vibration magnitude on the median moduli and phases of the fore-and-aft apparent mass of the entire back with ten subjects: 0.1 m s^{-2} r.m.s. (———), 0.2 m s^{-2} r.m.s. (– – – –), 0.4 m s^{-2} r.m.s. (–· –· –· –), 0.8 m s^{-2} r.m.s. (··· ··· ··· ···) and 1.6 m s^{-2} r.m.s. (▬▬▬).

resonance frequency of the apparent mass—consistent with a 'stiffening' of the body (e.g. [1]). There is no known study of the effects of such variations in sitting posture on the apparent mass at a backrest during fore-and-aft excitation. With a rigid vertical backrest, a change in posture (e.g. 'relaxed' to 'erect') will change the

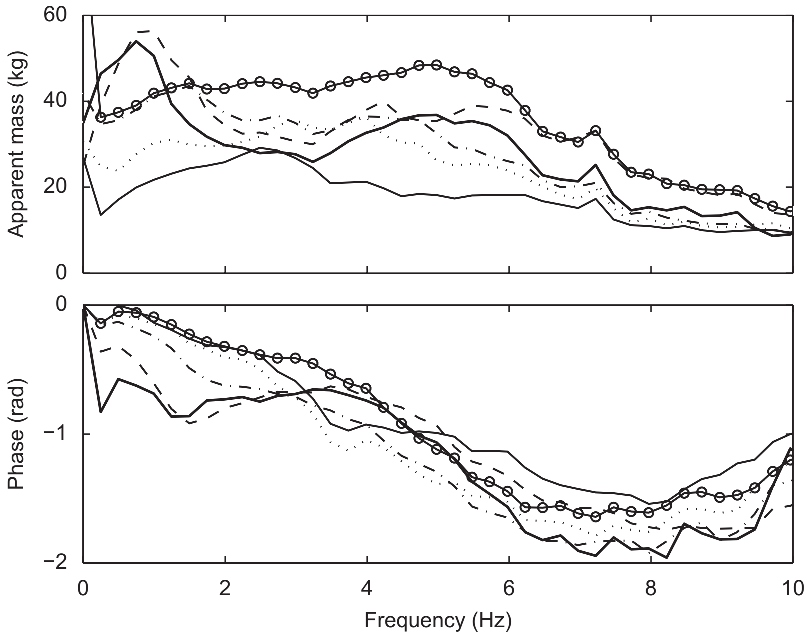

Fig. 10. Comparison of median moduli and phases of the apparent masses of the back at five locations with the median apparent mass of the entire back at a vibration magnitude of $0.8\,\mathrm{m\,s^{-2}}$ r.m.s. Key: Location 1 (———); Location 2 (– – – –); Location 3 (–· –· –· –); Location 4 (··········); Location 5 (———); Entire back (–○–○–○–). (Median of 10 subjects).

curvature of the spine, and may alter the location of the interface between the back and the backrest and the location of the vibration input to the back. A 'relaxed' posture will tend to result in less upper-back contact with a backrest but more contact around the middle back, whereas an 'erect' posture will tend to have more contact with a backrest in the lower and the upper back. The five locations studied here may resemble the various interface points between the back and a rigid flat backrest with different sitting postures. A cushioned backrest will tend to follow the contours of the back and so some contact over the entire back may occur irrespective of variations in the curvature of the spine in different postures.

4.1. Use the 'cross-spectral density' method

The 'CSD' method used to calculate apparent mass is a linear analysis method. This method has been used widely in previous studies to quantify biodynamic responses of the human body to vibration, either the transmissibility or the apparent mass. In the present experiment, a high coherency between fore-and-aft acceleration and fore-and-aft force at the back at all locations and at all magnitudes might suggest that the body was behaving approximately linearly during each measurement. However, increases in vibration magnitude decreased the resonance frequency of the apparent mass of the body, suggesting the body was behaving nonlinearly. The 'CSD' method of analysis was therefore compared with the 'power-spectral density' (PSD) method, in which the apparent mass of the back is given by the square root of the ratio of the PSD of the output (i.e. force) and the PSD of the input (i.e. acceleration). This method, which only produces the modulus of the apparent mass, includes both correlated and uncorrelated signals and therefore includes 'noise' and does not assume linearity. Comparisons of the apparent mass of the back obtained using CSD and PSD methods revealed that the two methods gave similar results (e.g. Fig. 11). This suggests that the CSD method used in this study gave representative values for apparent mass. The differences in the apparent mass between the two methods at any one vibration magnitude were less than differences in apparent mass at different magnitudes.

