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Evaluation of perception threshold of whole-body vibration for the assessment of building vibration

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Abstract

Evaluation of the perception threshold of whole-body vibration was investigated for the assessment of building vibration. The experimental data obtained in previous studies were summarised and used in this study. The frequency dependence of perception threshold was investigated with the data for continuous sinusoidal vibrations. The time dependence was examined with the data for transient vibrations. It appeared that the current evaluation defined in the international standard did not necessarily represent the characteristics of human perception of whole-body vibration.

1. Introduction

In the assessment of building vibrations caused by various external and internal sources, there has been no standardised evaluation of vibration accepted worldwide, although the international standard for the evaluation of human exposure to whole-body vibration in buildings, i.e., ISO 2631-2 [1], applies the methods defined in ISO 2631-1 [2]. There are countries, including Japan, that define different evaluations for the assessment of building vibration in their national law, standard, and so on. Most of current evaluations used in different countries include the application of frequency weightings and the running root-mean-square, i.e., r.m.s., method by use of a short integration time. The differences in the current evaluations are, for example, the differences in the frequency weighting and the integration time. It would be ideal if an evaluation accepted worldwide could be established for sharing information and experiences accumulated in different countries.

The objective of the present study was to investigate the frequency dependence and time dependence of human response to building vibration based on human perception of whole-body vibration, because the perception of vibration is one of the important factors to be considered, as stated in ISO 2631-2 [1]. The data obtained in experiments involving human subjects in previous studies, including recent studies by the authors, were summarised and used in this study.

2. Threshold of continuous sinusoidal vibration - frequency dependence -

The frequency dependence of the perception thresholds of whole-body vibration was investigated based on the thresholds of continuous sinusoidal vibrations determined in the previous studies shown in Table 1. The previous studies used here include those referred to in ISO 2631-1 [2], ISO 2631-2 [1] and some recent studies. The data shown with white markers in Figures 1 and 2 are the mean or median perception thresholds determined in each of the previous studies for vertical and horizontal vibrations, respectively. Those data were weighted by the number of subjects in the corresponding studies and averaged over different studies at each frequency if there were more than two studies reporting the data at that frequency. Those weighted average were calculated for three postures, i.e., seated, standing and recumbent, and are shown in Figures 1 and 2 with black markers. In Figures 1 and 2, the frequency dependence represented by the frequency weightings defined in ISO 2631-1 [2], and -2 [1] are shown also, assuming that the average perception thresholds were the weighted acceleration of 0.01 ms^{-2} r.m.s., which was equivalent to the perception threshold of "fifty percent of alert, fit persons" given in ISO 2631-1 [2].

Figure 1 and 2 show that the frequency dependence of the perception threshold of whole-body vibration differs among different postures, as already reported by Miwa [3], Miwa and Yonekawa [4] and Parsons and Griffin [7]. In the assessment of building vibration, the posture of occupants in building may not be defined clearly so that it may be appropriate to determine the frequency dependence of the perception thresholds to cover the least thresholds among different postures.

For vertical vibration, the weighted acceleration of 0.01 ms^{-2} r.m.s. appeared to be equivalent to the minimum values of the average thresholds shown with the black markers in Figure 1. The W_k weighted acceleration of 0.01 ms^{-2} r.m.s. was greater than the average thresholds at frequencies below 2 Hz and above 31.5 Hz. These frequency ranges may be different from frequencies at which building vibration has dominant a component, in general, although a high frequency component may sometimes be dominant in vibration induced by train. The W_m weighted acceleration of 0.01 ms^{-2} r.m.s. was greater than the average thresholds at frequencies above 5 Hz. Vertical building vibration tended to have a dominant frequency component in the frequency range from 10 to 20 Hz. In this frequency range, the W_m weighted acceleration of 0.01 ms^{-2} r.m.s. was more than twice as great as the average threshold, so that the assessment of building vibration with respect to the perception threshold might not be appropriate by the W_m weighting.

