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Discomfort from sinusoidal oscillation in the pitch and fore-and-aft axes at frequencies between 0.2 and 1.6 Hz

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Abstract

Low frequency pitch and fore-and-aft oscillations arise in many modes of transport. Pitch oscillation rotates a seat through the gravity vector giving rise to a fore-and-aft acceleration in the plane of the seat: the measurement of fore-and-aft acceleration does not discriminate between the component of this acceleration arising from pitch and the component arising from horizontal acceleration in the fore-and-aft direction. The objectives of this study were to investigate whether fore-and-aft acceleration in the plane of the seat was an adequate predictor of vibration discomfort arising from low frequency oscillation in both the pitch and fore-and-aft axes, and to determine the effect of a backrest on discomfort during pitch and fore-and-aft oscillation at low frequencies. Twelve male subjects used the method of magnitude estimation to judge the discomfort produced by sinusoidal oscillations in the pitch and fore-and-aft axes at 10 frequencies between 0.2 and 1.6 Hz, while seated with and without a backrest. For both pitch and fore-and-aft oscillation, the rate of growth of discomfort with increasing vibration magnitude decreased with increasing frequency of oscillation, indicating that the frequency-dependence of discomfort is magnitude-dependent. At frequencies greater than about 0.4 Hz with a backrest, and at frequencies greater than about 0.8 Hz without a backrest, fore-and-aft acceleration in the plane of the seat arising from pitch oscillation caused greater discomfort than the same acceleration produced by fore-and-aft oscillation. A backrest increased discomfort with pitch oscillation at frequencies greater than about 0.63 Hz, but tended to decrease discomfort during fore-and-aft oscillation. The prediction of discomfort caused by low frequency pitch and fore-and-aft oscillation requires that both components are measured and assessed according to their separate effects, taking into account any beneficial and detrimental effects of a backrest.

1. Introduction

Low frequency variations in fore-and-aft acceleration form part of the motion spectra in many modes of transport including road vehicles, off-road vehicles, trains, maritime vessels, and aircraft. Often, fore-and-aft acceleration is accompanied by pitch motion, and the measured low frequency fore-and-aft acceleration is influenced by gravitational components. Understanding the contributions of these low frequency oscillations to operator and passenger discomfort is incomplete.

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Miwa [1] concluded the discomfort caused by fore-and-aft and lateral acceleration was independent of both frequency and direction at frequencies between 0.5 and 1.0 Hz. Other studies have reported a slight decrease in discomfort from fore-and-aft oscillation of a seat (with stationary feet) as the frequencies reduce below 2 Hz, possibly influenced by relative motion between the seat and feet [2]. Rao and Jones [3] reported a slight decrease in sensitivity at frequencies below 2 Hz when subjects were exposed to whole-body fore-and-aft vibration on a flat cushioned seat. Donati et al. [4] found similar trends from a study in which subjects were seated on an agricultural tractor seat with a low backrest.

Price [5] reported the rate of growth and degree of discomfort arising from exposure to low frequency fore-and-aft vibration at frequencies between 0.5 and 16 Hz for magnitudes between 0.08 and 0.8 m s^{-2} rms. The rate of growth of discomfort decreased by 50% as the frequency increased from 0.5 to 1.0 Hz. The associated equivalent comfort contours showed that sensitivity to acceleration increased gradually with frequency increasing above 0.5 Hz, reaching a maximum around 3.0 Hz.

There has been limited investigation of the discomfort caused by rotational oscillation. Pradko [6] found that for rotational oscillation of a seat at frequencies less than 30 Hz, lower magnitudes of pitch than roll were required to cause similar discomfort. A similar finding has been reported by Parsons and Griffin [7]. Both Pradko [6] and Parsons and Griffin [7] found that the discomfort caused by roll and pitch acceleration of a seat surface decreased as the frequency increased from 1.0 Hz, the lowest frequency studied. For roll acceleration (in rad s^{-2}), Wyllie and Griffin [8] found that discomfort decreased with increasing frequency from 0.2 to 1.6 Hz.

For roll and pitch oscillation, Parsons and Griffin [9] found that as the distance of a seat from the centre of rotation increased, the frequency-dependence of equivalent comfort contours over the range 1–30 Hz became increasingly similar to those for translational oscillation having a magnitude equivalent to the basal chord of the rotation—implying that when subjects are sufficiently far from the centre of rotation their discomfort is dominated by the translational motion caused by the rotation rather than by their rotation.

The prediction of discomfort arising from vibration requires knowledge of the relationship between characteristics of the vibration (e.g. direction, magnitude, frequency, and duration) and subjective reaction (e.g. discomfort). One strategy is to quantify the effects of the influencing factors through systematic laboratory research assigning them ‘weightings’ in proportion to their relative importance. With a large number of influencing factors, and the potential for interactions between factors, this requires much knowledge and the careful application of the knowledge gleaned from laboratory experiments.

Current standards offer weightings for the accelerations measured in translational and rotational axes at a supporting seat surface (e.g. BS 6841 [10]; ISO 2631-1 [11]). Low frequency pitch (or roll) oscillations rotate a seat through the gravity vector resulting in the measurement of fore-and-aft (or lateral) acceleration in the plane of the seat. At high frequencies the gravitational component is negligible because the angle of rotation is small. At low frequencies the angles can be large and the motions measured by accelerometers orientated in the fore-and-aft (or lateral) direction may contain substantial gravitational components. The standards imply that pitch (and roll) oscillation should be evaluated twice (i.e. in terms of both the rotational acceleration and also in terms of the ‘horizontal’ translational acceleration measured due to rotation through the gravitational vector). The two components are summed (using the root-sums-of-squares, r.s.s.) to determine the total effect (i.e. the overall ride value) [21]. This involves ‘double counting’ the contribution of pitch (and roll) oscillation to discomfort, because it includes both the rotational component (measured in rad s^{-2}) and the translational component (measured in m s^{-2} in an approximately horizontal direction) arising from tilting in the gravitational field.

The standards allow for the prediction of the relative importance of vibration at different locations (i.e. at the seat, the feet, and the back) by combining the frequency-weighted single-axis accelerations using the root-sum-of-squares. This neglects any effect of phase between locations, although studies with fore-and-aft oscillation [12] and vertical oscillation [13,14] have found that phase affects comfort at low frequencies. With low frequency oscillation, backrests and footrests that move with a seat provide support and may result in less discomfort than when sitting with the back or the feet stationary—whereas the standards imply that such additional vibration inputs always increase vibration discomfort.

The present investigation was designed to determine how discomfort depends on the frequency of oscillation (at frequencies between 0.2 and 1.6 Hz), the direction of oscillation (pitch or fore-and-aft), and the seating condition (with or without a backrest). It was hypothesised that discomfort would be dependent on the frequency of oscillation and the presence of the backrest, and that the discomfort caused by acceleration in the plane of the seat would depend on whether it was caused by fore-and-aft or pitch oscillation. The objectives were similar to those of a previous study with roll and lateral oscillation reported by Wyllie and Griffin [8].

