DISCOMFORT CAUSED BY *x*-AXIS VIBRATION OF THE BACK: EFFECT OF BACKREST INCLINATION

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Abstract

Vibration of the back is a potential source of discomfort for car passengers, with vibration in the *x*-axis (i.e. fore-and-aft with an upright backrest) often dominant. This study investigated how vibration discomfort depends on both the frequency of *x*-axis backrest vibration and the inclination of the backrest. Twelve subjects seated with a rigid backrest inclined by 0, 30, 60, or 90 degrees rated the discomfort caused by *x*-axis backrest vibration at 11 frequencies (between 2.5 and 25 Hz) at 9 levels (from about 3 to 24 dB above the absolute threshold in 3 dB steps) relative to the discomfort caused by 0.15 ms^{-2} r.m.s. 8-Hz *x*-axis backrest vibration. The subjects also rated the discomfort caused by 9 levels of 8-Hz *x*-axis backrest vibration relative to the discomfort caused by 2.0 ms^{-2} r.m.s. 8-Hz *x*-axis (i.e. vertical) vibration of the hand. The vibration acceleration of the backrest required to cause discomfort tended to be least at 8 Hz with the upright backrest and at 10 or 12.5 Hz with the backrest inclined by 30°, 60°, or 90°. At frequencies from 4 to 8 Hz, about 30 to 40% less acceleration was required to cause discomfort with the upright backrest than with the inclined backrests. It is concluded that frequency weighting W_c is appropriate for predicting vibration discomfort caused by *x*-axis vibration of an upright backrest, but that another frequency weighting (e.g. W_b) would be more appropriate for inclined backrests.

1. Introduction

The backrest of a car seat should provide support for the back and promote the comfort of car drivers and passengers. However, a backrest inevitably transmits vibration to the body and so may increase vibration discomfort: *x*-axis vibration of backrests is one of the primary sources to vibration discomfort for car passengers (e.g. BS6841:1987; ISO2631-1:1997; Griffin, 1990). An appropriate method for evaluating backrest vibration is required to assist the optimisation of the design of seat backrests.

Current standards suggest the use of the W_c frequency weighting for evaluating *x*-axis vibration of the back so as to predict its contribution to the overall vibration discomfort of passengers. The W_c weighting was developed from equivalent comfort contours for fore-and-aft (i.e. *x*-axis) vibration of a full upright backrest (with no vibration at the seat or the feet) over the frequency range 2 to 63 Hz (Parsons *et al*., 1982). The contour was determined from the acceleration magnitudes of *x*-axis backrest vibration required at each frequency to produce discomfort equivalent to that caused by 0.8 ms^{-2} r.m.s. 10-Hz vertical seat vibration. To cause similar discomfort, lower acceleration magnitudes were required at 8 Hz and lower frequencies than at higher frequencies: the equivalent comfort contour was represented by approximately constant acceleration at frequencies less than 8 Hz and constant velocity at higher frequencies. This asymptotic approximation to the equivalent comfort contour subsequently formed the basis for the shape of the W_c frequency weighting. Later studies have determined equivalent comfort contours with lower magnitudes of the reference vibration (0.25

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ms^{-2} r.m.s. 10-Hz vertical seat vibration in Kato and Hanai, 1998; 0.315 ms^{-2} r.m.s. 10-Hz *x*-axis backrest vibration in Morioka and Griffin, 2009), but similar equivalent comfort contours have been reported, suggesting the W_c weighting may be suitable for a range of vibration magnitudes.

Vibration discomfort may change with variations in the inclination of a backrest, but there is not much evidence for predicting discomfort for a range of backrest inclinations from upright to fully reclined. Miwa and Yonekawa (1969) investigated the discomfort caused by vertical whole-body vibration of persons lying flat on their backs (i.e. prone). The frequencies of greatest discomfort were centred around 4 Hz and the overall shapes of the equivalent comfort contours were more similar to the reciprocal of frequency weighting W_b than frequency weighting W_c. Kato and Hanai (1998) investigated the discomfort caused by *x*-axis vibration of a backrest inclined at 20° and 40° from the vertical plane. Comparison their equivalent comfort contours for both inclined backrests and an upright backrest suggests less discomfort at lower frequencies but greater discomfort at higher frequencies when seated with an inclined backrest than when seated with an upright backrest. Arrowsmith *et al.* (2005) found that the discomfort caused by vertical whole-body vibration was least when seated with a backrest inclined 22.5° or 45° from the vertical and maximum when recumbent (lying flat on the back), but the study did not allow the identification of the role of backrest vibration in causing discomfort.

