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The vibration of inclined backrests: perception and discomfort of vibration applied normal to the back in the *x*-axis of the body

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ABSTRACT

The vibration of backrests contributes to the discomfort of drivers and passengers. A frequency weighting exists for evaluating the vibration of vertical backrests but not for reclined backrests often used during travel. This experimental study was designed to determine how backrest inclination and the frequency of vibration influence perception thresholds and vibration discomfort when the vibration is applied normal to the back (i.e. fore-and-aft vibration when seated upright and vertical vibration when fully reclined). Twelve subjects experienced the vibration of a backrest (at each of the 11 preferred one-third octave centre frequencies in the range 2.5 to 25 Hz) at vibration magnitudes from the threshold of perception to 24 dB above threshold. Initially, absolute thresholds for the perception of vibration were determined with four backrest inclinations: 0° (upright), 30°, 60° and 90° (recumbent). The method of magnitude estimation was then used to obtain judgements of vibration discomfort with each of the four backrest angles. Finally, the relative discomfort between the four backrest angles, and the principal locations for feeling vibration discomfort in the body, were determined. With all backrest inclinations, absolute thresholds for the perception of vibration acceleration were dependent on the frequency of vibration. As the backrest inclination became more horizontal, the thresholds increased at frequencies between 4 and 8 Hz. For all backrest inclinations, the rate of growth of discomfort with increasing magnitude of vibration was independent of the frequency of vibration, so the frequency-dependence of discomfort was similar over the range of magnitudes investigated (0.04 to 0.6 ms^{-2} r.m.s.). With an upright backrest, the discomfort caused by vibration acceleration tended to be greatest at frequencies less than about 8 Hz. With inclined backrests (at 30°, 60°, and 90°), the equivalent comfort contours were broadly similar to each other, with greatest discomfort caused by acceleration around 10 or 12.5 Hz. At frequencies from 4 to 8 Hz, 30 to 40% greater magnitudes of vibration were required with the three inclined backrests to cause discomfort equivalent to that caused by the upright backrest. It is concluded that with an upright backrest the frequency weighting W_c used in current standards is appropriate for predicting the discomfort caused by fore-and-aft backrest vibration. With inclined and horizontal backrests, a weighting similar to frequency weighting W_b (used to predict discomfort caused by vertical seat vibration) appears more appropriate.

Keywords: Backrest angle; equivalent comfort contours; relative discomfort; absolute thresholds.

1. INTRODUCTION

Knowing human sensitivity to different frequencies of vibration, the dynamic performance of a seat can be evaluated using the 'seat effective amplitude transmissibility' (i.e. SEAT value, Griffin [1,2]). This procedure, used in ISO 10326-1 [3] and ISO 7096 [4], indicates the extent to which a seat reduces (or increases) vibration discomfort. The SEAT value is mostly used to evaluate the transmission of vertical vibration from the floor to the seat surface, but it can also be applied with other directions of vibration and with other locations of vibration on the seat (e.g. backrest). The method cannot currently be used with confidence to evaluate the dynamic performance of backrests when sitting in a semi-supine posture often adopted when travelling, because there is no standardised frequency weighting for predicting the discomfort caused by the vibration of inclined backrests.

