DISCOMFORT CAUSED BY MULTIPLE FREQUENCY FORE-AND-AFT, LATERAL OR VERTICAL WHOLE-BODY VIBRATION

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Abstract

The practical application of currently standardised methods of evaluating whole-body vibration assumes the discomfort caused by a combination of frequency components can be predicted using time averaging methods, such as the root-mean-square, r.m.s., or vibration dose value, VDV. This study investigated whether the discomfort produced by random vibration depends on the frequency of the vibration (three bands of octave-bandwidth random vibration with frequencies in the range 1.4 to 11.3 Hz) or the direction of vibration (fore-and-aft, lateral, or vertical). The study was conducted with frequency-weighted vibration magnitudes in the range 0.40 to 0.78 ms^{-2} r.m.s. Eighteen subjects provided magnitude estimates of their discomfort when exposed to single and multiple bands of the octave-bandwidth random whole-body vibration. With each of the three directions of vibration, the linear sum of the magnitude estimates of the discomfort overestimated the discomfort caused by the combination of 2 or 3 bands, whereas the magnitude estimate of discomfort caused by the worst band underestimated the discomfort caused by the combination of 2 or 3 bands. Over all the vibration stimuli investigated, the optimum power for summating magnitude estimates to predict vibration discomfort was 2.54, with no statistically significant differences between frequencies or directions of vibration. It is explained that the optimum power for summating vibration magnitudes differs from the optimum power for summing magnitude estimates of vibration discomfort, because vibration discomfort is not usually linearly related to the magnitude of vibration and the rate of growth of vibration discomfort varies with the frequency and the direction of vibration.

1. Introduction

When attempting to reduce vibration discomfort in transport, it is common practice to use vibration attenuating devices (e.g., vehicle suspensions and seats) tuned to reduce vibration at frequencies expected to cause greatest discomfort. However, reductions in vibration over one frequency range will increase vibration over other ranges of frequency and there is limited evidence as to how increasing and decreasing vibration at different frequencies affects the total discomfort produced by a complex motion containing multiple frequencies.

Studies of the frequency-dependence of the discomfort caused by whole-body vibration have mostly employed single frequency sinusoidal vibration (e.g., Griffin *et al.*, 1982; Parsons and Griffin, 1982; Morioka and Griffin, 2006; Wylie and Griffin, 2009). Narrow-bandwidth random vibration has also been used to investigate the frequency-dependence of vibration discomfort (e.g., Griffin, 1976; Howarth and Griffin, 1991; Thuong and Griffin, 2011).

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Very few studies have investigated the discomfort produced by combinations of two or more sinusoidal motions. Fothergill and Griffin (1977) described three experiments with vertical vibration investigating the discomfort produced by two non-harmonically matched sinusoidal motions, the discomfort produced by two motions with noticeable beating, and the discomfort produced by a combination of up to four sinusoidal motions. It was discovered that the 'worst component' method then recommended in an ISO standard (International Organization for Standardization, 1974) was a very poor predictor of vibration discomfort, as was the linear sum of vibration magnitudes. Two methods (the root-mean-square and a masking method) were found to be reasonable predictors of vibration discomfort, with the root-mean-square (r.m.s.) method being favoured because it was easy to apply electronically.

It was found that the discomfort caused by one-third octave bandwidth, octave bandwidth, and three-octave bandwidth random whole-body vertical vibration could be predicted from the discomfort caused by sinusoidal vibration (Griffin, 1976). A single standardised frequency weighting overestimated the discomfort of some subjects exposed to random vibration and underestimated the discomfort of others. The discomfort of individuals exposed to random vibration was better predicted by the frequency-weighted r.m.s. value when the frequency weighting was derived for each individual using their individual judgements of vibration discomfort when exposed to sinusoidal vibration.