The study reported here was undertaken to enhance understanding of the discomfort caused by *x*-axis vibration of the back for a wide range of backrest inclinations (0°, 30°, 60°, and 90° from vertical) and consider the suitability of frequency weighting W_c for predicting the discomfort caused by backrest vibration. It was hypothesised that the frequency-dependence of vibration discomfort would vary with backrest inclination.

2. Method

2.1 <u>Apparatus</u>

The *x*-axis vibration of a backrest was produced by a Derritron VP85 electrodynamic vibrator powered by a 1500 watt amplifier. The rigid wooden backrest was 500 mm high by 310 mm wide. Backrest inclinations of 0, 30, 60, and 90 degrees were achieved by rotating the vibrator in its trunnion. A stationary seat-pan, stationary footrest, and stationary headrest were used and adjusted to provide a comfortable sitting posture for a 50th percentile British male aged 19 to 45 years (Pheasant, 1990). The sitting height was adjusted so that contact with the backrest was predominantly at the upper back, with no contact around the lumbar or pelvic region. The backrest and headrest were covered with 1-mm thick neoprene rubber to provide friction between the backrest and the body.

Vertical vibration of the hand was produced by a Derritron VP4 electrodynamic vibrator powered by a 100 watt amplifier via a cylindrical wooden handle (31.8 mm in diameter and 120 mm in length). The location and height of the vibrator were adjusted for each subject so as to maintain a similar posture of the hand with a comfortable grip on the handle at all four backrest inclinations.

The vibration was 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 piezoresistive accelerometers (Entran Model EGCSY-240D-10) were mounted on the rear of the backrest and the base of the handle. Signals from the accelerometer on the backrest and the handle were filtered at 40 Hz and 20 Hz, respectively, by a Techfilter anti-aliasing filter and sampled at 1000 samples per second.

2.2 Stimuli

All vibration stimuli (i.e. test and reference stimuli) were 2-second duration sinusoidal vibrations with 0.25-second cosine-tapering at both ends. The test stimuli were *x*-axis backrest vibration at each of the eleven preferred one-third octave centre frequencies between 2.5 and 25 Hz presented at nine magnitudes (from about 3 dB to 24 dB above absolute thresholds in 3-dB steps). The reference stimuli were 0.15 ms^{-2} r.m.s. 8-Hz *x*-axis vibration of the back (used to determine equivalent comfort contours within backrest inclinations) and 2.0 ms^{-2} r.m.s. 8-Hz *x*-axis (i.e. vertical) vibration of the hand (used to determine relative discomfort between backrest inclinations).

2.3 Procedure

The experiment reported here is part of a larger study that also measured thresholds for the perception of backrest vibration. Subjects were required to complete four sessions corresponding to four backrest inclinations: 0° (upright), 30°, 60°, and 90° (recumbent) on four different days with the order of conditions balanced over the sessions. Subjects sat on the seat with their backs and heads leaning comfortably against the backrest and headrest. When the backrest was at 0° (upright) or inclined by 30°, subjects sat with their hands resting on their laps; when the backrest was inclined at 60° and 90° (recumbent) the hands were folded together over their stomach or chest. For backrest inclinations of 0°, 30°, and 60°, the feet were supported, but when recumbent (at 90°) the calves were supported.

Subjects wore headphones presenting white noise at 75 dB and were required to hold a stop button for emergency use. Subjects were trained and had practice trials on their first session to get familiar with the procedure.

2.3.1 Equivalent comfort contours within backrest inclinations

Subjects were presented with 99 pairs of reference and test vibration stimuli applied to their backs. The method of magnitude estimation was employed where subjects rated the discomfort caused by each test stimulus relative to the discomfort caused by the reference stimulus, assumed to be 100.