British Standard 6841 [5] and ISO 2631-1 [6] suggest how vibration can be weighted according to human sensitivity to the frequency and direction of vibration so as to predict the likely vibration discomfort. Such frequency weightings can be developed from experimentally determined 'equivalent comfort contours' showing the vibration acceleration required to produce a similar degree of vibration discomfort at each frequency. The W_c frequency weighting in BS 6841 [5] and ISO 2631-1 [6] for the fore-and-aft vibration of backrests was based on the findings of a study by Parsons *et al.* [7] in which the discomfort caused by fore-and-aft vibration of a full upright backrest was determined at frequencies from 2 to 63 Hz. Subjects provided judgements showing the acceleration required at each frequency to produce the same degree of discomfort as that caused by 0.8 ms^{-2} r.m.s. 10-Hz vertical seat vibration. Over the range 2 to 80 Hz, a broadly similar equivalent comfort contour for the fore-and-aft vibration of a full upright backrest has been found when using a lower vibration magnitude of 0.25 ms^{-2} r.m.s. 10-Hz vertical seat vibration [8]. These studies suggest the frequency weighting W_c may be appropriate for upright backrests over the range of vibration magnitudes often encountered in cars and public transport. However, Kato and Hanai found that the discomfort caused by vibration applied normal to the back changed when the backrest was reclined by 20° and 40°. There were no differences in discomfort between the two inclinations, but compared to the upright backrest the equivalent comfort contours were higher at low frequencies and lower at higher frequencies. Their findings suggest that discomfort from vibration applied normal to the back would be over-estimated at low frequencies and underestimated at high frequencies when using frequency weighting W_c with a reclined backrest.

A wide range of backrest inclinations is now used in various forms of travel. This study was undertaken to improve understanding of the discomfort arising from the vibration of inclined backrests in a direction normal to the back (i.e. x_{back}). The study investigated backrests inclined at 0° (upright), 30°, 60°, and 90° (horizontal, a recumbent posture) so as to consider the suitability of frequency weighting W_c for predicting vibration discomfort over the widest possible range of backrests inclinations. It was hypothesised that within each backrest inclination the vibration acceleration required to produce similar discomfort over the frequency range would vary with the frequency of the vibration. It was also hypothesised that the frequency-dependence of vibration discomfort would vary with backrest inclination.

The experiment consisted of four parts. In Part 1, the absolute thresholds for the perception of vibration at the back were determined. In Part 2, the rates of growth of vibration discomfort were determined and a series of equivalent comfort contours within each backrest angle were derived. In Part 3, the relative discomfort between the four backrest angles were determined. In Part 4, the location of principal discomfort in the body caused by backrest vibration at each frequency were determined. All parts of the experiment investigated frequencies over the range 2.5 to 25 Hz with each of four backrest inclinations: 0° (upright), 30°, 60° and 90° (recumbent).

2. METHOD

2.1 Apparatus

The apparatus comprised a vibrating backrest connected to a Derritron VP85 vibrator, with a stationary seat-pan, a stationary footrest, and a stationary headrest. The inclination of the backrest was adjustable to 0, 30, 60, and 90 degrees from vertical by rotating the vibrator within a trunnion. The vibration was applied in a direction normal to the surface of the back (x_{back}) via a rigid flat wooden backrest (500 mm high by 310 mm wide).

With each backrest angle, the height of the seat-pan, the angle and height of the footrest, and the position of the headrest were adjusted to a comfortable sitting posture for a 50th percentile British male aged 19-45 years [9] (Figure 1). The positions were achieved using an H-point manikin with knee and ankle angles set to 120° and 100°, respectively. The sitting height was adjusted so that contact between the back and the backrest was mostly at the upper back, with no contact around the lumbar and pelvic region. The backrest and headrest were covered with 1-mm thick neoprene rubber to provide friction between the supports and the body.

Figure 1 ABOUT HERE

It was not possible to arrange for the subjects to compare directly the discomfort caused by *x*-axis vibration of the back at different backrest inclinations. When sitting with each backrest inclination, subjects were therefore asked to compare their discomfort with that caused by vibration of their hand (in Part 3 of the experiment). A cylindrical wooden handle (3.18-cm diameter and 12-cm long) was attached to the table of a vertically-orientated Derritron VP4 vibrator supported on a height-adjustable stand. The location and height of the handle were adjusted for each subject so as to maintain the posture of the hand at a similar and comfortable position with each of the four backrest inclinations. The upper-arm and fore-arm were maintained with a slight bend (about 90 to 120° degrees) to avoid 'locking' at the elbow, and thereby reducing the transmission of vibration to the shoulders, so that discomfort caused by vibration of the handle was localized around the hand (Figure 2).

