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# Nonlinear subjective and dynamic responses of seated subjects exposed to horizontal whole-body vibration

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**Abstract**

The effect of the magnitude of fore-and-aft and lateral vibration on the subjective and mechanical responses of seated subjects has been investigated experimentally using simultaneous measurements of relative discomfort and apparent mass. Twelve male subjects were exposed to sinusoidal vibration at nine frequencies (between 1.6 and 10 Hz) at four magnitudes (in the range 0.125–1.0 m s$^{-2}$ r.m.s.) in both horizontal directions (fore-and-aft and lateral). The method of magnitude estimation was used to estimate discomfort relative to that caused by a 4 Hz reference vibration in the same axis. The apparent mass was calculated from the acceleration and the applied force so as to quantify the mechanical response of the body. With each direction of excitation, the apparent mass was normalised by dividing it by the apparent mass obtained at 4 Hz, so that the mechanical responses could be compared with the subjective responses.

The relative discomfort and the normalised apparent mass were similarly affected by the frequency and magnitude of vibration, with significant correlations between the relative discomfort and the normalised apparent mass. The results indicate that the discomfort caused by horizontal whole-body vibration is associated with the apparent mass in a frequency range where motion of the whole body is dominant. In this frequency range, the nonlinear subjective responses may be attributed, at least in part, to the nonlinear dynamic responses to horizontal whole-body vibration.


## 1. Introduction

People in sitting postures may be exposed to horizontal vibration while in transport and in working environments. A reduction of discomfort caused by such vibration will improve the quality of environments where people cannot avoid vibration exposure. When the vibration is complex and contains many components, one way to reduce vibration discomfort is to reduce the magnitude of the vibration component that is perceived as greatest.

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Current standards (e.g., ISO 2631–1 [1] and BS 6841 [2]) define methods of evaluating human exposures to vibration using frequency weightings believed to represent the dependence of human response to vibration on vibration frequency. These frequency weightings have been based on the frequency-dependence of subjective responses, mainly vibration discomfort, found in experimental studies. Donati et al. [3] found that sitting subjects may be less sensitive to fore-and-aft acceleration at 1 Hz than at 2 or 3 Hz. Corbridge and Griffin [4] found that maximum sensitivity to lateral acceleration occurred between 1.25 and 2 Hz, with sensitivity decreasing at higher and lower frequencies. Miwa [5] found that sensitivity to lateral acceleration decreased at frequencies greater than about 3.15 Hz.

Previous frequency weightings have mainly been based on the assumption that the frequency-dependence of vibration discomfort is independent of vibration magnitude. A few studies have investigated the effect of vibration magnitude on subjective responses to horizontal vibration [6–8]. Griffin et al. [6] investigated the effect of vibration magnitude on equivalent comfort contours with horizontal vibration at frequencies from 1 to 63 Hz in the magnitude range between 0.5 and 1.25 m s$^{-2}$ r.m.s. They reported ‘‘over the range of levels investigated the differences in shape of contours of equivalent discomfort for translational vibration are small compared with differences between individuals’’ and that ‘‘for this range of levels it therefore seems reasonable to determine and apply a single equivalent comfort contour’’. Howarth and Griffin [7] investigated the effect of vibration magnitude on subjective reaction to vibration at frequencies between 4 and 63 Hz at low magnitudes between 0.04 and 0.4 m s$^{-2}$ r.m.s. They concluded that the frequency weighting $W_d$ in BS 6841 [2] provided a ‘‘reasonable approximation to the frequency dependence of subjective response’’ to lateral vibration measured in the experiment, although some evidence of the effect of vibration magnitude can be seen in the frequency weightings determined from their experimental results at different vibration magnitudes. Morioka and Griffin [8] investigated the effect of vibration magnitude on equivalent comfort contours more comprehensively with frequencies from 2–315 Hz and velocities from 0.02–1.25 m s$^{-1}$ r.m.s. They concluded that ‘‘the shapes of the equivalent comfort contours depended on vibration magnitude’’ and ‘‘no single linear frequency weighting can provide accurate predictions of discomfort caused by a wide range of magnitudes of whole-body vibration’’.

The biodynamic responses of the body exposed to horizontal vibration have been found to be nonlinear: the resonance frequencies of the apparent mass (or the mechanical impedance) decrease with increases in vibration magnitude [9–12]. There appear to be three resonances in the fore-and-aft apparent mass of the seated body over the frequency range below 10 Hz. A first resonance has been found at around 1 Hz [9,10], with no influence of vibration magnitude on the resonance frequency of this mode [9]. A second resonance frequency has been found between 1 and 3 Hz, with the frequency decreasing with increasing vibration magnitude [9–11]. A third resonance, between 3 and 5 Hz, also shows a nonlinear characteristic [10–12] and is more visible with low vibration magnitudes than high vibration magnitudes. With lateral excitation of the seated body, the first resonance appears at about 0.7 Hz and does not seem to be affected by vibration magnitude [9]. A second resonance has been identified between 1.5 and 3 Hz [9,11] and decreases with increasing vibration magnitude. A third resonance in the apparent mass has been reported between 5 and 6 Hz and appears to decrease with increasing vibration magnitude [11,12].

A comparison of previous studies of subjective responses and dynamic responses suggests that the seated human body is more sensitive to fore-and-aft (or lateral) acceleration at frequencies close to peaks in the apparent mass. The similarity between subjective and dynamic responses of the seated body suggests the subjective responses may be associated with the dynamic responses. If the subjective responses are related to the dynamic responses, the subjective responses will show a nonlinearity similar to the nonlinearity in the dynamic responses.

There is some evidence that the subjective responses are correlated with the dynamic responses of the seated body exposed to vertical vibration [13,14]. Griffin and Whitham [13] found a relation between the subjective response and the transmissibility to the head at frequencies less than 6.3 Hz and greater than 16 Hz. Matsumoto and Griffin [14] found that subjective responses were correlated with the mechanical impedance and the apparent mass in the frequency range between 3.15 and 8.0 Hz. There is no known study of an association between the subjective and dynamic responses of the body exposed to horizontal vibration (i.e., fore-and-aft or lateral vibration), although horizontal vibration is present on the seats of vehicles and can contribute to discomfort [15,16].

The objective of this study was to investigate the correlation between subjective and dynamic responses of seated subjects exposed to fore-and-aft and lateral vibration, focusing on the effects of vibration magnitude with both responses. It was hypothesised that subjective and dynamic responses to fore-and-aft and lateral vibration would be nonlinear. It was also hypothesised that the nonlinearity in the subjective response would be related to the nonlinearity in the dynamic response. The subjective responses were represented by magnitude estimates of discomfort and the dynamic responses were represented by the apparent mass frequency response functions. The effects of the frequency and magnitude of the input vibration on the correlation between the magnitude estimates of discomfort and the apparent mass were investigated by obtaining simultaneous measurements of subjective and dynamic responses.

## 2. Method

### 2.1. Apparatus

A slip table made by Kinball Industries, Inc. was driven by an electro-dynamic vibrator, Derritron VP 85, to produce horizontal vibration. A tri-axial force platform, Kistler 9281 B, was rigidly fixed on the top plate of the slip table so as to measure the forces at the interface between the vibrating surface and seated subjects. A piezoresistive uni-axial accelerometer, Entran, EGCSY-240D*-50, was mounted on the top surface of the force platform to measure the acceleration in the direction of excitation. Subjects were seated on the top surface of the force platform. Their feet were supported on a stationary footrest with the upper surface of their upper legs horizontal when at rest. A photograph of experimental setup with a seated subject is shown in Fig. 1.

### 2.2. Subjects

Twelve male volunteers from the staff and students of the University of Southampton participated in the experiment. Their characteristics were represented by a median age of 27 years (range 23–51 years), median height 1.78 m (range 1.70–1.86 m) and median weight 73 kg (range 60–85 kg). 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 the commencement of the experiment that was conducted in a laboratory at the ISVR.

### 2.3. Experimental conditions

Sinusoidal vibration having frequencies of 1.6, 2.0, 2.5, 3.15, 4.0, 5.0, 6.3, 8.0, and 10.0 Hz were used in the experiment. The duration of vibration was 4 s with the first 0.5 s and last 0.5 s tapered by cosine functions.

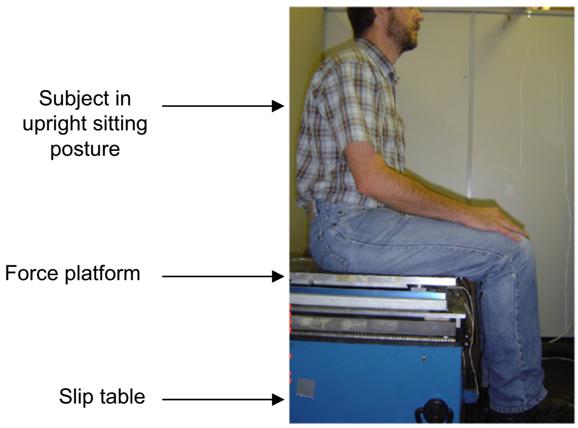


Fig. 1. A photograph of experimental setup with a seated subject.