Two experiments are reported. A 'between axes' experiment investigated the relative discomfort caused by pitch and fore-and-aft oscillation at 0.2 Hz. A 'within axis' experiment investigated for both pitch and fore-and-aft oscillation the rate of growth in discomfort with increasing vibration magnitude, the variation in discomfort with the frequency of oscillation (between 0.2 and 1.6 Hz), the effect of a backrest on discomfort, and the principal locations of discomfort in the body.

2. Method

In both experiments, subjects were asked to judge the discomfort of various test motions relative to the discomfort caused by a reference motion using the method of magnitude estimation Stevens [15]. The reference motion and all test motions were sinusoidal with durations of 30 s. The magnitudes of the motions (both the fore-and-aft and the pitch oscillations) are reported in terms of translational acceleration (i.e. $\mathrm{m\,s^{-2}}$ rms). For pitch oscillation, this is the gravitational component in the plane of the seat arising from pitch of the seat through the gravitational vector (i.e. $g \sin\theta$, where θ is the angle of pitch).

2.1. 'Between axes' experiment

In the 'between axes' experiment, the reference motion was fore-and-aft oscillation at a frequency of 0.2 Hz and a magnitude of $0.45\,\mathrm{ms^{-2}}$ rms, with subjects seated on a flat rigid seat supported by a backrest. The test motions were also at 0.2 Hz but at five magnitudes in a logarithmic series between 0.2 and $1.0\,\mathrm{ms^{-2}}$ rms. These five test motions were presented in four conditions: two directions of oscillation (fore-and-aft and pitch) combined with two sitting postures (with and without a backrest). This experiment was completed in one session with the order of presentation of the four conditions balanced across subjects.

The simulator reproduced the fore-and-aft oscillations with acceleration distortions less than 8% and the pitch oscillations with acceleration distortions less than 4%. The vertical (i.e. z-axis) cross-axis acceleration was less than 8% of the fore-and-aft (x-axis) acceleration.

2.2. 'Within axis' experiment

In the 'within axis' experiment, the reference motion was always 0.5 Hz at a magnitude of $0.315\,\mathrm{m\,s^{-2}}$ rms. The test motions were at the 10 preferred one-third octave centre frequencies from 0.2 to 1.6 Hz and were presented in random order from an array of frequencies and magnitudes (see below). There were four separate sessions, corresponding to the two directions of oscillation (fore-and-aft and pitch) combined with the two sitting postures (with and without backrest). The order of sessions was balanced across subjects who attended only one session, of approximately 1-hour duration, per day.

With fore-and-aft oscillation, at each of the 10 frequencies there were six magnitudes of oscillation in logarithmic series from 0.2 to $0.63\,\mathrm{ms^{-2}}$ rms (except for 0.2 Hz where the greatest magnitudes was $0.5\,\mathrm{ms^{-2}}$ rms due to simulator displacement limitations).

With pitch oscillation, at each of the 10 frequencies there were six magnitudes of oscillation. At frequencies between 0.2 and 0.4 Hz, the magnitudes were in the same logarithmic series used with fore-and-aft oscillation (i.e. 0.2 to $0.63\,\mathrm{m\,s^{-2}}$ rms). At frequencies greater than 0.4 Hz, the acceleration magnitudes decreased in inverse proportion to frequency such that at 1.6 Hz the magnitudes ranged from 0.05 to $0.16\,\mathrm{ms^{-2}}$ rms. The reduction in the magnitude of pitch at higher frequencies was decided upon after preliminary experimentation indicated this was necessary to obtain a reasonable range of discomfort at each frequency.

For one magnitude of oscillation at each frequency, subjects indicated verbally the location in their body at which they felt the greatest discomfort. With all frequencies of fore-and-aft oscillation, they judged the location of discomfort with $0.4\,\mathrm{m\,s^{-2}}$ rms. With pitch oscillation at frequencies between 0.2 and 0.63 Hz, subjects judged the location of discomfort with $0.4\,m\,s^{-2}$ rms, whereas at greater frequencies they made the judgments at magnitudes that decreased in inverse proportion to frequency.

Fore-and-aft oscillation was reproduced with unweighted acceleration distortions less 28%, and much less than 20% for the majority of motions. After frequency weighting using W_d to reflect the expected sensitivity to differing frequencies, the fore-and-aft distortion was between 7% and 16% at all frequencies except 0.63 and 1.0 Hz, where it was between 16% and 20%. The simulator reproduced the pitch oscillation with acceleration distortions of less than 8%.

2.3. Subjects

Twelve male subjects, staff or students of the University aged between 18 and 30 years, participated in both experiments. Five subjects participated in both experiments. In the 'between axes' experiment the mean subject mass was 75.6 kg (range 54.5–100 kg) and the mean stature was 1.78 m (1.69–1.86 m). In the 'within axis' experiment the mean mass was 71.5 kg (range 54–90 kg) and the mean stature 1.77 m (1.70–1.86 m).

2.4. Equipment

2.4.1. Seating

Two seats, constructed from steel and aluminium alloy frames and with flat wooden seat pans and removable backrests were used in the experiments. The angle between the backrest and the seat was 90° and the height of the seat pan was 420 mm above the simulator platform. When used with a backrest, the height of the top of the backrest was adjusted to the sitting shoulder height of each subject—the backrest was adjustable in 30-mm increments within the 5th to 95th percentile of British male adult sitting shoulder heights [16].

When subjects sat so as to be in contact with the backrest they also wore a four-point harness. The harness restrained subjects around the waist and above each shoulder. The harness was loosened before each test session and the subjects were instructed to tighten the harness to a 'comfortably tight' setting, adjusting first the waist and then the shoulder restraints. The experimenter assisted the subject where necessary and ensured that the harness was symmetrically adjusted.

2.4.2. Equipment used in the 'between axes' experiment

Oscillatory motion was produced by a simulator capable of 12-m of horizontal motion and $\pm 10^\circ$ of rotation located in the Human Factors Research Unit at the Institute of Sound and Vibration Research. Fore-and-aft oscillation was measured with an accelerometer (Smiths type AV-L-692) mounted on a non-rotating portion of the chassis immediately below the seat. Pitch oscillation was measured with a similar accelerometer located at the centre of pitch, which passed through the seat reference point in the plane of the seat surface.

2.4.3. Equipment used in the 'within axis' experiment

Fore-and-aft oscillation was produced by a 1-metre stroke horizontal hydraulic vibrator in the Human Factors Research Unit at the Institute of Sound and Vibration Research. The acceleration was measured using a capacitive accelerometer (Setra type 141A) mounted on the platform of the vibrator immediately below the seat.

