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EFFECT OF PHASE, FREQUENCY, MAGNITUDE AND POSTURE ON DISCOMFORT ASSOCIATED WITH DIFFERENTIAL VERTICAL VIBRATION AT THE SEAT AND FEET

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The interaction between the frequency of vibration and the relative phase between vibration at the seat and the feet on the discomfort of seated subjects exposed to vertical vibration has been investigated in an experimental study. Twelve seated subjects were exposed to sinusoidal vibration at five frequencies (2·5, 3·15, 4, 5 and 6·3 Hz) by means of two vibrators, one under the seat and the other under the footrest. A total of 100 combinations of vibration stimuli with two phases (0 and 180°) between the seat and the footrest at five acceleration levels (0·25, 0·4, 0·63, 1·0 and 1·6 m/s^2 r.m.s.) and the five frequencies were presented to subjects in two postures (with and without thigh contact with the seat). The subjects judged that the differential vibrations with greater phase difference caused greater discomfort at frequencies up to 4 Hz. The subjects were most sensitive to phase changes at the lowest frequency and the lowest magnitude of vibration. In the equation, $\psi = k\phi^n$, between the discomfort, ψ, and the magnitude of vibration, ϕ, the exponent n had a maximum of 1·34 "with thigh contact" and 1·24 "without thigh contact" for the in-phase vibration at around 4 Hz. The exponent had a minimum of 0·63 "without thigh contact" for the out-of-phase motion at 2·5 Hz. The results indicate that vibration discomfort is influenced by the phase between the seat and the feet, but that the effect depends on the frequency and magnitude of vibration and the posture of the body. The phase effect seems to be particularly important with low magnitudes of vibration at low frequencies.

1. INTRODUCTION

The dynamics of seats in vehicles modify the vibration experienced by drivers and passengers. As a consequence, the vibration at the seat differs from that at the floor and there is differential vibration between the seat and the floor. Although the

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discomfort caused by vibration of the seat and vibration of the floor has been investigated, there has been little consideration of the extent to which discomfort may be influenced by the differential vibration occurring at the seat and the floor. This motion is likely to be more significant in commercial vehicles where there are large magnitudes of low-frequency vibration and the compliance of seats results in differential movement at frequencies of vibration at and above about 2 Hz. In order to optimize vehicle ride and seating dynamics, it is necessary to understand how the phase between the seat vibration and the floor vibration affects judgements of discomfort and the manner in which discomfort depends on the various characteristics of the vibration.

British Standard 6841 [1] offers frequency weightings for a seated human body in contact with components of vibration at a supporting seat surface, a seat back or the feet for vibration in any direction [1]. International Standard 2631 [2] offers a similar, though not identical, set of frequency weightings [2]. Both standards define a method of calculating the total ride comfort from two or more components of such vibration, but there is no guidance on the effect of different phases at the different contact points. Griffin and Whitham [3] and Fairley and Griffin [4] concluded that the root-sums-of-squares of the weighted vibration in the separate axes was an appropriate procedure for predicting the discomfort of combined vertical and either lateral or fore-and-aft vibration [3, 4]. In these studies they varied the phase between axes of motion presented at the same position on the body (i.e., at the seat).

Entrekin *et al.* [5] investigated the effect of phase on the differential vibration of the seat and the floor and determined the frequency range over which subjects could detect the phase between the seat and the feet. With sinusoidal vibration from 3 to 12 Hz at constant magnitude ($1{\cdot}0\,\mathrm{m/s^2}$ peak to peak) with three phase differences between seat and feet (0, 90 and 180°) they concluded that up to 4 Hz most of the subjects could detect a 180° phase difference between the seat and the feet. They concluded that the subjects preferred a stationary footrest at high frequencies but preferred in-phase motion at frequencies below about 5 Hz.

Using 4 Hz vertical vibration, the present authors have previously investigated the effect of phase between the vertical seat vibration and vertical floor vibration on judgements of discomfort [6]. The results showed that subjects judged conditions with a phase shift as being more uncomfortable than in-phase motions. The effect of phase was greatest at low vibration magnitudes. When the vibration magnitude was greater than $1{\cdot}0\,\mathrm{m/s^2}$ r.m.s., the discomfort judgements of subjects were not affected by the phase. It was also found that the exponent, n, in the equation, $\psi = k\phi^n$, between the discomfort, ψ, and the magnitude of vibration, ϕ, decreased with increasing phase angle.

The principal objective of the present study was to investigate the manner in which the discomfort of seated subjects depends on the interaction between vibration frequency and magnitude and on the phase difference between vertical seat and vertical floor vibration. The study was conducted with two different body postures (with and without thigh contact) as this had previously been found to influence judgements of vibration discomfort.

