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Experimental Investigation of Evaluation Method of Horizontal Vibration in Building Caused by External Vibration Sources

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ABSTRACT

The purpose of this study was to examine the evaluation method based on subjective responses to vibration caused by external vibration source including road traffic and railroads for building habitability. The target buildings were small-scale buildings, such as detached houses in Japan whose main structure was wooden or steel frame. The first natural frequency of vibration mode of those building which has dominant horizontal vibration has been known to be in the range from 4Hz to 8Hz. Horizontal vibrations at the ground in that frequency range can be amplified due to the dynamic characteristics of buildings. An experiment involving human subjects were conducted to investigate relationship between subjective responses and evaluation value computed from vibration acceleration time histories. The input stimuli consisted of sinusoidal vibrations at 4Hz and 8Hz for several different durations and vibrations based on building vibrations measured in actual residential buildings. 7-step evaluation scales composed of expressions to provide equal psychological intensity intervals about magnitude, concern and discomfort were used to measure subjective responses in the experiment. It was found that Vibration Dose Value, *VDV*, which evaluated the effect of vibration duration by the 1/4 power, with W_d frequency weighting was most appropriate among the evaluation methods used in this study.

Keywords: Building Vibration, External Vibration Sources, Subjective Response, Vibration Evaluation

1. INTRODUCTION

In Japan, especially in urban areas, houses are adjacent to roads and railways. Since the distance from road or railway to building cannot be sufficiently secured, the building can be affected by traffic induced vibration. The natural frequency of the fundamental horizontal vibration mode of wooden or steel frame 2 or 3 story small-scale housing in Japan was in the frequency band of 4 to 8 Hz. In this frequency range, vibrations of small-scale buildings can be induced by external sources like road traffic and railways, with some amplification due to the dynamic characteristics of buildings. Although vibration at the ground due to an external vibration source is below the human vibration perception threshold, a vibration problem can be caused by the vibration amplification due to building. For this reason, when designing building at a site with ground vibration at a concerned magnitude, it is necessary to design it for the performance for environmental vibration.

The ISO 2631 series (1,2), which is an international evaluation method, is not often used for the vibration evaluation of buildings in Japan, and the evaluation method of Architectural Institute of Japan, AIJ (3), which has just been revised is generally used. However, there are some issues recommended for further investigation in the evaluation method of AIJ, such as the evaluation of subjective response to horizonal transient vibration.

Therefore, this study carried out an experiment with human subjects using input stimuli consisting of 4 Hz and 8 Hz sinusoidal vibration and real vibrations measured in the actual residential buildings. The relation between subjective responses, which were subjective magnitude, concern and discomfort, and some evaluation methods of environmental vibration were examined.

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2. Method

2.1 Apparatus

An electrodynamic shaker, Asahi Corporation VSR-S150H, in a laboratory of Saitama University used in the experiment can produce horizontal vibration in a single-axis. Subjects sat on an aluminum-framed seat mounted on the shaker platform whose size was 800 × 800 mm. The seat was set to expose subjects vibrations in the lateral direction. The horizontal acceleration of the seat surface was measured with a uniaxial piezoelectric accelerometer, RION PV-87. A charge amplifier, RION UV-06, was used for the amplification of signals from the accelerometer. A Vibration Level Meter, RION VM-53A, was used to measure the accelerations at the shaker platform in three orthogonal directions, which showed that cross-axis accelerations were negligible. Signals from all transducers were recorded in a PC-based data acquisition system, National Instruments Corporation, NI cDAQ-9178 and NI 9234. Figure 1 shows the electrodynamic shaker used in the experiment.

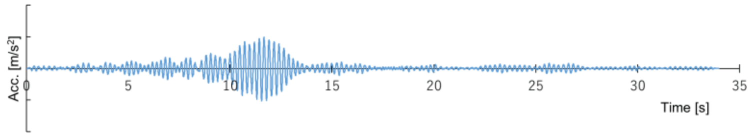
Figure 1 – Electrodynamic shaker

2.2 Subjects

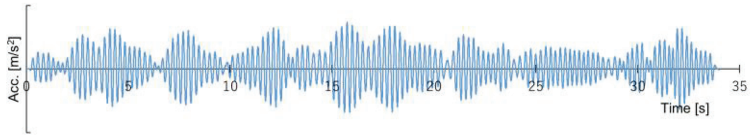
The twenty-five subjects (14 male and 11 female), with median age 22 years (range 20 - 24 years), stature 168 cm (range 151 - 179 cm), and weight 56 kg (range 43 -92 kg) participated in the experiment. They were all students of Saitama University. The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Saitama University. Informed consent to participate in the experiment was given by all subjects.

