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THE EFFECT OF PHASE OF DIFFERENTIAL VERTICAL VIBRATION AT THE SEAT AND FEET ON DISCOMFORT

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This experiment investigated whether the discomfort of seated subjects exposed to vertical vibration was influenced by the relative phase between vibration at the seat and the feet. Twelve seated subjects were exposed to sinusoidal 4 Hz vibration by means of two vibrators, one under the seat and the other under a footrest. A total of seventy combinations of vibration stimuli with seven phases (0, 30, 60, 90, 120, 150, 180°) between the seat and the footrest and five acceleration levels (0·25, 0·4, 0·63, 1·0, 1·6 ms^{-2} r.m.s.) 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. The subjects were most sensitive to phase changes at low magnitudes of vibration and with thigh contact. In the equation, $\psi = K\phi^n$, between the discomfort, ψ, and the magnitude of vibration, ϕ, the exponent n had a maximum of 1·48 with thigh contact and 1·24 with no thigh contact, and decreased to approximately 1·0 with increasing phase between the seat and the feet. The results indicate that vibration discomfort is influenced by the phase between the seat and the feet, but that the effect depends on the magnitude of vibration and the posture of the body.

1. INTRODUCTION

Most vehicles expose operators or passengers to differential vibration between 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 greater than about 2 Hz. As part of the process of optimising the ride comfort of vehicles, the differential vibrations in the low frequency range requires consideration. It is necessary to know whether the phase between the seat vibration and the floor vibration affects judgements of discomfort and, if so, the

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extent to which the discomfort caused by out-of-phase motion differs from that caused by in-phase motion.

Most previous studies have considered seat vibration and floor vibration separately, and there are now standardised methods for evaluating the discomfort caused by seat and floor vibration which do not take into account any difference in the phase of the vibration at the seat and the floor. Since the human body is more sensitive to vibration at the seat than the floor, most previous studies have concentrated on seat vibration, and this has stimulated attempts to improve seat isolation. However, the more effective the seat isolation, the more pronounced will be the differential vibration between the seat and the floor.

1.1. PREVIOUS WORK

British Standard 6841 (1987) and International Standard 2631 (1997) offer frequency weightings for a seated human body in contact with vibration on a supporting seat surface, a seat back or at the feet [1, 2]. Both standards also offer a method of calculating the total ride comfort from components of vibration occurring at two or more locations. The method of summation over the various input positions is based on the root-sums-of-squares of the frequency weighted vibration occurring at each location. This method gives a result that is unaffected by the phases between motions at the different contact points.

Few studies have investigated the effect of phase on the discomfort caused by combined vibration of a seat and the feet. 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 lateral or combined vertical and fore-and-aft vibration occurring on a supporting seat surface. In these studies they varied the phase between axes of motion but the vibration was presented at the same location on the body.

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 ($1{\cdot}0\ \mathrm{ms}^{-2}$ peak to peak) with three phase differences between seat and feet (0, 90, 180°) they concluded that at frequencies 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.

1.2. PRESENT EXPERIMENT

The principal objective of the present study was to investigate whether phase differences between vertical seat vibration and vertical floor vibration affect the discomfort of the seated human body. In order to investigate the effect of vibration magnitude and body posture on the effect of phase, five different vibration magnitudes and two different body postures were selected. The frequency of the vibration was fixed at 4 Hz throughout the experiment.

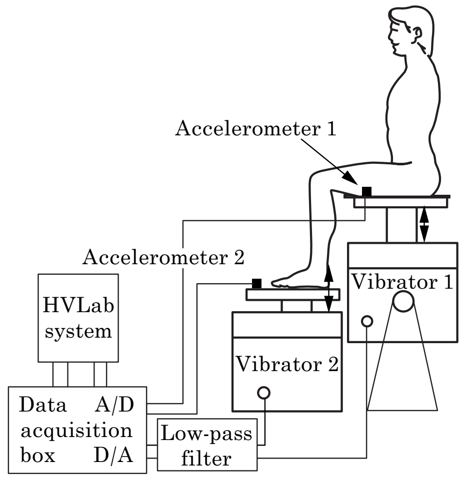

Figure 1. Experimental arrangement.

