Recent research activities for the assessment of vibration in living environment with respect to human perception in Japan

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The number of complaints against vibration has been increasing gradually in recent years in Japan. This fact implies possible problems of the Vibration Regulation Law that was implemented almost 30 years ago so as to regulate vibrations caused by factories and construction works and to mitigate vibration problems caused by road traffic. A group of experts has been investigating possible improvement of the assessment method defined in the law so as to assess current and future vibration problems reasonably since 2004. This paper presents a group research activity that aims at improving the understanding of human vibration perception and applying it in vibration assessment in living environment. The characteristics of human perception of transient vibrations and dual-frequency vibrations were investigated in two separate experiments. Additionally, an attempt was made to determine perception thresholds in a test wooden building in one of the two experiments. The results obtained in those experiments were summarised in this paper.

1 Introduction

Ground-borne vibration in living environment was designated as one of the typical environmental problems in Japan by the Basic Law for Environmental Pollution Control in 1967. In 1976, the Vibration Regulation Law went into effect so as to regulate vibrations caused by factories and construction works and also to mitigate problems due to vibrations caused by road traffic. The method of vibration evaluation provided in the law is defined in JIS C 1510 [1], which is based on frequency weighed r.m.s. acceleration as the evaluation method defined in ISO 2631-1 [2]. The number of complaints caused by vibrations within the scope of the law had decreased since the implementation of the law, which may indicate the effectiveness of the law. However, the number of complaints against vibration has been increasing gradually in recent years [3]. This may imply some discrepancies between current vibration problems and the assessment based on the Vibration Regulation Law implemented more than 30 years ago.

A group of experts has been formed by the Institute of Noise Control Engineering/Japan (INCE/J) so as to investigate possible improvement in the evaluation and assessment method for vibrations in living environment. The group has been involved in an investigation supported by the Ministry of the Environment so as to seek a method that can assess recent and future vibration problems more reasonably than the current method. There have been several sub-investigations of different aspects of evaluation method conducted by the group. Among those sub-investigations, the present paper reports the investigation of human perception of vibration.

Human perception of vibration is a necessary factor to be considered in the establishment of the evaluation and assessment method of vibration in living environment, as stated in ISO 2631-2 [4]. There have been previous studies of human perception thresholds of whole-body vibration, as summarised by Griffin [5]. Although most previous studies investigated perception thresholds of continuous sinusoidal vibrations, vibrations observed in living environment show more complex nature depending on characteristics of vibration source, ground, and building.

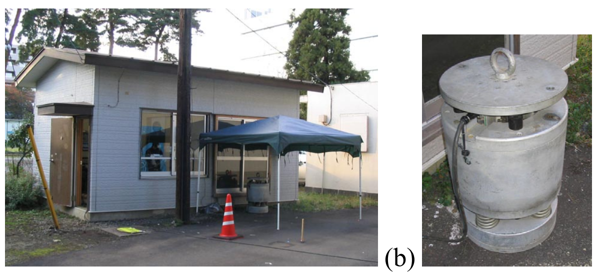
In the first experiment reported in the present paper, perception thresholds of transient vibration was measured in a test house that was exposed to ground vibrations induced by an exciter placed outside the house [6]. Understanding of perception of transient vibrations should have practical importance, because vibrations caused by many different sources, such as road traffic, show transient nature. An occupant of building may perceive vibration of a floor over which the magnitude of vibration varies depending on the location of measurement. This may make it difficult to ensure that the measured values of floor vibration represents the vibration perceived by the occupant and is comparable to the perception thresholds obtained in previous laboratory studies. An attempt was made in this experiment to determine perception thresholds in a test house that is more practical situation than a laboratory.

In the second experiment described in the present paper, perception of dual-frequency vibrations was investigated in a laboratory. Dual-frequency vibration was considered as a simplification of vibrations that consist of more than one frequency components, such as those observed often in practice. Although the number of frequency components of the vibrations used in the experiment was limited to two, the results obtained in the experiment may have some practical meanings because vibrations observed in living environment often have only a few dominant frequency components caused by dominant frequency component of vibration source and/or natural frequencies of ground and building.