For horizontal vibration, the minimum values of the average thresholds were less than the weighted acceleration of 0.01 ms^{-2} r.m.s. at 1 Hz (0.0082 ms^{-2} r.m.s., seated) and 4 Hz (0.0085 ms^{-2} r.m.s., recumbent), as shown in Figure 2. These differences may have some effect on the assessment of building vibration because these frequencies can correspond to a natural frequency of building vibration in the horizontal direction depending on the height of building. The W_d weighted acceleration of 0.01 ms^{-2} r.m.s. was also greater than the average thresholds at frequencies above 5 Hz, although horizontal vibration in building may not be dominant in this frequency range. The W_m weighted acceleration of 0.01 ms^{-2} r.m.s. was greater than the average thresholds at frequencies above 60 Hz. Although these difference are significant as observed in Figure 2, their effect on the assessment of building vibration may be limited as there may not be many cases where horizontal vibration at those frequencies are dominant in the assessment.

Table 1 Previous studies of perception thresholds of whole-body sinusoidal vibration reviewed

Authors	Year	Ref.	Direction	Frequency [Hz]	Posture	Subject
Miwa	1967	[3]	Vertical	0.5 - 300	Seated	10
			Vertical	0.5 - 300	Standing	10
			Fore-and-aft	0.5 - 300	Seated	10
			Fore-and-aft	0.5 - 300	Standing	10
Miwa, Yonekawa	1969	[4]	Vertical	0.5 - 300	Recumbent	10
			Head-feet	0.5 - 300	Recumbent	10
Mckay	1972	[5]	Vertical	1.5 - 100	Seated	48
Miwa *et al*.	1984	[6]	Vertical	1 - 100	Recumbent	10
			Lateral	1 - 100	Recumbent	10
			Head-feet	1 - 100	Recumbent	10
Parsons, Griffin	1988	[7]	Vertical	2- 100	Seated	36
			Vertical	2- 100	Standing	36
			Vertical	10 - 63	Recumbent	8
			Fore-and-aft	2- 100	Seated	12
			Fore-and-aft	2- 100	Standing	12
Okamoto *et al*.	2001	[8]	Vertical	1 - 80	Seated	10
			Vertical	1 - 80	Standing	10
			Vertical	1 - 80	Recumbent	10
			Fore-and-aft	1 - 80	Seated	10
			Fore-and-aft	1 - 80	Standing	10
			Fore-and-aft	1 - 80	Recumbent	10
			Lateral	1 - 80	Seated	10
			Lateral	1 - 80	Standing	10
			Lateral	1 - 80	Recumbent	10
Morioka, Griffin	2008	[9]	Vertical	2 - 315	Seated	12
			Fore-and-aft	2 - 315	Seated	12
			Lateral	2 - 315	Seated	12
Matsumoto *et al*.	2010	[10]	Lateral	4, 6.3, 10	Seated	40
Matsumoto *et al*.	2011	[11]	Vertical	2 - 63	Recumbent	24
Matsumoto *et al*.	2011	[12]	Vertical	10, 12.5, 16	Seated	20