Four different magnitudes of vibration were used in the experiment: 0.125, 0.25, 0.5, and 1.0 $m\,s^{-2}$ r.m.s. Stimuli with a frequency of 1.6 Hz at 0.5 and 1.0 $m\,s^{-2}$ r.m.s., and stimuli with frequencies of 2.0 and 2.5 Hz at 1.0 $m\,s^{-2}$ r.m.s. were not presented due to a displacement limitation of the vibrator.

Subjects were exposed to a series of two vibrations: a 4 s 'reference' stimulus and a 4 s 'test' stimulus presented with an interval of 2 s. The reference stimulus was at 4 Hz. The acceleration magnitude of the reference stimulus was the same as that of the test stimulus. The order of presenting the magnitudes and the frequencies of the test stimuli was randomized among the 12 subjects. An experimental session consisted of two parts: exposure to fore-and-aft vibration and exposure to lateral vibration, achieved by changing the orientation of the seated subjects.

### 2.4. Measurements

Relative discomfort was measured using the method of magnitude estimation. The magnitude of discomfort assigned to all reference stimuli was 100. Subjects were asked to estimate the discomfort caused by the test stimuli relative to the discomfort caused by the reference stimulus. For example, a subject who considered that a test stimulus was half as uncomfortable as the reference stimulus should assign it the value of 50. A subject who considered a test stimulus to be twice as uncomfortable as the reference stimulus should assign it the value of 200.

For each stimulus, the acceleration and the force in the direction of excitation were measured. The signals were digitised at 1000 samples per second after low pass filtering at 12 Hz.

### 2.5. Analysis of dynamic response

The apparent mass was determined from the ratio of the r.m.s. value of the force and the r.m.s. value of the acceleration in the direction of excitation:

$$M_f = \frac{F_{\mathrm{r.m.s.},f}}{a_{\mathrm{r.m.s.},f}} \tag{1}$$

where $M_f$ is the apparent mass at the frequency $f$ (Hz), $F_{\mathrm{r.m.s.},f}$ and $a_{\mathrm{r.m.s.},f}$ represent the r.m.s. values of the force and the acceleration at this frequency, respectively.

The r.m.s. values were calculated for a period when the input signals had a constant magnitude (i.e., the middle 3 s of the 4 s period of vibration). Before the calculation of the r.m.s. value of the force, the product of the mass of the parts of the force platform above the transducers and the acceleration in the direction of excitation was subtracted from the measured force signal so as to eliminate the effect of the mass of the parts of the force platform above the transducers on the measured force. The apparent mass was determined for the two directions of excitation (i.e., the fore-and-aft and lateral directions).

The apparent mass, $M_f$, calculated with the above method was normalised by dividing it by the value of the apparent mass obtained at 4 Hz, $M_{4\,\mathrm{Hz}}$. This normalisation was intended to compare the apparent mass directly with the magnitude estimates of discomfort that were obtained relative to the discomfort caused by the 4 Hz reference stimulus. The purpose of this normalisation was different from the normalisation of the apparent mass with respect to subjects' static mass, which is usually carried out to reduce the effect of static mass on the apparent mass in biodynamic studies.

## 3. Results with fore-and-aft excitation

### 3.1. Subjective response in the fore-and-aft direction

The magnitude estimates of the relative discomfort indicated by subjects exposed to fore-and-aft vibration varied depending on the frequency and the magnitude of the vibration (Fig. 2). The median magnitude estimate was greatest at 2.5 Hz at vibration magnitudes of 0.125, 0.25, and 0.5 $m\,s^{-2}$ r.m.s. The magnitude estimates were significantly affected by the frequency at all magnitudes of vibration ($p<0.0001$, Friedman two-way analysis of variance). The statistical significance of the effect of frequency on the magnitude estimates

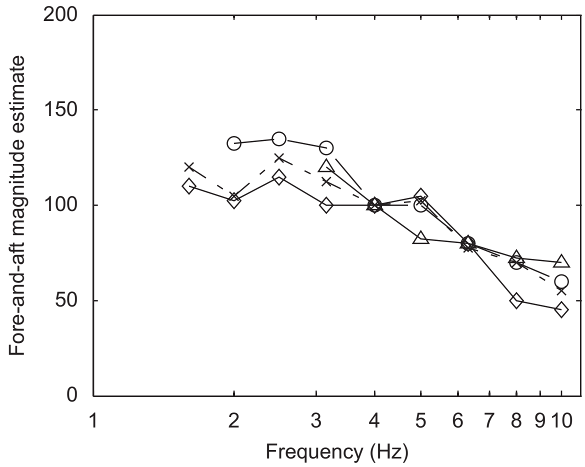


Fig. 2. Medians of magnitude estimates of relative discomfort by 12 subjects exposed to fore-and-aft vibration at four magnitudes: ◇——: $0.125\,\mathrm{m\,s^{-2}}$ r.m.s.; × -.-.-: $0.25\,\mathrm{m\,s^{-2}}$ r.m.s.; o– – – –: $0.5\,\mathrm{m\,s^{-2}}$ r.m.s.; and Δ—: $1.0\,\mathrm{m\,s^{-2}}$ r.m.s.

was investigated further using the Wilcoxon matched-pairs signed ranks test. At 0.125 and $0.25\,\mathrm{m\,s^{-2}}$ r.m.s., the magnitude estimate at 2.5 Hz was greater than that at 2.0 Hz ($p<0.05$, Wilcoxon) and greater than that at 3.15 Hz ($p=0.072$, Wilcoxon for $0.125\,\mathrm{m\,s^{-2}}$ r.m.s., $p=0.028$, Wilcoxon for $0.25\,\mathrm{m\,s^{-2}}$ r.m.s.).

The median magnitude estimate of discomfort caused by vibration at 4 Hz was exactly 100 for all vibration magnitudes. This is consistent with the 4 Hz test stimulus having the same magnitude as the 4 Hz reference stimulus for all magnitudes. Friedman two-way analysis of variance showed that the difference in the magnitude estimates at 4 Hz at different magnitudes was not statistically significant ($p>0.1$). The magnitude estimates were significantly affected by the vibration magnitude at 2.0, 2.5, 3.15 Hz ($p<0.01$, Friedman) and at 10.0 Hz ($p=0.025$, Friedman). For these frequencies, the magnitude estimates at $0.125\,\mathrm{m\,s^{-2}}$ r.m.s. were significantly less than those at the higher magnitudes ($p<0.05$, Wilcoxon, Table 1). At 3.15 Hz, the magnitude estimates at $0.25\,\mathrm{m\,s^{-2}}$ r.m.s. were significantly less than those at $0.5\,\mathrm{m\,s^{-2}}$ r.m.s. ($p=0.044$, Wilcoxon, Table 1).

### 3.2. Dynamic response in the fore-and-aft direction

The apparent mass changed depending on the frequency and magnitude of vibration (Fig. 3). At $0.25\,\mathrm{m\,s^{-2}}$ r.m.s, the fore-and-aft apparent mass was greatest at 2.5 Hz. The effect of frequency on the apparent mass was statistically significant for all magnitudes of vibration ($p<0.0001$, Friedman two-way analysis of variance). At 0.125 and $0.25\,\mathrm{m\,s^{-2}}$ r.m.s., the apparent mass at 2.5 Hz was significantly greater than that at 2.0 Hz ($p<0.05$, Wilcoxon). There was a significant decrease in the apparent mass with each increase in frequency above 5 Hz at 0.125 and $0.25\,\mathrm{m\,s^{-2}}$ r.m.s. ($p<0.05$, Wilcoxon). At 0.5 and $1.0\,\mathrm{m\,s^{-2}}$ r.m.s., the apparent mass decreased significantly with each increase in frequency above 3.15 Hz ($p<0.05$, Wilcoxon).