Figure 2 ABOUT HERE

2.2 Vibration and signal generation

The vibration signals were generated and sampled using *HVLab* software (version 3.81) and output via a digital-to-analogue converter (PCL-818) at 1000 samples per second after low - pass filtering at 40 Hz.

Single-axis piezo-resistive accelerometers (Entran Model EGCSY-240D-10) were attached to the back of the backrest and the base of the handle. Signals from the accelerometers were filtered at 40 Hz (via a Techfilter anti-aliasing filter) and then sampled at 1000 samples per second.

The background vibration on the backrest was predominantly caused by electrical noise at 50 Hz and was imperceptible at a magnitude less than 0.008 ms^{-2} r.m.s.

2.3 Vibration stimuli

All vibration stimuli were sinusoidal with durations of 2 seconds, including 0.25-second cosine-tapering at the start and end. For both the study of perception thresholds and the study of discomfort, the frequencies were the 11 preferred one-third octave centre frequencies from 2.5 to 25 Hz.

When investigating vibration discomfort in Part 2 (see below), a reference vibration of 0.15 ms^{-2} r.m.s. at 8 Hz was applied to the back. In this part, there were 99 test stimuli (in an array of 11 frequencies and 9 magnitudes, from slightly above threshold at each frequency and then increasing by 3 dB steps).

When investigating the relative discomfort between backrest angles in Part 3, the reference vibration at the hand was 2.0 ms^{-2} r.m.s. at 8 Hz. The same nine magnitudes of 8-Hz vibration were applied to the back as in Part 2.

When investigating the location of discomfort in Part 4, two magnitudes of vibration were applied to the back at each frequency: the middle magnitudes and the greatest magnitudes used in Part 2.

2.4 Procedure

The experiment was conducted in four sessions corresponding to four backrest angles (i.e. 0° (upright), 30°, 60°, and 90° (recumbent), with each session conducted on a different day and the order of sessions balanced between subjects. Each session lasted less than one hour and comprised four parts corresponding to four psychophysical tests:

Part 1: Perception thresholds within backrest angle,

Part 2: Equivalent comfort contours within backrest angle,

Part 3: Relative discomfort between backrest angles, and

Part 4: Location of principal discomfort

There was a short break between Part 1 and Part 2.

Subjects were requested to sit on the seat with their backs and heads leaning comfortably against the backrest and headrest and their hands resting on their laps, or folded together on top of their stomach when the backrest was inclined to 60° and 90° (recumbent). For backrest inclinations of 0°, 30°, and 60°, the feet were supported, whereas when recumbent (at 90°), the calves were supported.

Subjects wore headphones presenting masking noise (white noise at 75 dB) and held an emergency stop button. They were given written instructions on a board in front of them. Subjects were trained and had practice trials during their first visit to familiarise them with the procedures.

2.4.1 Perception thresholds (Part 1)

The up-down transformed response (UDTR) method was employed to determine absolute thresholds for the perception of *x*-axis vibration of the back [10]. After each presentation of a stimulus, subjects were requested to indicate whether they could feel the vibration by saying ‘yes’ or ‘no’. The magnitude of the vibration was increased by 2 dB after each ‘no’ response (i.e. the subject did not feel the vibration) and decreased by 2 dB after two consecutive ‘yes’ responses (i.e. the subject did feel the vibration) (see Figure 3). The procedure was terminated after six reversals (3 peaks and 3 valleys). This part was completed in approximately 30 minutes.

Figure 3 ABOUT HERE

Thresholds were determined at each frequency from the average of the last two pairs of reversals at peaks, p_i, and valleys, v_i, as suggested by Levitt [11]:

$$\text{Perception threshold} = 0.25\sum_{i=2}^{3}\left(p_i + v_i\right) \qquad \text{Equation 1}$$

The method determines thresholds at 70.7% probability of perception [11].