To produce pitch oscillation, the same 1-metre stroke horizontal vibrator was coupled via a crank to a rotational simulator. The axis of rotation was in the plane of the seat surface at the seat reference point and the acceleration arising from tilt through the gravitational vector (i.e. $g\sin\theta$) was measured using a capacitive accelerometer (Setra type 141A) orientated in the fore-and-aft direction and mounted at the centre of rotation.

2.4.4. Signal generation and acquisition

The motion stimuli were generated and monitored using an *HVLab* data acquisition system and software (version 3.81). The drive signals were converted from digital to analogue at 30 samples per second and low pass filtered at 10 Hz. Analogue to digital conversion of the measured acceleration also took place at 30 samples per second after low pass filtering at 10 Hz.

2.5. Procedure

Prior to participating in the study, which was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research, subjects were screened using a list of medical contraindications [17] and instructed in the method of magnitude estimation. Subjects then practiced judging the lengths of lines using the method of magnitude estimation before an experiment commenced.

Subjects were asked to sit in a comfortable upright posture, with their feet shoulder-width apart, and to use the method of magnitude estimation to express the vibration discomfort caused by the test motions relative to the discomfort caused by the reference motion, ignoring any audible noise. The subjects assigned a number that represented the discomfort of the test motion relative to the discomfort of the reference motion, assuming the discomfort caused by the reference motion corresponded to '100'. Subjects were permitted to use any positive number for their estimates of discomfort.

During both the 'within axis' and the 'between axes' experiments, subjects wore a blindfold so that their visual perception of the motion would not alter their responses. The subjects wore headphones through which noise at 80 dB (A) was delivered to mask the operating noise of the simulator. The headphones also facilitated communication between the experimenter and the subject. The experimenter was able to observe subjects at all times, either directly or via a closed circuit television system.

3. Results

3.1. Rate of growth of discomfort

The magnitudes of the physical stimuli, φ (accelerations in the plane of the floor), were related to the magnitudes of the sensations, ψ (magnitude estimates of discomfort), using Stevens' power law [15]:

$$\psi = k\varphi^n \tag{1}$$

The rates of growth in discomfort, n, were determined for each subject by regression between the logarithm of the vibration magnitude, φ, and the logarithm of the magnitude estimates, ψ:

$$\log_{10}\psi = \log_{10}k + n\log_{10}\varphi \tag{2}$$

Median rates of growth at each frequency were calculated from the individual slopes, n, and individual intercepts, k (Fig. 1).

With pitch oscillation, the rate of growth of vibration discomfort with increasing vibration magnitude varied significantly with frequency, both with and without the backrest ($p<0.01$; Friedman). In both cases, analysis of the trend showed that the median rate of growth of discomfort was negatively correlated with increasing frequency ($p<0.01$; Spearman).

With fore-and-aft oscillation and no backrest, the rate of growth of discomfort varied significantly with frequency ($p=0.001$; Friedman) and analysis of the trend showed that the median rate of growth of discomfort was negatively correlated with increasing frequency ($p=0.002$; Spearman). With the backrest, the rate of growth of discomfort did not vary significantly with frequency ($p=0.295$; Friedman).

The presence of a backrest had no significant effect on the rate of growth of discomfort with pitch oscillation at any frequency ($p>0.05$; Wilcoxon). With fore-and-aft oscillation the rate of growth of discomfort was significantly lower when subjects were seated with a backrest than when seated without a backrest at 0.25 Hz ($p=0.034$) and at 0.315 Hz ($p=0.002$).

The direction of oscillation appeared to affect the rate of growth of discomfort differently according to whether the backrest was present or not. With no backrest, the median rate of growth of discomfort was lower with pitch than with fore-and-aft oscillation at 0.2, 0.25, 0.4, 0.5, 1.0, 1.2, and 1.6 Hz, although the differences did not approach significance at any frequency ($p>0.2$) Wilcoxon). With the backrest, the median rate of growth of discomfort was greater with pitch than with fore-and-aft oscillation at 0.2, 0.25, 0.315, 0.63, and 0.8 Hz, with the difference significant at only 0.315 Hz ($p=0.019$) and 0.10 Hz ($p=0.004$).

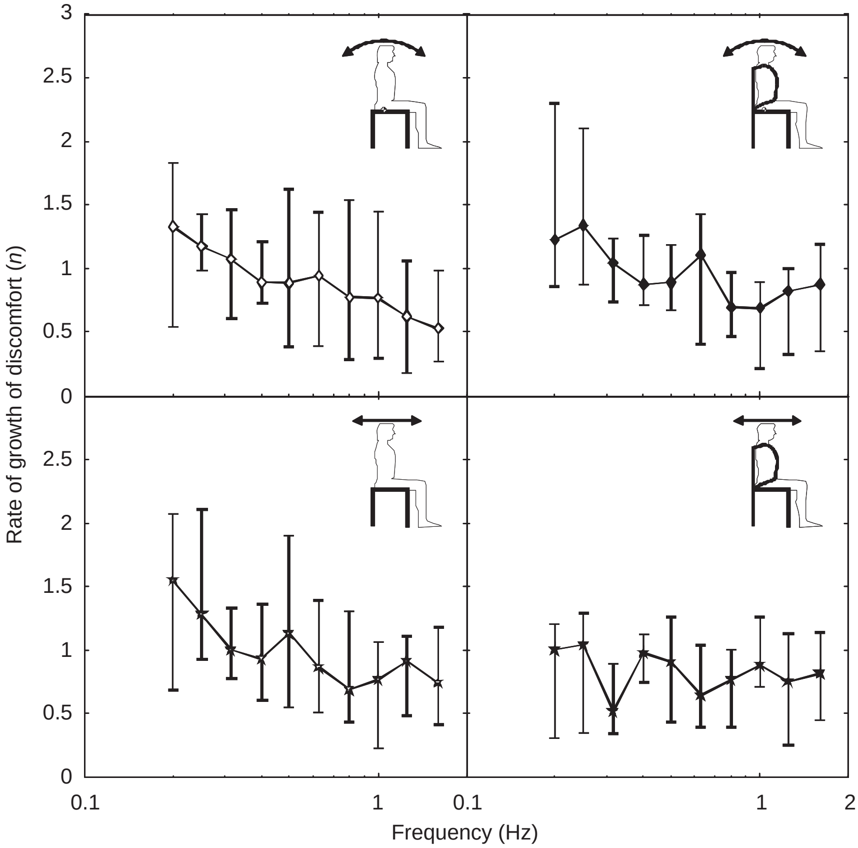

Fig. 1. Median rates of growth of discomfort, *n*, for pitch oscillation (top figures) and fore-and-aft oscillation (bottom figures) without a backrest (left figures) and with a backrest (right figures) from 12 subjects in the 'within axes' experiment. Error bars show the 75th and 25th percentile rates of growth of discomfort.

The rates of growth in discomfort determined at 0.2 Hz during the 'between axes' experiment and the 'within axes' experiment were not significantly different for either pitch or fore-and-aft oscillation ($p > 0.10$, Mann–Whitney U).