The fore-and-aft apparent mass was dependent on vibration magnitude at all frequencies except at 1.6 and 3.15 Hz (at 2.5 and 4.0 Hz, $p<0.01$, Friedman; at 2.0, 5.0, 6.3, 8.0 and 10.0 Hz, $p<0.0001$, Friedman). Statistical significances of the effect of vibration magnitude were determined using Wilcoxon matched-pairs signed ranks test. At 5.0, 6.3, 8.0 and 10.0 Hz, the fore-and-aft apparent mass decreased with each increase in vibration magnitude ($p<0.01$, Wilcoxon), except between 0.125 and $0.25\,\mathrm{m\,s^{-2}}$ r.m.s. at 5 Hz. At 4.0 Hz, the apparent mass at $1.0\,\mathrm{m\,s^{-2}}$ r.m.s. was significantly less than at other vibration magnitudes ($p<0.05$, Wilcoxon). At 2.0 and 2.5 Hz, the apparent mass at $0.5\,\mathrm{m\,s^{-2}}$ r.m.s. was significantly greater than that at other vibration magnitudes ($p<$ 0.05, Wilcoxon), except between 0.125 and $0.25\,\mathrm{m\,s^{-2}}$ r.m.s. at 2.5 Hz.

Table 1
Statistical significance of the effect of vibration magnitude on the magnitude estimates determined by Wilcoxon matched-pairs signed ranks test for fore-and-aft vibration: $^{**}p<0.01$, $^{*}p<0.05$

| Vibration magnitude (m s$^{-2}$ r.m.s.) | 0.250 | 0.500 | 1.000 |
|---|---|---|---|
| At 2.0 Hz | | | |
| 0.125 | 0.041* | 0.002** | – |
| 0.250 | … | 0.154 | – |
| 0.500 | | … | – |
| At 2.5 Hz | | | |
| 0.125 | 0.029* | 0.002** | – |
| 0.250 | … | 0.167 | – |
| 0.500 | | … | – |
| At 3.15 Hz | | | |
| 0.125 | 0.040* | 0.003** | 0.025* |
| 0.250 | … | 0.044* | 0.159 |
| 0.500 | | … | 0.798 |
| At 10.0 Hz | | | |
| 0.125 | 0.040* | 0.040* | 0.012* |
| 0.250 | … | 0.887 | 0.345 |
| 0.500 | | … | 0.138 |

The data for which Friedman two-way analysis of variance showed statistical significance are presented.
For the comparisons showing statistical significance, the magnitude estimate for the lower vibration magnitude is significantly less than that for higher vibration magnitude.

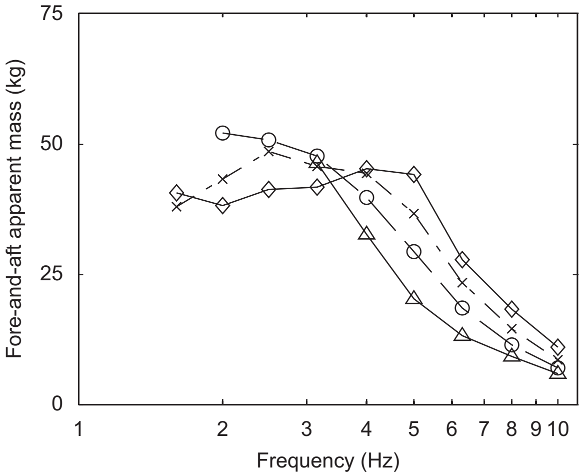


Fig. 3. Median apparent mass of 12 subjects exposed to fore-and-aft vibration at four magnitudes: ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o– – – –: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s.

### 3.3. Comparison between subjective and dynamic responses in the fore-and-aft direction

Fig. 4 shows the median normalised apparent mass determined by dividing the median apparent mass at all frequencies by the median apparent mass at 4 Hz, so as to compare the apparent masses with the magnitude estimates of relative discomfort. At low frequencies, the dependence of the median normalised apparent masses on vibration magnitude is similar to that of the median magnitude estimates of the relative discomfort presented in Fig. 2. The magnitude-dependence of the normalised apparent mass was statistically significant at all frequencies except at 1.6 Hz ($p = 0.026$ at 3.15 Hz, $p<0.01$ at 2.0, 2.5 and 10 Hz, $p<0.0001$ at 5.0, 6.3 and 8.0 Hz; Friedman). The statistical significance of the effect of vibration magnitude on the normalised apparent

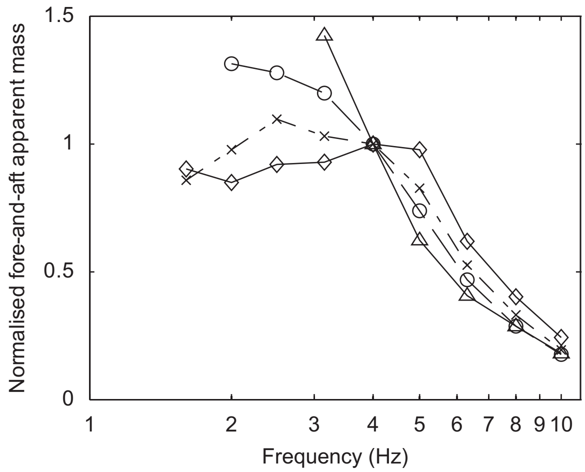


Fig. 4. Median normalised apparent mass of 12 subjects exposed to fore-and-aft vibration at four magnitudes ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o– – – –: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s.

mass is shown in Table 2. The effect of vibration magnitude on the normalised apparent mass was similar to the effect of vibration magnitude on the magnitude estimates of discomfort (Table 1) at 2.0, 2.5 and 3.15 Hz. At 2.0 and 2.5 Hz, the normalised apparent mass at 0.125 m s$^{-2}$ r.m.s. was significantly less than at 0.5 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon, Table 2) and less than at 0.25 m s$^{-2}$ r.m.s. with marginal non-significance ($p<0.1$, Wilcoxon, Table 2), while the magnitude estimate at 0.125 m s$^{-2}$ r.m.s. was significantly less than at 0.25 and 0.5 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon, Table 1). At 3.15 Hz, the normalised apparent mass at 0.125 m s$^{-2}$ r.m.s. was significantly less than at 1.0 m s$^{-2}$ r.m.s. ($p = 0.034$, Wilcoxon, Table 2) and less than at 0.5 m s$^{-2}$ r.m.s. with marginal non-significance ($p = 0.099$, Wilcoxon, Table 2), while the magnitude estimate of discomfort at 0.125 m s$^{-2}$ r.m.s. was significantly less than at 0.5 and 1.0 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon, Table 1).

The normalised apparent mass decreased with an increase in each vibration magnitude at 5.0, 6.3, and 8.0 Hz, except between 0.125 and 0.25 m s$^{-2}$ r.m.s. at 5.0 Hz, between 0.25 and 0.5 m s$^{-2}$ r.m.s. at 6.3 Hz, and between 0.5 and 1.0 m s$^{-2}$ r.m.s. at 8.0 Hz (Table 2). At these frequencies, there was no significant effect of vibration magnitude on the magnitude estimate of discomfort, as shown in Table 1. At 10.0 Hz, the normalised apparent mass at 0.125 m s$^{-2}$ r.m.s. was significantly greater than that at other vibration magnitudes ($p<0.05$, Wilcoxon, Table 2), whereas the magnitude estimate at 0.125 m s$^{-2}$ r.m.s. was significantly less than at other vibration magnitudes ($p<0.05$, Wilcoxon, Table 1).

A comparison between the median magnitude estimates and the median normalised fore-and-aft apparent masses measured over all frequencies and all magnitudes is shown in Fig. 5. Table 3 shows the Spearman rank order correlation coefficient, $r_s$, between the median magnitude estimates and the median normalised apparent masses at each vibration magnitude so as to investigate whether or not the effects of vibration frequency on both responses were similar. Except for the lowest vibration magnitude, the positive correlation between the median magnitude estimates and the median normalised apparent masses was statistically significant ($p<0.01$). At 0.125 m s$^{-2}$ r.m.s., the correlation between the magnitude estimates and the normalised apparent masses was marginally non-significant ($p = 0.097$). At all vibration magnitudes, there were statistically significant correlations between magnitude estimates of discomfort and the normalised apparent masses in the data from individual subjects: five subjects at 0.125 m s$^{-2}$ r.m.s., seven subjects at 0.25 m s$^{-2}$ r.m.s., nine subjects at 0.5 m s$^{-2}$ r.m.s., and six subjects at 1.0 m s$^{-2}$ r.m.s. ($p<0.05$).