2.3.2 Relative discomfort between backrest inclinations

The cross modality matching technique was employed where subjects rated the discomfort of nine 8-Hz test vibration stimuli at the back relative to the discomfort caused by the 8-Hz reference vibration at the hand, assumed to be 100.

2.4 Subjects

Twelve male subjects with a mean age 27.8 years (range: 21 to 40), height of 171.8 cm (165 to 185), and weight 66.7 kg (53 to 90) participated in the study. The subjects were students and staff of the University of Southampton and were healthy with no history of serious illness, injury, or disability expected to influence their judgements of discomfort.

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

3. Results

3.1 Rate of growth of discomfort

A linear relationship between the logarithm of the magnitude estimates of discomfort and the logarithm of the physical magnitudes of the test stimuli does not hold when stimuli are close to the threshold. The inclusion of an additive constant, φ_0, the absolute threshold of perception, in Stevens' power law can provide a better fit at low magnitudes (Gescheider, 1976):

$$\psi = k(\varphi - \varphi_0)^n \qquad \text{Equation 1}$$

Linear regression was performed between the logarithm of the magnitude estimates of discomfort, ψ, and the logarithm of the differences between the acceleration magnitude of the test stimulus, φ, and the absolute thresholds, φ_0, at each frequency (where individual values of φ_0 were obtained in a part of the study not reported here (see Basri and Griffin, 2009):

$$\log_{10} \psi = n \log_{10}(\varphi - \varphi_0) + \log_{10} k \qquad \text{Equation 2}$$