3.2. Relative discomfort between pitch and fore-and-aft oscillation

The magnitudes of 0.2 Hz oscillation required in both axes and with both seating conditions to elicit a discomfort judgment of 100 (i.e. discomfort equivalent to the 0.2 Hz sinusoidal reference motion at 0.45 m s^{-2} rms in the fore-and-aft axis on the rigid seat with backrest) differed significantly ($p = 0.016$; Friedman). In order of increasing sensitivity, the equivalent magnitudes were: fore-and-aft oscillation without backrest (0.31 m s^{-2} rms), pitch without backrest (0.41 m s^{-2} rms), fore-and-aft with backrest (0.44 m s^{-2} rms), and pitch with backrest (0.47 m s^{-2} rms).

To adjust the level of the contours obtained in the 'within axis' experiment to allow for the differing sensitivity found at 0.2 Hz in the 'between axis' experiment, a correction factor was calculated for each of the four conditions:

$$C_{\mathrm{Si}} = \varphi_{\mathrm{Si}}/\varphi_{\mathrm{SR}} \tag{3}$$

where φ_{Si} is the magnitude of a 0.2 Hz oscillation in the 'between axis' experiment that gave discomfort equivalent to 0.2 Hz 0.45 m s^{-2} rms fore-and-aft oscillation with the backrest, and φ_{SR} is the magnitude of a 0.2 Hz test motion in the 'within axis' experiment corresponding to a magnitude estimate of 100 when using a 0.5 Hz 0.315 m s^{-2} rms sinusoidal reference motion in the same axis and seating condition as the test motions.

Correction factors calculated from the medians of the individual slopes and intercepts were: pitch without backrest, 0.79; pitch with backrest, 0.63; fore-and-aft without backrest, 0.71; fore-and-aft with backrest, 0.97. Stevens [15] concluded that the *n* value was independent of the reference condition, so it was assumed that the same correction factor could be applied at all frequencies. To allow statistical comparisons across axes (see below), the individual contours obtained in the 'within axis' experiment were adjusted by these median correction factors.

3.3. Equivalent comfort contours for fore-and-aft and pitch oscillation

Equivalent comfort contours were determined within each axis for each subject by calculating the vibration acceleration, φ, corresponding to each of five subjective magnitudes, ψ, (i.e. 63, 80, 100, 125 and 160) where 100 corresponds to the discomfort produced by 0.315 ms^{-2} rms at 0.5 Hz in that axis, for each frequency (from 0.2 to 1.6 Hz) using Eq. (2). Five median equivalent comfort contours were then generated from the medians of the contours of individual subjects and adjusted according to differences between axes as stated above (Eq. (3)). Apart from fore-and-aft oscillation with a backrest, the adjusted contours for a subjective magnitude of 100 were highly dependent on vibration frequency ($p \leqslant 0.002$, Friedman; Fig. 2).

For pitch oscillation, the level of the 100 comfort contour declines at more than 6 dB per octave between 0.2 and 1.6 Hz, both with and without the backrest.

For fore-and-aft oscillation without the backrest, the level of the 100 comfort contour declines at less 3 dB per octave between 0.2 and 1.6 Hz.

Without the backrest at 0.8, 1.2, and 1.6 Hz, and with the backrest at frequencies greater than 0.4 Hz, the comfort contours corresponding to a subjective judgment of 100 were significantly lower for pitch oscillation than for fore-and-aft oscillation ($p < 0.05$), indicating greater sensitivity to pitch oscillation.

3.4. Effect of backrest

With pitch oscillation, the presence of the backrest reduced discomfort at 0.2 Hz ($p < 0.01$; Wilcoxon), but increased discomfort at frequencies greater than 0.63 Hz ($p < 0.05$; Wilcoxon).

With fore-and-aft oscillation, at frequencies between 0.25 and 1.25 Hz, subjects were significantly less uncomfortable when the backrest was present ($p < 0.05$ Wilcoxon).

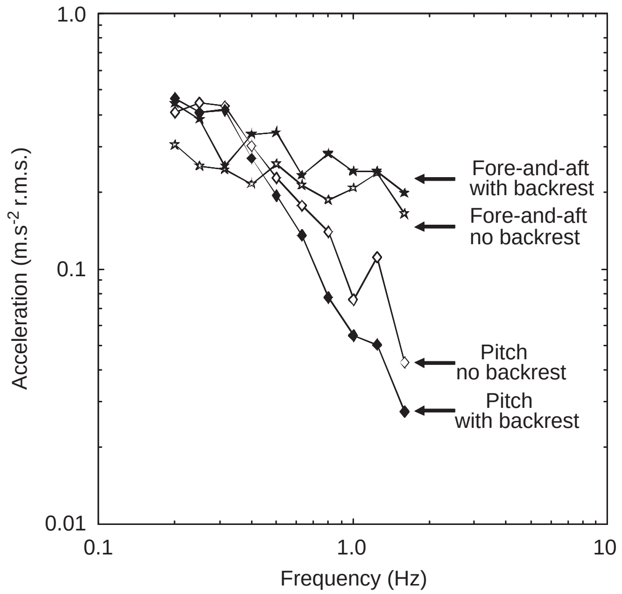

Fig. 2. Comparison of adjusted pitch and fore-and-aft equivalent comfort contours, each producing discomfort equivalent to that arising from exposure to sinusoidal fore-and-aft oscillation on a rigid seat with a backrest at 0.2 Hz, 0.45 $\mathrm{m\,s}^{-2}$ rms.

3.5. Effect of magnitude on the frequency-dependence of equivalent comfort contours

The magnitudes of pitch and fore-and-aft oscillation equivalent to subjective magnitudes between 63 and 160 are shown in Fig. 3. These median contours were produced using Eq. (2) from individual subject k and n values. The reference condition for these contours is a $0.315\,\mathrm{m\,s^{-2}}$ rms sinusoidal oscillation at 0.5 Hz in the same axis as the test motion, so the levels of these contours in one axis should not be compared with those in another axis.

Within the limited range of magnitudes employed in this study, the shapes of the equivalent comfort contours are not greatly affected by the magnitude of the motions.

3.6. Location of discomfort

There were no clear variations in the locations of discomfort with frequency. However there was a higher incidence of subjects reporting discomfort at the head, neck, or shoulders when seated with the backrest than when seated without the backrest (Fig. 4). This trend reached statistical significance with pitch oscillation at most frequencies between 0.5 and 1.2 Hz ($p<0.05$; McNemar) and at 0.25, 0.315, and 1.0 Hz with fore-and-aft oscillation ($p<0.05$; McNemar).