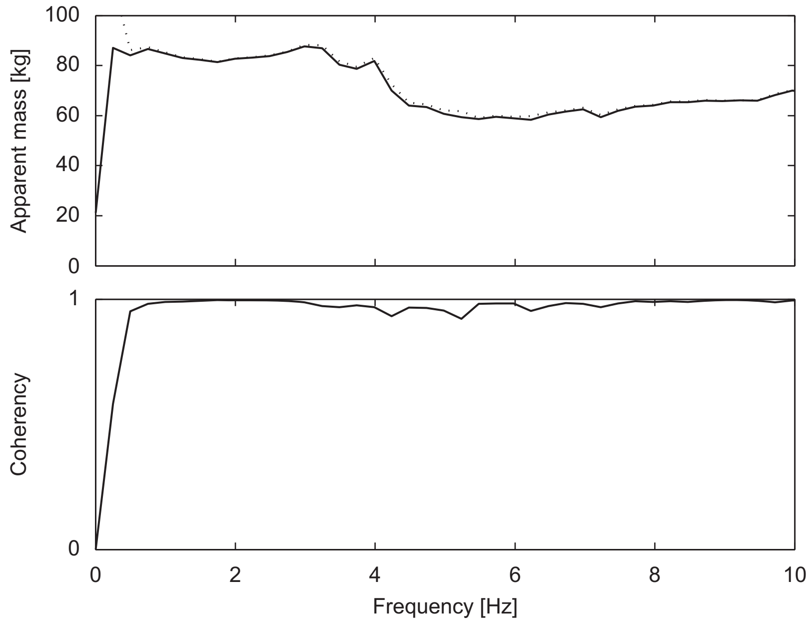

Fig. 11. Comparison of apparent mass of the back at location 3 (middle back) of one subject at $0.4\,\mathrm{m\,s^{-2}}$ r.m.s. calculated using the CSD method (———) and the PSD method (…………).

4.2. Modes of vibration in the body

The three peaks in the apparent masses of the back observed in this study are consistent with the peaks found by Nawayseh and Griffin [11], who exposed 12 subjects to four magnitudes of fore-and-aft vibration and measured the apparent mass of the entire back in the fore-and-aft direction and the 'cross-axis' apparent mass in the vertical and lateral directions. They found a first peak in the fore-and-aft apparent mass of the entire back at a frequency less than 2 Hz, with a second peak between 3 and 5 Hz, and a third peak in the frequency range 4–7 Hz. A previous study by the same authors found that in subjects exposed to vertical vibration the 'cross-axis' fore-and-aft apparent mass at the back had a principal resonance between 5 and 10 Hz, with evidence of a first resonance in the range 2–3 Hz for some subjects [4].

During vertical excitation, a bending deformation of the spine between 2 and 3 Hz results in two body modes associated with fore-and aft motion of the head and the pelvis in opposite phase and in phase, respectively [5], and a pitching mode in the pelvis [6]. If the body has a pitching mode during vertical excitation at 2–3 Hz, the same mode may be expected to occur during fore-and-aft excitation. Nawayseh and Griffin [11] reported a first peak of the apparent mass of the entire back at a similar frequency (1–2 Hz), when they exposed seated subjects to whole-body fore-and-aft excitation. They suggested that the first mode at the back might be associated with a pitching mode of the body. In this study, the first peak at the back was observed at 2 Hz, with the peak clearer at the middle and lower back. This, together with the findings of previous studies, suggests that the first peak in the apparent mass of the back in the fore-and-aft direction may be associated with a pitching mode of the pelvis.

