Influence of Frequency on Difference Thresholds for Magnitude of Vertical Sinusoidal Whole-Body Vibration

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Abstract: Differences in vibration magnitude required for a human subject to differentiate whole-body vertical sinusoidal vibrations, difference thresholds for amplitude of sinusoidal vibration, have been determined at a vibration magnitude of 0.7 m/s² r.m.s. at five octave band center frequencies from 4 to 63 Hz and at 80 Hz. The median difference thresholds of 16 male subjects seated on a flat rigid seat were found between 0.037 and 0.046 m/s² r.m.s. at the frequencies used in this study. The subjects tended to be more sensitive to the change in vibration magnitude at 4 Hz than at 16, 31.5 and 63 Hz and less sensitive to the magnitude difference at 31.5 Hz than at 4, 8 and 80 Hz. The median relative difference thresholds, Weber’s ratios, varied from 5.2% to 6.5% which were lower compared to the relative difference thresholds determined in the previous studies at frequencies where comparable data were available. The causes of the difference in the relative difference thresholds observed between this study and previous studies may include the difference in the psychophysical method used to determine the difference threshold.

Key words: Whole-body vibration, Human response, Difference threshold, Just noticeable difference, Magnitude, Frequency

Introduction

People are exposed to many kinds of whole-body vibration on a daily basis while involved in various activities for occupational, leisure, or other purposes. The exposures to whole-body vibration may cause adverse effects on occupants, ranging from uncomfortable feeling to injuries such as disorders of the spine¹¹. One of the differences between the occupational vibration exposures and other exposures is that occupants cannot easily avoid or control vibration exposures by themselves in occupational situation. In Japan, the Labour Standards Bureau Notification No. 547 reported that operations of various vehicles for a long period was included in five major causes of low back pain in workplaces². It can be assumed that low back pain in workers occurs when they are exposed to vibrations for a period longer than a certain period at magnitudes higher than a certain level. This does not mean that vibrations at low magnitudes which may not cause low back pain in workers are not required to address. Such vibrations can cause discomfort in workers or disturb their concentration on their work. It is therefore important for governments, employers or managers to reduce such vibration exposures as an improvement of occupational environment for health, including mental health, and productivity of workers.

When the reduction of the magnitude of vibration which causes adverse effects on people is sought, the knowledge about the amount of reduction in vibration magnitude that people can notice is useful information. In general, a minimum change in some aspect of stimulus that a human
observer can detect is called by different terms: ‘difference threshold’, as used in this paper, ‘difference limen (DL)’ or ‘just noticeable difference (JND)’. The difference thresholds for the vibration magnitude may be considered as a minimum target when the reduction of the vibration magnitude in workplaces is sought.

There have been some studies which investigates difference thresholds for magnitude of vibration. Two earlier studies have determined difference thresholds for random vibrations related to vibrations experienced in a car\(^3,4\). Although these studies may have provided useful information about difference thresholds to car industries, understanding of the nature of difference thresholds for vibration magnitude, such as the effect of vibration frequency or the effect of vibration magnitude, may be improved more clearly in laboratory studies with more controlled input stimuli.

Two recent studies have investigated difference thresholds for amplitude of sinusoidal vibration with subjects seated on a flat rigid seat. Morioka and Griffin\(^5\) have determined difference thresholds for vertical sinusoidal vibrations at two frequencies, 5 and 20 Hz, at two magnitudes, 0.1 and 0.5 m/s\(^2\) r.m.s. The statistical analysis of the experimental data showed that the relative difference thresholds of about 10% did not differ significantly between the two vibration magnitudes or the two frequencies. It was stated that this finding was consistent with Weber’s law: a change in a stimulus of any type that a person just notices is proportional to the size of the stimulus (i.e., the relative difference threshold obtained by dividing the difference threshold by the magnitude of the stimulus, ∆S/S, or Weber’s ratio, is constant for the stimulus). Difference thresholds for vertical sinusoidal vibration have also been determined by Bellmann et al.\(^6\) at eight frequencies between 10 and 50 Hz at a vibration magnitude of 0.063 m/s\(^2\). It was reported that the relative difference thresholds were about 1.5 dB (i.e. about 19%) and there was no statistically significant differences between the eight frequencies.

The perception thresholds of seated subjects exposed to vertical whole-body vibration determined in previous studies (e.g. Miwa\(^7\), Parsons and Griffin\(^8\), summarized in Griffin\(^9\)) tended to be dependent on frequency: for example, lower thresholds at frequencies around 4 Hz. It might not be unreasonable to expect that the difference thresholds have a characteristic of frequency dependence similar to that of the perception thresholds, although the results of the two previous studies with sinusoidal vibration supported that the difference thresholds are independent of the vibration frequency.