2. APPARATUS

2.1. VIBRATION GENERATION

Subjects sat on a rigid, but slightly contoured, horizontal wooden seat secured to a Derritron VP85-6LA vibrator with their feet supported on a flat horizontal plate secured to a Derritron VP85 vibrator. Figure 1 shows the experimental arragement.

The position of the seat was fixed but the height of the footrest was adjusted to provide the desired posture. For a "thigh contact" posture, the level of the footrest was adjusted such that the upper surface of the upper legs was horizontal with the lower legs vertical. To achieve a "without thigh contact" posture, the footrest was raised by 150 mm from the position used for the "thigh contact" posture.

2.2. SIGNAL GENERATION

The vibration signals were generated from *HVLab* software installed on a IBM Notebook PC and transferred to the vibrator amplifiers via digital-to-analogue converters at a sample rate of 375 samples/s. In order to remove unwanted high-frequency components from the digital signal, low-pass filters were used with a cut-off frequency of 10 Hz. Throughout the experiment, the motions on the two vibrators were sinusoidal, but they differed in phase, frequency and magnitude. The maximum acceleration distortion was 14% and occurred with the lowest frequency.

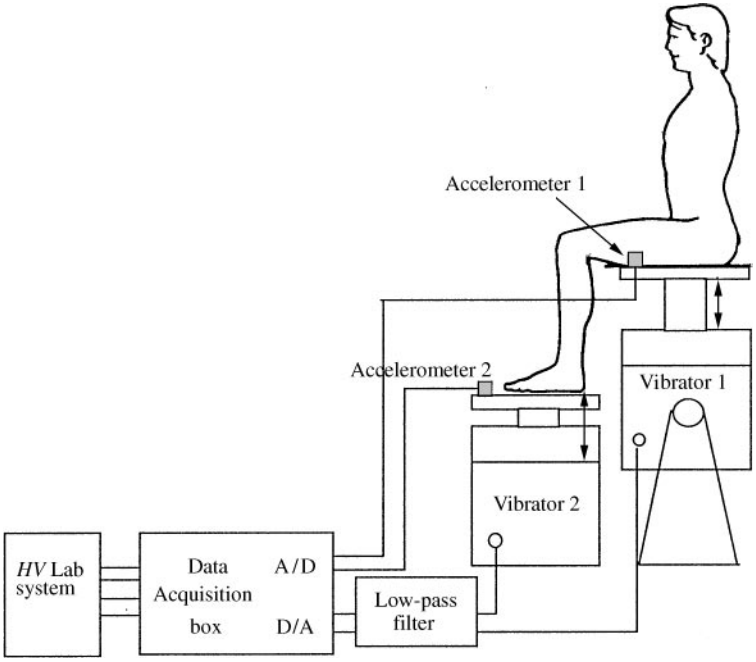

Figure 1. Experimental arrangement.

2.3. ENVIRONMENTAL CONDITIONS

During the experiment the temperature ranged from 20 to 25°C. The background noise level at the subject's ears was 60–65 dBA.

3. METHOD

The experiment was conducted at five frequencies (2·5, 3·15, 4, 5 and 6·3 Hz). At each frequency, a combination of two phase angles (0 and 180°) and five magnitudes (0·25, 0·4, 0·63, 1 and 1·6 m/s^2 r.m.s.) were presented. Due to a limited capability of the vibrators at lower frequencies, the vibration magnitude was limited to the range of 0·16–1·0 m/s^2 at 2·5 Hz. For each of the 50 conditions, the subjects were asked to estimate their discomfort relative to that produced by a reference motion consisting of in-phase motions at the seat and feet. The same conditions were repeated with both postures: with thigh contact and without high contact. A third part of the experiment required subjects to compare the discomfort with and without thigh contact.

3.1. DESIGN AND PROCEDURE

The experiment was performed in three sessions: two for the two different postures of with and without thigh contact and the other for comparisons of discomfort ratings using different reference stimuli.

The first and second sessions of the experiment consisted of five sections, each investigating one of the five vibration frequencies. Within each section, an identical sinusoidal reference stimulus was presented at both vibrators: the two motions were in-phase (i.e., 0° phase angle between the seat and feet) at 0·63 m/s^2 r.m.s. In each section, subjects were required to judge the relative discomfort of the reference motion and 10 test motions of the same frequency (2 phase angles at 5 magnitudes). One of the sessions investigated conditions with thigh contact and the other investigated conditions without thigh contact. The order of presenting the vibration frequencies, the vibration magnitudes, and conditions with and without thigh contact were randomized.