2 Perception of transient vibration measured in a test house

2.1 Method

An experiment was conducted in a one-storey wooden test house in Kobayashi Physical Research Institute shown in Fig. 1(a). Vibrations of the house used in the experiment were generated by a vertical exciter located close to the house on a paved ground, as shown in Fig. 1(b). Vibration perception thresholds of recumbent subjects were determined in a room of the test house. A subject lay down on a wooden platform placed on the floor of the room during the experiment. Five accelerometers were mounted on the bottom surface of the platform at the positions of the head, chest, buttocks, calves and heels of a subject with



(a) (b)

Fig.1 (a) test house and (b) exciter used in experiment.

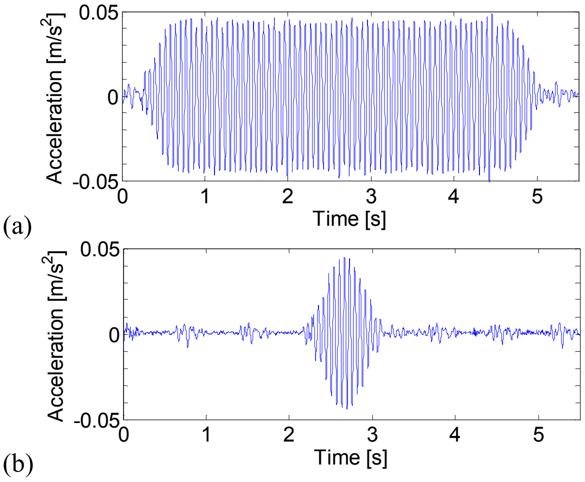


Fig.2 Example of acceleration waveform. 16 Hz.
(a) continuous vibration, (b) transient vibration..

average height. A tri-axis accelerometer, RION PV-83C, was used for the measurement at the buttocks, while a single-axis accelerometer, RION PV-87, was used at the other locations for the measurement of vertical vibration.

Vibrations used in the experiment were continuous sinusoidal vibrations and transient vibrations. The duration of the continuous vibrations was 5.0 s with the first and last 0.5 s tapered. The duration of the continuous vibrations at a constant amplitude was 4.0 s. The transient vibrations were formed by modulating amplitude of sinusoidal vibration with the Hanning window for the duration of 1 s. An envelope of acceleration waveform similar to the Hanning window was often observed in field records of vibration measured on the ground and in a building caused by road traffic. Five different frequencies, i.e., 8, 16, 31.5, 63 and 80 Hz, were used for both continuous and transient vibrations. Fig. 2 shows an example of acceleration waveform for the continuous and transient vibrations measured in the experiment.

Perception thresholds were measured with 30 subjects, 20 male and 10 female, aged from 21 to 61 yrs. The method of limit was used for the measurement of thresholds. The magnitude of vibration was changed at about 2 dB step. The experiment was conducted with two subjects at a time, as shown in Fig. 3. A response of a subject to each vibration exposure was obtained by using a hand-held switch. For each input vibration condition, the measurement was made

Fig.3 Inside of test house during experiment.

with three ascending and three descending series and the threshold was determined from the average of those six measurements. The order of presentation of vibration conditions and order of ascending and descending series was randomised among pairs of subjects.

For each input vibration condition, subjects were asked to report in what parts of their body they perceived vibration. The magnitude of acceleration measured was dependent on measurement location, particularly, at higher frequencies. The threshold was determined by using a measurement obtained at a measurement location closest to the body part that the subject felt vibration. If there were more than one corresponding locations, the lowest magnitude obtained among those locations was used to determine the threshold.

2.2 Thresholds measured in test house

Fig. 4 compares the median thresholds of the 30 recumbent subjects measured in the present study and the median or mean thresholds determined in laboratory experiments in previous studies [7-12]. The thresholds presented in the figure were determined by root-mean-square (r.m.s.) acceleration. At 16, 31.5 and 63 Hz, the thresholds measured in the present study were comparable with those obtained in more than one previous study. At 8Hz, the threshold in the present study was equivalent to that in Miwa *et al.* [7] but lower than the other three studies. At 80 Hz, although the difference between the thresholds determined in the three previous studies were not significant, the threshold in the present study was lower than those by about 40%. Possible reason for this lower threshold at 80 Hz in the present study may be an effect of

