EFFECT OF A BACKREST ON THE DISCOMFORT CAUSED BY PITCH OSCILLATION IN THE FREQUENCY RANGE 0.5 TO 5 Hz

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Abstract

There are standardised methods of predicting the vibration discomfort of a seated person caused by translational and rotational vibration at the seat pan, the backrest, and the support for the feet. However, the predictions are based on various assumptions that have not been fully investigated. This study was designed to determine how the discomfort caused by pitch oscillation depends on seating conditions (with and without a backrest). For a rigid seat with and without a rigid flat backrest, 15 subjects judged the discomfort caused by pitch oscillation over the frequency range 0.5 to 5 Hz at magnitudes in the range 0.05 to 5.0 rad.s^{-2} r.m.s. The rate of growth of discomfort varied between frequencies and depended on whether the backrest was present, so the relative discomfort between frequencies and the effect of the backrest on discomfort depended on the magnitude of vibration. Although the appropriate frequency weighting depends on the magnitude of vibration, at frequencies less than about 1 Hz, the discomfort caused by pitch oscillation is similar with and without a backrest, whereas at frequencies greater than about 1 Hz a backrest will tend to increase the discomfort caused by pitch oscillation.

1. Introduction

The discomfort experienced by vehicle drivers and passengers depends on the frequency, the magnitude, the direction, and the duration of the vibration. British Standard 6841:1987 and International Standard 2631-1:1997 define frequency weightings and multiplying factors for predicting the discomfort caused by different directions of vibration at different input locations to the body. These weightings were mainly derived from laboratory studies of the discomfort caused by sinusoidal vibration (Griffin, 2007).

The vibration measured in a 2,260 kg sports utility vehicle (SUV) indicated that the overall ride included an appreciable contribution from fore-and-aft vibration at the backrest of the driver's seat. The spectra of fore-and-aft vibration at the backrest showed greater similarity with the pitch motion of the vehicle (measured beneath the seat) than fore-and-aft vibration at the same location (Figure 1). This is consistent with other studies showing that pitch oscillation of a vehicle can be a principal cause of the fore-and-aft vibration at a backrest (Qiu and Griffin, 2005). Understanding the role of pitch oscillation is therefore important when measuring the ride in a vehicle and when predicting and optimising vehicle vibration.

In one of a four-part series of studies, Parsons and Griffin (1982) determined equivalent comfort contours for rotational whole-body vibration (i.e., roll, pitch and yaw oscillation) over the frequency range of 1 to 31.5 Hz relative to the discomfort caused by vertical whole-body vibration. The final paper in the series presented median equivalent comfort contours for all twelve axes by fitting lines of constant

Presented at the 50th United Kingdom Conference on Human Responses to Vibration, held at ISVR, University of Southampton, Southampton, England, 9 - 10 September 2015.