2. APPARATUS

2.1. VIBRATION GENERATION

The experiments were conducted with two vertically orientated electrodynamic vibrators. 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 arrangement.

The position of the seat was fixed but because the popliteal heights of subjects vary it was necessary to adjust the height of the footrest to fit the required 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 leg 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 an 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. The phase responses of the two electrodynamic vibrators were compensated by generating two digital signals having appropriate phase differences so that the required differences in phase between the motions occurred on the two vibrators.

Throughout the experiment, the motions on the two vibrators were sinusoidal at 4 Hz and of equal magnitude, but they differed in phase from 0° to 180°. The total harmonic distortion of every acceleration waveform was less than 10% and dominated by the third harmonic.

2.3. ENVIRONMENTAL CONDITIONS

During the experiment the temperature ranged from 22 to 27°C. The background noise level at the subject's ears was 60–65 dB(A).

3. METHOD

The experiment was conducted at a fixed frequency of 4 Hz. Experimental conditions consisted of a combination of seven phase angles (0, 30, 60, 90, 120, 150 and 180°) and five vibration magnitudes (0·25, 0·4, 0·63, 1 and 1·6 ms^{-2} r.m.s.). For each of these 35 conditions, subjects were asked to estimate their discomfort relative to a reference motion consisting of in-phase motions at the seat and feet. The conditions were repeated with both postures: with thigh contact and without thigh contact. Subjects made a total of 70 judgements.

3.1. DESIGN AND PROCEDURE

The experiment was performed in two sessions: one for the posture with thigh contact and the other with no thigh contact. The reference stimulus was comprised of identical 4 Hz sinusoidal vibrations at both vibrators: an in-phase (0° phase angle between the seat and the feet) vibration at 0·63 ms^2 r.m.s. In both sessions subjects were required to judge the relative discomfort of the reference motion and each of the 35 test motions (7 phase angles and 5 magnitudes).

Ten male and two female subjects participated in the experiment (aged 24 to 39 years). The heights and weights of the subjects ranged from 164 to 183 cm and from 51 to 83 kg, respectively. Subjects wore trousers and were asked to sit on the seat with a straight back with their hands on their knees.

Subjects were presented twice with both the reference and the test motions before making their judgements; 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.

3.2. RESULTS

Figures 2 and 3 show the individual judgements of relative discomfort made by the 12 subjects sitting in the two postures with the five magnitudes of vibration. As the magnitude of the test motions increased, the discomfort of the test motions relative to the 0·63 ms^{-2} r.m.s. reference motion increased.

The medians and inter-quartile ranges of the subject judgements are shown in Figure 4 using a logarithmic scale. With the two postures there is a similar trend: as the magnitude increases from 0·25 to 1·6 ms^{-2} r.m.s. the slope between