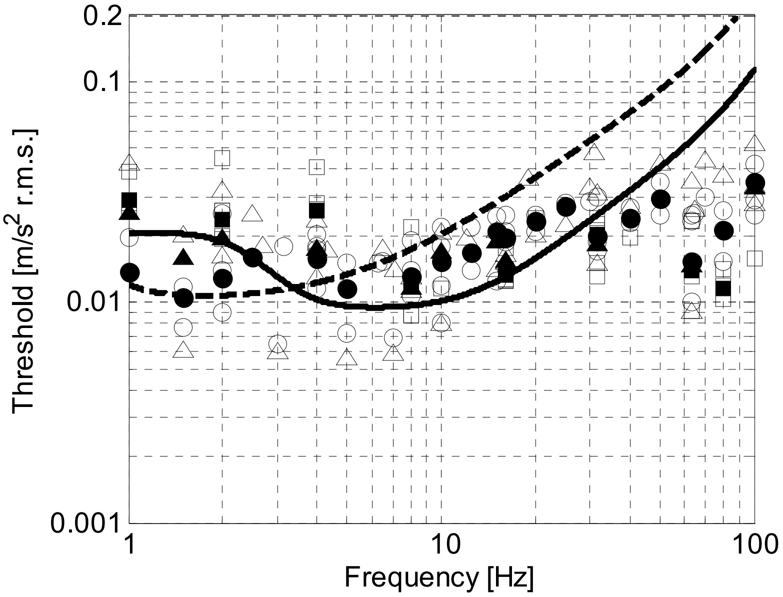


Figure 1 Thresholds of vertical sinusoidal vibrations determined in previous studies shown in Table 1. White marks: mean or median values in each study; ○: seated; △: standing; □: recumbent. Black marks: average of the thresholds in different studies weighted by the number of subjects; ●: seated; ▲: standing; ■: recumbent. Solid line: W_k weighted acceleration of 0.01 ms^{-2} r.m.s.; broken line: W_m weighted acceleration of 0.01 ms^{-2} r.m.s.

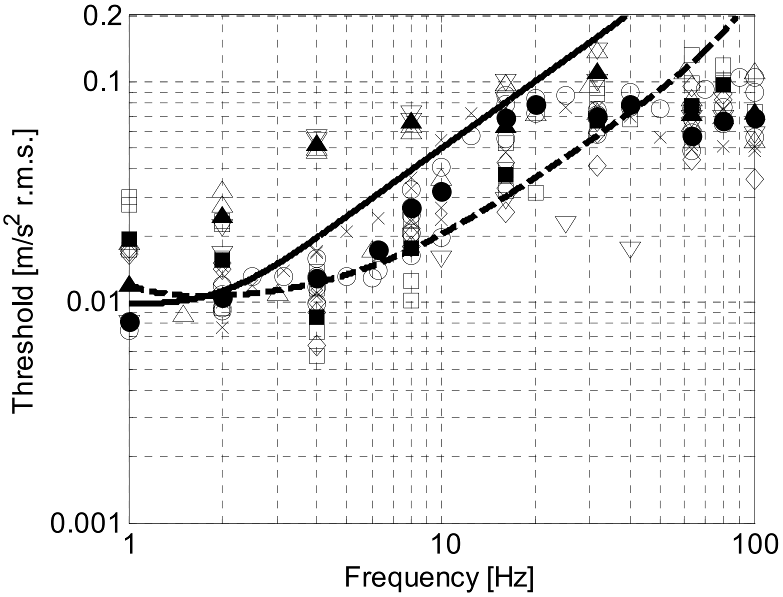


Figure 2 Thresholds of horizontal sinusoidal vibrations determined in previous studies shown in Table 1. White marks: mean or median values in each study; ○: seated, fore-and-aft; ×: seated, lateral; △: standing, fore-and-aft; ▽: standing, lateral; □: recumbent, head-feet; ◇: recumbent lateral. Black marks: average of the thresholds in different studies weighted by the number of subjects; ●: seated; ▲: standing; ■: recumbent. Solid line: W_d weighted acceleration of 0.01 ms^{-2} r.m.s.; broken line: W_m weighted acceleration of 0.01 ms^{-2} r.m.s.

3. Threshold of transient vibration - time dependence -

The time dependence of the perception thresholds of whole-body vibration was investigated based on the thresholds of transient vibrations determined in the previous studies shown in Table 2. There have been limited number of previous studies of the thresholds of transient vibrations as implied in the table. The waveforms of transient vibration used in the previous studies in Table 2 included toneburst, sinusoidal vibration modulated by the Hanning window, and impulse response of single degree-of-freedom system.