In sessions 1 and 2 of the experiment, the reference motion varied in vibration frequency (so as to be the same as the test motion) and the subject posture (thigh contact or no thigh contact) also varied. Consequently, the reference motion may have caused a different degree of discomfort with each condition. The first part of the third session of the experiment was designed to investigate the frequency dependence of the discomfort caused by the reference motion: the five reference conditions used in session 2 were used as test motions and compared with a similar reference motion of 4 Hz. The second part of the third session investigated the effect of thigh contact on discomfort at each frequency: the five reference conditions used in session 2 were used as test motions and compared with reference motions at the same frequency and magnitude but with subjects sitting in a thigh contact posture.

The experimental conditions are summarized in Table 1.

TABLE 1

Experimental conditions in sessions 1, 2 *and* 3

	Test motion			Reference motion Magnitude, phase, frequency and posture
Posture	Frequency (Hz)	Vibration magnitude (m/s^2)	Phase angle	
Session 1				
Thigh contact	2·5	(0·16)	0°	0·63 m/s^2 at 0° (at the same frequency as the test motion) with no thigh contact
	3·15	0·25	180°	
	4	0·4		
	5	0·63		
	6·3	1·0		
		1·6		
Session 2				
No thigh contact	2·5	(0·16)	0°	0·63 m/s^2 at 0° (at the same frequency as the test motion) with no thigh contact
	3·15	0·25	180°	
	4	0·4		
	5	0·63		
	6·3	1·0		
		1·6		
Session 3(a)				
No thigh contact	2·5	0·63	0°	4 Hz at 0° at 0·63 m/s^2 r.m.s. with no thigh contact
	3·15			
	4			
	5			
	6·3			
Session 3(b)				
No thigh contact	2·5	0·63	0°	0° at 0·63 m/s^2 r.m.s. with thigh contact (at the same frequency as the test motion)
	3·15			
	4			
	5			
	6·3			

Twelve male subjects participated in the experiment. The heights and weights of the subjects ranged from 168 to 184 cm and from 60 to 84 kg. Subjects were asked to sit on the seat with a straight back with their hands on their knees. For the "thigh contact" posture, the subjects sat with the upper surface of their upper legs horizontal, so that the thighs were fully in contact with the seat. For the "without thigh contact" posture, the height of the footrest was raised by 150 mm so that the thighs did not contact the seat surface.

Subjects were presented twice with both the reference motion and the test motion before making their judgement: the order of presentation was "reference motion", "test motion", "reference motion", "test motion". Each motion lasted 5 s, with an interval of 1 s between the reference and the test motions. At the end of the series of four motions a subject was asked to judge the relative discomfort of the motions on the basis that the reference stimulus caused a discomfort of 100.

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

4. RESULTS

4.1. EFFECT OF VIBRATION FREQUENCY AND THIGH CONTACT

Judgements of discomfort within the first two sessions of the experiment were made relative to reference motions which differed in frequency and thigh contact. So each discomfort judgement was re-scaled using the scaling factors obtained from the discomfort judgements obtained in the third session of the experiment.

The effects of vibration frequency and thigh contact (i.e., the conditions of sessions 3a and 3b in Table 1) are shown in Figure 2. The first graph shows the relative discomfort at the five test frequencies (2·5, 3·15, 4, 5, 6·3 Hz) compared to that at the reference frequency (4 Hz) for the 12 subjects (when using a magnitude of 0·63 m/s^2 r.m.s. with in-phase motion at the seat and feet). The relative discomfort increased with increasing frequency, showing maximum discomfort at 5 Hz. The relative discomfort decreased slightly at 6·3 Hz, but the inter-subject variability was greater at this frequency.

The second graph in Figure 2 shows the relative discomfort of the test motions, without thigh contact, judged relative to reference motions with thigh contact (using 2·5, 3·15, 4, 5, 6·3 Hz vibration at a magnitude of 0·63 m/s^2 r.m.s.). Although the discomfort ratings in the previous study [6] and the present study appear to vary with posture, the difference associated with posture in Figure 2(b) was not statistically significant (Wilcoxon matched-pairs signed ranks, $p > 0{\cdot}05$).

4.2. EFFECT OF VIBRATION MAGNITUDE

Figures 3 and 4 show the scaled relative discomfort judgements from the 12 subjects sitting in the two postures. The scaling was achieved using the frequency weighting given by the ratio shown in Figure 2(a), and then data obtained without thigh contact were multiplied by the ratio shown in Figure 2(b). This made it possible to compare the data in sessions 1 and 2 directly, even though the data were obtianed with different reference motions. Each graph in Figures 3 and 4 shows the effect of vibration magnitude at the five frequencies with both 0 and 180° phase difference between the seat and the feet. The median and inter-quartile ranges of the subject judgements are shown using logarithmic scales relative to their judgements of the discomfort caused by 0·63 m/s^2 r.m.s. Because of the displacement limitation of the vibrators at low frequencies, the vibration magnitude at 2·5 Hz ranged from 0·16 to 1·0 m/s^2 r.m.s.