The r.m.s. method of averaging is not considered sufficiently sensitive to occasional peaks in a motion (e.g., British Standards Institution, 1987; International Organization for Standardization, 1997). For example, increasing the number of peaks in a stimulus increases vibration discomfort even if the r.m.s. magnitude is unchanged (Howarth and Griffin, 1991). Investigations of the time-dependency of vibration discomfort found that discomfort changed at a rate different from the squared relationship between vibration acceleration, a, and the duration of exposure, t predicted from r.m.s. averaging (i.e., a^2t = constant; e.g., Griffin and Whitham, 1980). A fourth-power relationship (a^4t = constant) appeared more appropriate and provided the basis for the root-mean-quad (r.m.q.) and the vibration dose value (VDV) that provide better predictions of the discomfort caused by signals with occasional bumps (Griffin, 1990).

When experimenting with random vibration, some measure, or control, of the amplitude distribution or the peaks in the motion is required. One method is to quantify the crest factor (ratio of the peak to the r.m.s. value of the motion), but this is highly dependent on the magnitude at one instant of time. Another method is to quantify the r.m.s. to r.m.q. ratio, as employed by Thuong and Griffin (2011).

The methods of predicting vibration severity in the current British and International standards (British Standards Institution, 1987 and International Organization for Standardization, 1997), are consistent with the findings of the studies by Fothergill and Griffin (1977) and Griffin (1976), both of which investigated only vertical vibration. It is unknown whether similar methods are applicable to the prediction of the discomfort caused by fore-and-aft and lateral vibration.

Fothergill and Griffin (1977) investigated power summation methods for predicting the total discomfort, ψ_{total}, caused by dual frequency vibration from the discomforts ψ_a and ψ_b caused by each of the two frequency components, a and b, when they are experienced separately. They investigated the power summation method with different powers, α:

$$\Psi_{total} = (\Psi_a^{\alpha} + \Psi_b^{\alpha})^{1/\alpha} \tag{1}$$

Two extreme conditions exist with α = 1.0 (discomfort is predicted from the linear summation of the discomfort caused by the two sources of discomfort) and $\alpha = \infty$ (discomfort is predicted from the discomfort of the 'worst' component). For the root-sums-of-squares (r.s.s.) method the value of α is 2.0 and for the r.m.q. method the value of α is 4.0. The optimal value of α is that giving the least difference between judgements of vibration discomfort and the predicted vibration Ψ_{total}.

This study was designed to investigate the vibration discomfort caused by single bands and multiple bands of one-octave bandwidth random motions in each of the three translational axes of seat vibration. It was hypothesised that the discomfort caused by multiple bands of one-octave bandwidth random vibration could be predicted from a power summation of the discomfort caused by each of the individual one-octave bandwidth random vibrations. However, it was also hypothesised that the optimum value of the power, α, would vary according to the frequencies being combined and the direction of vibration.

2. Method

2.1. Subjects

Eighteen subjects, nine males and nine females, who were students and office workers at 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 25213).

Table 1 Medians and ranges of subject characteristics.

Gender	Age (years)	Stature (m)	Weight (kg)
Male	29 (22– 33)	1.83 (1.69 – 1.88)	71 (65 - 130)
Female	27 (20 - 31)	1.61 (1.53 -1.69)	55 (50 - 67)

2.2. Apparatus

Fore-and-aft, lateral, and vertical random vibration was produced by a six-axis vibration simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton (Figure 1).

A rigid seat with no backrest (seat-pan height 0.570 m, seat-pan depth 0.493 m) was mounted on the vibration simulator. Subjects sat on a beanbag with a rigid frequency response over the frequency range investigated. Subjects wore a loose lap belt and held an emergency stop button for safety. A rigid footrest was adjusted so that the lower surfaces of the thighs were in contact with the beanbag surface when the heels of the subjects rested on the footrest.

Simulator noise was masked by white noise at 65 dB (A) produced through headphones worn by the subjects. The experimenter could see the subjects at all times and communicate with them through the headphones via a microphone.