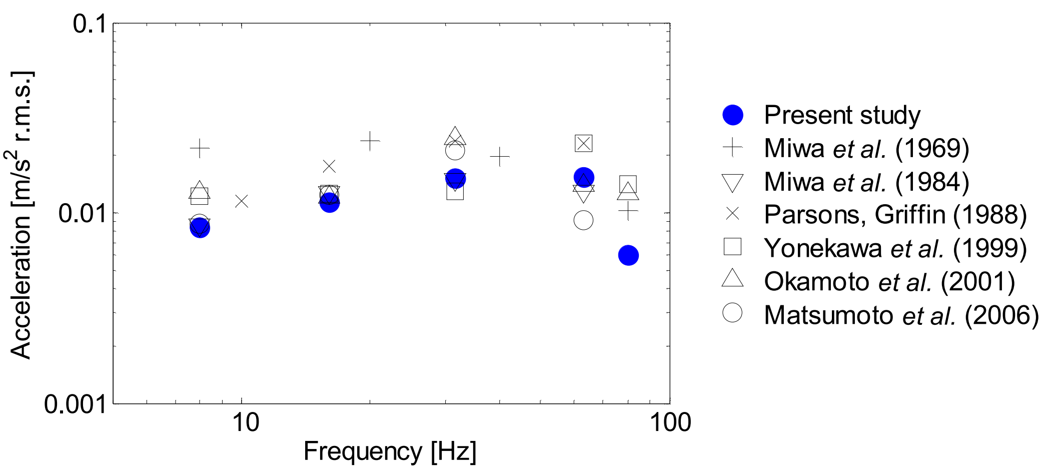


Fig.4 Perception thresholds of continuous vibration measured with recumbent subjects. Comparison between present and previous studies.

structure-borne sound and an effect of horizontal vibration that might be occurred at this frequency.

2.3 Thresholds of transient vibration

Fig. 5 compares the thresholds of transient and continuous vibrations represented by peak acceleration. For clarity of the figure, the data for the transient vibrations are plotted at a frequency slightly lower than the frequency used, and the data for the continuous vibrations are plotted at a slightly higher frequency. The figure shows that the thresholds of the transient vibrations represented by peak acceleration tended to be higher than the thresholds of the continuous vibration. The differences in the median threshold between the transient and continuous vibrations were 10% to 80% in peak acceleration. For the thresholds determined by peak acceleration, the differences between the transient and continuous vibrations were statistically significant at all frequencies except for 8 Hz (p<0.05, Wilcoxon matched-pairs signed ranks test).

For the evaluation of transient vibrations, the use of running r.m.s. acceleration, such as the maximum transient vibration value (MTVV) defined in ISO 2631-1 [2], may be more suitable than peak acceleration, as shown above, and r.m.s. acceleration determined for the whole length of a vibration record. Fig. 6 compares the thresholds of transient and continuous vibrations represented by maximum running r.m.s. acceleration obtained without a frequency weighting,

$$a = \max\left[\left\{\frac{1}{\tau}\int_{t-\tau}^{t}\left(a(\xi)\right)^2 d\xi\right\}^{\frac{1}{2}}\right] \quad (1)$$

where the integration time τ was 1 s, as recommended in ISO 2631-1 [2]. The differences in the median threshold observed between the transient and continuous vibrations were -30% to 20%. For the thresholds determined by maximum running r.m.s. acceleration, the differences between the transient and continuous vibrations were not statistically significant at all frequencies except for 8 Hz (p>0.05, Wilcoxon matched-pairs signed ranks test).

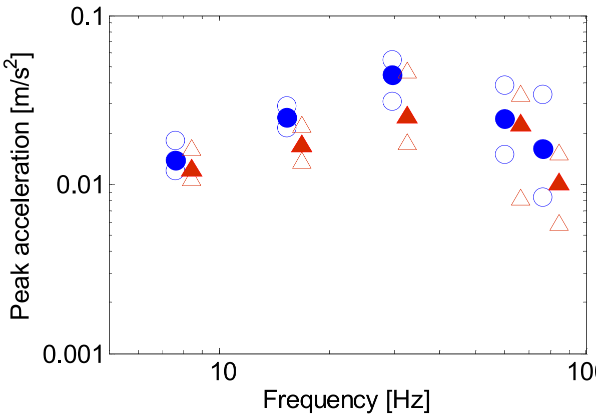


Fig.5 Thresholds of transient and continuous vibrations represented by peak acceleration.
Medians and inter-quartile ranges of 30 subjects.
○: transient vibration, △: continuous vibration.