The Spearman rank order correlation coefficient, $r_s$, between the median magnitude estimates and the medians of the normalised apparent masses at each frequency was determined so as to investigate whether the effects of vibration magnitude on both responses were related, although the size of each data set to test the correlation was small (Table 4). The correlation between the median magnitude estimate and the median normalised apparent mass was positive at low frequencies (i.e., between 2 and 5 Hz), whereas the correlation was negative at high frequencies (i.e., between 6.3 and 10.0 Hz). The positive correlations found at low

Table 2
Statistical significance of the effect of vibration magnitude on the normalised fore-and-aft apparent mass determined by Wilcoxon matched-pairs signed ranks test: **$p<0.01$, *$p<0.05$, and ***$p<0.1$

| Vibration magnitude ($m\,s^{-2}$ r.m.s.) | 0.250 | 0.500 | 1.000 |
|---|---|---|---|
| At 2.0 Hz | | | |
| 0.125 | 0.084***[b] | 0.005**[b] | – |
| 0.250 | … | 0.008**[b] | – |
| 0.500 | | … | – |
| At 2.5 Hz | | | |
| 0.125 | 0.071***[b] | 0.009**[b] | – |
| 0.250 | … | 0.034*[b] | – |
| 0.500 | | … | – |
| At 3.15 Hz | | | |
| 0.125 | 0.814 | 0.099***[b] | 0.034*[b] |
| 0.250 | … | 0.136 | 0.049*[b] |
| 0.500 | | … | 0.209 |
| At 5.0 Hz | | | |
| 0.125 | 0.388 | 0.012*[a] | 0.002**[a] |
| 0.250 | … | 0.012*[a] | 0.003**[a] |
| 0.500 | | … | 0.012*[a] |
| At 6.3 Hz | | | |
| 0.125 | 0.010*[a] | 0.002**[a] | 0.002**[a] |
| 0.250 | … | 0.060***[a] | 0.005**[a] |
| 0.500 | | … | 0.002**[a] |
| At 8.0 Hz | | | |
| 0.125 | 0.019*[a] | 0.006**[a] | 0.003**[a] |
| 0.250 | … | 0.010*[a] | 0.002**[a] |
| 0.500 | | … | 0.158 |
| At 10.0 Hz | | | |
| 0.125 | 0.042*[a] | 0.012*[a] | 0.004**[a] |
| 0.250 | … | 0.117 | 0.041*[a] |
| 0.500 | | … | 0.480 |

The data for which Friedman two-way analysis of variance showed statistical significance are presented.
[a]The normalised apparent mass at lower vibration magnitude is significantly greater than that at higher vibration magnitude.
[b]The normalised apparent mass at lower vibration magnitude is significantly less than that at higher vibration magnitude.

frequencies were statistically significant ($p<0.01$), whereas the negative correlations found at 8.0 and 10.0 Hz were marginally non-significant ($p = 0.051$).

## 4. Results with lateral excitation

### 4.1. Subjective response in the lateral direction

Fig. 6 shows the effect of the frequency and the magnitude of vibration on the magnitude estimates of relative discomfort indicated by subjects exposed to lateral vibration. The median magnitude estimate was greatest at 2.5 Hz at vibration magnitudes of 0.125 and 0.25 $m\,s^{-2}$ r.m.s. The effect of vibration frequency on the magnitude estimates was statistically significant for all vibration magnitudes ($p<0.0001$, Friedman). At 0.125, 0.25 and 0.5 $m\,s^{-2}$ r.m.s., the magnitude estimate at 2.5 Hz was significantly greater than that at 3.15 Hz ($p<0.01$, Wilcoxon), although the difference in magnitude estimates between 2.5 Hz and 2.0 Hz was not statistically significant ($p>0.1$, Wilcoxon).

As expected, the median magnitude estimates of vibration at 4 Hz were the same (i.e., 100) for all magnitudes ($p>0.1$, Friedman). The effect of vibration magnitude on the magnitude estimates was statistically

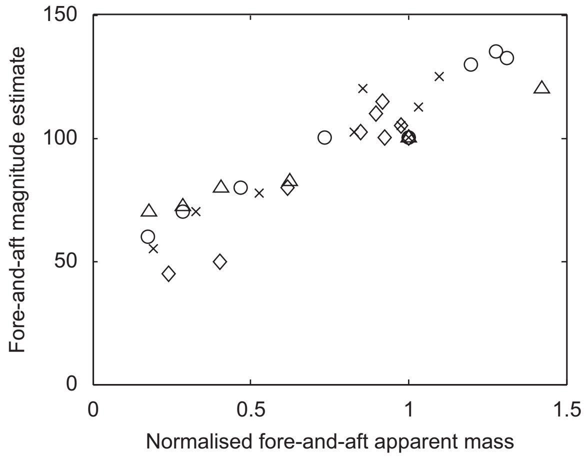


Fig. 5. Median magnitude estimates compared with the normalised apparent mass for fore-and-aft vibration at four magnitudes: ◇: 0.125 m s$^{-2}$ r.m.s.; ×: 0.25 m s$^{-2}$ r.m.s.; o: 0.5 m s$^{-2}$ r.m.s.; and Δ: 1.0 m s$^{-2}$ r.m.s.

Table 3
Correlations between median magnitude estimates and medians of the normalised fore-and-aft apparent mass at four vibration magnitudes: Spearman rank order correlation coefficient, $r_s$

| Vibration magnitude (m s$^{-2}$ r.m.s.) | Correlation coefficient | Number of samples |
|---|---|---|
| 0.125 | 0.586*** | 9 |
| 0.25 | 0.833** | 9 |
| 0.5 | 0.970** | 8 |
| 1 | 1.000** | 6 |

**$p<0.01$ and ***p<0.1.

Table 4
Correlations between median magnitude estimates and medians of the normalised fore-and-aft apparent mass at nine frequencies: Spearman rank order correlation coefficient, $r_s$

| Frequency (Hz) | Correlation coefficient | Number of samples |
|---|---|---|
| 1.60 | −1.000 | 2 |
| 2.00 | 1.000** | 3 |
| 2.50 | 1.000** | 3 |
| 3.15 | 1.000** | 4 |
| 4.00 | – | – |
| 5.00 | 1.000** | 4 |
| 6.30 | −0.258 | 4 |
| 8.00 | −0.949*** | 4 |
| 10.00 | −0.949*** | 4 |

**$p<0.01$ and ***$p<0.1$.

significant at 1.6, 2.0, 3.15, 10.0 Hz ($p<0.01$, Friedman) and at 6.3 Hz ($p = 0.045$, Friedman), and marginally non-significant at 2.5 and 5.0 Hz ($p<0.1$, Friedman). At 2.0, 2.5 and 5.0 Hz, magnitude estimates at 0.125 m s$^{-2}$ r.m.s. were significantly less than at 0.5 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon, Table 5). At 6.3 and 10 Hz, the magnitude estimates at 0.125 m s$^{-2}$ r.m.s. were significantly less than at other vibration magnitudes ($p<0.05$, Wilcoxon). At 3.15 Hz, the magnitude estimates at 1.0 m s$^{-2}$ r.m.s. were significantly greater compared to other vibration magnitudes ($p<0.05$, Wilcoxon). At the frequencies of 1.6 and 3.15 Hz, the magnitude estimates obtained with a vibration magnitude of 0.125 m s$^{-2}$ r.m.s. were significantly less than that obtained with a vibration magnitude of 0.25 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon).

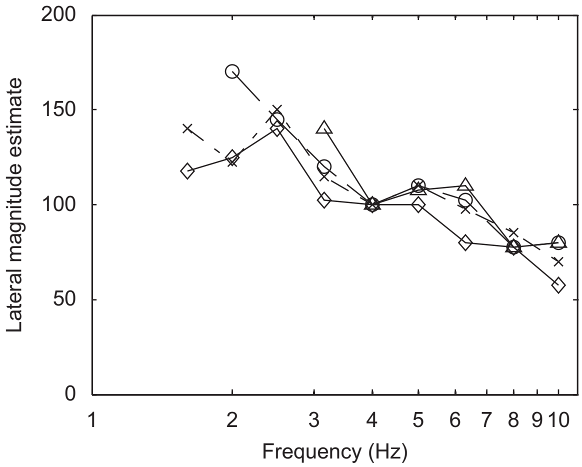


Fig. 6. Medians of magnitude estimates of relative discomfort by 12 subjects exposed to lateral vibration at four magnitudes: ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o– – – –: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s.

### *4.2. Dynamic response in the lateral direction*

For all magnitudes of vibration, the apparent mass was significantly affected by frequency ($p<0.0001$, Friedman, Fig. 7). The apparent mass was greatest at 2.0 Hz with a vibration magnitude of 0.125 and 0.25 m s$^{-2}$ r.m.s. and was greatest at the lowest frequencies used with a vibration magnitude of 0.5 and 1.0 m s$^{-2}$ r.m.s. (2.0 and 3.15 Hz, respectively). At 0.125 and 0.25 m s$^{-2}$ r.m.s., the difference in the apparent mass between 1.6 and 2.0 Hz was marginally non-significant ($p<0.1$, Wilcoxon). The apparent mass at 2.0 Hz was significantly greater than that at 2.5 Hz for vibration magnitudes of 0.25 and 0.5 m s$^{-2}$ r.m.s. ($p<0.01$, Wilcoxon). At 0.125 m s$^{-2}$ r.m.s., the difference in the apparent mass between 2.0 and 2.5 Hz was marginally non-significant ($p = 0.084$, Wilcoxon). At all magnitudes, the apparent mass decreased significantly with each increase in frequency above 2.5 Hz ($p<0.05$, Wilcoxon), except between 4 and 5 Hz at 0.125 and 0.25 m s$^{-2}$ r.m.s., and between 8 and 10 Hz at 0.125 m s$^{-2}$ r.m.s.