2.4.2 Equivalent comfort contours within backrest angle (Part 2)

Subjects were requested to estimate the magnitude of discomfort, ψ, caused by each test stimulus of acceleration magnitude, φ. They made their judgements relative to the discomfort caused by a reference vibration (0.15 ms^{-2} r.m.s. at 8 Hz), assumed to correspond to a magnitude estimate of 100. The reference stimulus and the test stimuli (both x_{back} vibration) were presented in pairs separated by 1-second pauses. The frequencies and magnitudes of the test stimuli were presented in randomized orders. This part was completed in approximately 20 minutes.

The method of magnitude estimation [12] was employed in tandem with the modified Stevens' power law (Equation 2) to determine a series of equivalent comfort contours within each backrest angle. The inclusion of the additive constant, φ_0, the absolute threshold of perception for the subject as determined in Part 1, was used to reduce bias at low magnitudes [13].

$$\psi = k(\varphi - \varphi_0)^n \qquad \text{Equation 2}$$

2.4.3 Relative discomfort between backrest angles (Part 3)

The method was similar to that used in Part 2, except the subjects estimated the discomfort caused by nine levels (0.04 to 0.6 ms^{-2} r.m.s.) of 8-Hz vibration of the back relative to the discomfort cause by a reference magnitude of vibration at the hand (2.0 ms^{-2} r.m.s. 8-Hz vertical vibration). This part was completed in approximately 3 minutes.

2.4.4 Location of discomfort (Part 4)

The middle magnitudes and the greatest magnitudes of backrest vibration used at each frequency in Part 2 were presented again in a randomised order. After experiencing each vibration, the subjects were requested to indicate the location of most discomfort in their body according to body map displayed in front of them.

2.5 Subjects

Using a within-subject experimental design, 12 male subjects aged between 21 and 40 years participated in all four sessions of the experiment. The subjects were students and staff of the University of Southampton and were healthy with no history of any serious illness, injury, or disability that might impair their judgement of vibration sensations.

The experiment was approved by the Human Experimentation Safety Ethics Committee of Institute of Sound and Vibration Research at the University of Southampton at the University of Southampton. All subjects gave their voluntary consent prior to each session.

3. RESULTS

3.1 Perception thresholds (Part 1)

3.1.1 Effect of vibration frequency

The median absolute thresholds for the perception of *x*-axis vibration of the back with each backrest inclination are presented in Table 1. Within each of the four backrest inclinations, absolute thresholds for vibration perception varied significantly with the frequency of vibration ($p<0.001$, Friedman; Figure 4).

Table 1 and Figure 4 ABOUT HERE

3.1.2 Effect of backrest angle

The acceleration thresholds were significantly dependent on backrest inclination at 4, 5, 6.3, and 8 Hz (Figure 5; $p<0.05$, Friedman). Multiple comparisons between each of the six possible pairs of backrest inclinations were then performed with an adjusted criterion of 0.008 for statistical significance ($p=0.05/6=0.008$). The acceleration threshold was significantly different between a 90° backrest inclination (recumbent) and 0° inclination (upright) at all frequencies between 4 and 8 Hz ($p<0.008$; Wilcoxon), between 60° and 0° at 6.3 Hz ($p=0.006$; Wilcoxon), and between 90° and 30° at 5 Hz ($p=0.003$, Wilcoxon).

Figure 5 ABOUT HERE

3.2 Equivalent comfort contours within backrest angle (Part 2)

3.2.1 Rate of growth of discomfort

For each subject and within each backrest inclination, linear regression was performed at each frequency between the logarithm of the discomfort, ψ, and the logarithm of the acceleration magnitude of the test stimulus, φ:

$$\log_{10} \psi = n \log_{10}(\varphi - \varphi_0) + \log_{10} k \qquad \text{Equation 3}$$

The individual rates of growth of discomfort, n, and the constant, k, were determined from the slopes and intercepts and used to derive individual equivalent comfort contours at nine levels of discomfort from $\psi = 40$ to $\psi = 250$ (relative to 100 with 0.15 ms^{-2} r.m.s. of 8-Hz x-axis back vibration).