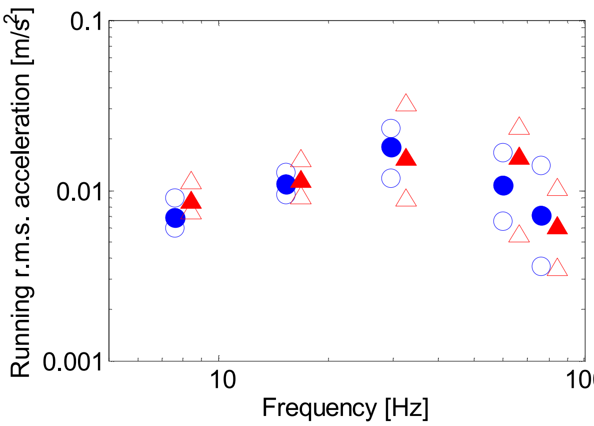


Fig.6 Thresholds of transient and continuous vibrations represented by maximum running r.m.s. acceleration with integration time of 1 s.
Medians and inter-quartile ranges of 30 subjects.
○: transient vibration, △: continuous vibration.

3 Perception of dual-frequency vibration

3.1 Method

Perception thresholds of lateral dual-frequency vibrations were determined with seated subjects in a laboratory experiment. Dual-frequency vibrations were produced with a frequency component at 6.3 Hz, as a base component, combined with another frequency component at either 0.4, 1.6, or 25 Hz, as an additional component. Normative magnitude of each frequency component was one of the six magnitudes: at 0.0063, 0.016, 0.040, 0.10, 0.25, or 0.63 m/s^2. The magnitude of base component, i.e., 6.3 Hz, was kept constant while the magnitude of additional component was increased step by step: the magnitude of additional component kept constant for about 40 s and then gradually increased to the next higher magnitude for 24 s. At each magnitude, subjects were asked to judge how they felt about the vibration. For comparison, thresholds of sinusoidal vibrations were also measured in a similar manner. The frequencies of sinusoidal vibrations were the same as those used for dual-frequency vibrations. The magnitude of sinusoidal vibrations was 0.016, 0.040, 0.10, 0.25, 0.63, or 1.6 m/s^2. The input vibration conditions described above were determined based on the results in the previous study [13] and records of field measurements. A total of 68 conditions for dual-frequency vibrations and 22 conditions for sinusoidal vibration were used in the experiment.

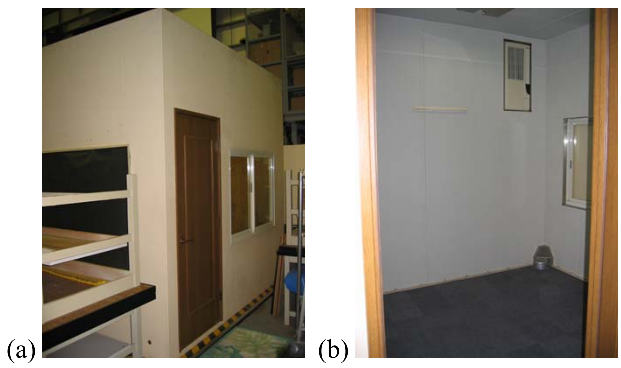


Fig.7 Steel room fixed on shaker.
(a) outside view, (b) inside view.

An electro-dynamic shaker in a laboratory at Japan Women's University was used in the experiment. A steel-made room with the size of 3 m × 3 m × 3 m was fixed to the platform of the shaker (Fig. 7). The motion of the shaker was controlled by input electrical signal fed from a computer and measured with a servo accelerometer.