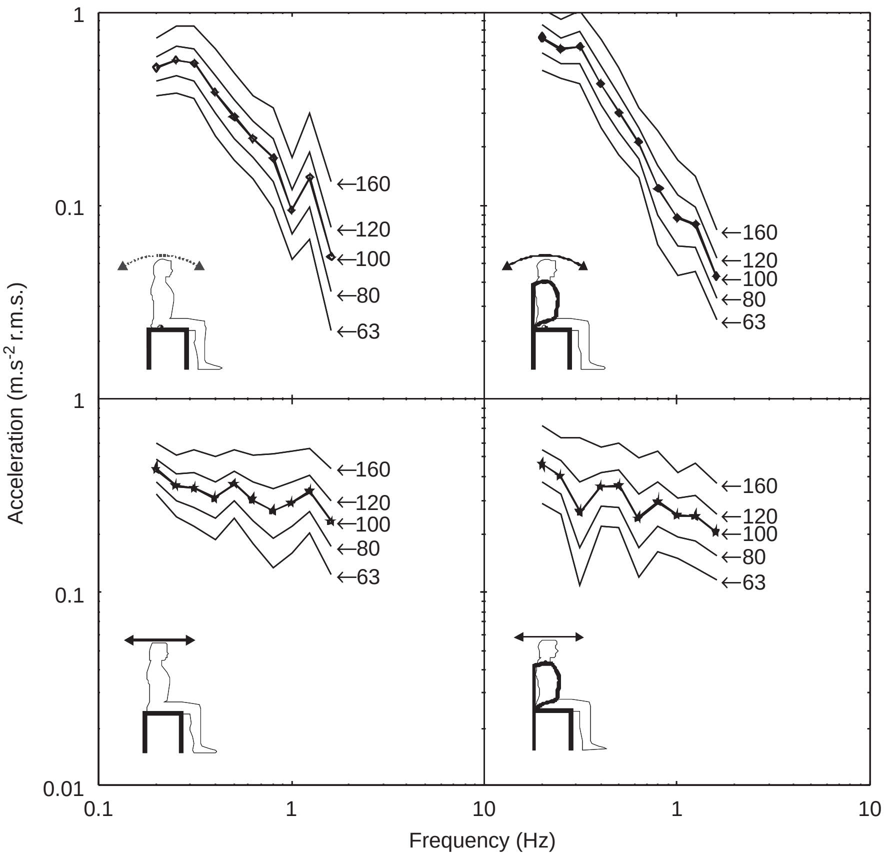

Fig. 3. The effect of frequency and magnitude on the level of the equivalent comfort contours arising from exposure to oscillation in the pitch axis (top figures) and fore-and-aft axis (bottom figures) without a backrest (left figures) and with a backrest (right figures). The 100 contour (bold) represents discomfort approximately equal to that caused by exposure to a 0.5 Hz, $0.315\,\mathrm{m\,s^{-2}}$ rms sinusoid in the same axis. Data from 12 subjects in the 'within axes' experiment.

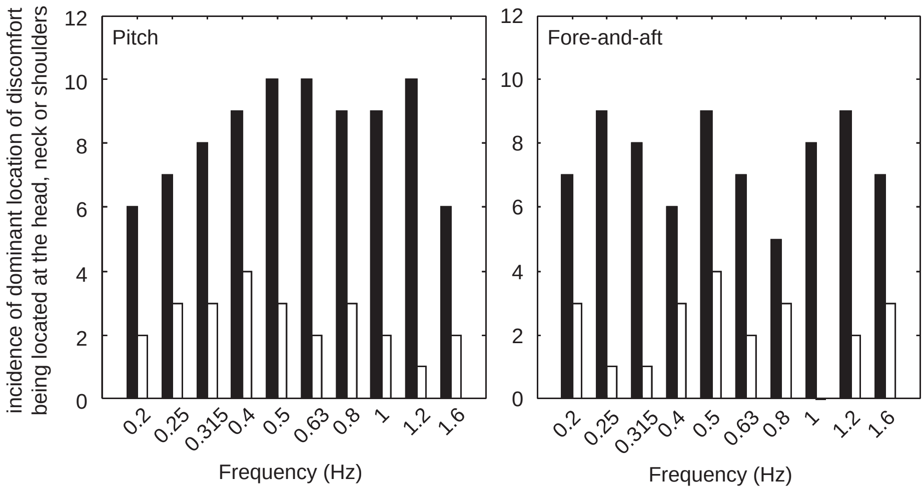

Fig. 4. The effect of backrest on the incidence of the dominant location of discomfort being at the head, neck, or shoulders during pitch and fore-and-aft oscillation as a function of the frequency of oscillation. Filled bars with backrest; empty bars without backrest.

4. Discussion

4.1. Rate of growth of discomfort caused by fore-and-aft and pitch oscillation

The variation in n value with frequency means that a unit increment in the magnitude of oscillation was associated with a greater increment in discomfort at low frequencies than at high frequencies. The contours of equivalent discomfort therefore change shape with the magnitude of oscillation, as seen in Fig. 3. Over a wider range of magnitudes, the change of shape would be greater and it would be seen that a frequency weighting appropriate for low magnitudes of oscillation would be inappropriate for high magnitudes.

The rates of growth in discomfort with increasing vibration magnitude (i.e. the value of n in Stevens' power law) showed a high level of inter-subject variability. At the lowest frequencies, some subjects were able to exercise voluntary control of the movement of their upper bodies in response to the motion, whereas at the higher frequencies the response may have been influenced by involuntary muscular activity. The experimental design presented motions in a random order of frequency and magnitude, so subjects experienced motions of the same frequency at widely separated points in time. They may have chosen to respond differently to motions of the same frequency at different times, although no evidence of a systematic effect could be found in the data. Such variability in their chosen response would reduce correlations between the magnitudes of the motions and the magnitude estimates of discomfort made by subjects.

4.2. Effect of frequency on discomfort caused by fore-and-aft and pitch oscillation

With a backrest, at frequencies less than 0.4 Hz, the comfort contours for pitch and fore-and-aft oscillation in Fig. 2 indicate that, very approximately, a similar level of discomfort arose irrespective of whether the acceleration in the plane of the seat arose from pitch or fore-and-aft oscillation. However, without a backrest, acceleration in the plane of the seat caused by pitch oscillation tended to cause less discomfort than the same acceleration caused by fore-and-aft oscillation. This may reflect difficulty maintaining stability during excursions of the centre of mass of the upper body with respect to the ischial tuberosities, particularly as the body was moved backwards. The difference between the findings of this study and those of Wyllie and Griffin [8] where the lowest frequencies of roll and lateral oscillation caused similar discomfort on a seat with and without a backrest, might be explained by the geometrical differences between the base of support during roll (or lateral) oscillation and pitch (or fore-and-aft) oscillation. During roll (or lateral) oscillation the centre of pressure can move between the ischial tuberosities without instability requiring compensatory muscular effort. During pitch (or fore-and-aft) oscillation, in order to maintain stability, muscular effort or a reaction force at the feet is required. In the absence of a backrest, the difference between fore-and-aft and pitch oscillation may have arisen because stability can be provided by exerting pressure at the feet, but this is more difficult when the footrest moves vertically due during pitch oscillation. It was observed that when subjects were seated without the backrest their posture was under some degree of voluntary control, especially at frequencies less than about 0.4 Hz. Different response strategies (e.g. riding in-phase or out-of-phase with the seat) may cause different discomfort and all subjects may not have found the same posture or adopted the most comfortable strategy. Furthermore, the different postures may be differently affected by fatigue, and the discomfort experienced during a short period of oscillation may not be a good predictor of discomfort arising from longer exposures.