The rates of growth of discomfort did not differ significantly with the frequency of the vibration within any backrest inclination (Figure 6; $p>0.098$, Friedman).

Figure 6 ABOUT HERE

3.2.2 Equivalent comfort contours

Using equation 2 with the individual values of n and k at each frequency from linear regression of the data in Part 2, and the individual perception thresholds, φ_0, at each frequency in Part 1, individual equivalent comfort contours were constructed for each of the nine levels of discomfort (for ψ =40 to 250). The median equivalent comfort contours for each of the four backrest inclinations were then calculated from the 12 individual contours (Figure 7).

Figure 7 ABOUT HERE

As expected, within each backrest inclination, the equivalent comfort contours for all sensation magnitudes varied significantly with frequency ($p<0.05$; Friedman).

3.3 Relative discomfort between backrest angles (Part 3)

Within each backrest inclination, an equivalent comfort contour was constructed for each subject so that each point on the contour indicated the acceleration of x-axis vibration of the back required to produce discomfort corresponding to a magnitude estimate of 100 (as produced by the common reference vibration of 8-Hz vertical hand vibration at 2.0 ms^{-2} r.m.s.). This was achieved by comparing magnitude estimates of 8-Hz x-axis backrest vibration obtained within each backrest inclination with the discomfort caused by the common reference vibration. The acceleration of x-axis vibration of the back that produced a magnitude estimate of 100 with the common reference, together with the individual n and k values, were substituted into Equation 2 to construct an equivalent comfort contour at the same sensation magnitude for each of the four backrest inclinations (i.e. at a sensation magnitude of 100). The differences in the vibration magnitudes required with each backrest inclination at each frequency can be seen in the medians of the 12 individual 'rescaled' equivalent comfort contours shown in Figure 8.

Figure 8 ABOUT HERE

The rescaled equivalent comfort contours (i.e. relative discomfort) were significantly dependent on backrest angle at 8 Hz (p=0.006; Friedman): the vibration magnitude required to cause discomfort with x-axis vibration of the upright backrest was significantly less than required with the inclined backrests. There were no significant differences between the contours with the three inclined backrests (p>0.05).

3.4 Location of discomfort (Part 4)

At all frequencies and with all backrest inclinations, subjects generally felt vibration discomfort in either their upper back or lower back, although a few felt vibration at the head, neck or shoulder, particularly at high frequencies. There were similar distributions of discomfort in the body at both vibration magnitudes (Figure 9).

Figure 9 ABOUT HERE

4. DISCUSSION

4.1 Perception thresholds

4.1.1 Effect of frequency

The vibration acceleration thresholds decreased at frequencies less than 4 Hz, implying greatly increased sensitivity to low frequency vibration (Figure 4). It seems likely this arose from the perception of relative motion between the moving backrest and the stationary seat. From 2.5 to 4 Hz, the rate of change is greater than 6 dB per octave, and close to 12 dB per octave with both 60° and 90° backrest inclinations, corresponding to constant relative displacement. A similar phenomenon has been observed with vibration of the seat and feet, where discomfort depends on the phase between the vertical motion of the feet and the vertical motion of the seat [14,15].

At frequencies between 10 and 25 Hz, the acceleration thresholds tend to increase at about 6 dB per octave, corresponding to approximately constant velocity.

4.1.2 Effect of backrest angle

Over the frequency range 4 to 8 Hz, thresholds decreased as the backrest inclination decreased (Figure 5). This frequency range coincides with principal resonance frequencies evident in the fore-and-aft apparent mass of the back when sitting upright [16,17], and in the vertical apparent mass of the back when fully recumbent [18]. The ratio of the apparent mass at resonance to the apparent mass at low frequencies (i.e. static mass) was greater when sitting with an upright backrest than when lying supine, by an approximately 3 to 1.5 ratio [16,18]. It seems reasonable to suppose that the greater amplification of vibration when sitting with an upright backrest may have been responsible for the greater sensitivity with the vertical backrest than when lying supine.