The apparent mass was affected by vibration magnitude at all frequencies except 1.6, 2.0 and 3.15 Hz (at 2.5, 4.0, 5.0 and 6.3 Hz, $p<0.01$, Friedman; at 8.0 and 10.0 Hz, $p<0.0001$, Friedman). The statistical significances of the effect of vibration magnitude were determined using the Wilcoxon matched-pairs signed ranks test. The apparent mass decreased with each increase in vibration magnitude at 2.5, 8.0 and 10.0 Hz ($p<0.05$, Wilcoxon), except between 0.125 and 0.25 m s$^{-2}$ r.m.s. at 8.0 Hz. At 4.0 Hz, the apparent mass at 1.0 m s$^{-2}$ r.m.s. was significantly less than at 0.25 and 0.5 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon). At 5.0 and 6.3 Hz, the apparent mass at 1.0 m s$^{-2}$ r.m.s. was significantly less than at other vibration magnitudes ($p<0.05$, Wilcoxon). In addition, the apparent mass at 5.0 Hz decreased significantly with an increase in vibration magnitude from 0.25 to 0.5 m s$^{-2}$ r.m.s., and the apparent mass at 6.3 Hz was significantly greater at 0.125 m s$^{-2}$ r.m.s. than at 0.5 m s$^{-2}$ r.m.s. ($p<0.05$, Wilcoxon).

### *4.3. Comparison between subjective and dynamic responses in the lateral direction*

Fig. 8 shows the median normalised apparent mass determined by dividing the median apparent mass at all frequencies by the median apparent mass at 4 Hz. The frequency-dependence of the normalised apparent mass may be compared with that of the magnitude estimates of discomfort shown in Fig. 6. Statistical significances of the effect of vibration magnitude on the normalised apparent mass were determined using Wilcoxon matched-pairs signed ranks test and are presented in Table 6.

At 2.5, 3.15, 6.3 and 10 Hz, the normalised apparent masses tended to decrease with increasing vibration magnitude, although a similar trend of magnitude-dependence was not clear in the magnitude estimates presented in Table 5. At 2.5 and 10 Hz, the normalised apparent mass at 0.125 m s$^{-2}$ r.m.s. was significantly

Table 5
Statistical significance of the effect of vibration magnitude on the magnitude estimates determined by Wilcoxon matched-pairs signed ranks test for lateral vibration: ** $p<0.01$, * $p<0.05$, and *** $p<0.1$

| Vibration magnitude ($m\,s^{-2}$ r.m.s.) | 0.250 | 0.500 | 1.000 |
|---|---|---|---|
| At 1.6 Hz | | | |
| 0.125 | 0.003** | – | – |
| 0.250 | … | – | – |
| 0.500 | | … | – |
| At 2.0 Hz | | | |
| 0.125 | 0.646 | 0.010* | – |
| 0.250 | … | 0.117 | – |
| 0.500 | | … | – |
| At 2.5 Hz | | | |
| 0.125 | 0.084*** | 0.017* | – |
| 0.250 | … | 0.593 | – |
| 0.500 | | … | – |
| At 3.15 Hz | | | |
| 0.125 | 0.024* | 0.054*** | 0.008** |
| 0.250 | … | 0.259 | 0.013* |
| 0.500 | | … | 0.040* |
| At 5.0 Hz | | | |
| 0.125 | 0.239 | 0.032* | 0.306 |
| 0.250 | … | 0.261 | 0.766 |
| 0.500 | | … | 0.553 |
| At 6.3 Hz | | | |
| 0.125 | 0.036* | 0.034* | 0.023* |
| 0.250 | … | 0.153 | 0.113 |
| 0.500 | | … | 0.838 |
| At 10.0 Hz | | | |
| 0.125 | 0.025* | 0.009** | 0.017* |
| 0.250 | … | 0.085*** | 0.157 |
| 0.500 | | … | 0.441 |

The data for which Friedman two-way analysis of variance showed statistical significance are presented.
For the comparisons showing statistical significance, the magnitude estimate for the lower vibration magnitude is significantly less than that for higher vibration magnitude.

greater than at other vibration magnitudes ($p<0.05$, Wilcoxon, Table 6), whereas the magnitude estimate of discomfort at $0.125\,m\,s^{-2}$ r.m.s. was significantly less than at other vibration magnitudes ($p<0.05$, Wilcoxon, Table 5), except at $0.25\,m\,s^{-2}$ r.m.s. at 2.5 Hz. At 3.15 and 6.3 Hz, the normalised apparent mass decreased significantly (Table 6) with increasing vibration magnitude, whereas the magnitude estimate of discomfort increased significantly (Table 5) with increasing vibration magnitude for some combinations: from 0.125 to $0.25\,m\,s^{-2}$ r.m.s. for 3.15 and 6.3 Hz, from 0.125 to $0.5\,m\,s^{-2}$ r.m.s. for 3.15 Hz, and from 0.125 to $1.0\,m\,s^{-2}$ r.m.s. for 6.3 Hz. However, at 3.15 Hz, the normalised apparent mass increased significantly with increasing vibration magnitude from 0.5 to $1.0\,m\,s^{-2}$ r.m.s. ($p = 0.049$, Wilcoxon, Table 6) and the magnitude estimate of discomfort also increased significantly with increasing vibration magnitude from 0.5 to $1.0\,m\,s^{-2}$ r.m.s. ($p = 0.040$, Wilcoxon, Table 5).

Fig. 9 compares the median magnitude estimates with the median normalised lateral apparent masses. Spearman rank order correlation coefficients, $r_s$, between the median magnitude estimate and the median normalised apparent mass at all magnitudes are presented in Table 7. The correlations between median magnitude estimates and the median normalised apparent masses were statistically significant for all vibration magnitudes except $1.0\,m\,s^{-2}$ r.m.s. ($p<0.01$). At all vibration magnitudes, the correlations between the magnitude estimates and the normalised apparent masses were statistically significant for many subjects: 10

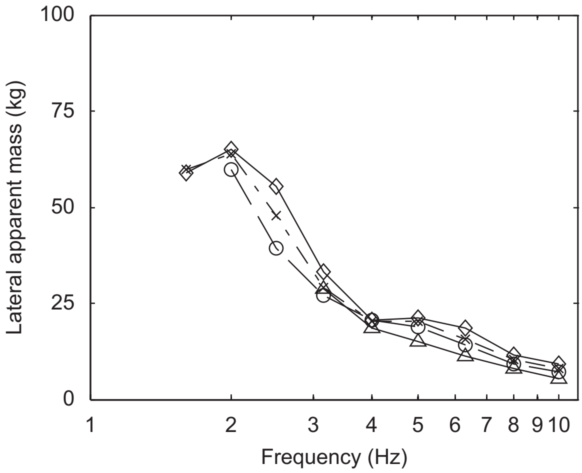


Fig. 7. Median apparent mass of 12 subjects exposed to lateral vibration at four magnitudes: ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o– – – –: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s.

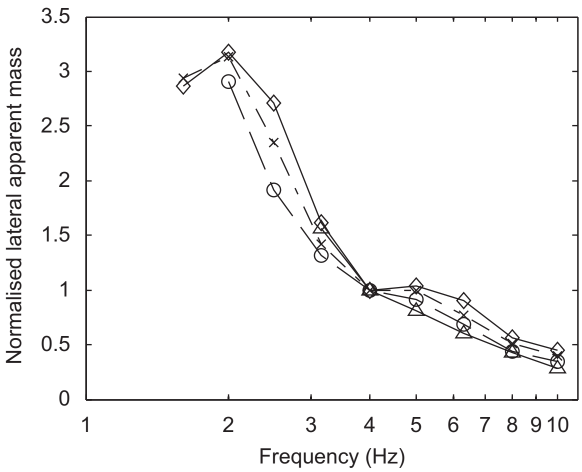


Fig. 8. Median normalised apparent mass of 12 subjects exposed to lateral vibration at four magnitudes: ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o– – – –: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s.

subjects at 0.125 m s$^{-2}$ r.m.s., 10 subjects at 0.25 m s$^{-2}$ r.m.s., 11 subjects at 0.5 m s$^{-2}$ r.m.s., and six subjects at 1.0 m s$^{-2}$ r.m.s. ($p < 0.05$).