2.3. Motion Stimuli

Motion stimuli were generated using MATLAB (version 2012a) and *HVLab* toolbox (version 2). The stimuli consisted of octave-bandwidth random vibrations centred at 2.0, 4.0 and 8.0 Hz (i.e., 1.4 – 2.8

Hz, 2.8 – 5.7 Hz, and 5.7 – 11.3 Hz). The stimuli had durations of 7 seconds to ensure the lowest frequency would achieve at least five cycles. The stimuli were selected from a large number of alternatives so that the ratio between the r.m.s. and r.m.q. was always 1.28. An example stimulus is shown in Figure 2.

Figure 1 Experimental setup on the 6-axis vibration simulator.

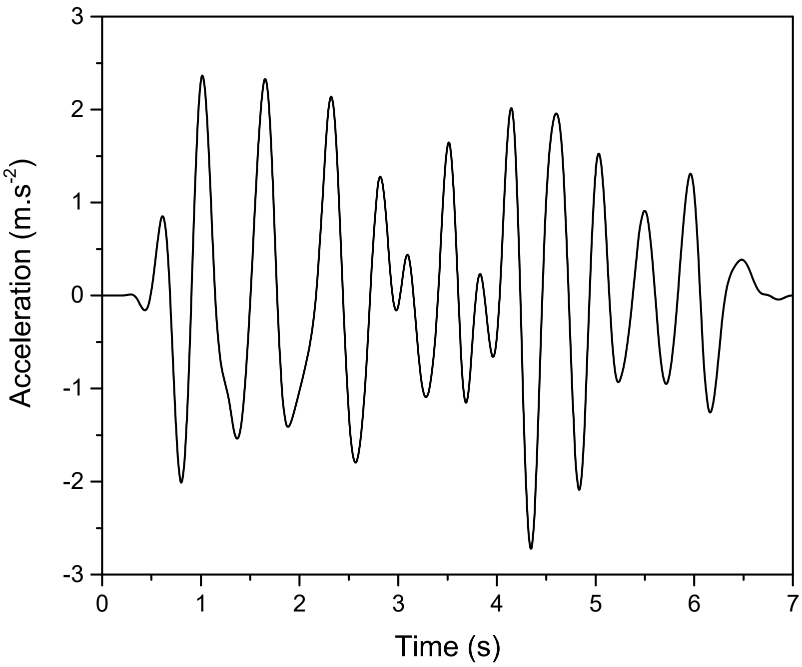

Figure 2 Example one-octave bandwidth of vertical vibration centred on 2.0 Hz.

Each vibration stimulus was adjusted to a frequency-weighted magnitude of 1.0 $m.s^{-1.75}$ VDV (using weighting W_b for vertical vibration and weighting W_d for fore-and-aft and lateral vibration, with unity multiplying factors in accord with British Standard 6841:1987).

The vibration stimuli presented to each subject consisted of the three one octave bandwidth motions (centred on 2.0, 4.0 and 8.0 Hz) in each of the three directions (fore-and-aft, lateral, vertical), and four motions consisting of all possible combinations of the three one octave bandwidths. These combined motions were simple summations of the two or three component waveforms. Depending on the phase, there was addition or cancellation of the acceleration magnitude at each instant in time and so the VDVs of the combined motions differed from the fourth root of the sum of the fourth powers of the component motions. An example of a combined stimulus formed from two one-octave bandwidths of random vibration is given in Figure 3.