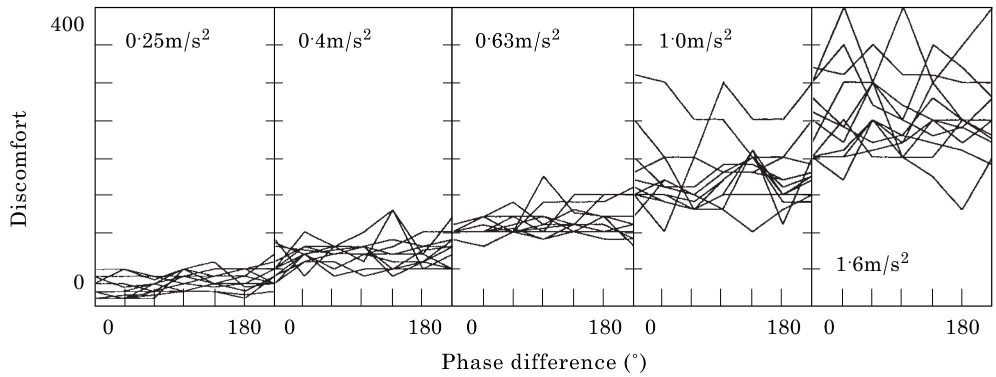

Figure 2. Effect of phase difference between the seat and feet on discomfort for five different magnitudes of vibration with thigh contact. (Reference stimulus: in-phase excitation at the seat and the feet at 0·63 ms^{-2} r.m.s.; 12 subjects).

increasing phase and increasing discomfort decreases. At the lower vibration magnitudes, an increase in phase difference increased discomfort. However, at magnitudes greater than about 1·0 ms^{-2} r.m.s. there seems to be no difference in discomfort with change of phase. The greatest difference in magnitude estimates occurred with thigh contact and 0·25 ms^{-2} r.m.s. vibration where the median magnitude estimate was 20 with the in-phase motion and 40 with the out-of-phase motion: a difference of two to one.

3.3. STATISTICAL ANALYSIS

A statistical analysis was undertaken to investigate the hypothesis that motions with increased phase angle between the seat and the feet are more uncomfortable than in-phase motions.

To compare the discomfort caused by the in-phase motions with the discomfort caused by motions with phases from 30° to 180°, the Wilcoxon

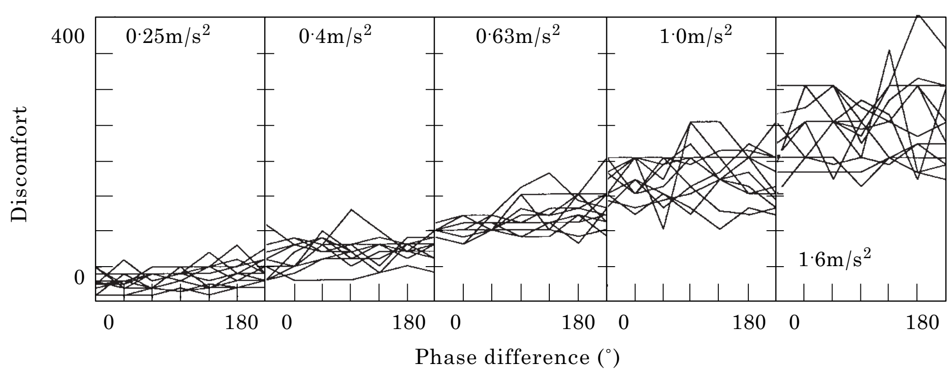

Figure 3. Effect of phase difference between the seat and feet on discomfort for five different magnitudes of vibration without thigh contact. (Reference stimulus: in-phase excitation at the seat and the feet at 0·63 ms^{-2} r.m.s.; 12 subjects).