The objective of the present study was to investigate the effect of vibration frequency on difference thresholds for amplitude of vertical sinusoidal vibration. A wider frequency range compared to those used in the previous studies was employed in the present study. Further understanding of the nature of the sensitivity of people to the change in magnitude of whole-body vibration was expected to be obtained in the present study so as to use better knowledge to improve occupational environment.

**Experimental Method and Analysis**

An experiment involving human subjects was conducted in the laboratory of the National Institute of Industrial Health, Kawasaki, Japan. An electro-magnetic shaker, Akashi AST-11V, with an amplifier, Akashi E-DA, was employed in the experiment. It was specified by the manufacturer that the shaker system could be operated with a waveform distortion below 2% in the frequency range between 0.5 and 300 Hz. Sixteen healthy male volunteers aged between 21 and 23 yr took part in the experiment. The height and weight of the subjects were ranged from 1.64 to 1.81 m and from 49 to 77 kg, respectively. A subject was seated on the top face of the shaker which was flat and had a circular shape with a diameter of 0.4 m. No backrest was provided during the experiment. The feet of the subject was supported by a stable footrest whose height was 0.39 m below the top of the shaker. The subject wore ear defenders so as to prevent from perceiving vibration by accompanied noise generated by the shaker. A vertical, or z-axis\(^9\), acceleration at the interface between the top face of the shaker and the subject was measured with a piezo-electric accelerometer, B&K 4322, with a charge amplifier, B&K 2635.

Difference thresholds for the perception of the change in the vibration magnitude, ∆S, was determined with vertical sinusoidal vibrations at six different frequencies: 4, 8, 16, 31.5, 63 and 80 Hz. For the vibrations at each frequency, a subject was exposed to pairs of sinusoidal vibrations. A pair of vibrations consisted of a reference vibration at a nominal magnitude of 0.7 m/s\(^2\) r.m.s. and a test vibration. The duration of each vibration was 4 seconds and the interval between the two vibrations was 2 seconds. For each vibration stimulus, the waveforms for the first and last 0.5 seconds were tapered so as to eliminate a transient response of the shaker that had an effect on the perception of input stimulus of the subject in a preliminary experiment conducted prior to the main experiment. At each trial, the subject was asked to judge the difference in the vibration magnitude between the reference vibration and the test vibration by using the following three wordings: ‘the first vibration was greater’. Industrial Health 2002, 40, 313–319
‘the second vibration was greater’, or ‘I did not perceive a difference between the two stimuli’.

The magnitude of the test vibration was either greater or lower than the magnitude of the reference vibration by 0.25 dB, about 2.9%, at the first trial. The magnitude difference between the two stimuli increased with 0.25 dB increment steps by changing the magnitude of the test vibration (i.e. either increasing or decreasing the magnitude of the test vibration, depending on the magnitude of the test vibration at the first trial) until the subject perceived the magnitude difference correctly. It was decided to terminate a series of trials if the magnitude difference reached 3.0 dB, although this rule did not apply to any series in this experiment. The difference threshold for a series of trials, \( \Delta S \), was then determined by calculating an arithmetic average of the magnitude difference at the last trial when the subject perceived the magnitude difference correctly and the magnitude difference at the second trial from the last trial. The vibration magnitude measured with an accelerometer was used to calculate the differences in magnitude between the reference vibration and the test vibration. The relative difference threshold for a series of trials was calculated by dividing the difference threshold obtained for the series of trials, \( \Delta S \), by the magnitude of the reference vibration, \( S \) (i.e. a relative difference threshold for a series = \( \Delta S / S \)).

The order of the reference vibration and the test vibration in a pair was changed for each series of trials so as to reduce the influence of the order of vibrations on the difference thresholds. Table 1 shows the four types of presentation of stimuli used in the experiment: whether the magnitude test vibration increased or decreased, and whether the reference vibration was presented first or second. The subject was presented stimuli in all four types shown in Table 1 in a randomized order for each frequency of vibration. A series of the four presentation types was repeated three times so that the difference thresholds for each presentation type were obtained by taking the average of three repetitions. The order of vibration frequencies presented was different for each subject. The subject completed the experiment with 72 series of trials (i.e. four series of trials with three repetitions for six frequencies), which took about one and a half hours, including a short break. The subject was informed when the frequency of vibration tested was changed, although any other methods of presentation of vibration were not known by the subject.