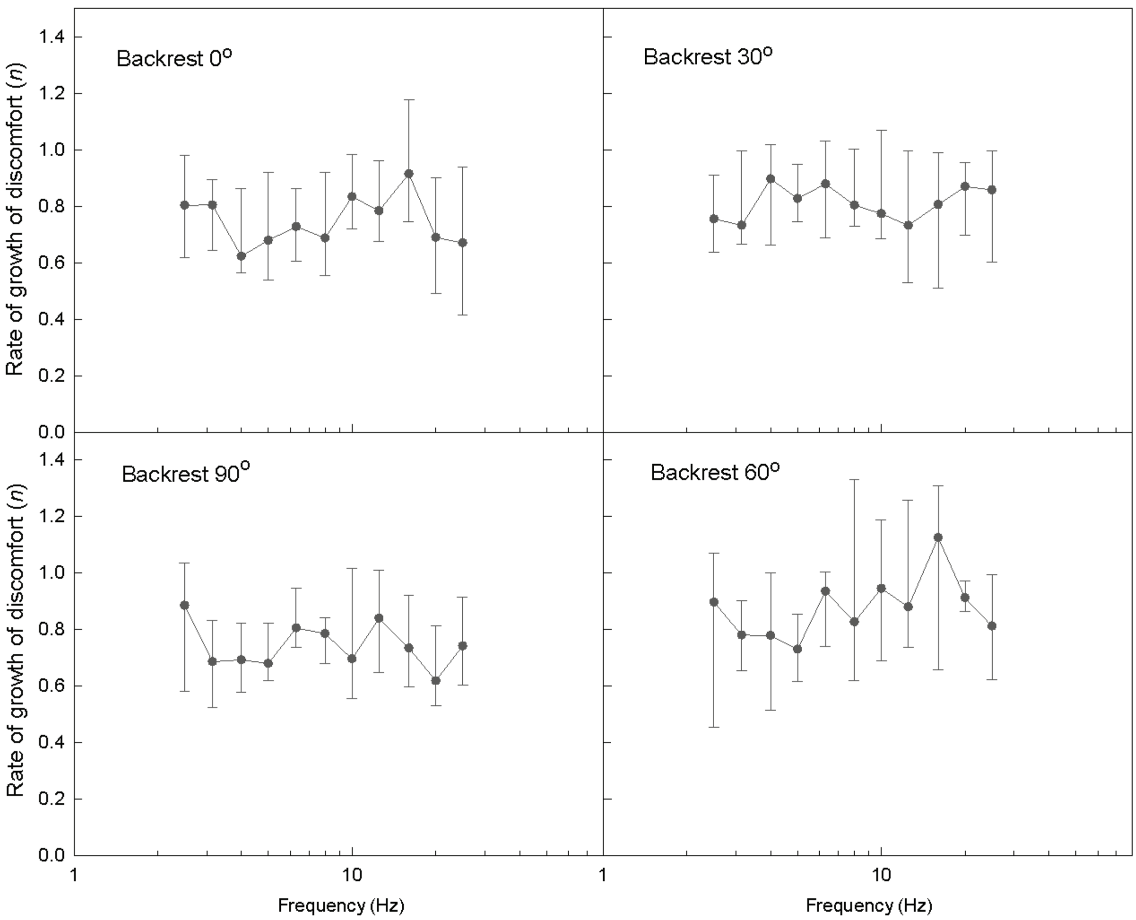

Figure 1 Median and interquartile rates of growth of discomfort (values of the exponent, n) with the four backrest inclinations.

The rates of growth of discomfort, n, did not differ significantly with frequency within backrest inclinations (Figure 1; p>0.098, Friedman). There was no significant difference in the rate of growth of discomfort across backrest inclinations at any frequency (except at 6.3 Hz; p=0.048; Friedman).

3.2 Equivalent comfort contours within backrest inclination

Individual equivalent comfort contours were constructed at nine levels of discomfort (from ψ = 40 to ψ = 250, relative to 100 with 0.15 ms^{-2} r.m.s. 8-Hz x-axis back vibration) based on individual values of n and k. The median equivalent comfort contours for the nine magnitude estimates were calculated from the 12 individual contours and are shown in Figure 2.

With each of the four backrest inclinations, the equivalent comfort contour corresponding to a discomfort of 100 varied significantly with the frequency of vibration (p≤0.002; Friedman).