Thirty-six female subjects, aged from 18 to 24 yrs, took part in the experiment. The subjects sat on the floor of the room fixed to the shaker. Nine subjects were exposed to vibrations simultaneously. While the magnitude of vibration was constant for about 40 s, the subjects were instructed to judge how they felt about the vibration by using a questionnaire. The questionnaire, which was used in the previous study [13], consisted of four questions about different feelings, i.e., discomfort, alert, intensity, and perception. For each question, the subjects were asked to select an answer among from five alternatives. The alternatives for the questions about perception were "Do not perceive vibration at all", "May perceive vibration", "Perceive vibration", "Feel strong vibration", and "Feel intolerable vibration".

In this paper, the ratio of subjects who selected "Do not perceive vibration at all" (referred to as the ratio of Answer 1) is used to investigate the characteristics of vibration perception of the subjects.

3.2 Frequency dependence of perception of horizontal sinusoidal vibration

Fig. 8 shows the relation between the r.m.s. acceleration of input vibration and the ratio of Answer 1 for the sinusoidal vibrations. The subjects were most sensitive to vibration acceleration at 0.4 and 1.6 Hz and least sensitive at 25 Hz. Similar trends were observed in a previous study [13] using a similar measurement method and previous studies summarised by Griffin [5].

The evaluation method defined in ISO 2631-1 [2] was applied to the results obtained in this experiment. The W_d frequency weighted r.m.s. acceleration was compared with the ratio of Answer 1 in Fig. 9. The results at 0.4 Hz are not shown in the figure because the frequency weighting is not defined at this frequency. If the W_d frequency weighting represent the thresholds of horizontal vibration reasonably, the relation between the frequency weighted r.m.s. acceleration and the ratio of Answer 1 will be independent

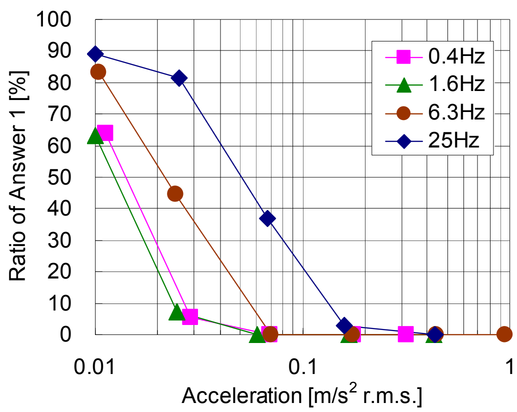


Fig.8 Relation between r.m.s. acceleration and ratio of subjects selected "Do not perceive vibration at all" (ratio of answer 1) for sinusoidal vibrations.

of frequency. However, there are clear differences between different frequencies.

3.3 Perception of dual-frequency vibration

For the evaluation of multi-frequency vibrations, the frequency weighted r.m.s. acceleration is the basic method

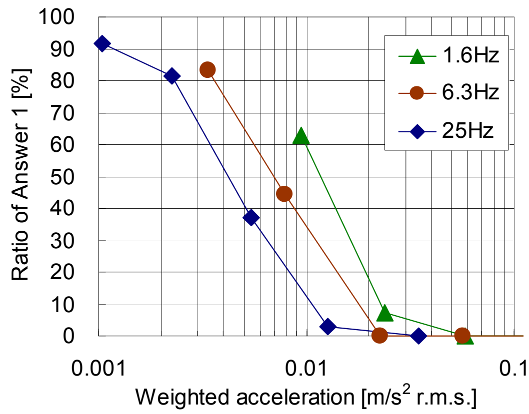


Fig.9 Relation between W_d frequency weighted r.m.s. acceleration and ratio of subjects selected "Do not perceive vibration at all" (ratio of Answer 1) for sinusoidal vibrations.