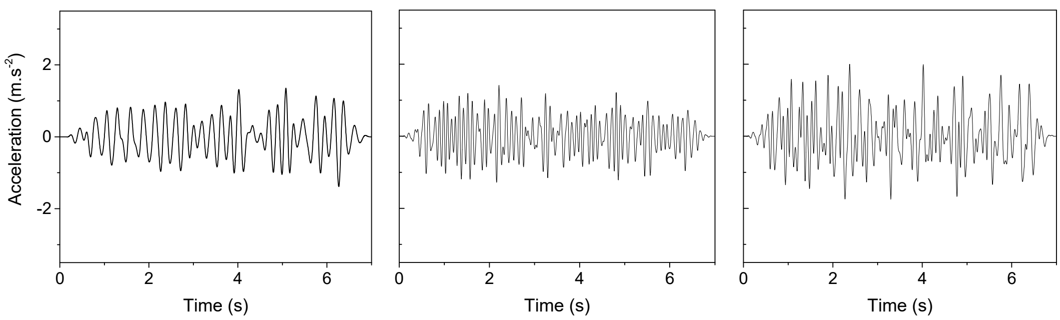

Figure 3 Example of two one-octave bandwidth random vibrations (centred on 4.0 and 8.0 Hz) combined to form a combined stimulus.

2.4. Procedure

Subjects attended one session lasting approximately 90 minutes, which included reading instructions, signing a consent form, practice, and participating in the experiment. Practice consisted of judging the length of lines on paper and judging vibration discomfort when exposed to six vibrations (over the range of frequencies and all three directions of vibration they would experience in the experiment).

During the experiment, the subjects closed their eyes to eliminate any influence of the visual perception of motion on their judgements. They were instructed to sit comfortably and maintain the same upright posture at all times.

Subjects rated the vibration discomfort caused by each of the motions using the method of absolute magnitude estimation. They were encouraged to give a rating of 100 for the first motion they experienced (one-octave bandwidth tri-axial random vibration centred on 4.0 Hz with a frequency-weighted vibration dose value of 0.87 $ms^{-1.75}$ in each direction). They were asked to rate the discomfort caused by all subsequent motions relative to the discomfort caused by the first motion. It was explained that a rating of 50 would mean the discomfort was half that caused by the first motion and a discomfort of 200 would mean the vibration discomfort was double that caused by the first motion. The order of presenting the frequency, direction, and number of frequency bands was randomised independently for each subject.

Every stimulus was presented to the subject three times in three separate blocks within the experiment. To adjust for any systematic change in ratings of discomfort given by each subject over the experiment, each block was adjusted to give a median magnitude estimate of 100. The median subjective value for each motion over the three blocks was used as the magnitude estimate given by the subject.

2.5. Analysis

The measured discomfort for each subject was compared with the predicted discomfort for each value of α between 1.0 and 6.0 in steps of 0.01. The difference between the measured and predicted discomfort was then calculated as a percentage of the measured discomfort for each individual with each combination of stimuli and each value of α. The median percentage difference over all 18 subjects was determined for each value of α, and the optimum value of α for each combination of stimuli identified where the median percentage difference was 0. The hypotheses were tested using non-parametric statistics in SPSS (version 22). The Friedman two-way analysis of variance was used to test for differences between related samples.

3. Results

The errors referred to in this section are the median percentage differences over subjects between the reported discomfort and the discomfort predicted for a given value of α using Equation 1. The median errors were calculated for each combined stimulus (i.e., octave bandwidth motions centred on 2 Hz and 4 Hz, 2 Hz and 8 Hz, 4 Hz and 8 Hz, and 2 Hz, 4 Hz, and 8 Hz within each of the three translational axes).

3.1. Predicting discomfort using the linear sum method and the worst component method

The linear sum of magnitude estimates of discomfort, corresponding to $\alpha = 1$ in Equation 1, gave median errors between 94% and 39% across all combinations of stimuli. This method therefore always overestimated vibration discomfort.

The worst component method of predicting vibration discomfort corresponds to $\alpha = \infty$ in Equation 1. This method gave median errors between -24% and -5% across all combinations of stimuli. This method therefore always underestimated vibration discomfort, although the error was not as great as the linear sum method.