As the magnitude of the test motions increased, the logarithms of the discomfort judgements relative to the 0·63 m/s^2 r.m.s. reference motion can be seen to have

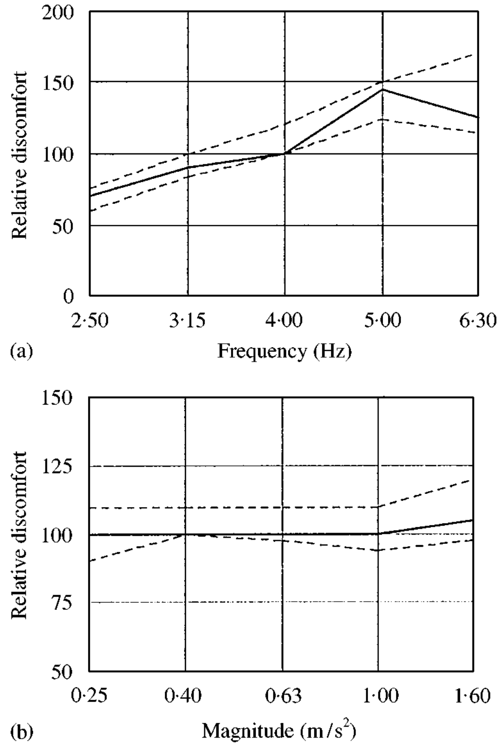

Figure 2. Relative discomfort estimated by 12 subjects for the different reference stimuli used in sessions 1 and 2 (vibration magnitude: 0·63 m/s^2, phase difference: 0°). (a) Variation of discomfort with vibration frequency relative to 4 Hz: - - - -, 25%; ——; Median - - - -, 75%. (b) Variation of discomfort with posture ("no thigh contact" relative to "thigh contact"): - - - -, 25%; ——, Median; - - - -, 75%.

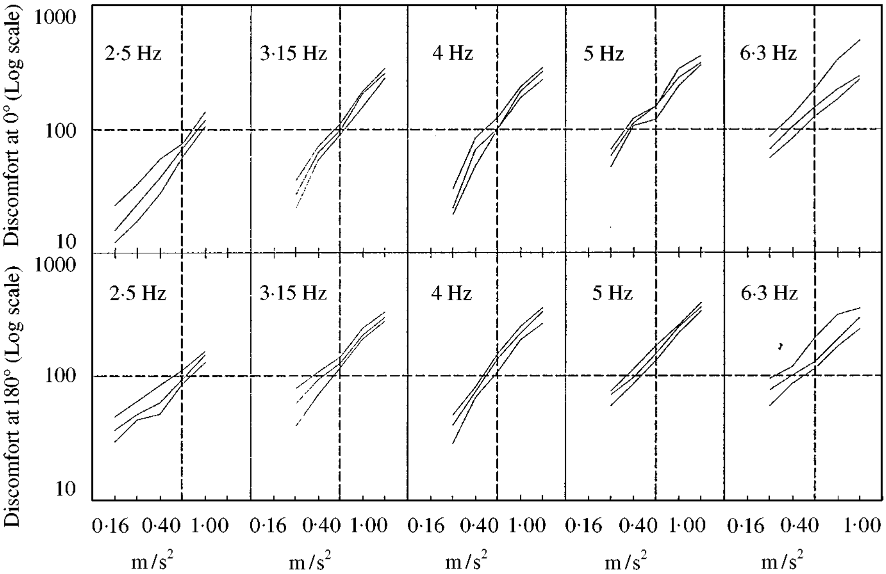

Figure 3. Median and inter-quartile range of relative discomfort with increasing vibration magnitude at five frequencies with thigh contact. (First row: in-phase motion, second row: out-of-phase motion).