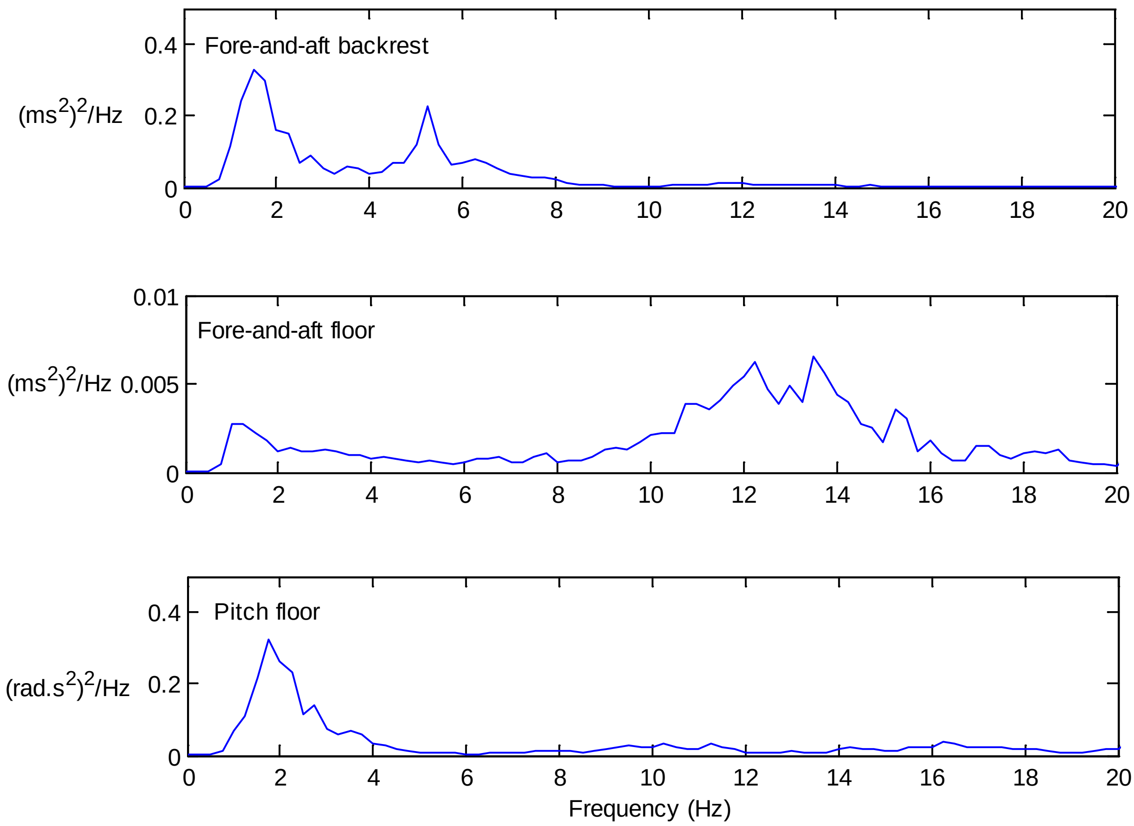

Figure 1 Acceleration power spectral densities for fore-and-aft acceleration at the backrest of the seat, fore-and-aft acceleration on the floor beneath the seat, and pitch acceleration on the floor beneath the seat. Measurements in a 2,260-kg SUV travelling at 40 miles per hour.

acceleration or constant velocity to the experimental data, so as to create simplistic frequency weightings (Griffin *et al.*, 1982). For pitch vibration at the seat, the experimentally derived equivalent comfort contour was approximated by a slope of constant velocity over the frequency range 1 to 31.5 Hz, although this slightly underestimated discomfort at frequencies greater than 10 Hz. The fitted slope was used to form the W_e weighting in BS 6841:1987 and, subsequently, ISO 2631-1:1997.

At the time when the standards were produced, the facilities for investigating the discomfort caused by pitch oscillation were very limited. The experimental studies were restricted to the frequency range 1 to 31.5 Hz and conducted with pitch oscillation of a rigid flat seat with no backrest and with the feet resting on a stationary support. With low frequencies of pitch oscillation of the seat, relative motion between the front of the seat and the stationary feet may have contributed to discomfort around the thighs that will not be present if the seat and feet move together, as in most transport environments (Jang and Griffin, 2000).

Rotational vibration produces translational oscillation at points away from the centre of rotation. Pitch oscillation of a floor supporting a seat causes fore-and-aft motion at the seat backrest, with the magnitude of fore-and-aft vibration increasing up the height of the backrest.

Equivalent comfort contours for fore-and-aft and pitch oscillation over the frequency range 0.2 to 1.6 Hz have been determined with and without a backrest (Wyllie and Griffin, 2009). It was concluded that at frequencies less than about 0.8 Hz, the main contributor to overall discomfort was acceleration in the plane of the seat due to gravity acting through the angle of pitch at the seat (i.e., g sin θ, where θ is the angle of pitch in degrees). At frequencies greater than about 0.8 Hz, the fore-and-aft acceleration of the backrest seemed to be the principal cause of discomfort.

The relationship between the magnitude of a vibration, φ, and the subjective response to the vibration, ψ, can be expressed using Stevens' power law:

$$\Psi = k.\ \varphi^{n} \tag{1}$$

where n is the 'rate of growth' of sensation (e.g., discomfort) and k is a constant.

During the past decade it has become recognised that n, the rate of growth of sensation with increasing vibration magnitude, varies according to the frequency, direction, and location of input of vibration to the body. This means that the shapes of equivalent comfort contours vary with the magnitude of vibration, and the equivalence between directions of vibration and locations of input of vibration to the body varies with the magnitude of vibration (e.g., Morioka and Griffin, 2006; Wyllie and Griffin, 2009; Basri and Griffin, 2013). The magnitude-dependence of equivalent comfort contours means that a single frequency weighting, as offered in the standards, cannot provide an optimum prediction of the discomfort caused by a range of vibration magnitudes, frequencies, and directions.