4.1.3 Comparison with previous studies

With an upright backrest, the frequency-dependence of the acceleration thresholds in the present study is similar to that obtained by Gallais *et al.* [19], although the thresholds are slightly higher (Figure 10). Gallais *et al.* used the method of limits with slightly longer duration stimuli (3 seconds) and detected thresholds with a 50% probability: Morioka and Griffin [20] have shown that the different psychophysical methods produce differences in vibration thresholds (e.g. by 3 to 6 dB). The frequency-dependence of the present thresholds is also consistent with the shape of an equivalent comfort contour equivalent to 50% of the discomfort caused by 0.315 ms^{-2} r.m.s. 10-Hz fore-and-aft vibration of a full upright backrest (Figure 10; [21]).

Figure 10 ABOUT HERE

With the backrest at 90° (recumbent), the absolute thresholds can be compared with thresholds for the perception of vertical (i.e. *x*-axis) whole-body vibration of supine recumbent subjects (e.g. [22,23,24]) (Figure 11). At frequencies greater than 5 Hz, the frequency-dependence of the thresholds in the present study is broadly consistent with the frequency-dependence of thresholds for supine subjects, although the thresholds are about 6 dB higher than those reported by Miwa *et al.* [23] and Yonekawa *et al*. [24] and about 3 dB higher than those reported by Parsons and Griffin [22]. Studies with supine subjects have involved whole-body vibration and may reflect sensitivity of body parts other than the back studied here. Different body parts may be expected to have different sensitivities [25] and may be maximally sensitive to vibration at different frequencies [22]. The different psychophysical methods used in these studies may also have contributed to the differences in thresholds. Miwa *et al.* [23] used the method of limits with 10-s stimuli whereas both Yonekawa *et al.* [24] and Parsons and Griffin [22] used the method of adjustment. At low frequencies, the increased sensitivity to backrest vibration evident in the thresholds of the present study is likely to have arisen from relative motion between the vibrating back and the stationary seat or stationary headrest.

Figure 11 ABOUT HERE

4.2 Vibration discomfort

4.2.1 Effect of frequency

With an upright backrest (i.e. 0° inclination), the shape of the equivalent comfort contour (for ψ = 100) is broadly similar to that reported in previous studies with fore-and-aft vibration of full-height upright backrests [7,8,21] (Figure 12). The discomfort caused by vibration acceleration tends to be greatest at frequencies less than about 8 Hz with sensitivity to acceleration roughly independent of frequency. At frequencies less than 3.15 or 4 Hz, there is evidence of a reduction in the acceleration (corresponding to increased discomfort), as seen in Figure 7 and similarly exhibited in the contours of Parsons *et al.* [7] and Morioka and Griffin [21], suggesting a contribution from relative motion between the moving backrest and the stationary seat pan used in these studies. The use of a stationary headrest in the present study may have stimulated a more upright upper-body posture. This may have increased contact with the backrest and produced more discomfort at frequencies greater than 8 Hz than in some previous studies.

With inclined backrests (i.e. 30°, 60°, and 90° inclinations), the shapes of the equivalent comfort contours are broadly similar (Figure 8). The frequency at which acceleration caused greatest discomfort was around 10 or 12.5 Hz, with an approximately constant velocity response at higher frequencies and constant jerk (-6 dB per octave) at frequencies between about 5 and 10 Hz. At frequencies less than 5 Hz, discomfort increased with decreasing frequency, suggesting relative motion contributed to discomfort, as with the upright backrest.