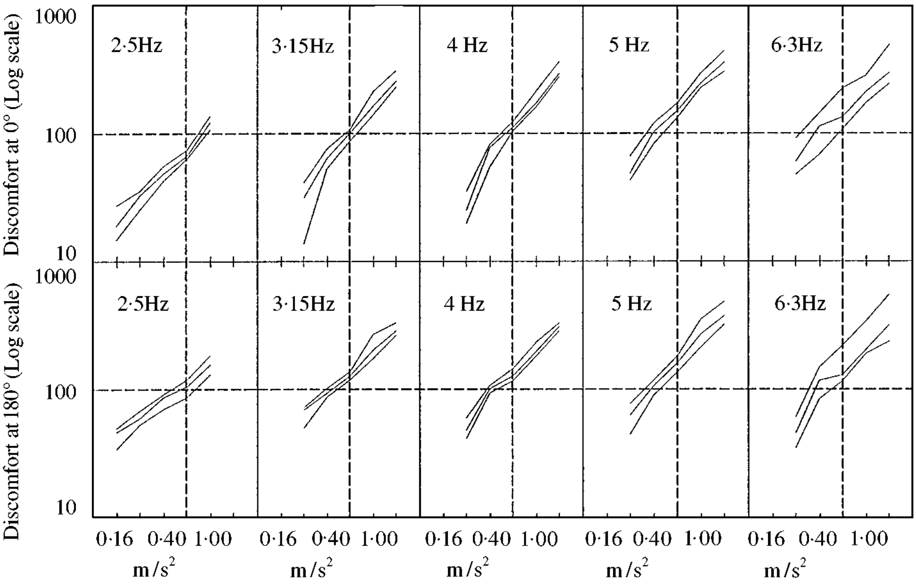

Figure 4. Median and inter-quartile range of relative discomfort with increasing vibration magnitude at five frequencies without thigh contact. (First row: in-phase motion, second row: out-of-phase motion).

increased in proportion to the logarithms of the vibration magnitudes. With both postures there is a similar trend: as the phase changed from 0 to 180° the discomfort judgements increased, but the difference depends on the experimental conditions. At frequencies above 4 Hz there seems to be little difference in discomfort between the in-phase and out-of-phase conditions. At 2·5 and 3·15 Hz, the slope of the relation between vibration magnitude and discomfort is less with 180° phase lag, than with no phase lag, regardless of the posture. The increased discomfort with 180° phase lag is greatest at the lowest magnitude (0·16 m/s^2 r.m.s.) and at the lowest frequency (2·5 Hz). At magnitudes greater than 1·0 m/s^2 r.m.s. there seems to be little change in discomfort with change of phase. The greatest difference in the magnitude estimates due to phase occurred in the condition without thigh contact at 0·16 m/s^2 r.m.s. with 2·5 Hz vibration, where the median magnitude estimate was 18·6 with the in-phase motion and 46·7 with the out-of-phase motion: a difference of 1:2·5. However, there is little difference between the two postures.

Figure 5 summarizes the difference in discomfort between the in-phase and out-of-phase conditions as a function of vibration magnitude at each frequency. Similarly, Figure 6 summarizes the difference in discomfort between the in-phase and out-of-phase conditions as a function of vibration frequency at each magnitude. It can be seen that the difference in discomfort between the in-phase motion and the out-of-phase motion decreased with increasing magnitude and with increasing frequency. At frequencies greater than 4 Hz and magnitudes greater than 1·0 m/s^2 r.m.s. there seems to be little effect of phase.

In order to quantify the effect of phase on discomfort in all conditions, the ratio of median discomfort from the out-of-phase motion to that from the in-phase

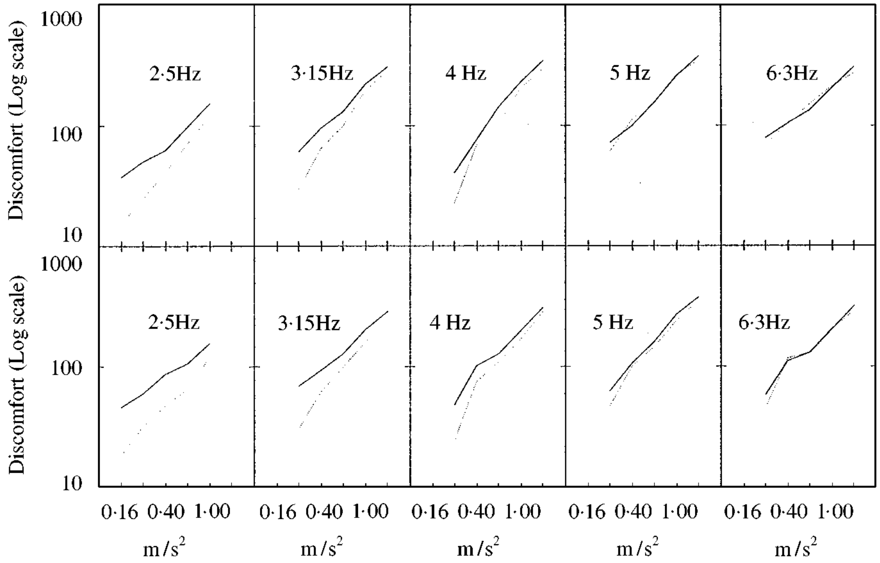

Figure 5. Comparison of discomfort ratings for the in-phase motions (dashed line) and the out-of-phase motions (solid line) with the various acceleration magnitudes at the five frequencies and the two postures (first row: thigh contact. second row: no thigh contact).