From the studies of Wyllie and Griffin it seems that the discomfort caused by pitch oscillation at the surface of a seat pan may often be predicted from the root-sums-of squares of the following components, where the frequency weightings W_c, W_d, and W_e are as defined in BS 6841:1987:

(a) pitch acceleration in the plane of the seat in rad.s^{-2} (using frequency weighting W_e, with a multiplying factor of 0.4),

(b) fore-and-aft acceleration calculated from the angular displacement, θ, at the seat multiplied by gravity (i.e., g sin θ) (using frequency weighting W_d, with a multiplying factor of 1.0),

(c) fore-and-aft acceleration at the backrest (if present) calculated from the height of the backrest, h, (in metres) and the pitch acceleration, $\ddot{\theta}$ (in radians) (i.e., $h.\ddot{\theta}$) (using frequency weighting W_c with a multiplying factor of 0.8).

The fore-and-aft acceleration at the feet caused by pitch oscillation (either due to the gravitational component, g sin θ, or because the feet are distant from the centre of rotation), is assumed to be negligible due to relatively low sensitivity to vibration of the feet in the fore-and-aft direction (see Wyllie and Griffin, 2009), and so vibration at the feet will be ignored.

Since pitch oscillation can produce motions that cause discomfort, it is desirable to understand better the role of pitch motion in a procedure for predicting the discomfort caused by multi-axis and multiple-input vibration. This study was designed to determine how the discomfort caused by pitch oscillation depends on the magnitude of pitch oscillation (0.05 to 5.0 rad.s^{-2} r.m.s.), the frequency of oscillation (0.5 to 5 Hz), and seating conditions (with and without a backrest). It was hypothesised that the rate of growth of discomfort would depend on the frequency of oscillation and that a backrest would have no effect on discomfort at frequencies less than about 1 Hz, because the gravitational component (g sin θ)

at the seat pan would dominate. At frequencies greater than about 1 Hz, greater discomfort was expected with the backrest, because fore-and-aft acceleration of the backrest would then be the dominant vibration input to the body arising from the pitch oscillation.

2. Method

2.1. Subjects

Fifteen subjects, eight male and seven female students and office workers from the University of Southampton, participated in the study. Their characteristics are summarised in Table 1. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application number 14510).

Table 1 Median and interquartile range of subject characteristics.

Gender	Age (years)	Height (m)	Weight (kg)
Male	28 (2.8)	1.80 (0.15)	91 (27.6)
Female	27 (4.5)	1.62 (0.05)	55 (7.5)

2.2. Apparatus

Pitch oscillation was produced by a six-axis motion simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton. Figure 2 shows the experimental set up.

A rigid seat with a removable backrest (seat-pan height 0.423 m, seat-pan depth 0.445 m, backrest height above the seat pan 0.558 m) was mounted on the motion simulator. The centre-of-rotation of the simulator was adjusted to be at the upper surface of the seat pan beneath the ischial tuberosities of the seated subjects.

Subjects wore a loose lap belt and held an emergency stop button for safety. A rigid footrest was used if necessary so that the upper surfaces of the thighs were horizontal when the subjects sat without motion.

Subjects wore headphones producing white noise at 65 dB (A) to mask sounds produced by motion of simulator. The experimenter communicated with subjects via a microphone and the headphones.

2.3. Motion Stimuli

Motion stimuli were generated using MATLAB (version 2012a) and the *HVLab* toolbox (version 2). The sinusoidal stimuli were at the eleven preferred one-third octave centre frequencies from 0.5 to 5 Hz. The stimuli had durations of approximately 11 seconds, adjusted to n+0.5 cycles of oscillation (where n is an odd number). These stimuli were then modulated by a half sine envelope so that each stimulus started and ended with zero displacement, zero velocity, and zero acceleration.

Figure 2 Experimental setup on the 6-axis simulator with backrest (left) and without backrest (right).