Table 8 shows Spearman rank order correlation coefficient, $r_s$, between median magnitude estimates and the median normalised apparent masses for each frequency. When changing vibration magnitude, there were negative correlations between the median magnitude estimates and the normalised apparent masses at most frequencies. However, the correlations were not statistically significant, except for a significant correlation at 6.3 Hz ($p = 0.001$) and a marginally non-significant correlation at 10.0 Hz ($p = 0.051$).

## 5. Discussion

### *5.1. Subjective response*

For fore-and-aft vibration, irrespective of vibration magnitude, the relative discomfort varied with the frequency of vibration (Fig. 2). The relative discomfort at 2.5 Hz was more than at 2.0 Hz and more than at

Table 6
Statistical significance of the effect of vibration magnitude on the normalised lateral apparent mass determined by Wilcoxon matched-pairs signed ranks test: $^{**}p<0.01$, $^{*}p<0.05$, $^{\dagger}p<0.1$

| Vibration magnitude ($\mathrm{m\,s^{-2}}$ r.m.s.) | 0.250 | 0.500 | 1.000 |
|---|---|---|---|
| At 2.5 Hz | | | |
| 0.125 | 0.041*[a] | 0.034*[a] | – |
| 0.250 | … | 0.117 | – |
| 0.500 | | … | – |
| At 3.15 Hz | | | |
| 0.125 | 0.071†[a] | 0.099†[a] | 0.209 |
| 0.250 | … | 0.814 | 0.182 |
| 0.500 | | … | 0.049*[b] |
| At 6.3 Hz | | | |
| 0.125 | 0.060†[a] | 0.117 | 0.041*[a] |
| 0.250 | … | 0.638 | 0.137 |
| 0.500 | | … | 0.136 |
| At 8.0 Hz | | | |
| 0.125 | 0.071†[a] | 0.041*[a] | 0.060†[a] |
| 0.250 | … | 0.239 | 0.084†[a] |
| 0.500 | | … | 0.433 |
| At 10.0 Hz | | | |
| 0.125 | 0.015*[a] | 0.005**[a] | 0.005**[a] |
| 0.250 | … | 0.084†[a] | 0.010*[a] |
| 0.500 | | … | 0.005**[a] |

[a]The normalised apparent mass at lower vibration magnitude is significantly greater than that at higher vibration magnitude.
[b]The normalised apparent mass at lower vibration magnitude is significantly less than that at higher vibration magnitude.

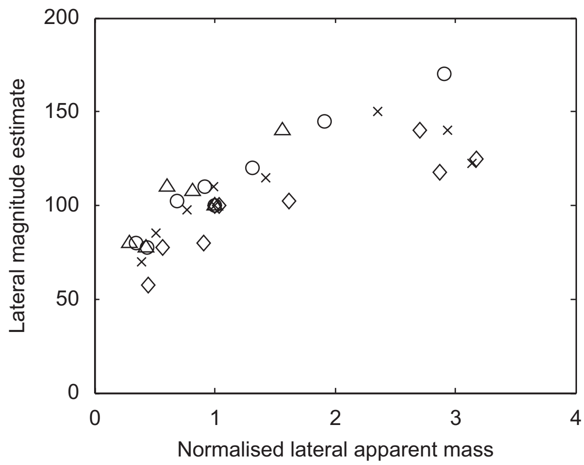


Fig. 9. Median magnitude estimates compared with the normalized apparent mass for lateral vibration at four magnitudes: ◇: 0.125 $\mathrm{m\,s^{-2}}$ r.m.s.; ×: 0.25 $\mathrm{m\,s^{-2}}$ r.m.s.; o: 0.5 $\mathrm{m\,s^{-2}}$ r.m.s; and Δ: 1.0 $\mathrm{m\,s^{-2}}$ r.m.s.

frequencies greater than 3.15 Hz for all three vibration magnitudes. This implies that the subjects were most sensitive to vibration around 2.5 Hz, as observed in previous studies: maximum sensitivity to fore-and-aft vibration was found between 2.5 and 3.25 Hz by Donati et al. [3], and at frequencies between 2 and 3.15 Hz by Griffin et al. [6].

For lateral vibration, the relative discomfort also tended to be greatest at 2.5 Hz, although there was no significant difference in magnitude estimates between 2.0 and 2.5 Hz (Fig. 6). The frequency range in which

Table 7
Correlations between median magnitude estimates and medians of the normalised lateral apparent mass at four vibration magnitudes: Spearman rank order correlation coefficient, $r_s$

| Vibration magnitude ($m\,s^{-2}$ r.m.s.) | Correlation coefficient | Number of samples |
|---|---|---|
| 0.125 | 0.946** | 9 |
| 0.25 | 0.917** | 9 |
| 0.5 | 0.905** | 8 |
| 1 | 0.714 | 6 |

**$p<0.01$.

Table 8
Correlations between median magnitude estimates and medians of the normalised lateral apparent mass at nine frequencies: Spearman rank order correlation coefficient, $r_s$

| Frequency (Hz) | Correlation coefficient | Number of samples |
|---|---|---|
| 1.60 | 1.000 | 2 |
| 2.00 | −0.500 | 3 |
| 2.50 | −0.500 | 3 |
| 3.15 | −0.400 | 4 |
| 4.00 | – | – |
| 5.00 | −0.316 | 4 |
| 6.30 | −1.000** | 4 |
| 8.00 | 0.258 | 4 |
| 10.00 | −0.949*** | 4 |

***$p<0.1$ and **$p<0.01$.

subjects were most sensitive to lateral vibration in the present study is partially consistent with previous studies: Corbridge and Griffin [4] found greatest sensitivity to lateral vibration in the frequency range 1.25 and 2.0 Hz, Griffin et al. [6] found sensitivity decreased with increasing frequency above 2.5 Hz, and Miwa [5] found sensitivity decrease above 3.15 Hz. The differences may be attributed to sitting posture: subjects sat on a seat having no backrest with feet supported on a non-vibrating height-adjustable footrest in the present study and in Griffin et al. [6], but on a seat with a 400-mm high backrest and feet supported on the moving vibrator table in Corbridge and Griffin [4], and on a seat having no backrest and feet unsupported in Miwa [5]. Inter-subject variability and vibration magnitude may also have contributed to the differences between the studies.

Relative discomfort was affected by vibration magnitude in the fore-and-aft direction (Fig. 2) and in the lateral direction (Fig. 6) over the frequency range 1.6–10 Hz. The effect of vibration magnitude on relative discomfort is similar to the effect of vibration magnitude on equivalent comfort contours found in previous studies: fore-and-aft vibration from 2–10 Hz by Morioka and Griffin [8] and lateral vibration from 4–8 Hz by Howarth and Griffin [7] and from 4–10 Hz by Morioka and Griffin [8]. The equivalent comfort contours from these previous studies were compared with the relative discomfort obtained in the present study by calculating the magnitude estimates relative to the discomfort at 4 Hz based on the equivalent comfort contours in those previous studies.

With fore-and-aft vibration, Morioka and Griffin [8] observed a magnitude-dependence in the equivalent comfort contours. Their study and the present study show that discomfort relative to 4 Hz tended to increase with increasing vibration magnitude at frequencies lower than 4 Hz. For example, the relative discomfort at 2 Hz calculated with respect to the discomfort at 4 Hz increased from about 117 to 237 with the vibration magnitude increasing from 0.125 to 0.5 $m\,s^{-2}$ r.m.s., while the median magnitude estimate in the present study increased from 102.5 to 132.5 (Fig. 2) (100 is equivalent to the discomfort caused by a 4 Hz reference stimulus). The differences in the magnitude estimates of the relative discomfort between the two studies may be partly because the reference vibrations used in the experiments were different: the frequency of the reference vibration was 4 Hz in the present study and 20 Hz in Morioka and Griffin [8].