In this study, the upper back showed a second resonance around 4–5 Hz, while the middle and lower back showed second peaks at higher frequencies (around 5 and 8 Hz). When using a backrest, there is a pronounced peak in the transmission of fore-and-aft seat vibration to the head around 6 Hz [14]. A pitching mode of the head and a bending mode of the entire spine around 5 Hz have been extracted from a modal analysis of the human body in the vertical direction using a finite-element model of the human body [5]. It seems possible that the second resonance of the apparent mass of upper back may be associated with combined pitching of the head and bending of the entire spine and the upper body.

A bending mode of the lumbar and the lower thoracic spine of the body during vertical vibration has been reported at 5.6 Hz, which may arise from pitching motion of the upper body [15]. The authors also found pitching in the pelvis around 8 Hz. Possibly, the second peak in apparent mass at the middle and lower back is associated with a mode of the entire body involving combined bending in the lower thoracic spine and pitching of the pelvis and the upper body.

A third peak was found around 7 Hz, and was clearest at the middle back. Nawayseh and Griffin [11] reported a third broad peak in the frequency range of 4–7 Hz in the fore-and-aft apparent mass of the entire back, but they did not suggest any associated mode. A resonance at approximately 6 Hz has been reported in the transmission of vertical seat vibration to fore-and-aft vibration at the abdomen [16]. Fore-and-aft transmissibilities to the tenth thoracic spine (T10) also showed a resonance around 6 Hz [3]. Although it is not clear which body mode was associated with the third resonance of the apparent mass of the back found here, it may have been influenced by the same mechanisms producing peaks in the fore-and-aft transmissibility to the abdomen and the lower spine during vertical excitation.

4.3. Apparent mass at very low frequency

During vertical excitation at very low frequencies (near to 0 Hz), the human body is rigid: the vertical apparent mass of a seated body is approximately equal to its static sitting mass and the force and acceleration are in phase. In the fore-and-aft direction, the interaction between the back and backrest are more complex. The results of this study suggest that at low frequencies (i.e. near to static conditions), the fore-and-aft forces at the back vary with the location of measurement: forces at the lower back were greater than at the middle and upper back and not solely determined by the acceleration and the mass in contact with the backrest.

If the back was only coupled to the backrest, it would be reasonable to expect the mass of the back to equal the apparent mass at low frequencies (similar to the static mass of the body equalling the low-frequency vertical apparent mass of a person sitting without support from a backrest or footrest). With the subjects supported in the current experiment on a surface that oscillated them backwards and forwards with the same vibration as appeared at the back, the situation is more complex, and the measured apparent mass different from that which would have been measured without this movement at the supporting seat. Other studies have found that during fore-and-aft excitation without a backrest but with feet supported and exposed to the vibration, the apparent mass of the body measured on a seat at low frequencies was about 80% of the subject static mass [10], but this reduced to about 35% of the static mass when a vertical backrest was present [11]. The apparent mass of the back measured in this study indicates the forces present at the back when the seat and back move together. During low-frequency fore-and-aft oscillation, the sum of the forces at back, the seat and the feet would be expected to equal the product of the acceleration and the subject static mass.

The positive correlation between subject mass and the apparent mass of the entire back at low frequencies (e.g. 0.5 Hz) in the current study means that heavier subjects produced a greater apparent mass of the back than lighter subjects at low frequencies. Fore-and-aft excitation was applied by a vertical surface normal to the surface of the backs of subjects, similarly to vertical vibration being applied normal to the horizontal surface that supports a seated person. A large part of the variability in the apparent masses of subjects measured at surfaces supporting seated persons during vertical excitation is due to differences in subject weights on the seat [1]. It seems possible that some of the variability in fore-and-aft apparent mass at the back in the current study was also due to differences in subject mass.

At low frequencies there were increasing phase shifts between the force and the acceleration as the measurement location moved down from the upper back to the lower back (Figs. 2 and 3). In addition to the influence of vibration at the supporting seat surface, the phase shifts may have arisen from reduced coherency at low frequencies as a result of measurement noise (e.g. due to the body losing contact with the back—as may be expected at greater vibration magnitudes), or from muscle activity attempting to stabilise the body and maintain an upright posture during low-frequency oscillation.