The magnitudes at 0.5 Hz were adjusted to 0.063, 0.10, 0.16, 0.25, 0.40, and 0.63 rad.s^{-2} (i.e., six magnitudes with 2 dB increments between magnitudes). To obtain a similar range of the subjective magnitudes across the frequency range with and without the backrest, the magnitudes at other frequencies were calculated so that they would be expected to produce similar overall discomfort (using the weightings and multiplying factors in BSI 6841:1987 with the addition of the gravitational factor and using the root-sums-of-squares, r.s.s., to combine the components). The ranges of stimuli are shown in Figure 5 (below).

The stimuli consisted of 66 motions with the backrest and 64 motions without the backrest. The greatest magnitudes at the two highest frequencies (4 and 5 Hz) without the backrest were not presented due to the high magnitudes of simulator pitch acceleration required.

2.4. <u>Procedure</u>

Subjects attended one session lasting approximately 90 minutes, which included reading instructions, signing a consent form, practice, and participating in the experiment. They received written instructions and were given practice to demonstrate they had understood their task of judging discomfort. The practice consisted of judging the length of lines on paper and judging vibration discomfort when seated without a backrest and exposed to eight motions over the ranges of frequency and magnitude they would experience in the experiment.

During the experiment, the subjects were instructed to close their eyes to eliminate the visual perception of motion from their evaluations. They were instructed to sit comfortably and maintain an upright posture. For the condition without backrest, the backrest was removed to avoid any unintentional contact between the subject and the backrest. In the condition with the backrest, they maintained contact with the backrest throughout the experiment.

Subjects rated the discomfort caused by the pitch oscillations using the method of absolute magnitude estimation. The order of presenting the seating conditions was balanced. The order of presenting the motion stimuli was randomised within each seating condition.

2.5. Data analysis

The magnitude estimates of vibration discomfort given by each subject over all frequencies and magnitudes and both seating conditions (with and without backrest) were normalised so that the median value was 100 for every subject.

Using Stevens' Power Law, the rate of growth of discomfort, *n,* and the constant, *k*, were determined at each frequency in both seating conditions for every subject by linear regression after logarithmic transformation of Equation 1:

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

where *n* represents the slope (rate of growth of discomfort) and *k* represents the intercept of the linear regression between $\log_{10} \psi$ and $\log_{10} \varphi$.

Equivalent comfort contours were then determined from Equation 2 by calculating for every individual subject the magnitude of pitch acceleration (i.e., φ in rad.s^{-2} r.m.s., unweighted) required to produce subjective magnitudes, ψ, of 50, 100 and 150.

The hypotheses were tested using non-parametric statistics in SPSS (version 22). To quantify differences between related samples, the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks were used. The probabilities shown are not adjusted for multiple comparisons.

3. Results

3.1. Rate of growth of discomfort

The medians and inter-quartile ranges of the rates of growth of discomfort (i.e., the exponent *n*) at each frequency of vibration are shown for the judgements obtained with a backrest (Figure 3, left) and without a backrest (Figure 3, right). In both seating conditions the rate of growth of discomfort depended on the frequency of vibration (p=0.002 with backrest, p<0.001 without backrest; Friedman).

With backrest, the rate of growth of discomfort was less at frequencies from 1 to 2 Hz than at 3.15 and 4 Hz (p<0.05, Wilcoxon), except between 1 and 3.15 Hz (p=0.164, Wilcoxon). Without backrest, the rate of growth of discomfort tended to decrease with increasing frequency: the rates of growth of discomfort at frequencies less than 1 Hz were greater than those at all other frequencies (p<0.05, Wilcoxon), and the rate of growth at 5 Hz was less than the rate of growth at all other frequencies (p<0.05, Wilcoxon).

The backrest increased the rate of growth of discomfort at 1 Hz (p=0.05, Wilcoxon) and at frequencies greater than 2 Hz (p<0.05 at 2 Hz, p<0.01 between 2.5 and 5 Hz; Wilcoxon; Figure 4).

3.2. Equivalent comfort contours

The median equivalent comfort contours for pitch vibration when sitting with and without a backrest are shown in Figure 5. As expected from the variation in the rate of growth of discomfort with frequency, the shapes of the contours vary according to the subjective magnitude, with the greatest change in the shapes of the contours when sitting with no backrest.