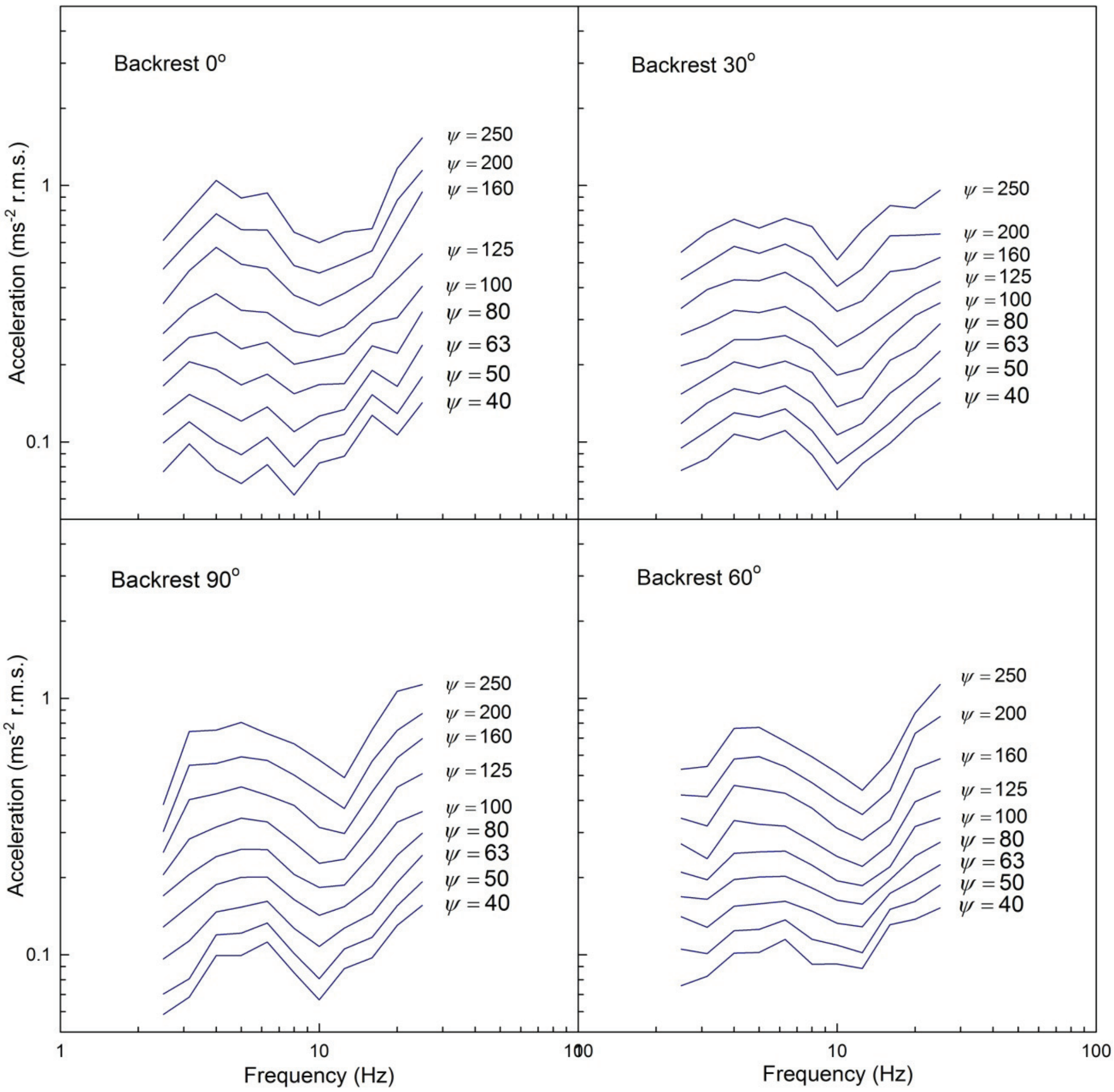

Figure 2 Median equivalent comfort contours for each backrest inclination at nine magnitude estimates of discomfort, where 100 correspond to the discomfort associated with the reference vibration (0.15 ms^{-2} r.m.s. of 8-Hz x-axis vibration of the back with the same backrest inclination).

3.3 Relative discomfort between backrest inclinations

The equivalent comfort contours obtained within each backrest inclination were adjusted so as to be expressed relative to the discomfort caused by the common reference (2.0 ms^{-2} r.m.s. of 8 Hz *x*-hand vibration). After adjustment, the contour for 100 indicates the vibration acceleration required at each frequency to cause discomfort equivalent to that caused by the common reference vibration. A comparison of the adjusted contours therefore shows differences in discomfort with the different backrest inclinations (Figure 3).

There is a consistent trend for greater sensitivity to vibration over the range 4 to 8 Hz with the upright backrest (0° inclination), although the relative discomfort contours were only significantly dependent on backrest inclination at 8 Hz (p=0.006; Friedman).

4. Discussion

4.1 Effect of frequency

For the upright backrest, the shape of the equivalent comfort contour (at ψ =100) is similar to that reported in previous studies with fore-and-aft vibration of full-height upright backrests (Parsons *et al.*, 1982; Kato and Hanai, 1998; Morioka and Griffin, 2009). Although the equivalent comfort contour varied with frequency, its shape in the region of greatest discomfort (at frequencies less than 8 Hz) can be approximated by a constant acceleration response (i.e. acceleration independent of frequency). At frequencies greater than 8 Hz, the equivalent comfort contour can be approximated by constant velocity response (i.e. 6 dB increase in acceleration per octave): a doubling of the frequency doubles the acceleration required to cause the same degree of vibration discomfort.