TABLE 2

Ratios between discomfort ratings from out-of-phase motions to ratings of discomfort from in-phase motions at the five vibration frequencies and the five vibration magnitudes

	0·16 m/s^2	0·25 m/s^2	0·4 m/s^2	0·63 m/s^2	1·0 m/s^2	1·6 m/s^2
(a) With thigh contact						
2·5 Hz	2·4	1·87	1·71	1·37	1·22	
3·15 Hz		1·86	1·35	1·31	1·16	1·08
4 Hz		1·56	1·05	1·4	1·12	1·17
5 Hz		1·13	0·88	1·0	0·99	1·07
6·3 Hz		0·97	1·13	0·9	0·97	1·14
(b) Without thigh contact						
2·5 Hz	2·51	1·87	1·83	1·58	1·31	
3·15 Hz		2·27	1·51	1·33	1·25	1·12
4 Hz		1·98	1·34	1·18	1·18	1·08
5 Hz		1·1	1·06	1·03	1·1	1·05
6·3 Hz		0·89	1·21	1·0	0·99	1·1

motion was calculated (see Table 2). A ratio greater than unity indicates greater discomfort with the out-of-phase condition. The ratios for the "no thigh contact" posture tend to be greater than those for the "thigh contact" posture, suggesting that the subjects were slightly more sensitive to the phase difference with no thigh contact.

4.3. STATISTICAL ANALYSIS

A statistical analysis was undertaken to investigate the hypothesis of out-of-phase motions caused more discomfort than in-phase motions.

To compare the discomfort caused by the in-phase motions with the discomfort caused by out-of-phase motions, Wilcoxon matched-pairs signed ranks tests were performed [7]. The hypothesis was accepted if the discomfort caused by the out-of-phase motions was significantly greater than that from the in-phase motion (using a one-tailed test at a significance level of $\rho < 0·05$). For each combination of the five frequencies, the five magnitudes and the two postures, a set of 12 discomfort judgements from the out-of-phase motions was compared with that from the in-phase motion. The results are listed in Table 3.

The effect of phase was similar for both postures. The subjects judged the out-of-phase motions as more uncomfortable than the in-phase motions at frequencies up to 3·15 Hz. At 5 and 6·3 Hz there was no significant effect of phase on discomfort ratings. Although the median discomfort ratings for the out-of-phase motions at 4 Hz were greater than those for the in-phase motions at all vibration magnitudes (as shown in Figure 6), the statistical analysis shows that the phase effect at 4 Hz depends on the magnitude of vibration.

A similar statistical analysis was performed on the effect of thigh contact using the discomfort ratings for each of the 50 combinations of the two phase-angles, the five frequencies and the five vibration magnitudes. From the 50 conditions, only four conditions (2·5 Hz at 0·4 m/s^2 r.m.s., 4 Hz at 0·25 m/s^2 r.m.s., 5 Hz at 0·4 m/s^2 r.m.s., and 6·3 Hz at 0·25 m/s^2 r.m.s.) yielded a significantly different discomfort due to thigh contact ($p < 0·05$). This is consistent with Figure 2. The absence of a clear

TABLE 3

Statistical comparisons of discomfort ratings from out-of-phase motions with those from the in-phase motions at the five vibration frequencies and the five vibration magnitudes

	0·16 m/s^2	0·25 m/s^2	0·4 m/s^2	0·63 m/s^2	1·0 m/s^2	1·6 m/s^2
(a) With thigh contact						
2·5 Hz	**	**	**	**	**	
3·15 Hz		**	**	**	**	**
4 Hz		**	—	**	—	**
5 Hz		—	—	—	—	—
6·3 Hz		—	—	—	—	—
(b) Without thigh contact						
2·5 Hz	**	**	**	**	**	
3·15 Hz		**	**	**	**	**
4 Hz		**	*	*	—	—
5 Hz		—	—	—	—	—
6·3 Hz		—	—	—	—	—

*Significantly different with $p < 0·05$.
**Significantly different with $p < 0·01$.