Figure 12 ABOUT HERE

4.2.2 Effect of vibration magnitude

Within each backrest inclination, there was no statistical evidence of a magnitude-dependence in the equivalent comfort contours over the range of vibration magnitudes investigated (0.04 to 0.6 ms^{-2} r.m.s.). The rate of growth, *n*, was independent of frequency and so the equivalent comfort contours are almost parallel to each other (Figure 7). Morioka and Griffin [21] reported a magnitude-dependence in equivalent comfort contours for fore-and-aft backrest vibration at frequencies associated with the 4 to 6 Hz resonance in fore-and-aft apparent mass of the back [16]. With a much wider range of vibration magnitudes (0.08 to 1.25 ms^{-2} r.m.s.), Morioka and

Griffin [21] found the frequencies of greatest discomfort reduced with increasing magnitude of vibration, consistent with the nonlinearity in the apparent mass of the back. The difference with the present study might be explained by the nonlinearity in the apparent mass of the back being insufficient to cause a large change over the range of lower magnitude vibration studied here (i.e. 0.04 to 0.6 ms^{-2} r.m.s.).

4.2.3 Effect of backrest angle

The effect of backrest inclination on the discomfort caused by *x*-axis vibration of the back was only statistically significant at 8 Hz. However, there was a consistent trend for greater sensitivity to vibration with the upright backrest (0° inclination) between 4 and 8 Hz, with 30 to 40% less vibration needed to cause discomfort with an upright backrest at these frequencies. This is partly consistent with the findings of Kato and Hanai [8] over the same frequency range. However, at frequencies greater than 10 Hz, they found that seating inclined by 20° and 40° required 40 to 50% less vibration to produce the same discomfort as an upright backrest. The present study found no significant differences at frequencies greater than 10 Hz, although there was an apparent increase in the frequency of greatest discomfort from 8 Hz with the upright backrest to 10 or 12.5 Hz with an inclined backrest. With inclined seating, the frequency of acceleration causing greatest discomfort was broadly similar to the second resonance in transmissibility from a back support to the sternum (a primary resonance around 6.25 Hz and a secondary resonance between 12 and 14 Hz) during vertical vibration of the supine body [26].

4.3 Frequency weightings

The acceleration thresholds shown in Figure 4 and the equivalent comfort contours (for ψ = 40 to 250) shown in Figure 7 were normalised relative to 1.00 at 8 Hz and then inverted and compared with the asymptotic forms of the frequency weightings W_b and W_c as defined in BS 6841 [5] (Figure 13).

For the upright backrest, the weightings seem reasonably similar to W_c, where sensitivity to vibration acceleration is roughly independent of frequency at frequencies less than 8 Hz and decreases as the frequency increases above 8 Hz. The present results suggest discomfort would be slightly overestimated at frequencies less than 8 Hz and slightly underestimated at frequencies greater than 8 Hz when using W_c, but any difference with previous studies may be due to differences in support for the back and the head.

For the backrests inclined by 30°, 60°, and 90°, the weightings seem more similar to weighting W_b than weighting W_c at frequencies greater than 8 Hz. The increased sensitivity at frequencies less than about 4 Hz is not predicted by either frequency weightings, and may not be needed unless there is relative motion between the backrest and the seat or headrest.

Figure 13 ABOUT HERE

The application of the results presented here should recognise that other factors may influence the dependence of vibration thresholds and vibration discomfort on the frequency of vibration and the inclination of a backrest. For example, differences between subjects, including gender and the extremes of age and body size beyond those included in the study may modify the perception of vibration and the discomfort it causes.

CONCLUSIONS

The frequency-dependence of equivalent comfort contours for low magnitudes of fore-and-aft vibration of an upright backrest have a similar frequency-dependence to absolute thresholds for vibration perception. A single frequency weighting, W_c as recommended in current standards, seems adequate.

With backrests inclined by 30°, 60°, or 90°, the frequency-dependence of the threshold for vibration perception and vibration discomfort changes to a shape more similar to frequency weighting W_b.

Relative motion between a backrest and other body supports can greatly increase sensitivity to vibration at low frequencies (e.g. less than about 4 Hz).

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REFERENCES

[1] M.J. Griffin, The evaluation of vehicle vibration and seats. *Applied Ergonomics* 9 (1) (1978) 15-21.

[2] M.J. Griffin, *Handbook of Human Vibration*, Academic Press Limited, 1990.