The perception threshold of transient vibration was determined in this study by

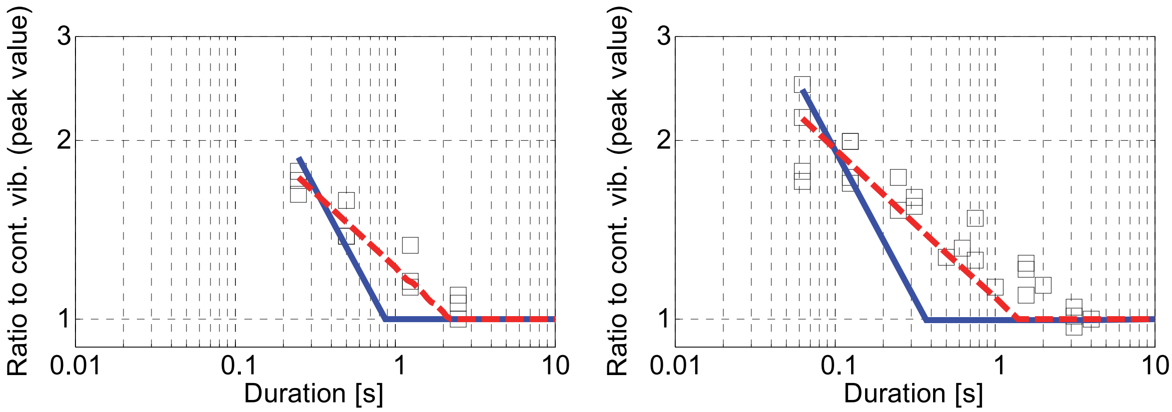
$$a_w = \max\left[a_w(t_0)\right], \quad a_w(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} \{a_w(\xi)\}^n d\xi\right]^{\frac{1}{n}} \tag{1}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration, τ is the integration time for running averaging, ξ is the time (integration variable), and t_0 is the time of observation (instantaneous time). In this study, 2 and 4 were used for n . $a_w(t_0)$ was the running root-mean-square, r.m.s., acceleration for $n = 2$, and the running root-mean-quad, r.m.q., acceleration for $n = 4$. The two values for n , an optimum integration time τ was determined by applying the least square method to the perception thresholds of transient vibration in the previous studies.

It appeared that the optimum integration time differed among different waveforms and frequencies. Figures 3 to 5 show examples of results: the mean or median thresholds of transient vibrations at 4 and 16 Hz for the three waveforms in the previous studies and the corresponding evaluation with the optimum integration time. From visual examination of the figures, the r.m.q. method represented by the broken line tended to yield less differences from the experimental data than the r.m.s. method represented by the solid line.

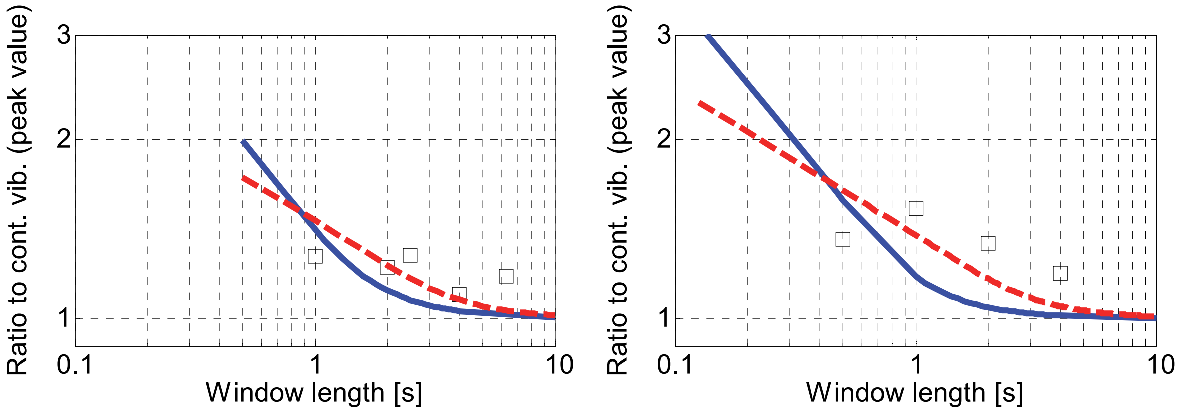
Table 2 Previous studies of perception thresholds of whole-body transient vibration reviewed