3.2. Individual axes

In the fore-and-aft direction, the power α giving the least error was 2.21 for predicting the discomfort caused by combined 2 Hz and 4 Hz vibration, 5.47 for combined 2 Hz and 8 Hz vibration, and 2.40 for combined 4 Hz and 8 Hz vibration. For combined 2 Hz, 4 Hz, and 8 Hz vibration, the power giving the least error was 2.38.

In the lateral direction, the power giving the least error was 2.36 for predicting the discomfort caused by combined 2 Hz and 4 Hz vibration, 2.10 for combined 2 Hz and 8 Hz vibration, and 5.30 for combined 4 Hz and 8 Hz vibration. For combined 2 Hz, 4 Hz, and 8 Hz vibration, the power giving the least error was 2.31.

In the vertical direction, the power giving the least error was 2.51 for predicting the discomfort caused by combined 2 Hz and 4 Hz vibration, 2.00 for combined 2 Hz and 8 Hz vibration, and 3.25 for combined 4 Hz and 8 Hz vibration. For combined 2 Hz, 4 Hz, and 8 Hz vibration, the power giving the least error was 2.92.

Comparisons between subjective judgements of vibration discomfort and predictions of vibration discomfort are shown in Figure 4, using the above values of α to give the least error for each condition. The dependence of the median error on the power α are shown for each direction of vibration in Figure 5.

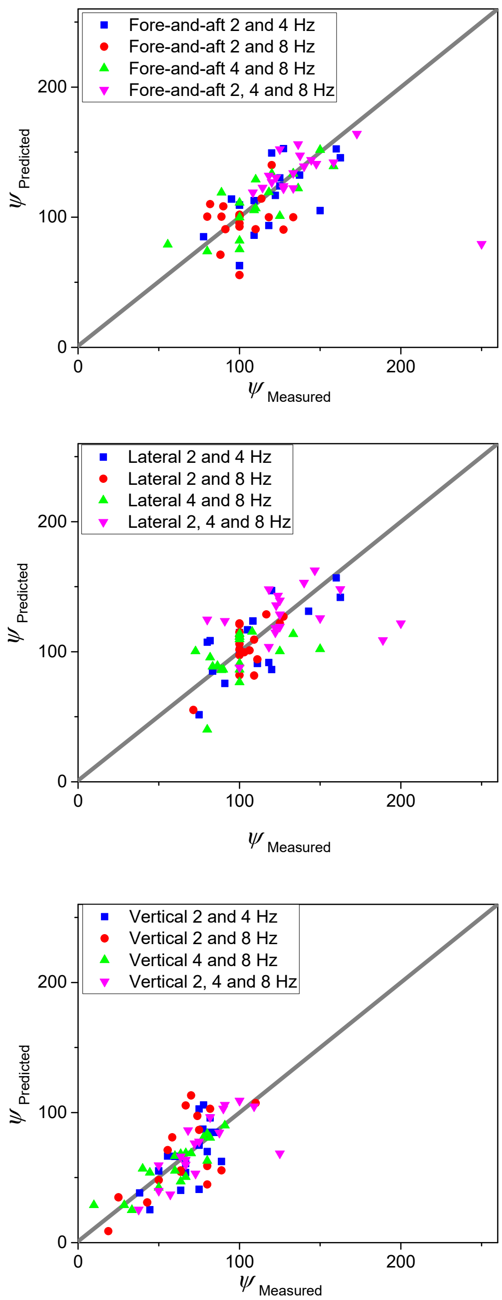

Figure 4 Scattergrams between ratings of vibration discomfort and predictions of vibration discomfort caused by combined frequency vibrations using optimum values of α for each condition (see Section 3.2). Ratings are from 18 subjects and 4 combinations of frequency for each direction. Conditions where $\psi_{\text{predicted}} = \psi_{\text{measured}}$ shown by diagonal lines.