With lateral vibration, Howarth and Griffin [7] indicated that the shapes of equivalent comfort contours depend on vibration magnitude in the frequency range from 4 to 63 Hz at vibration magnitudes from 0.04 to 0.4 m s$^{-2}$ r.m.s. They showed that the magnitude estimate of relative discomfort with respect to 4 Hz decreased with decreasing vibration magnitude at frequencies greater than 4 Hz. The present study found a similar trend with relative discomfort decreasing with decreasing vibration magnitude, as shown in Fig. 6, although this trend was not necessarily statistically significant. At frequencies of 6.3 and 10 Hz, Morioka and Griffin [8] also indicated that the discomfort relative to 4 Hz decreased with decreasing vibration magnitude showing a similar trend that found in the present study (Fig. 6, Table 5). At frequencies lower than 4 Hz, the effect of vibration magnitude on relative discomfort found by Morioka and Griffin [8] appears different from the present study. Their study found that discomfort relative to 4 Hz tended to decrease with increasing vibration magnitude whereas the present study found the relative discomfort tended to increase with increasing vibration magnitude (Fig. 6). Possible reasons for the difference may include differences in sitting posture: subjects had no thigh contact with a vibrating surface on the small seat used by Morioka and Griffin [8] while subjects had their thighs in contact with the vibrating surface in the present study. In addition, subjects kept their hands on stationary cylindrical handles in Morioka and Griffin [8] while subjects kept their hands on their laps in the present study. These differences in sitting posture may have a greater effect on discomfort caused by lateral vibration than discomfort caused by fore-and-aft vibration because the hands and the thighs may have more effect on the stability of the body exposed to lateral vibration than fore-and-aft vibration. At frequencies from 2 to 4 Hz, the ranges of vibration magnitudes used by Morioka and Griffin [8] (i.e., 0.05–0.4 and 0.05–0.8 m s$^{-2}$ r.m.s., respectively) were slightly lower than the range used in the present study (i.e., 0.125–0.5 m s$^{-2}$ r.m.s. at 2 Hz and 0.125–1.0 m s$^{-2}$ r.m.s. at 4 Hz). This difference may have an effect on the accuracy of the calculated magnitude estimate obtained from extrapolation of the equivalent comfort contours derived in Ref. [8].

The single frequency weighting for fore-and-aft and lateral vibration in the current principal standards for evaluating horizontal vibration (e.g., ISO 2631–1 [1] and BS 6841 [2]) implies that the frequency-dependence of subjective response is independent of the magnitude of vibration. In contrast, a significant nonlinearity in the subjective response has been found in the present and previous studies. The frequency weighting, $W_d$, given in both ISO 2631–1 and BS 6841 for the evaluation of horizontal vibration has been compared with the magnitude estimates obtained at four magnitudes of fore-and-aft vibration (Fig. 10) and lateral vibration (Fig. 11). In the figures, the relative discomfort has been converted to dB with respect to the reference of 100, and the $W_d$ frequency weighting has been adjusted so that the weighting factor at 4 Hz is 0 dB to allow comparison with the relative discomfort at 4 Hz in the present study. Figs. 10 and 11 indicate that the nonlinearity in the subjective responses is sufficiently great to be considered when formulating frequency weightings for horizontal vibration. Relative to lower frequencies, the frequency weightings derived from the present study suggest that the standard weighting, $W_d$, underestimates discomfort caused by vibration at frequencies greater than about 4 Hz.

In the present study, relative discomfort was measured using vibration stimuli with a duration of 4 s. It is expected that vibration discomfort will increase with increasing duration of vibration. Miwa [17] investigated discomfort produced by sinusoidal vertical and horizontal vibration with durations in the range 0.005–6 s and concluded that the discomfort caused by vibration did not increase with increasing duration in the range 2–6 s. Griffin and Whitham [18] investigated whether the discomfort produced by 4, 8, 16 and 32 Hz whole-body vertical vibration was dependent on the duration of exposure up to 32 s and concluded that there was, very approximately, a fourth-power relationship such that a sixteen-fold increase in duration was equivalent to a doubling of vibration magnitude. The effect of vibration duration on discomfort may differ at different frequencies and with different axes of excitation so that the relative discomfort, and therefore the optimum frequency weighting, depends on the exposure duration.

### 5.2. Biodynamic responses

The peak frequencies of the apparent mass found in the present study with sinusoidal vibration (i.e., 2.5 Hz in the fore-and-aft direction (Fig. 3) and 2.0 Hz in the lateral direction (Fig. 7)) are consistent with those found in previous studies with random vibration. Fairley and Griffin [9] found a resonance, corresponding to the

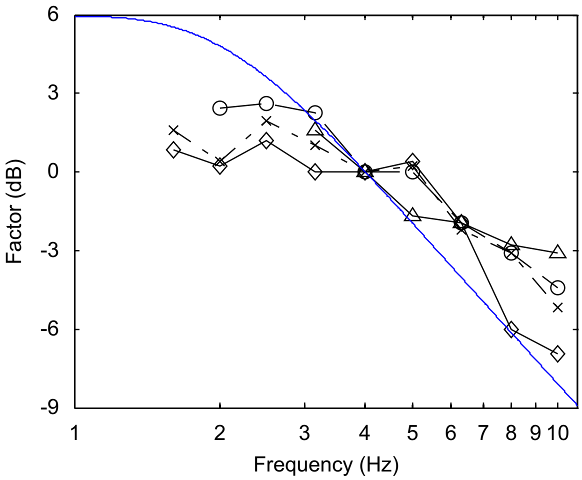


Fig. 10. Comparison between $W_d$ frequency weighting, ISO 2631-1 and BS 6841, and magnitude estimates obtained with fore-and-aft vibration at four magnitudes: ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o––––: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s., — $W_d$. The $W_d$ weighting was raised to have a value of 0 dB at 4 Hz.

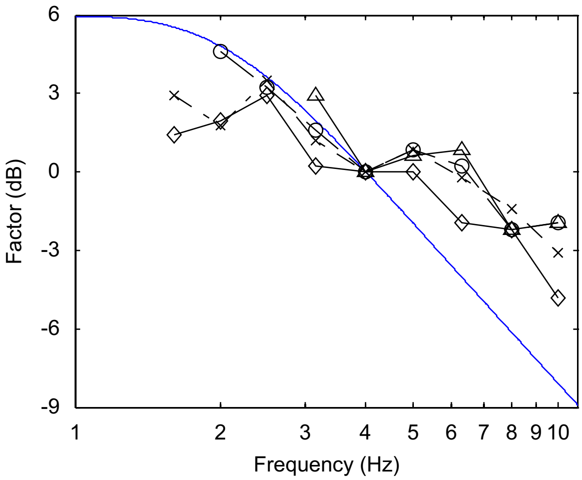


Fig. 11. Comparison between $W_d$ frequency weighting, ISO 2631-1 and BS 6841 and magnitude estimates obtained with lateral vibration at four magnitudes: ◇——: 0.125 m s$^{-2}$ r.m.s.; × -.-.-: 0.25 m s$^{-2}$ r.m.s.; o––––: 0.5 m s$^{-2}$ r.m.s.; and Δ—: 1.0 m s$^{-2}$ r.m.s., —— $W_d$. The $W_d$ weighting was raised to have a value of 0 dB at 4 Hz.

second mode, around 2.5 Hz with fore-and-aft excitation and around 2.0 Hz with lateral excitation using random vibration over the frequency range 0.25–20 Hz. Mansfield and Lundström [12] measured the apparent masses of seated subjects exposed to random vibration over the frequency range 1.5–20 Hz. A first resonance, according to these authors, was around 3.0 Hz with fore-and-aft vibration and around 1.9 Hz with lateral vibration, although low coherency between the acceleration and the force measured at low frequencies might have affected the accuracy of the resonances observed in the apparent mass. The peak frequencies in the apparent masses obtained with sinusoidal vibration in the present study are not necessarily the same as the resonance frequencies of the apparent masses obtained with random vibration: the coarse frequency resolution achieved with sinusoidal vibration prevents accurate definition of the resonance frequency.

The peak frequency in the fore-and-aft apparent mass (Fig. 3) and the lateral apparent mass (Fig. 7) tended to decrease with increasing vibration magnitude, consistent with the nonlinearity in the dynamic response reported in previous studies [9,11,12]. With random vibration, Fairley and Griffin [9] found that the frequency of the second mode of vibration decreased by 1 or 2 Hz with vibration magnitude increasing from 0.5 to 2.0 m s$^{-2}$ r.m.s., with both fore-and-aft and lateral excitation. With increasing vibration magnitude from 0.25 to 0.5 m s$^{-2}$ r.m.s., Mansfield and Lundström [12] concluded ''increases in vibration magnitude caused the first apparent mass peak to reduce in frequency''. Using sinusoidal vibration, Holmlund and Lundström [11] reported the ''normalised mechanical impedance spectra for *X* direction showed in principal one peak at about 3–5 Hz'' and ''corresponding spectra for the *Y* direction showed two peaks at about 2 and 6 Hz at low vibration levels''. With increasing vibration magnitude, the results of their study showed that the mechanical impedance at frequencies less than the peak frequency increased while that at the frequencies greater than the peak frequency decreased [11].

### 5.3. Comparison between subjective and biodynamic responses

In the present study, there was evidence of a relation between subjective and dynamic responses of seated subjects exposed to horizontal vibration.