## Results

### Example of exposure history to determine difference threshold

Figure 1 shows an example of the history of vibration exposures recorded for a subject from which the difference threshold for sinusoidal vibration at a frequency was determined. The history of exposures was represented by the magnitude of reference and test vibrations. □ : reference vibration; △ : test vibration. A line indicates a series of trials with a type of presentation of stimuli. The order of the presentation types shown in Table 1 was Type IV \( \Rightarrow \) Type III \( \Rightarrow \) Type I \( \Rightarrow \) Type II, which was repeated three times.
Influence of magnitude of test vibration on difference threshold

The median difference thresholds of the 16 subjects determined with the test vibrations at magnitudes greater than the magnitude of the reference vibrations, 0.7 m/s² r.m.s., (i.e. Types I and III in Table 1) and with test vibrations at magnitudes lower than the magnitude of the reference vibrations (i.e. Types II and IV) were compared in Fig. 2. The difference threshold determined with test vibrations greater than 0.7 m/s² r.m.s. tended to be greater than the difference threshold determined with test vibrations lower than 0.7 m/s² r.m.s. at 31.5 Hz as observed in Fig. 2. However, there was no statistically significant difference in the difference thresholds caused by the difference in the magnitude of test vibration with the Wilcoxon matched-pairs signed ranks test (p>0.05). The difference thresholds determined in the two conditions have, therefore, been combined in the analysis presented later in this paper.

Influence of order and relative magnitude of two vibrations

It is generally known that when the magnitudes of two stimuli of any type in a series are compared the magnitude of the stimulus presented second tends to be judged relatively greater than the magnitude of the stimulus presented first (i.e. negative time error\(^{10}\)). This order effect was observed in the results of this experiment. Figure 3 compares the median difference thresholds of the 16 subjects obtained when the magnitude of the vibration presented first was greater than the magnitude of the second vibration (i.e. Types II and III in Table 1) and when the magnitude of the vibration presented second was greater than the magnitude of the vibration presented first (i.e. Types I and IV).

Influence of frequency

The difference thresholds obtained with all the presentation types shown in Table 1 were averaged to determine the difference thresholds at each frequency used for each subject.
It was intended that the combination of the difference thresholds obtained with the four presentation types reduced the effect of the order of vibration presentation on the difference thresholds mentioned in the preceded section. The medians and inter-quartile ranges of the difference thresholds of the 16 subjects are presented in Fig. 4. The difference thresholds determined for different frequencies by averaging the difference thresholds obtained with the four presentation types are compared by using the Wilcoxon matched-pairs signed ranks test in Table 2. These results show that the difference thresholds at 4 Hz tended to be lower than the difference thresholds at the other frequencies (significantly lower than those at 16, 31.5 and 63 Hz (Wilcoxon, $p<0.05$)).

The difference thresholds at 31.5 Hz tended to be higher compared to the difference thresholds at the other frequencies (significantly higher than those at 4, 8 and 80 Hz (Wilcoxon, $p<0.05$)).

**Discussion**

The difference thresholds determined in this study showed that the sensitivity of the subjects to the change in vibration magnitude around the reference vibration magnitude used tended to be dependent on frequency: higher sensitivity at frequencies of 4 and 8 Hz, particularly at 4 Hz, than at frequencies around 31.5 Hz. The perception thresholds of seated subjects exposed to whole-body vibration measured in previous studies (e.g. Miwa7, Parsons and Griffin8) showed a similar trend to the frequency dependence observed in the difference thresholds measured in this study: lower perception thresholds in the frequency range around 4 Hz. This may be consistent with a hypothesis that a subject tend to be sensitive to the change in vibration magnitude at frequencies where he/she can perceive vibration at lower magnitude.

In the previous studies of the difference thresholds by Morioka and Griffin5 and Bellmann et al.6, it was concluded that there was no frequency dependence of difference thresholds found. It was reported by Morioka and Griffin5 that there was no statistically significant difference in the difference thresholds between the two vibration frequencies at the two vibration magnitudes used. Although there was a statistically significant difference between the difference thresholds obtained at frequencies of 4 and 16 Hz in this study, the frequencies used in Morioka and Griffin5, 5 and 20 Hz, were not used in this study so that discussion based

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**Table 2. Results of Wilcoxon matched-pairs signed ranks test for comparison of difference thresholds determined for 6 frequencies with the 16 subjects ($^*p<0.05$, $^{**}p<0.01$).** *(16>4), for example, indicates that the difference threshold at 16 Hz appeared to be statistically significantly greater than the difference threshold at 4 Hz* 