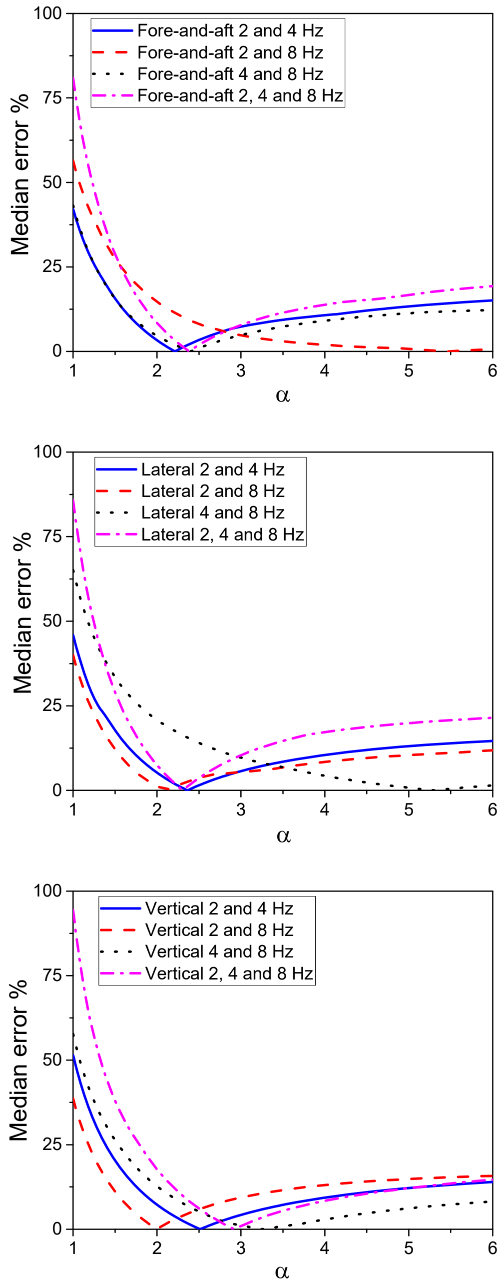

Figure 5 Dependence of median error between judgements of vibration discomfort and predictions of vibration discomfort for values of *α* between 1.0 and 6.0 in steps of 0.01.

3.3. Predicting discomfort over all combinations of stimuli

There were no statistically significant differences in the optimum values of *α* across combinations of frequencies within an axis (p>0.05, Friedman) or between axes for the same spectrum of motion (p>0.05, Friedman). With no statistically significant effects of frequency or direction of vibration on the optimum power of summation, it seems reasonable to determine an optimum single value of *α* across all combinations of frequency over all three directions. Percentage errors were calculated for each participant for all combinations of two and three frequency bands in all three axes. The median error over all combinations of frequency in all three directions over the group of subjects was 0 when α = 2.54. The median percentage difference between the measured discomfort and the predicted discomfort when the exponent α was 2.54 is shown for each combination of two and three frequency bands in Table 2. A positive percentage error overestimates the vibration discomfort and a negative percentage error underestimates vibration discomfort. Comparisons between the predicted discomfort and the given subjective estimates of discomfort when α = 2.54 are shown in Figure 6.