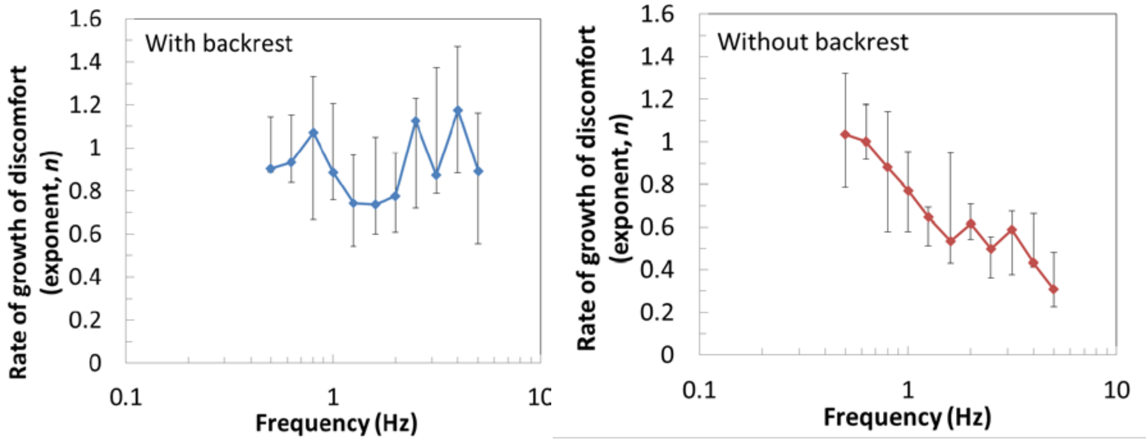

Figure 3 Rate of growth of discomfort, *n*, for pitch oscillation when sitting with a backrest (left) and sitting without a backrest (right). Median values and inter-quartile ranges from 15 subjects.

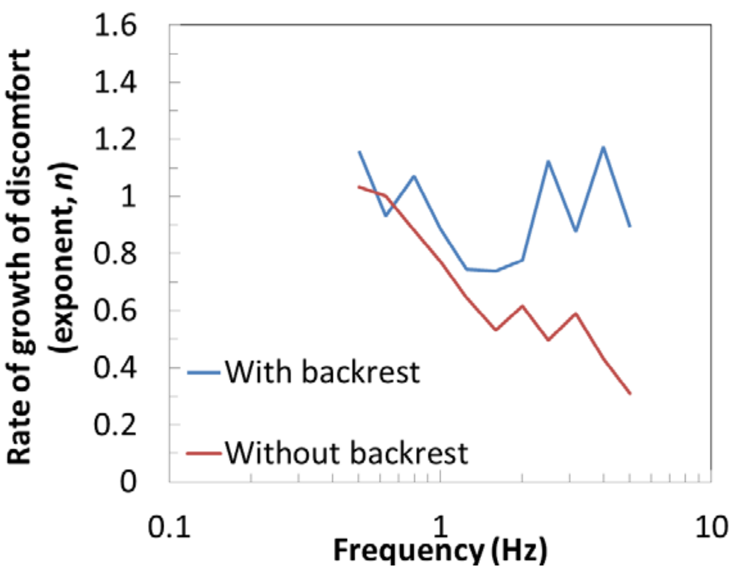

Figure 4 Rates of growth of discomfort, *n*, for pitch oscillation when sitting with a backrest (blue) and sitting without backrest (red). Median values from 15 subjects.

3.2.1. <u>Comparing discomfort with and without backrest</u>

With a subjective magnitude of 100, the presence of the backrest had no effect on vibration discomfort caused by frequencies less than 1.25 Hz (p>0.1, Wilcoxon), but the backrest increased discomfort at 1.6 Hz (p=0.005; Wilcoxon) and at 3.15 and 4 Hz (p<0.01, Wilcoxon).

When the subjective magnitude increased to ψ = 150, there was still no significant difference between the contours for the two seating conditions at frequencies less than 1.25 Hz (p>0.1, Wilcoxon) but the presence of the backrest increased discomfort at 1.6 Hz (p=0.001, Wilcoxon) and at all frequencies greater than 2 Hz (p<0.02, Wilcoxon) (see Figure 6).