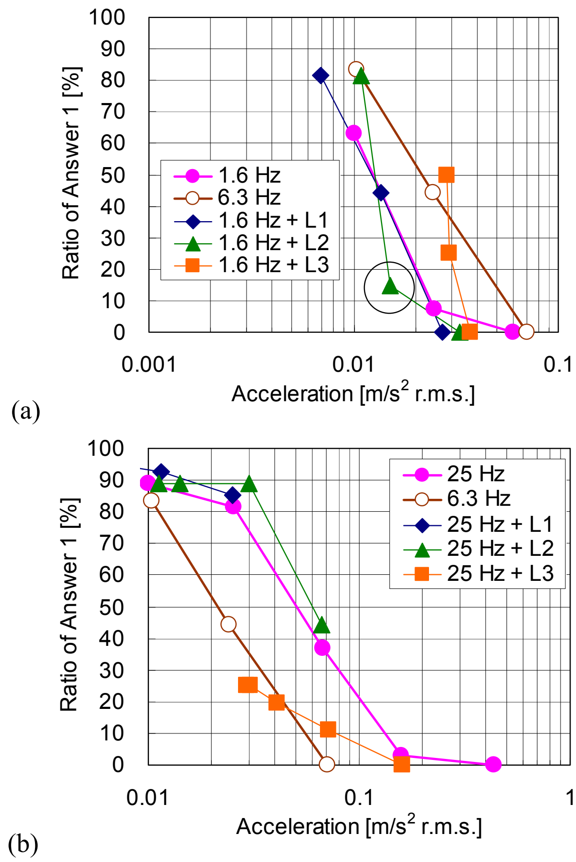


Fig.10 Relation between r.m.s. acceleration and ratio of subjects selected "Do not perceive vibration at all" (ratio of Answer 1) for dual-frequency and sinusoidal vibrations.
(a) 1.6 and 6.3 Hz, (b) 25 and 6.3 Hz.
For example, "1.6 Hz + L1" denotes dual-frequency vibration consisting of 6.3 Hz at 0.0063 m/s^2 and 1.6 Hz.
L1: 0.0063 m/s^2; L2: 0.016 m/s^2; L3: 0.04 m/s^2.

defined in ISO 2631-1 [2]. However, the frequency dependence of perception thresholds of lateral vibrations measured with the subjects in this experiment may not be consistent with the W_d frequency weighting defined in ISO 2631-1, as shown in Fig. 9. Therefore, the dual-frequency vibrations were evaluated with unweighted r.m.s. acceleration and compared with the responses of the subjects.

Fig. 10 shows the relation between the r.m.s. acceleration and the ratio of Answer 1 for the dual-frequency vibration consisting of 1.6 and 6.3 Hz and 25 and 6.3 Hz. For comparison, the results for the corresponding sinusoidal vibrations are also shown in the figure. If an evaluation method based on frequency weighted r.m.s. acceleration, as defined in ISO 2631-1 [2], can reasonably represent perception thresholds of multi-frequency vibrations, the results of this experiment, as presented in Fig. 10, will show a trend that the results for dual-frequency vibrations will be somewhere between the results for two corresponding sinusoidal vibrations. Fig. 10 shows that the ratios of Answer 1 for the dual-frequency vibrations tended to be between the ratios of Answer 1 for the two corresponding sinusoidal vibrations, although it was difficult to investigate precisely if such a trend was observed in this experiment because the intervals of magnitudes used in the experiment were not fine and linear interpolation was made between the results obtained at adjacent vibration magnitudes. However, the ratio of Answer 1 for the dual-frequency vibration consisting of 6.3 Hz at 0.016 m/s^2 and 1.6 Hz at 0.016 m/s^2 (indicated by an additional circle in Fig. 10(a)) was less than the ratio of Answer 1 for the sinusoidal vibration at 1.6 Hz that may have a dominant effect on perception of that dual-frequency vibration.

4 Summary

In the first experiment, it was implied that the perception thresholds determined in the previous studies in laboratories may be able to apply to the assessment of building floor vibration provided that the measurement location is selected appropriately. For the experimental conditions used in the present investigation, the evaluation method based on running r.m.s. acceleration with integration time of 1.0 s may represent the vibration perception thresholds appropriately, irrespective of the type of vibration, although there was a difference in the threshold between two types of vibration at 8 Hz.

From the second experiment, a frequency weighted r.m.s. acceleration may evaluate perception thresholds of dual-frequency vibrations reasonably provided that the frequency weighting represent the frequency dependence of human vibration perception appropriately. However, there was a result that was inconsistent with the evaluation by r.m.s. acceleration, which may indicate needs of further investigation.

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