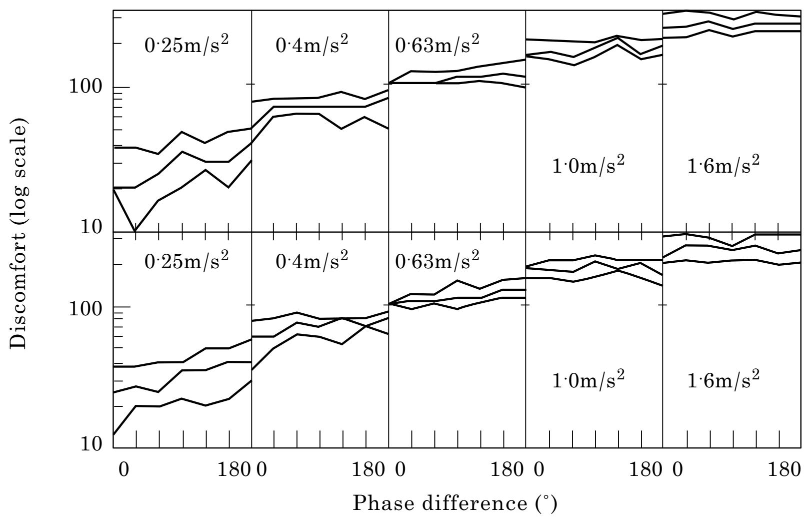

Figure 4. Median and inter-quartile range of discomfort showing the effect of phase difference between the seat and feet for five different magnitudes of vibration with thigh contact (upper figure) and without thigh contact (lower figure). (Reference stimulus: in-phase excitation at the seat and the feet at 0·63 ms^{-2} r.m.s.).

matched-pairs signed ranks test was used [6]. If the discomfort caused by the motions with a phase difference was greater than that from the in-phase motion, the hypothesis was accepted at the 0.05 level of significance for a one-tailed test. At each combination of the six phases, five magnitudes and two postures, a set of twelve discomfort judgements from the vibration with a phase difference was compared with the equivalent set with no phase difference. The results are listed in Table 1.

TABLE 1

Statistical comparison of discomfort ratings with differential vibration between seat and feet with phases from 30 to 180°

	Phase difference (°)					
Magnitude (m/s^2)	30	60	90	120	150	180
(a) With thigh contact						
0·25	–	–	*	**	–	*
0·4	*	*	*	**	*	**
0·63	*	*	*	**	*	*
1·0	–	–	–	–	–	–
1·6	–	–	–	–	–	–
(b) Without thigh contact						
0·25	–	–	–	*	–	*
0·4	–	–	–	*	*	*
0·63	–	*	*	**	**	**
1·0	–	–	–	–	–	–
1·6	–	–	–	–	–	–

* $p < 0·05$; ** $p < 0·01$.

At vibration magnitudes up to 0·63 ms^{-2} r.m.s., the phase affected subjects' judgements of discomfort, but at greater magnitudes the phase had no statistically significant effect. With thigh contact, and vibration magnitudes up to 0·63 ms^{-2} r.m.s., the discomfort judgements were significantly increased with phase angles of 30° and greater (except for the two lower phase angles at 0·25 ms^{-2} r.m.s.). Without thigh contact, discomfort judgements were less affected by small phase changes but significantly increased by phases greater than 120°. The results suggest that the subjects were more sensitive to differential vibration with thigh contact. The differences may be particularly evident at the magnitude of 0·63 ms^{-2} r.m.s. as this was the level of the reference stimulus and judgements may have been easier.

3.4. 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 phase condition and both postures. 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.

The exponent, n, systematically reduced as the phase increased in both postures (see Figures 5 and 6). For the in-phase motion the exponent was 1·35 (with thigh contact) and 1·24 (without thigh contact) and decreased to approximately 1·0 as the phase reached 180°. An exponent of 1·0 means that the vibration discomfort is linearly proportional to the vibration magnitude.