Authors	Year	Ref.	Waveform	Direction	Frequency [Hz]	Posture	Subject
Miwa *et al*.	1984	[6]	Toneburst	Vertical	1 - 100	Recumbent	10
			Toneburst	Lateral	1 - 100	Recumbent	10
			Toneburst	Head-feet	1 - 100	Recumbent	10
Takahashi *et al*.	1987	[13]	Impulse	Vertical	5, 10, 15, 20	Seated	19
Parsons, Griffin	1988	[7]	Toneburst	Vertical	16	Seated	12
Matsumoto *et al*.	2010	[10]	Hanning	Lateral	4, 6.3, 10	Seated	20
			Impulse	Lateral	4, 6.3, 10	Seated	20
Matsumoto *et al*.	2011	[11]	Hanning	Vertical	2 - 63	Recumbent	12
Matsumoto *et al*.	2011	[12]	Impulse	Vertical	10, 12.5, 16	Seated	20



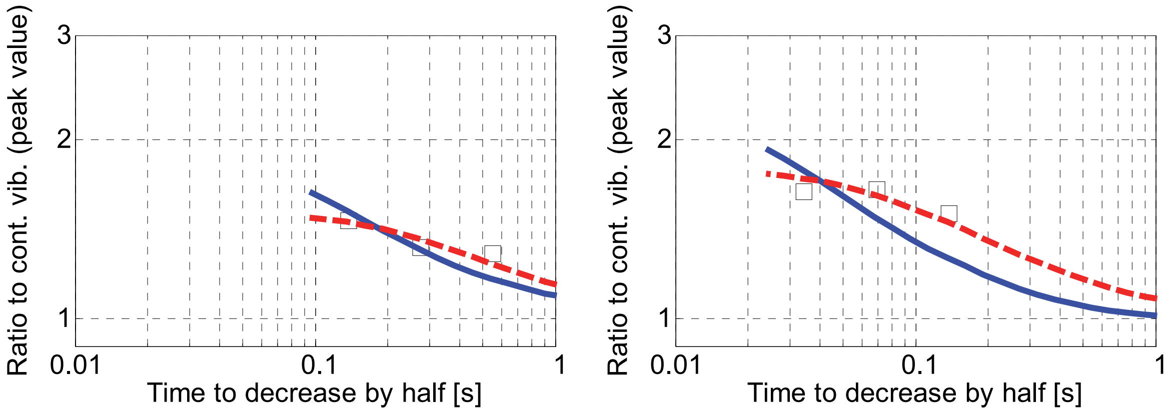
(a) 4 Hz (r.m.s.: τ = 0.875 s ; r.m.q.: τ = 2.24 s) (b) 16 Hz (r.m.s.: τ = 0.373 s ; r.m.q.: τ = 1.41 s)

Figure 3 Perception thresholds of toneburst and evaluation with the optimum integration time. Solid line: r.m.s. (n = 2); broken line: r.m.q. (n = 4).



(a) 4 Hz (r.m.s.: τ = 0.749 s ; r.m.q.: τ = 1.24 s) (b) 16 Hz (r.m.s.: τ = 0.469 s ; r.m.q.: τ = 0.993 s)

Figure 4 Perception thresholds of sinusoidal vibration modulated by the Hanning window and evaluation with the optimum integration time. Solid line: r.m.s. (n = 2); broken line: r.m.q. (n = 4).