4.3. Effect of backrest

With pitch oscillation, the backrest increased discomfort at frequencies greater than about 0.63 Hz (Fig. 2). With constant acceleration in the plane of the seat (i.e. constant $g \sin \theta$, due to a constant angle of oscillation), the fore-and-aft acceleration at the top of the backrest increases in proportion to the square of the frequency of oscillation, so causing increased discomfort with increasing frequency. Without a backrest, there appeared to be less motion of the upper bodies and heads of subjects.

With fore-and-aft oscillation and no backrest, the motion of the head and upper body appeared to lag behind the oscillation of the seat. If subjects' had sat perfectly upright this lag would have increased the probability that their centre of pressure moved behind the ischial tuberosities with potentially undesirable implications for their stability. Observation showed that subjects' posture tended to be slightly kyphotic during fore-and-aft oscillation, presumably to mitigate this risk. The backrest tended to reduce discomfort at most frequencies during fore-and-aft oscillation. This was probably because the backrest reduced the instability due to the displacement of the centre of mass of the upper body, and thus the discomfort caused by its motion relative to the seat.

This study employed seating conditions that may appear to be extremes, but it is conceivable that in these axes they do not represent the extremes of discomfort, since the presence of a harness removes the possibility of loss of contact with the backrest and subsequent risk of impact with the backrest.

4.4. Location of discomfort

At higher frequencies than studied here, the location of discomfort during exposure to whole-body vibration is highly frequency-dependent (due to the complex biodynamic responses of the body that include various resonances), varying between the ischial tuberosities and the head according to the direction and frequency of the vibration [18–20]. During vertical oscillation, movement between the seat and the feet can contribute to a frequency-dependent discomfort evident in the localisation of discomfort [14]. A similar effect has been found with fore-and-aft oscillation when there is differential vibration at the seat, feet and back at frequencies between 0.5 and 16 Hz [12]. The present study found that discomfort caused by frequencies less than 1.6 Hz did not show a clear frequency-dependence, although the presence of a backrest strongly influenced the location of discomfort (Fig. 4). This presumably arose because the backrest reduced the opportunity for subjects to minimise the acceleration at the head.

4.5. Comparison with previous research

Parsons and Griffin [7] investigated the discomfort caused by roll vibration at frequencies between 1 and 30 Hz with subjects seated on a flat rigid seat with no backrest. They found that as the frequency decreased the sensitivity to pitch acceleration (in rad s^{-2}) increased. When the results of the present study are expressed in terms of angular acceleration, an overall trend for increased sensitivity to pitch acceleration at lower frequencies continues at a similar rate down to 0.2 Hz (Fig. 5).

With fore-and-aft vibration of subjects on a rigid seat with their feet moving in-phase, contours of equivalent comfort similar to those in Fig. 5 have been reported, with the rate of growth of discomfort (the *n* value in Stevens' power law) declining from around 1.4 at 0.5 Hz to about 1.0 at 1.6 Hz [5]. These trends

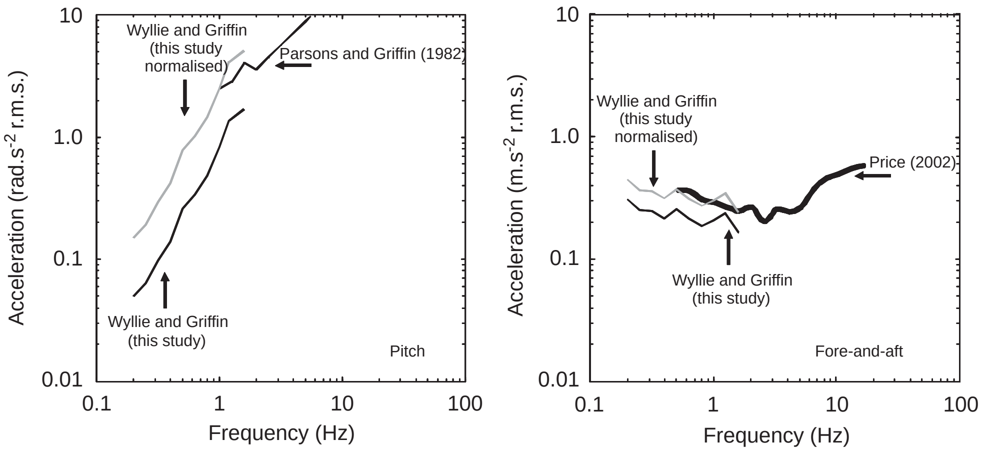

Fig. 5. Comparison of equivalent comfort contours for fore-and-aft vibration (Price [5]) and pitch vibration (Parsons and Griffin [7]) with equivalent comfort contours determined in this study. Data normalised to coincide at 1.0 Hz.

in n values are also compatible with those determined in the present study, and the generally higher n values in the previous study could be explained by the much wider range of magnitudes investigated.

4.6. Prediction of discomfort caused by pitch oscillation

According to current standards, the discomfort caused by mechanical oscillation in the frequency range 0.5–80 Hz can be predicted using frequency weightings for translational and rotational vibration at the seat and from translational vibration at the feet and the backrest [10,21]. The method means that with combined pitch and fore-aft oscillation, seven components can theoretically contribute to discomfort:

(i) horizontal acceleration in the plane of the seat (weighted by frequency weighting W_d);
(ii) translational acceleration in the plane of the seat due to pitch—i.e. $g \sin \theta$ (weighted by frequency weighting W_d);
(iii) pitch acceleration in the plane of the seat in rad s^{-2} (weighted by frequency weighting W_e, with a multiplying factor of 0.4);
(iv) fore-and-aft acceleration at the backrest (weighted by frequency weighting W_c, with a multiplying factor of 0.8);
(v) translational acceleration at the backrest in the plane of the seat—i.e., $g \sin \theta$ (weighted by frequency weighting W_c, with a multiplying factor of 0.8);
(vi) fore-and-aft acceleration at the feet (weighted by frequency weighting W_b, with a multiplying factor of 0.25);
(vii) translational acceleration at the feet in the plane of the seat—i.e, $g \sin \theta$ (weighted by frequency weighting W_b, with a multiplying factor of 0.25).

In practice, many of these components are sufficiently small to be neglected. For example, with high frequencies of vibration the angle of pitch is small, so $g \sin \theta$ is small, and the contribution of components (ii), (v) and (vii) is insignificant.