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<th>4 Hz</th>
<th>8 Hz</th>
<th>16 Hz</th>
<th>31.5 Hz</th>
<th>63 Hz</th>
<th>80 Hz</th>
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<td>4 Hz</td>
<td></td>
<td>0.079</td>
<td>0.011*</td>
<td>0.004**</td>
<td>0.039*</td>
<td>0.148</td>
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<td></td>
<td>0.223</td>
<td>0.026*</td>
<td>0.756</td>
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<td>0.609</td>
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<td>31.5 Hz</td>
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<td>63 Hz</td>
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on a direct comparison between the results from the two studies may not be reasonable. The data reported by Bellmann et al.\(^6\) show that the mean difference threshold was greatest at a frequency of 31.5 Hz. This trend is consistent with the results obtained in this study. It was reported by Bellmann et al.\(^6\) that there was no significant difference between the difference thresholds measured at eight frequencies investigated at \(p<0.01\), a lower level than \(p<0.05\) used in this study. The frequencies for which the difference threshold was significantly different from the difference threshold measured at 31.5 Hz in this study were 4, 8 and 80 Hz that were not covered by the frequency range used by Bellmann et al.\(^6\). Therefore, with respect to the influence of vibration frequency, although the results of this study implies that the difference threshold is dependent on frequency while Bellmann et al.\(^6\) reported no statistically significant difference between the difference thresholds at the eight frequencies investigated, the results obtained in this study might not be inconsistent with the data reported by Bellmann et al.\(^6\).

The relative difference thresholds determined by combining the relative difference thresholds obtained with the four presentation types in this study are compared with the relative difference thresholds measured by Morioka and Griffin\(^5\) and Bellmann et al.\(^6\) in Fig. 5. The data presented for Morioka and Griffin\(^5\) in Fig. 5 are the medians and interquartile ranges of the difference thresholds for 12 male seated subjects measured with sinusoidal vibrations at two frequencies, 5 and 20 Hz, at a magnitude of 0.5 m/s\(^2\) r.m.s. They also measured the difference thresholds at a vibration magnitude of 0.1 m/s\(^2\) r.m.s., which are not presented in Fig. 5. The results presented for Bellmann et al.\(^6\) are the means and standard deviations of the difference thresholds of two female and six male seated subjects determined with sinusoidal vibrations at eight third-octave band center frequencies from 10 to 50 Hz with a reference vibration magnitude of 0.063 m/s\(^2\).

If the difference threshold for the magnitude of whole-body vibration followed Weber’s law, the difference threshold obtained at different vibration magnitudes would be constant. Morioka and Griffin\(^5\) concluded that their results were approximately consistent with Weber’s law, although there was a trend for the relative difference thresholds to reduce with increasing vibration magnitude. However, if Weber’s law holds for the magnitude of whole-body vibration, the results from the three different studies shown in Fig. 5 should not be expected to be constant, partly because the psychophysical method used to determine the difference threshold in the three studies were different. The method used in this study may be categorized as the ‘method of limits’: if the response that a subject can detect the difference in the magnitude between the reference vibration and the test vibration is defined as the ‘positive’ response and this response follows a typical psychometric function, the method used in this study estimates difference thresholds at the probability of the positive response of 50%.\(^11\) The two previous studies mentioned above used the up-and-down transformed response (UDTR) methods: Morioka and Griffin\(^5\) used the method that estimates difference thresholds at 79.4% positive response and Bellmann et al.\(^6\) used the method that estimates difference thresholds at 70.7% positive response. Maeda and Griffin found that vibrotactile thresholds on the finger were influenced by psychometric methods that estimate positive responses at different probabilities\(^12\). Other factors, including the posture of subjects, the condition of footrest and backrest, the increment size for vibration magnitude, used in this study was similar to those used in Morioka and Griffin\(^5\), but different from those in Bellmann et al.\(^6\). Therefore, the difference in the psychophysical method may have contributed to lower relative difference thresholds obtained in this study compared to those obtained in Morioka and Griffin\(^5\), while the causes of the differences in the relative thresholds observed between this study and Bellmann et al.\(^6\) could include various other factors. The details of experimental conditions and

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![Fig. 5. Comparison of the relative difference thresholds determined in this study and in previous studies.](image)
procedures were not given fully by Bellmann et al. so that it was difficult to identify the causes of the differences between their experimental results and the results obtained in this study. The influence of the psychophysical method on the difference thresholds may be required to be investigated in future study.

Conclusions

For vertical sinusoidal vibrations at octave band center frequencies from 4 to 63 Hz and at 80 Hz, difference thresholds for vibration magnitude have been measured with 16 male subjects. The median difference thresholds ranged from 0.037 to 0.046 with a reference vibration magnitude of 0.7 m/s^2 r.m.s. The difference thresholds may be dependent on frequency as the perception thresholds for whole-body vibration are: it was found that the difference threshold determined at 4 Hz was lower than the difference thresholds at 16, 31.5 and 63 Hz and the difference threshold determined at 31.5 Hz was greater than those at 4, 8 and 80 Hz.

The median relative difference thresholds, Weber’s ratios, of the 16 subjects were found to vary from 5.2% to 6.5%. The relative difference thresholds obtained in this study tended to be lower than the relative difference thresholds reported in available previous studies at frequencies where the comparison was possible. The effect of the psychophysical method to determine the difference threshold may be one of the causes of the difference observed between this study and previous studies and needs to be investigated in further study.

References