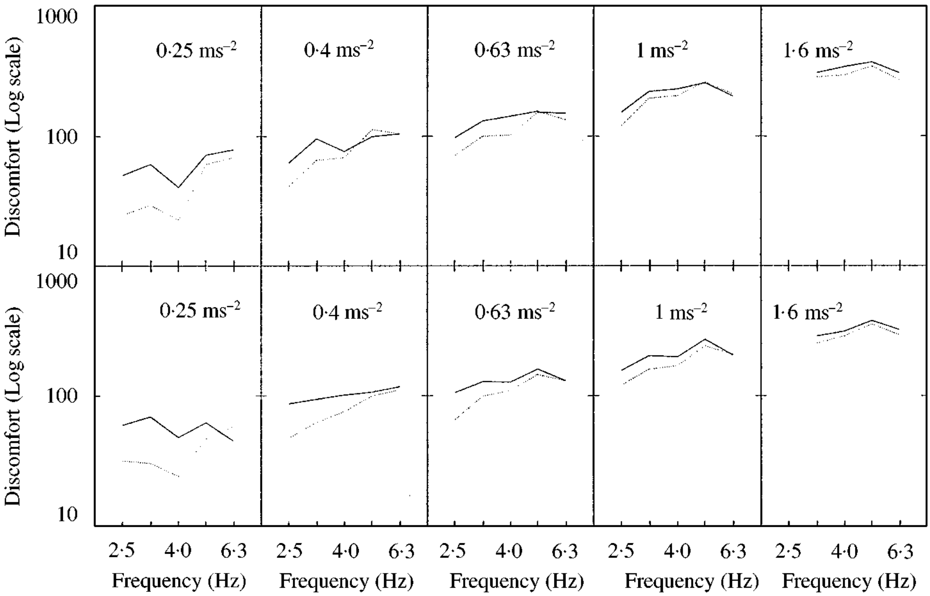

Figure 6. Comparison of discomfort ratings for the in-phase motions (dashed line) and the out-of-phase motions (solid line) with the various frequencies at the five acceleration magnitudes and the two postures (first row: thigh contact, second row: no thigh contact).

effect of posture on discomfort ratings differs from the results of previous work of the current authors [6].

4.4. REGRESSION BETWEEN DISCOMFORT JUDGEMENTS AND VIBRATION MAGNITUDE

Linear regression analysis was performed between the logarithm of the magnitude estimates of discomfort and the logarithm of the vibration magnitude for each combination of vibration frequency, phase and posture. This provided the psychophysical power functions for each condition using the relation, $\psi = k\phi^n$, where ψ is the magnitude estimate of discomfort and ϕ is the vibration magnitude. Values of the exponent, n, are shown in Figure 7 as a function of vibration frequency.

With and without thigh contact, the variation in the exponents for the in-phase motions are similar. The exponent increased with increased frequency up to about 4 Hz and then decreased with increased frequency up to 6·3 Hz. At 2·5 Hz, the difference in the exponents with in-phase and out-of-phase motions is greatest. The exponents for the out-of-phase motions without thigh contact show a trend different from the other conditions: the exponent increased with increasing frequency. With and without thigh contact, the exponents for the in-phase and out-of-phase motions are almost the same at 5 Hz. In summary, there is a large difference in the exponents for in-phase and out-of-phase motions, especially at frequencies from 2·5 to 4 Hz.

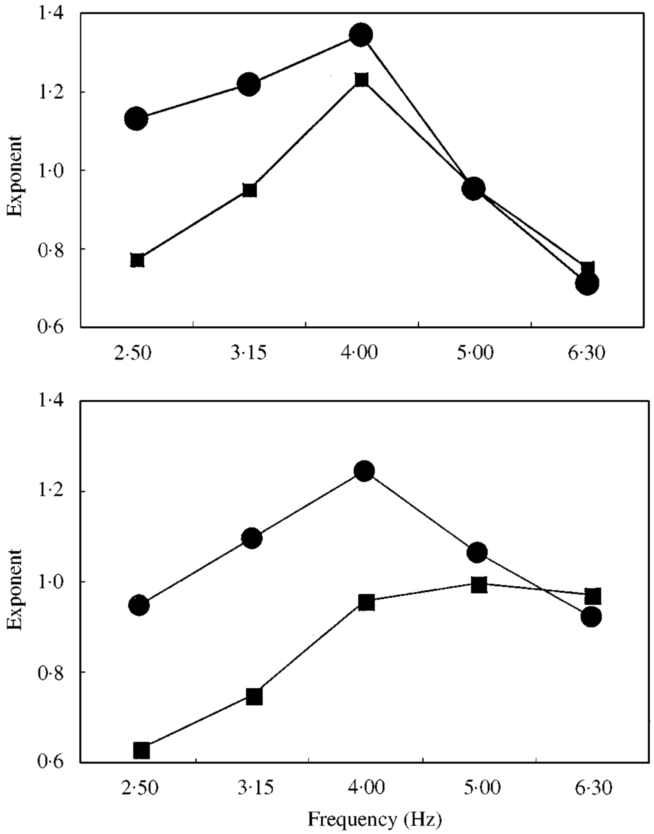

Figure 7. Variation of the exponent n in the equation ($\psi = k\phi^n$) between discomfort (ψ) and vertical acceleration magnitude (ϕ) at the five frequencies and the two postures. Upper graph with thigh contact; lower graph without thigh contact: —●—, in phase; —■—, out-of-phase.