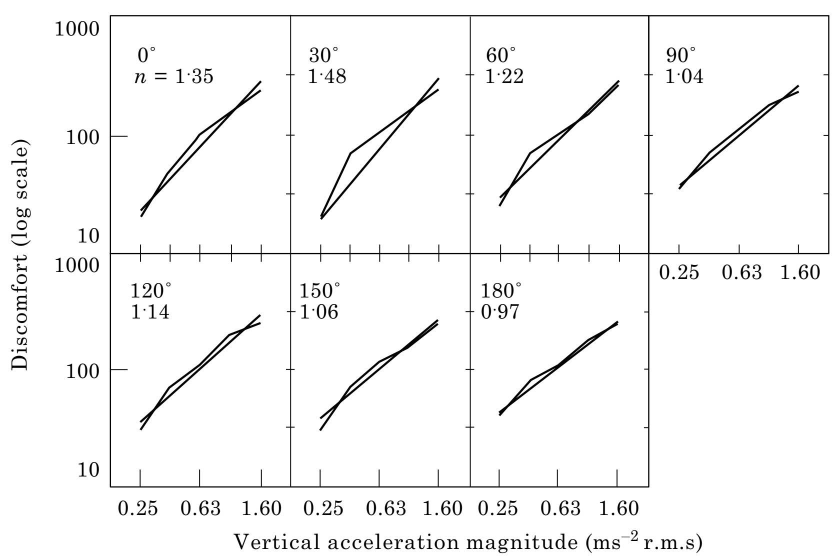

Figure 5. Median magnitude estimates, ψ, as a function of vertical (z-axis) acceleration magnitude, ϕ, ($\psi = k\phi^n$) for the various phase differences between the seat and the feet with thigh contact.

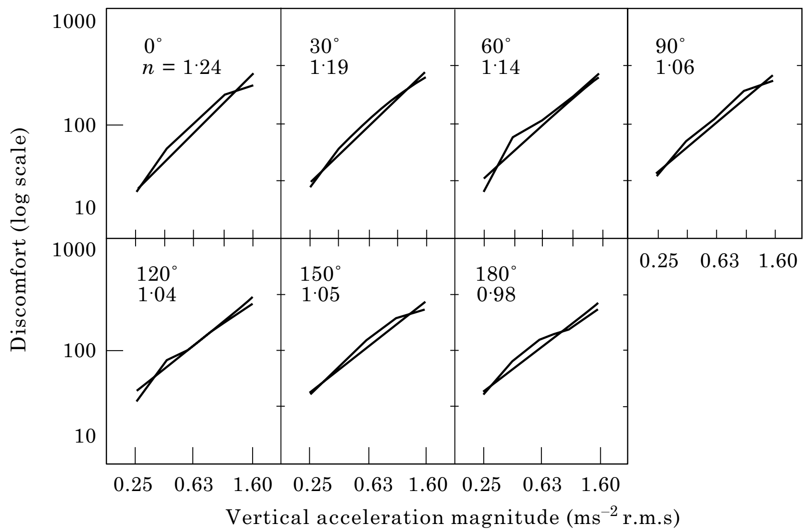

Figure 6. Median magnitude estimates, ψ, as a function of vertical (z-axis) acceleration magnitude, ϕ, ($\psi = k\phi^n$) for the various phase differences between the seat and the feet without thigh contact.

4. DISCUSSION AND CONCLUSIONS

At vibration magnitudes up to 0·63 ms^{-2} r.m.s., the discomfort judgements of most subjects were affected by the phase between the seat and the feet. The magnitude of the effect depended on the phase difference, the vibration magnitude and the thigh contact. Increasing the phase difference generally increased discomfort.

With increasing magnitude of vibration above 0·63 ms^{-2} r.m.s. the effect of phase decreased. This might 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 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.

With thigh contact, subjects were slightly more sensitive to the effect of phase. This increase probably arises because of the differential vibration being felt in the thighs.

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

Discomfort judgements were obtained with only the single frequency of 4 Hz. Since low frequency vibration at large displacements plays an important role in judgements of discomfort, a wider frequency range, to include lower frequencies (where the relative displacement between the seat and the feet will be greater) and higher frequencies (in the range of the principal vertical resonance of the seated human body) should be investigated in further studies. It may be expected that the effect of phase between the seat and the feet will depend on vibration frequency and vibration magnitude in a complex manner. The effect may sometimes be greater than the maximum 2 to 1 change between in-phase and out-of-phase motions found in this study.

The effect of phase may have implications for the frequency weightings used to evaluate vehicle vibration with respect to discomfort. The weightings for low frequency vertical seat vibration in British Standard 6841 (1987) 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 low vibration magnitudes. It may in future be necessary to quantify the phase difference at low frequencies and allow for the effect of phase if vibration discomfort is to be accurately predicted at low magnitudes.

The effect of phase may also have implications for 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 seating, such as full-depth foam seats. Future investigations should consider the implications of the effect of phase on the optimisation of seating dynamics.

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