Hitherto, it has been assumed that either the components due to $g \sin \theta$ are small (as with high frequency vibration) or that the effects are adequately reflected in the combination of this component with the fore-and-aft acceleration measured by nominally horizontal accelerometers. The results of the present study allow the assumption to be tested but only provide definitive information about the relative discomfort of pitch and fore-and-aft oscillation when the centre of pitch is in the plane of the seat surface. This may not be the case in some practical applications.

The four equivalent comfort contours shown in Fig. 2, correspond to conditions in which there was the same discomfort at all frequencies—hence the root-sums-of-squares (i.e. r.s.s.) summation of weighted components for each of these four conditions should be the same if the standardised weighting method is appropriate—at least at frequencies greater than 0.5 Hz where it is intended to be used. Fig. 6 shows the various components to which subjects were exposed in the four conditions, weighted as suggested in BS6841 [10] (assuming the weightings are extrapolated to frequencies less than 0.5 Hz, see Fig. 7), together with the root-sums-of-squares of these weighted components so as to produce an 'overall ride value'.

The prediction method in BS 6841 [10] allows for the assessment of discomfort caused by complex motions containing both rotational and translational components using weightings that assume the rotational components are measured in rad s^{-2} and the translational components are measured in m s^{-2}. In principal, after frequency weighting according to the weightings and multiplying factors in the standard, components in any axis (translational or rotational) can be compared and combined (using root-sums-of-squares summation) such that the 'overall ride value' is appropriately influenced by each component according to its importance.

It may be seen in Fig. 6 that for fore-and-aft oscillation without a backrest, the equivalent comfort contour (i.e. the r.s.s. of the weighted fore-and-aft seat and fore-and-aft floor accelerations) corresponds to a similar overall ride value at all frequencies from 0.5 to 1.6 Hz, as expected. The main contributor to the overall ride value is the fore-and-aft acceleration at the seat, with acceleration at the feet making a negligible contribution using the standardised method. However, the r.s.s. of the weighted contours appears to have underestimated the subject's sensitivity as the contour level is somewhat below the level of the reference motion (0.2 Hz, 0.45 m s^{-2} rms in the fore-and-aft axis).

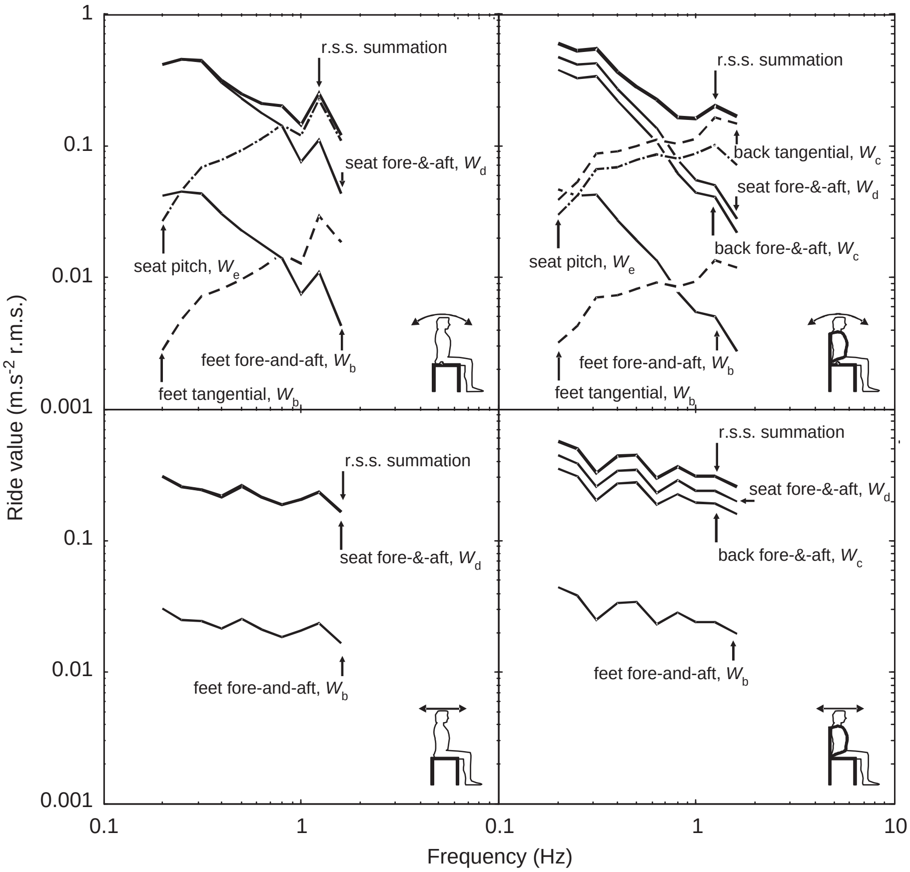

Fig. 6. Frequency-weighted accelerations and the seat, backrest and feet corresponding to the adjusted equivalent comfort contours generated from the median individual k and n values. (Values calculated using BS 6841 (1987) [10] asymptotic frequency weightings extrapolated below 0.5 Hz without band-pass filtering). Components of motion at the seat, backrest and feet shown together with the root-sums-of-squares of the weighted values in each axis and seating condition.

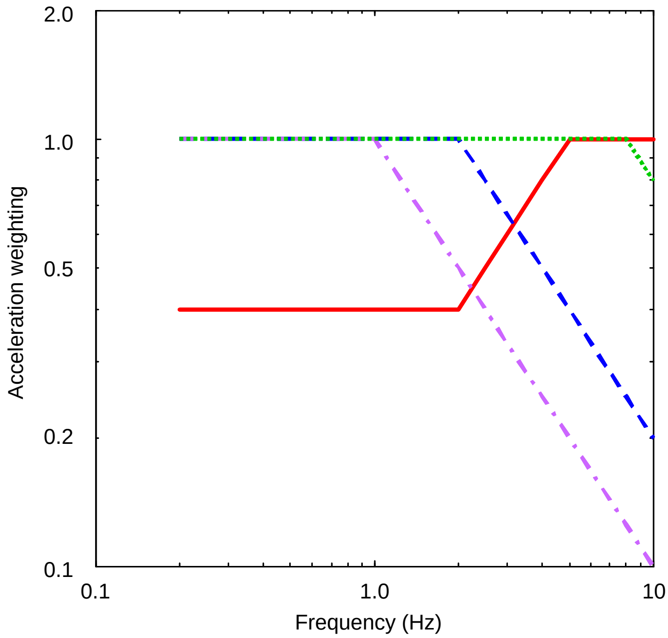

Fig. 7. Asymptotic frequency weightings according to BS 6841 (1987) [10] extrapolated below 0.5 Hz without band-pass filtering: ——— W_b; ⋯⋯ W_c; – – – – W_d; –·–·–·– W_e.