[3] International Organization of Standardization ISO 10326-1, Mechanical vibration - Laboratory method for evaluating vehicle seat vibration - part 1: basic requirements, 1992.

[4] International Organization of Standardization ISO 7096, Earth-moving machinery - laboratory evaluation of operator seat vibration, 2000.

[5] British Standards Institution BS 6841, Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock, 1987.

[6] International Organization of Standardization ISO 2631-1, Mechanical vibration and shock - evaluation of human exposure to whole-body vibration - part 1: general requirements, 1997.

[7] K.C. Parsons, M.J. Griffin, E.M. Whitham, Vibration and comfort III. Translational vibration of the feet and back. *Ergonomics* 25 (8) (1982) 705-719.

[8] K. Kato, T. Hanai, The effect of backrest angles on discomfort caused by fore-and-aft back vibration. *Industrial Health* 36 (1998) 107-111.

[9] S. Pheasant, *Bodyspace: Anthropometry, Ergonomics and the Design of Work*. 2nd. ed., Taylor & Francis, 1990.

[10] G.B. Wetherill, H. Levitt, Sequential estimation of points on a psychometric function. *The British Journal of Mathematics and Statistical Psychology* 18 (1) (1965) 1-10.

[11] H. Levitt, Transformed up-down methods in psychoacoustics. *Journal Acoustical Society of America* 49 (2B) 1971 467-477.

[12] S.S. Stevens, *Psychophysics: Introduction to its perceptual, neural, and social prospects*. New York. John Wiley & Sons, Inc, 1975.

[13] G.A. Gescheider, *Psychophysics: method and theory*. John Wiley & Sons, 1976.

[14] 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.

[15] 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 (2) (2000) 273-286.

[16] N.A. Abdul Jalil, M.J. Griffin, Fore-and-aft apparent mass of the back: Nonlinearity and variation with vertical location. *Journal of Sound and Vibration*, 318 (4-5) (2008) 1348-1363.

[17] N. Nawayseh, M.J. Griffin, Tri-axial forces at the seat and backrest during whole-body fore-and-aft vibration. *Journal of Sound and Vibration* 281 (3-5) (2005) 921-942.

[18] Y. Huang, M.J. Griffin, Nonlinear dual-axis biodynamic response of the semi-supine human body during vertical whole-body vibration. *Journal of Sound and Vibration* 312 (1-2) (2008) 296-315.

[19] C.H.R. Gallais, M. Morioka, M.J. Griffin, Thresholds for the perception of fore-and-aft whole-body vibration (personal communication, unpublished).

[20] M. Morioka, M.J. Griffin, Dependence of vibrotactile thresholds on the psychophysical measurement method. *International Archives of Occupational and Environmental Health* 75 (1-2) 2002 78-84.

[21] M. Morioka, M.J. Griffin, Frequency weightings for fore-and-aft vibration at the back: Effect of contact location, contact area, and body posture. 4th International Conference on Whole-body Vibration Injuries, Montreal, Canada, 2-4 June 2009.

[22] K.C. Parsons, M.J. Griffin, Whole-body vibration perception thresholds. *Journal of Sound and Vibration* 121 (2) (1988) 237-258.

[23] T. Miwa, Y. Yonekawa, K. Kanada, Thresholds of perception of vibration in recumbent person. *Journal Acoustical Society of America* 75 (3) (1984) 849-854.

[24] Y. Yonekawa, S. Maeda, K. Kanada, Y. Takahashi, Whole-body vibration perception thresholds of recumbent subjects – Part 1: supine posture. *Industrial Health* 37 (1999) 398-403.

[25] T. Miwa, Y. Yonekawa, Evaluation methods for vibration effect. Part 9. Response to sinusoidal vibration at lying posture. *Industrial Health* 7 (1969) 116-126.

[26] Y. Huang, M.J. Griffin, Nonlinearity in apparent mass and transmissibility of the supine human body during vertical whole-body vibration. *Journal of Sound and Vibration* 324 (2009) 429-452.