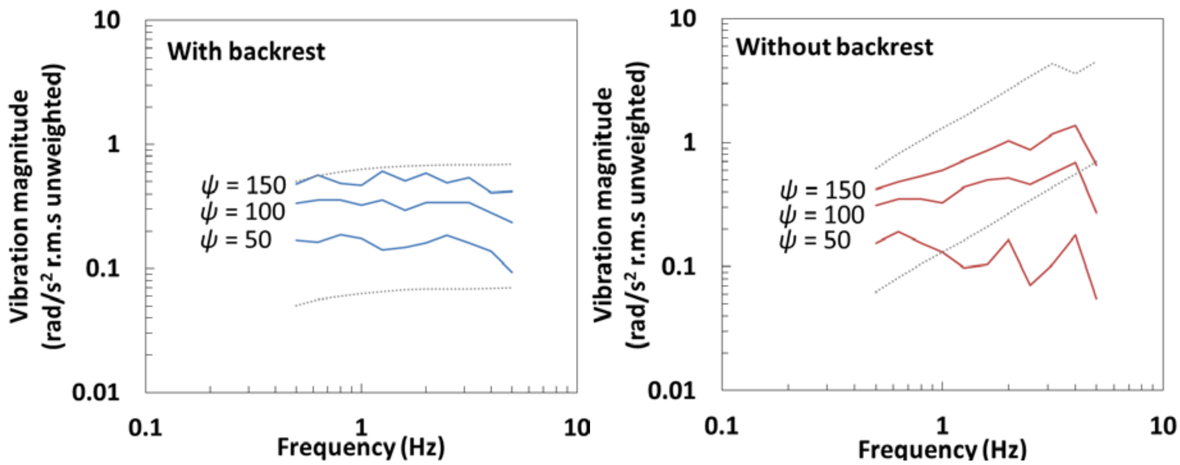

Figure 5 Equivalent comfort contours for subjective magnitudes ψ = 50, 100 and 150 in terms of unweighted r.m.s. acceleration calculated from the median equivalent comfort contours of 15 subjects with backrest (left) and without backrest (right). Minimum and maximum magnitudes of vibration employed in the study (**……..**).

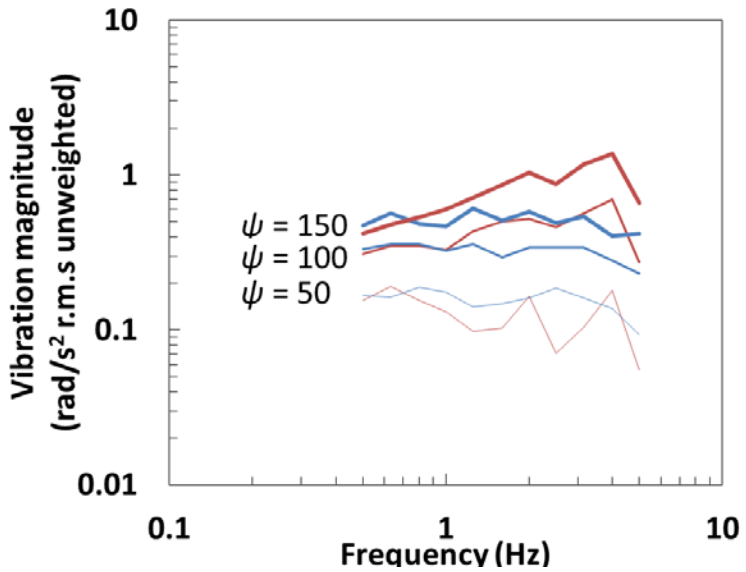

Figure 6 Comparison of equivalent comfort contours for a subjective magnitude ψ = 100 in terms of unweighted r.m.s. pitch acceleration calculated from the median equivalent comfort contours of 15 subjects sitting with and without a backrest.

4. Discussion

4.1. Rate of growth of discomfort

With no backrest, the rate of growth of discomfort decreased with increasing frequency of vibration. At low frequencies, the rotational displacement was large and so there was greater acceleration in the plane of the seat (i.e., g sin θ) which probably dominated discomfort. At higher frequencies the rotational displacement was small and so the acceleration in the plane of the seat due to gravity was small, and the relative displacement between the moving legs and the torso was reduced, and there was no backrest to cause vibration discomfort at the back. In these conditions the discomfort increased at a slow rate when the magnitude of vibration increased.

With the backrest, the rate of growth of discomfort was similar to that without backrest at low frequencies (less than 1 Hz), consistent with discomfort being caused by acceleration in the plane of the seat due to gravity in both cases. No significant effect of a backrest on the rate of growth of discomfort over the frequency range 0.2 to 1.6 Hz has also been reported by Wyllie and Griffin (2009). In the present study, at frequencies greater than 1 Hz, the rate of growth of discomfort was greater with the backrest than without the backrest, consistent with backrest vibration being a more important source of discomfort.