The magnitude estimates of relative discomfort had a peak at 2.5 Hz with fore-and-aft excitation and between 2.0 and 2.5 Hz with lateral excitation (Figs. 2 and 6). These frequency ranges are consistent with the ranges in which the normalised apparent mass was greatest (Figs. 4 and 8). The significant correlations found between the median relative discomfort and the median normalised apparent mass (Figs. 5 and 9, Tables 3 and 7) are consistent with the motion of major body segments being associated with discomfort over the range of frequencies investigated, but they are not proof of a causal relation.

The movements of body segments are reflected in the apparent mass, although the movements responsible for resonances in the fore-and-aft and lateral apparent masses are not yet understood. The vibration mode contributing to the peak in the fore-and-aft apparent mass around 2.5 Hz in the present study might be attributed to shear deformation of the buttocks tissue and pitching, or bending, of the upper-body giving fore-and-aft motion of the buttocks and the hips out of phase with fore-and-aft motion of the shoulders and the head, as hypothesised by Fairley and Griffin [9]. At a similar frequency, Kitazaki and Griffin [19] found that fore-and-aft motion of the head was out of phase with motion of the pelvis caused by bending of the spine during vertical excitation. Also, shear deformation of buttocks tissues was observed during vertical excitation at vibration modes greater than 1.49 Hz, and was dominant around 5 and 9 Hz. The peak of the lateral apparent mass observed around 2.0 Hz might be attributed to lateral motion of the upper-body similar to the hypothesis made by Fairley and Griffin [9]: lateral motion at the hips caused by shear deformation of the buttocks and rocking of the upper body out of phase with lateral motion of the shoulders and the head.

With increases in the vibration magnitude there were significant increases in the relative discomfort at 2.0, 2.5 and 3.15 Hz caused by fore-and-aft excitation (Fig. 2). At the same frequencies, the normalised fore-and-aft apparent mass increased with increasing vibration magnitude (Fig. 4). This is consistent with a relation between relative discomfort and normalised apparent mass at these frequencies. The increases in the apparent mass with increasing vibration magnitude might be attributed to increases in the ratio of motion of the body segments to seat motion or increases in the parts of the body mass excited by input vibration, or both, according to Newton's second law of motion. Increases in the motion of the body segments relative to the seat, or increases in the body portions excited, may also be expected to increase discomfort. This relation between the motion of the body and discomfort may be a cause of the similar nonlinear characteristics found in the relative discomfort and in the normalised apparent mass. The nonlinearity in magnitude estimates and normalised apparent mass found with lateral vibration seems similar to those with fore-and-aft vibration, although less clear.

With fore-and-aft excitation, there were significant positive correlations between the median relative discomfort and the median normalised apparent mass at 2.0, 2.5, 3.15 and 5.0 Hz (Table 4). This implies that the magnitude-dependence of relative discomfort was associated with the nonlinear characteristics observed in the apparent mass of the body. There was a negative correlation between median relative discomfort and the median normalised apparent mass at 8.0 and 10 Hz, with marginal statistical significance. Fig. 12a and b compare the magnitude estimates of all subjects with their normalised apparent mass obtained at a vibration magnitude of 0.25 m s$^{-2}$ r.m.s. at 2.5 Hz (a low frequency) and at 8.0 Hz (a high frequency), respectively. It can be seen in the data from individual subjects shown in Fig. 12 that there appears to be a positive correlation

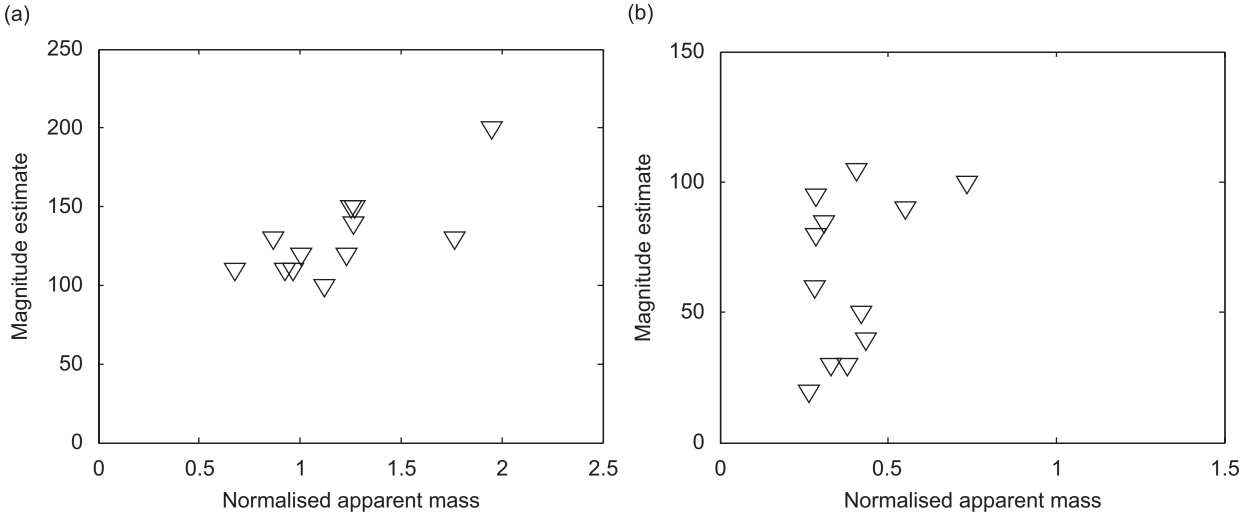


Fig. 12. Magnitude estimates compared with the normalised fore-and-aft apparent mass at 0.25 ms$^{-2}$r.m.s. for two frequencies: (a) at 2.5 Hz and (b) at 8 Hz.

between the magnitude estimate and the normalised apparent mass at 2.5 Hz while there was no correlation at 8.0 Hz. At 2.5 Hz, the positive correlation between the magnitude estimates and the normalised apparent masses was statistically significant at 0.25 m s$^{-2}$ r.m.s. ($r_s = 0.712$, $p = 0.009$) and marginally non-significant at 0.125 m s$^{-2}$ r.m.s. ($r_s = 0.530$, $p = 0.072$). In Appendix A, the Spearman rank order correlation coefficients, $r_{s,}$ between the magnitude estimates and the normalised apparent masses are shown for each frequency and magnitude investigated. At low frequencies the correlations are generally positive and sometimes statistically significant while at high frequencies the correlations are variable in direction and generally not statistically significant (see Appendix A). With lateral vibration, the Spearman rank order correlation coefficients, $r_s$, between the magnitude estimates and the normalised apparent masses were variable in direction. The correlations were statistically significant at 0.5 m s$^{-2}$ r.m.s. for 3.15 Hz ($r_s = 0.723$, $p = 0.008$) and marginally non-significant at 0.25 m s$^{-2}$ r.m.s. for 2 Hz ($r_s = 0.508$, $p = 0.092$) and 5 Hz ($r_s = 0.550$, $p = 0.064$).

It appears that the discomfort caused by horizontal whole-body vibration of seated subjects is associated with the apparent mass of the whole-body in the frequency range where motions of the upper-body dominate both responses. However, at higher frequencies, where the local vibrations at various parts of the body dominate discomfort, the subjective responses are not likely to be associated with the apparent mass of the whole body.

## 6. Conclusions

When seated subjects are exposed to fore-and-aft or lateral whole-body vibration in the frequency range 1.6–10 Hz, their discomfort and apparent mass are similarly affected by the frequency and magnitude of vibration, and there are correlations between subject apparent mass and subject discomfort.

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## Appendix A. Correlation between magnitude estimates and normalised apparent masses in the fore-and-aft axis for individual data

For further details see Table A1.

Table A1
Correlations between magnitude estimates and the normalised fore-and-aft apparent masses at nine frequencies and at four vibration magnitudes: Spearman rank order correlation coefficient, $r_s$

| Vibration magnitude ($m\,s^{-2}$ r.m.s.) | Correlation coefficient | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1.6 | 2.0 | 2.5 | 3.15 | 4.0 | 5.0 | 6.3 | 8.0 | 10.0 |
| 0.125 | −0.118 | 0.615* | 0.530*** | 0.456 | – | 0.058 | 0.239 | −0.299 | 0.450 |
| 0.25 | 0.283 | 0.430 | 0.712** | 0.542*** | – | 0.052 | 0.126 | 0.340 | 0.283 |
| 0.5 | – | 0.299 | 0.416 | 0.025 | – | 0.425 | 0.594* | −0.028 | 0.430 |
| 1 | – | – | – | 0.412 | – | −0.459 | 0.155 | −0.092 | −0.078 |

**$p<0.01$, *$p<0.05$, ***$p<0.1$.

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