5. DISCUSSION AND CONCLUSIONS

The discomfort judgements of most subjects were affected by the phase between the seat and the feet, but the effect depends on vibration frequency, vibration magnitude and thigh contact. There was generally more discomfort with the out-of-phase motions.

With increasing vibration frequency (at about 5 Hz and above) the effect of phase decreased irrespective of the posture, similar to the findings of Entrekin [5]. It is concluded that as the frequency increases subjects are less able to detect phase differences between the seat and the feet. The decrease in the effect of phase with increase in frequency may be caused by the reduction in displacement that occurs with increased frequency and the consequent reduction in the relative displacement between seat and feet as the frequency increases.

By increasing vibration magnitudes above 0·63 m/s^2 r.m.s., the effect of phase differences between the seat and the feet decreased. This may arise because different sensations, possibly occurring in different parts of the body, give rise to the judgements of discomfort at different magnitudes. Possibly, judgements with low magnitudes of vibration are influenced by the relative motion occurring around the upper legs and hips, whereas judgements with higher magnitudes are more affected by vibration in the torso of the body.

In the present experiment, the effect of thighs on discomfort was not significant. The greater discomfort ratings with the out-of-phase motions with no thigh contact may have arisen because in this posture more effort is required to keep a "straight-back" when there is a pitching motion caused by the differential motion of the seat and the footrest. Another possible reason for the greater sensitivity to phase with no thigh contact is that thigh contact may have occurred during part of the cycle of motion, thus causing intermittent impacts between the seat and the thighs, as opposed to continuous thigh contact in the "thigh contact" posture.

The relation between vibration discomfort and vibration magnitude varied with the phase between the motion at the seat and the feet. Regardless of whether there was thigh contact, the rate of increase in discomfort with increasing vibration magnitude was greater with in-phase motion and less when there was 180° phase difference. This means that although the subjects felt the out-of-phase motions to be more uncomfortable, increases in the magnitude of out-of-phase motions resulted in slower rates of increase in discomfort. Again, this may have arisen from discomfort at low magnitudes being caused by sensations in the region of the thighs but discomfort at high magnitudes being dominated by sensations elsewhere in the body. An increased perception of low magnitude out-of-phase motions would result in a decrease in the value of the exponent, n, in the regression between vibration discomfort and vibration magnitude.

Discomfort judgements were obtained over the frequency range from 2·5 to 6·3 Hz, which includes the principal vertical resonance of the seated human body. At frequencies up to 4 Hz, subjects were clearly sensitive to the phase effect, but became less sensitive at higher frequencies. The more sensitivity of discomfort to vibration magnitude in the lower frequency range is caused by the larger differential displacement at the low frequency. The difference in discomfort ratings due to the phase effect had a maximum of 2·51 to 1 between in-phase and out-of-phase (obtained at 2·5 Hz using 0·16 m/s^2 r.m.s. vibration).

The effect of phase has implications on the frequency weightings used to evaluate vehicle vibration with respect to discomfort. The weightings for vertical seat vibration in British Standard 6841 [1] were mainly derived from studies with simultaneous in-phase motion of the seat and feet. The weightings for feet vibration were determined with no vibration occurring at the seat. Although this may be appropriate with high magnitudes of vibration, there is increasing need to be able to predict discomfort caused by lower vibration magnitudes. This study shows that the phase effect should be included in the determination of ride comfort, at least with low magnitudes of vibration at low frequencies.

The effect of phase may also have implications on the design of seating, since all compliant seats introduce a phase difference between the floor and the seat surface. The effect may be expected to be greatest with suspension seats having a low-frequency resonance but may also be significant with conventional seats.

Future work will need to consider the implications of the effect of phase on the optimization of seating dynamics.

The conditions investigated in the experiment reported here are more simple than those occurring in real vehicles. In practice, there may be phase differences in other axes and between other locations of contact between the vehicle and the driver or passenger. In addition, phase may have an effect on the visual perception of low-frequency relative movement between the body and the vehicle. The identification and subsequent quantification of the conditions where phase has an effect is required before its influence can be properly taken into consideration during the optimization of vehicle ride.

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