4.4. Influence of the legs and feet

When subjects, with their foot height adjusted to produce 'average thigh contact' on a seat, were exposed to vertical vibration, the 'cross-axis' fore-and-aft apparent mass at the back was greater than when there was 'maximum thigh contact' or their feet were hanging, but the 'cross-axis' fore-and-aft apparent mass was greatest when there was 'minimum thigh contact' [4]. The authors suggested that when the feet were raised (i.e. minimum thigh contact), a greater contact force between the back and the backrest might have arisen from push forces applied by the feet reacting to the pitch motion of the body, and this may have also increased the fore-and-aft dynamic force on the backrest during vertical excitation. Fore-and-aft vibration at the backrest may also cause the body to pitch, and result in a reaction force from the feet to control the pitching motion. With a subject exposed to fore-and-aft vibration, and the fore-and-aft push force at the feet increased from 'no force' up to 25 N, the apparent mass of the entire back increased and the resonance frequency and apparent mass at resonance also increased (Abdul Jalil, unpublished). Together with findings of Nawayseh and Griffin [4], this suggests that during fore-and-aft excitation some of the variation in force at the back may arise from variations in push force at the feet reacting with pitch movements of the upper body.

4.5. Nonlinearity of the body with vibration magnitude

Previous studies have found that the response of the body is nonlinear with vibration magnitude during vertical excitation—the resonance frequency of the body decreases with increasing vibration magnitude (e.g. [1–4,16–18]). The causes of the nonlinearity are not understood but may include muscle activity and nonlinear mechanical properties of the soft tissues [19]. It has been suggested that the nonlinearity seen in biodynamic responses during vertical excitation is associated with involuntary changes in muscle tension within the body (e.g. [1]). With increases in vibration magnitude, Matsumoto and Griffin [3] found that the resonance frequency of the body decreased when both the buttock and abdomen muscles were tensed and they suggested the nonlinearity may be partly caused by involuntary changes in muscle tension. A few studies have monitored the activity of muscles using electromyography and observed phasic contractions of erector spinae muscles in subjects exposed to whole-body vertical or lateral vibration at low frequencies (e.g. [20–22]). There is a variation in muscle activity with vibration magnitude [21] that may cause, or contribute to, the nonlinearity.

A few studies have investigated the nonlinearity of the body during fore-and-aft excitation, mainly measuring the response at a seat surface supporting subjects without backrest (e.g. [7–11]). When seated with a backrest, Nawayseh and Griffin [11] found that the apparent mass of the back varied nonlinearly with vibration magnitude, similar to the present study.

4.6. Biodynamic models

Biodynamic models of seated persons in the vertical direction generally have one connecting point at the interface between the seat and the body, assumed to be at the principal load-bearing area around the ischial tuberosities [23–25]. The principal area bearing the static load between the back and a backrest may either be the lower back (around the lumbar area), the middle back or the whole back [26]. The present study has shown that the fore-and-aft dynamic response of the back is highly dependent on the location on excitation of the back. This suggests that a dynamic model of the back of a seated person should be represented by at least two points representing two different responses of the back, the middle and lower back, and the upper back. A biodynamic model of the fore-and-aft response of a combined backrest and body may need to represent the impedance of the back at these locations, as well as the fore-and-aft impedance of the body at the interface between the buttocks and the seat surface. Such a model of the back might be combined with a backrest cushion model so as to predict and optimise backrest transmissibility.

5. Conclusions

Three resonances were evident in forces measured at the back–backrest interfaces of seated subjects exposed to fore-and-aft vibration. A first resonance around 2 Hz was visible at all five measurement locations on the back. There was a clearer, second resonance between 4 and 5 Hz at the upper back (and with the entire back), and between 5 and 8 Hz at the middle and lower back. A third resonance was observed around 7 Hz at all locations, although only for some subjects.

The forces at the back varied greatly with location on the back. The lower back showed greatest force and the upper back showed the least force. The forces measured with the entire back differed from those measured at all five locations, but showed some similarity with forces at the middle back.

The apparent mass of the back measured at all locations, and with the entire back, was significantly nonlinear: the principal resonance frequency and the apparent mass at resonance tended to decrease with increasing vibration magnitude.

The results suggest that biodynamic models of the seated human body used to predict fore-and-aft vibration at the back, including the transmission of fore-and-aft vibration through backrests, should recognise the variation in forces with measurement location and vibration magnitude in addition to vibration frequency.

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