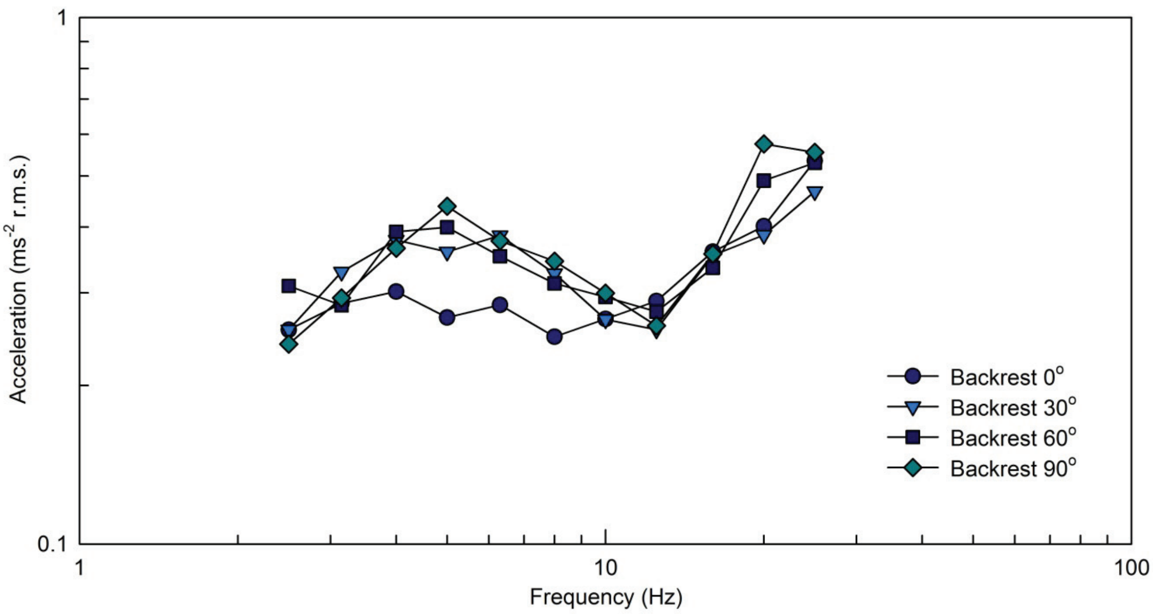

Figure 3 Equivalent comfort contours for the four backrest inclinations. Contours show the vibration required to produce discomfort equivalent to the common reference (2.0 ms^{-2} r.m.s. of 8-Hz *x*-hand vibration).

With the backrest inclined by 30°, 60° or 90°, the shapes of the equivalent comfort contours are broadly similar but somewhat different from the contour obtained with the upright backrest (Figure 3). The region of greatest discomfort is centred 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. The shapes of the equivalent comfort contours are broadly similar to the contours obtained with vertical whole-body vibration of recumbent subjects, although the region of greatest discomfort was at lower frequencies, around 4 Hz (Miwa and Yonekawa, 1969).

Relative motion between the moving backrest and the stationary seat pan and the stationary headrest seems to have contributed to discomfort at low frequencies with all backrest inclinations. A similar phenomenon has been reported by Jang and Griffin (1999, 2000) when the feet are supported on a stationary footrest and a seat is vibrated vertically with low magnitudes of 4-Hz vibration. With the upright backrest, an increase in discomfort associated with relative motion can be seen at frequencies less than 3.15 or 4 Hz for the present study (Figure 3) and also in the contours of Parsons *et al.* (1982) and Morioka and Griffin (2009).

4.2 <u>Effect of backrest inclination</u>

The effect of backrest inclination was pronounced at frequencies between 4 and 8 Hz, with approximately 30 to 40% less vibration required to produce the same discomfort with the upright backrest than the inclined backrests. The backrest inclination had no effect on vibration discomfort at frequencies greater than 8 Hz. Kato and Hanai (1998) reported a similar influence of the effect of backrest inclination at frequencies less than 8 Hz, with approximately 40 to 50% less vibration required to produce discomfort with an upright backrest than with a backrest inclined by 20° or 40°.

4.3 <u>Frequency weightings</u>

The shapes of the equivalent comfort contours (for ψ = 40 to ψ = 250 as shown in Figure 2) are compared in Figure 4 with the reciprocal of frequency weighting W_b (used to predict the discomfort caused by vertical vibration of recumbent persons in BS 6841:1987) and the reciprocal of frequency weighting W_c (used to predict the discomfort caused by fore-and-aft vibration of backrests in BS 6841:1987).The equivalent comfort contours for an upright backrest are reasonably consistent with the W_c weighting (where the acceleration required to cause vibration discomfort is roughly independent of frequency at frequencies less than 8 Hz and decreases at approximately 6 dB per octave as the frequency increases above 8 Hz). However, the equivalent comfort contours for inclined backrests seem more consistent with frequency weighting W_b than frequency weighting W_c at frequencies greater than 8 Hz.

The design of the present study does not permit the investigation of the suitability of the frequency weightings at low frequencies: the difference between the equivalent comfort contours and the weightings at low frequencies can be attributed to relative motion between the moving backrest and the stationary seat pan that may not be significant in a car environment.