(a) 4 Hz (r.m.s.: τ = 0.386 s ; r.m.q.: τ = 0.576 s) (b) 16 Hz (r.m.s.: τ = 0.135 s ; r.m.q.: τ = 0.296 s)

Figure 5 Perception thresholds of impulse response and evaluation with the optimum integration time. Solid line: r.m.s. (n = 2); broken line: r.m.q. (n = 4).

4. Summary

This study investigates the evaluation of building vibration based on the perception threshold of whole-body vibration determined in previous studies. The frequency dependence of the perception thresholds was investigated using the previous data of the thresholds of continuous sinusoidal vibrations, while the time dependence was examined using the thresholds of transient vibrations. The evaluation of the perception thresholds was investigated based on the evaluation defined in the current standard methods. The frequency weightings defined in the current international standards appeared not to represent necessarily the frequency dependence of the perception thresholds observed in the previous studies. Appropriate time constant for the integration used in the running r.m.s. and r.m.q. acceleration to represent the thresholds depended on the frequency and waveform of input motion. From the result of this paper, a better evaluation might be, for example, to apply one-third octave band filter to a target vibration to be evaluated, calculate the maximum r.m.q. acceleration in each frequency band with optimum integration times depending on the frequency band, and compare those r.m.q. values with limit values defined for each frequency band.

5. References

[1] International Organization for Standardization (2003) Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings (1 Hz to 80 Hz). International Standard, ISO 2631-2.

[2] International Organization for Standardization (1997) Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 1: General requirements. International Standard, ISO 2631-1.

[3] Miwa T (1967) Evaluation methods for vibration effect, Part 1. Measurements of threshold and equal sensation contours of whole body for vertical and horizontal vibrations. Industrial Health, 5, 183-205.

[4] Miwa T, Yonekawa Y (1969) Evaluation methods for vibration effect, Part 9. Response to sinusoidal vibration at lying posture. Industrial Health, 7, 116-126.

[5] Mckay JR (1972) Human response to vibration: some studies of perception and startle. PhD thesis, University of Southampton, England.

[6] Miwa T, Yonekawa Y, Kanada K (1984) Thresholds of perception of vibration in recumbent men. Journal of Acoustical Society of America, 75(3), 849-854.

[7] Parsons KC, Griffin MJ (1988) Whole-body vibration perception thresholds. Journal of Sound and Vibration, 121(2), 237-258.

[8] Okamoto N, Hirao Y, Yamamoto K, Yokota A, Maeda S (2001) Examination about whole-body vibration perception thresholds - Difference by the postures -. Proceedings of the 2001 Annual Meeting, the Institute of Noise Control Engineering of Japan, 97-100. (In Japanese)

[9] Morioka M, Griffin MJ (2008) Absolute thresholds for the perception of fore-and-aft, lateral, and vertical vibration at the hand, the seat, and the foot. Journal of Sound and Vibration, 314, 357–370.

[10] Matsumoto Y, Kunimatsu S (2010) Evaluation of perception thresholds of horizontal transient vibrations in the lateral direction. Proceedings of the 2010 Autumn Meeting, the Institute of Noise Control Engineering of Japan, 183-186. (In Japanese)

[11] Matsumoto Y, Maeda S, Iwane Y, Iwata Y (2011) Factors affecting perception thresholds of vertical whole-body vibration in recumbent subjects: Gender and age of subjects, and vibration duration. Journal of Sound and Vibration, 330, 1810-1828.

[12] Matsumoto Y, Kunimatsu S, Dung CV (2011) Experimental investigation of the effects of evaluation methods on human perception thresholds of transient vibrations. Internoise 2011, 431540, 1-6.

[13] Takahashi Y, Murakami N, Maeda S (1987) Relationship between sense of vibrations and damping of building floors. Summary of Technical Papers of Annual Meeting, Architectural Institute of Japan 1987, 77-78. (In Japanese)