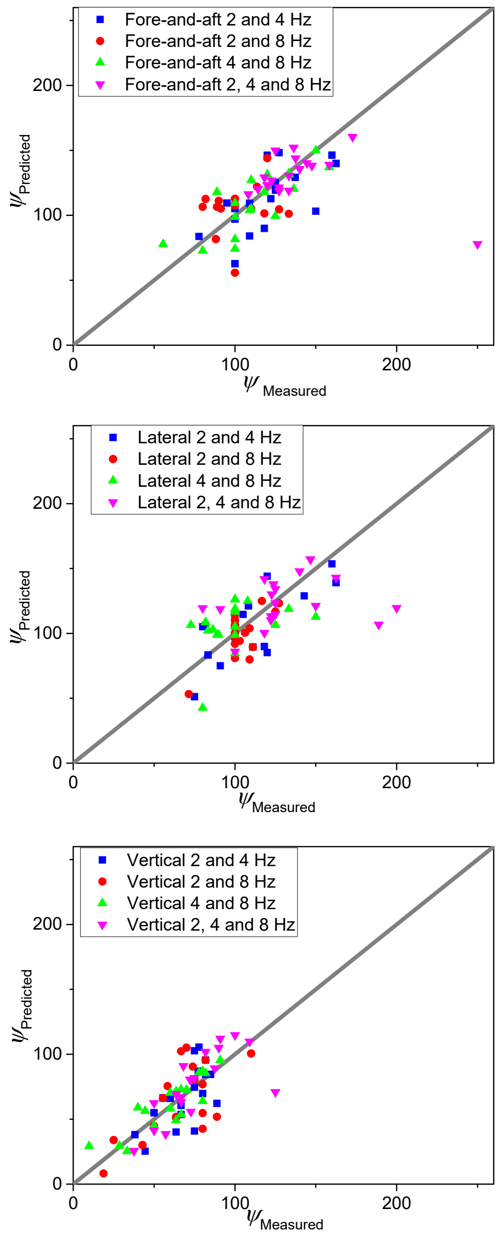

Figure 6 Scattergrams between ratings of vibration discomfort and predictions of vibration discomfort predicted with α =2.54 over all combinations of frequency with each of the three directions of vibration. Conditions where $\psi_{\text{predicted}} = \psi_{\text{measured}}$ shown by diagonal lines.

Table 2: Median percentage errors across 18 subjects between judgements of discomfort and discomfort for each combined stimulus predicted with α =2.54. A positive error indicates that the discomfort is overestimated and a negative error indicates that the discomfort is underestimated.

Frequency combination	Fore-and-aft vibration	Lateral vibration	Vertical vibration
2 and 4 Hz	-4%	-2%	0%
2 and 8 Hz	8%	-4%	-6%
4 and 8 Hz	-1%	14%	5%
2, 4 and 8 Hz	-3%	-4%	5%

4. Discussion

4.1. Constructive and destructive interference

The combined stimuli used in this experiment were filtered-random signals in the same axis. An unavoidable consequence was constructive and destructive interference when superimposing one signal on another and this will have affected the various measures of signal magnitude such as the peak, r.m.s., VDV, and r.m.s. to VDV ratio. Different pseudo-random signals were used for each frequency band in each direction so the r.m.s. values and the VDVs of the combined signals were not the same for all combinations of the two or three stimuli. In this paper the interference has been treated as a random error and the predicted discomfort of the combined motions have not been adjusted to compensate for interference.

4.2. Rate of growth of discomfort

The rate of growth of vibration discomfort with increasing magnitude of vibration varies across the frequency range and differs between directions of vibration excitation (e.g., Morioka and Griffin, 2006). This experiment investigated methods of calculating vibration discomfort for multiple frequency motions using the known discomfort of individual components in the motion. Unless vibration discomfort is linearly related to vibration magnitude (a rate of growth of 1.0 in Stevens' power law) the power, α, for combining magnitude estimates of vibration discomfort will not be the same as the power for combining vibration magnitudes. The appropriate power for combining vibration magnitudes will depend on the rate of growth, n, for the components in the motion, and so the optimum power will vary according to the frequency and the direction of the components. This requires further consideration, but it should be recognised that from the results presented here it is not possible to conclude how to evaluate vibration acceleration to predict vibration discomfort.

5. Conclusions

The findings of this current study suggest the discomfort caused by combinations of vibration components in different frequency bands can be predicted from the discomfort caused by the individual vibration components using a power summation method. Ideal values of the power to be used in the power summation did not differ significantly for different frequencies of vibration (in the range 1.4 to 11.3 Hz) or different directions of vibration (fore-and-aft, lateral, or vertical).

6. Acknowledgement

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