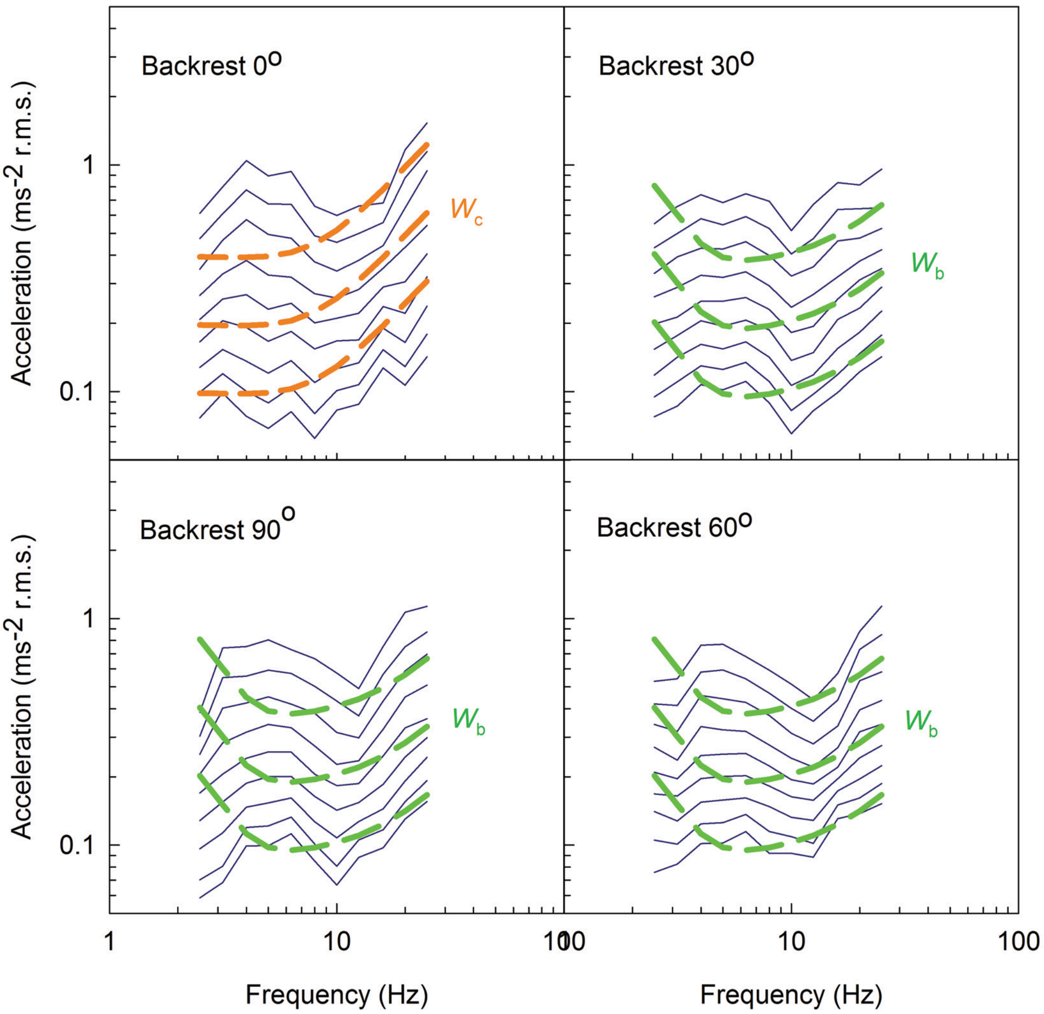

Figure 4 Comparison of equivalent comfort contours with reciprocals of realisable frequency weightings W_b and W_c from BS 6841 (1987).

5. Conclusions

The discomfort caused by fore-and-aft (*x*-axis) vibration of an upright backrest can be predicted adequately using frequency weighting W_c, as recommended in current standards. The discomfort caused by *x*-axis vibration of inclined backrests (inclined by 30° or more) can be predicted more appropriately using frequency weighting W_b. However, the suitability of these frequency weightings for predicting the influence of backrest inclination on vibration discomfort at low frequencies requires further study.

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