For fore-and-aft oscillation on a seat with a backrest, the r.s.s. summation of the weighted components produced values which declined from close to the predicted value (0.45 m s^{-2} rms) as the frequency increased from 0.2 to 1.6 Hz. This implies that the discomfort caused by the higher frequencies was underestimated by the weightings. The principal contribution to the r.s.s was the fore-and-aft oscillation at the seat, with a high contribution from the backrest and a negligible contribution from the oscillation of the feet.

For pitch oscillation with no backrest, the seat fore-and-aft acceleration is the dominant term in the r.s.s summation at frequencies less than 0.5 Hz. At greater frequencies, the summation is dominated by the seat pitch component. The root-sum-of-squares of all components are variable but, overall, decrease with increasing frequency. The level at 0.2 to 0.315 Hz is only slightly below the reference condition (0.45 m s^{-2} rms) but at greater frequencies the reduction indicates that discomfort was underestimated by the standard method.

For pitch oscillation with a backrest, the seat fore-and-aft acceleration remains the dominant term between 0.2 and 0.63 Hz. According to the standard method, the response at frequencies greater than 1.0 Hz is dominated by the backrest tangential term. The r.s.s. of the weighted components is at approximately the correct level (0.45 m s^{-2} rms) at the three lowest frequencies, but declines indicating underestimation of discomfort by the standard method.

The standards were evolved from studies with vibration in individual axes, so if one axis dominates they should provide a good prediction. However, this assumes that the weightings for different axes are given the appropriate relative weight and that relative motion between axes, and the phase of any relative motion, does not influence discomfort. In practice the relative motion between inputs (e.g. between the seat and the feet) can have a large influence on discomfort [13,14]. In this case, even though the seat and feet moved in phase with one another, relative motion may still be an important variable since, particularly at the lowest frequencies, there was opportunity for voluntary control over the movement of the upper body, and the relative motion between the seat and upper torso may have been important factors in producing discomfort.

4.7. Implications of the findings

The finding that fore-and-aft acceleration in the plane of the seat is not a reliable predictor of discomfort has implications for the prediction of discomfort in vehicles and vessels. Where there is significant oscillation at frequencies similar to those in this study it will be necessary to determine what proportion of the fore-and-aft acceleration in the plane of the seat is due to pitch oscillation and what is due to fore-and-aft oscillation. The influence of the presence or absence of a backrest on vibration discomfort should also be taken into account.

5. Conclusions

At frequencies greater than about 0.4 Hz with a backrest, and at frequencies greater than about 0.8 Hz without a backrest, pitch oscillation producing acceleration in the plane of a seat causes greater discomfort than the same acceleration arising from fore-and-aft oscillation. At frequencies less than 0.4 Hz, acceleration in the plane of the seat may be used to estimate the approximate discomfort arising from pitch or fore-and-aft oscillation, irrespective of whether the source of the acceleration is rotation or translation.

During low frequency oscillation, a backrest tends to increase discomfort caused by pitch oscillations at frequencies greater than about 0.63 Hz, but tends to decrease discomfort caused by very low frequency fore-and-aft oscillation.

In general, the prediction of discomfort caused by low frequency pitch and fore-and-aft oscillation requires knowledge of the underlying cause of the oscillation: acceleration in the plane of the seat arising from pitch motion will often produce greater discomfort than the same acceleration arising from fore-and-aft oscillation. Both fore-and-aft and pitch motions should measured and evaluated according to their separate importance, taking into account any effects of a backrest.

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References

[1] T. Miwa, Evaluation methods for vibration effects. Part 2. Measurement of equal sensation level for whole body between vertical and horizontal sinusoidal vibrations, *Industrial Health* 5 (1967) 206–212.
[2] M.J. Griffin, K.C. Parsons, E.M. Whitham, Vibration and comfort—3. Translational vibration of the feet and back, *Ergonomics* 25 (8) (1982) 705–719.
[3] B.K.N. Rao, B. Jones, Equal sensation study of seated subjects in three translational modes, *Ergonomics* 21 (2) (1978) 123–134.
[4] P.M. Donati, A. Grosjean, P. Mistrot, L. Roure, Subjective equivalence of sinusoidal and random whole-body vibration in the sitting position (an experimental study using the "floating reference vibration method"), *Ergonomics* 26 (3) (1983) 251–273.
[5] F.A. Price, Effect of foot motion on the rate of increase in discomfort with increase in vibration magnitude during fore-aft whole-body vibration, *Presented at the UK Group meeting on Human Response to Vibration*, Loughborough, 18–20th September 2002, pp. 43–51.
[6] F. Pradko, Human response to random vibration, *Shock and Vibration Bulletin* 34 (4) (1965) 173–190.
[7] K.C. Parsons, M.J. Griffin, Vibration and comfort—2. Rotational seat vibration, *Ergonomics* 25 (7) (1982) 631–644.
[8] I.H. Wyllie, M.J. Griffin, Discomfort from sinusoidal oscillation in the roll and lateral axes at frequencies between 0.2 and 1.6 Hz, *Journal of the Acoustical Society of America* 121 (5) (2007) 2644–2654.
[9] K.C. Parsons, M.J. Griffin, Effect of the position of the axis of rotation on the discomfort caused by whole-body roll and pitch vibrations of seated persons, *Journal of Sound and Vibration* 58 (1) (1978) 127–141.
[10] British Standards Institution, BS 6841, Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock, 1987.
[11] ISO 2631-1, International Organization for Standardization, Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—part 1: general requirements, 1997.
[12] F.A. Price, Private communication, 2006.
[13] H.K. Jang, M.J. Griffin, The effect of phase of differential vertical vibration at the seat and feet on discomfort, *Journal of Sound and Vibration* 223 (5) (1999) 785–794.
[14] H.K. Jang, M.J. Griffin, Effect of phase, frequency, magnitude and posture on discomfort associated with differential vertical vibration at the seat and feet, *Journal of Sound and Vibration* 229 (2000) 273–286.
[15] S.S. Stevens, Psychophysics: introduction to its perceptual, neural, and social prospects. in: G. Stevens (Ed.), *Transaction Edition*. Transaction Publishers, Oxford, 1975.
[16] S. Pheasant, *Bodyspace—anthropometry, ergonomics and the design of work*, second ed, Taylor and Francis, London, 1996.
[17] BS 7085, British Standards Institution, Guide to the safety aspects of human vibration experiments, 1973.

[18] M. Morioka, M.J. Griffin, Difference thresholds for intensity perception of whole-body vertical vibration: effect of frequency and magnitude, *Journal of the Acoustical Society of America* 107 (1) (2000) 620–624.
[19] E.M. Whitham, M.J. Griffin, Effects of vibration frequency and direction on the location of areas of discomfort caused by whole-body vibration, *Applied Ergonomics* 9 (4) (1978) 231–239.
[20] N.G. Forta, Effect of whole-body vertical vibration on difference thresholds, *Presented at the UK Group meeting on Human Response to Vibration*, Liverpool, 17–19th September 2005.
[21] M.J. Griffin, *Handbook of Human Vibration*, Academic Press, London, 1990.