The variations in the rates of growth of discomfort over frequency and between backrest conditions are consistent with the rate of growth being greater when discomfort is dominated by factors affecting the whole body and less when discomfort is not localised in the torso (Jang and Griffin, 2000).

4.2. Equivalent comfort contours

The frequency-dependence in the rate of growth of discomfort causes the equivalent comfort contours to change shape according to the magnitude of the vibration. The effect is far greater without the backrest because the rate of growth of discomfort changes more over the frequency range 0.5 to 5 Hz when there is no backrest.

The difference in the rate of growth of discomfort between sitting with a backrest and sitting without a backrest (at frequencies greater than about 1 Hz) means that the extent to which the backrest increased discomfort depends on the magnitude of the vibration, as can be seen in Figure 6.

At frequencies less than about 1 Hz, the equivalent comfort contours are similar with and without a backrest, indicating that the rigid backrest had no overall negative or positive effect on the discomfort caused by pitch oscillation at these frequencies. Because the rate of growth is similar with and without a backrest at these frequencies it may be concluded that the negligible effect of the backrest on discomfort will apply over a wide range of magnitudes of pitch oscillation at frequencies less than about 1 Hz. At higher frequencies, the addition of the backrest increases discomfort, and the obvious explanation is the contribution from fore-and-aft vibration of the backrest caused by the pitch oscillation at the seat pan. These findings are broadly consistent with those of Wyllie and Griffin (2009) who found increased discomfort with a backrest at frequencies greater than 0.63 Hz, but they did not investigate frequencies greater than 1.6 Hz.

To predict the discomfort caused by the fore-and-aft vibration at the back arising from pitch oscillation it is necessary to assume the effective height above the seat pan where the fore-and-aft backrest vibration has the contact with the body that causes discomfort within the body. The flat vertical backrest employed in this study extended 0.558 m above the seat pan, but subjects would not have been in contact with the backrest at the highest point on this backrest. Half way up the backrest, the fore-and-aft motion caused by pitch oscillation about the seat pan would have been half the magnitude of the fore-and-aft motion at the top of the backrest. A reduction in backrest height will therefore reduce the discomfort arising from the fore-and-aft backrest vibration caused by pitch oscillation, and probably increase the range of frequencies over which discomfort is similar with and without a backrest.

British Standard 6841:1987 states: "*Measurements on the seat-back should be made at the position with the greatest effective vibration in contact with the body*", whereas ISO 2631-1:1997 states: "*Measurements on the seat-back should be made in the area of principal support of the body*". Neither of these is sufficiently specific to identify where vibration between a backrest and the back should be measured.

In this study, the centre of pitch was located at the upper surface of the seat pan. If pitch motion of a vehicle is measured beneath a seat, the fore-and-aft vibration at the seat back arising from this pitch motion will tend to be greater, and the role of pitch motion of the vehicle in causing discomfort will also tend to be greater than implied here. Additionally, a non-rigid backrest will exhibit amplification of vibration at some frequencies and attenuation of vibration at some other frequencies (Basri and Griffin, 2014), further complicating the prediction of vibration discomfort caused by pitch oscillation.

5. Conclusions

The rate of growth of discomfort caused by pitch oscillation of a seat depends on the frequency of oscillation and whether there is a backrest to the seat. The relative discomfort between frequencies and between seating conditions (backrest or no backrest) therefore depends on the magnitude of vibration.

Although the appropriate frequency weighting depends on the magnitude of vibration, at frequencies greater than about 1 Hz a backrest will tend to increase the discomfort caused by pitch oscillation. At frequencies less than about 1 Hz, the discomfort caused by pitch oscillation seems to be similar with and without a backrest.

When fore-and-aft vibration at a backrest contributes to vibration discomfort it should be recognised that the cause may be pitch motion of the vehicle. Pitch oscillation of the floor of a vehicle, how it is transmitted to drivers and passengers, and how it contributes to the perception of vehicle vibration discomfort requires more consideration.

6. Acknowledgement

The authors gratefully acknowledge Technology Strategy Board IDP 9 - Technology challenge in low carbon vehicles - Application number 31020-216137: ULTRAN (Ultra-Lightweight Transmission and Driveline).

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