2.3 Input stimuli

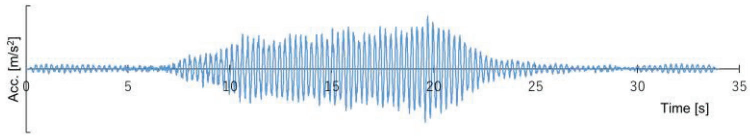
Input stimulus used in the experiment consisted of 12 types of vibration measured in real buildings and 2 types of sinusoidal vibration. The actual vibrations measured within houses were caused by external causes such as road traffic and railways. The frequency of sinusoidal vibration selected at 4Hz and 8Hz, which were determined based on the dynamic characteristics of ordinary residential buildings in Japan. The vibration duration varied in the range shorter than 35 s. The amplitude was adjusted so that the evaluation value by *VDV* of each input stimulus become equal interval by the logarithmic law, because the previous study showed the most appropriate correspondence with the subjective responses with the evaluation determined by *VDV* (4). For sinusoidal vibration, the frequency-weighted acceleration was adjusted by a factor of 2 (0.022, 0.011, 0.043, 0.086 m/s^2 at 4 Hz) and the duration by a factor of 4 (0.5, 2, 8 s). The magnitude of the acceleration amplitude was adjusted to be 0.11 - 2.02 m/s^2 so that the acceleration amplitude was in the range which can occur in an actual building. A total of 68 types of vibrations, 20 types for sinusoidal vibration and 48 types for actual vibration, were prepared. Figure 2 shows examples of input acceleration.



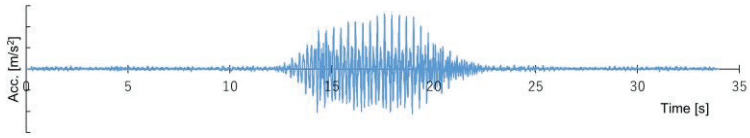
(a) Road traffic



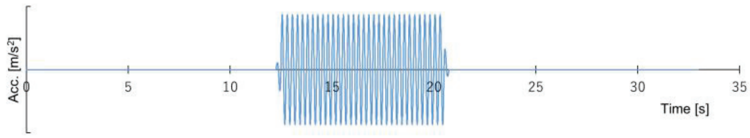
(b) Elevated Road



(c) Railway



(d) Shinkansen



(e) Sinusoidal (4 Hz - 8 s)

Figure 2 – Example of input vibrations

2.4 Measurement of subjective responses

The subjects were asked to assume that they sat down on a seat in a living room. They were exposed to the input vibrations and asked to rate those vibrations using the rating scale for subjective magnitude of vibration, concern and discomfort.

Category scales based on the method of psychological measurement was adopted to rate the subjective magnitude of vibration, concern vibration and vibration discomfort. These rating scales were set up as 7-step category rating scales with semantic labels, which were Japanese adverbial expressions, for the evaluation of building vibration. For example, for each subjective scale, the label of the top category 1 contains the adverb corresponding to “Extremely” and the lowest category 7 contains the adverb corresponding to “Not at all”.

2.5 Evaluation method of vibration

The several domestic and international evaluation methods of environmental vibration were applied to the accelerations measured in the experiment.

2.5.1 Evaluation of Habitability, AIJES

The Evaluation of Habitability, *AIJES* was defined in AIJES-V001-2018 (3). The vibration acceleration measured at floor surface in a building is plotted on criteria curve after 1/3 octave frequency analysis, and the evaluation is carried out at the maximum acceleration of main vibration components. In the case of unsteady vibration, the maximum value of acceleration can be reduced by calculating the effect of duration of vibration by 1/4 power.

2.5.2 Maximum Transient Vibration, MTVV

The Maximum Transient Vibration, *MTVV*, defined in ISO 2631-1 and -2 (1,2), was calculated by:

$$MTVV = \max[a_w(t_0)] \tag{1}$$

$$a_W(t_0) = \left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} \{a_w(\zeta)\}^2 d\zeta\right]^{1/2} \tag{2}$$

Here, the acceleration was frequency-weighted by W_d weighting defined in ISO ISO 2631-1 (1). The integration time τ was 1.0 s.

2.5.3 Vibration Dose Value, VDV

The Vibration Dose Value, *VDV*, was defined in ISO 2631-1 and -2 (1,2), was calculated by:

$$VDV = \left[\int_0^T \{a_w(\zeta)\}^4 d\zeta\right]^{1/4} \tag{3}$$

where T is the duration of vibration.

2.5.3 Root Mean Square, RMS

The Root Mean Square, *RMS*, was calculated by:

$$RMS = \left[\frac{1}{T}\int_0^T \{a_w(\zeta)\}^2 d\zeta\right]^{1/2} \tag{4}$$

In this study, the vibration duration T in the calculation was the same for all vibration stimuli. Therefore, *RMS* was essentially equivalent to the time-averaged value of *VDV* with the power of two, instead of fourth power, and used for investigating the effect of duration of vibration.

3. Results

3.1 Evaluation of influence of vibration duration and frequency weighting

For investigating the influence of the duration of vibration and the frequency weighting characteristics, Figure 3 shows the correspondence between subjective responses and all evaluation values for sinusoidal vibrations only using Spearman's rank correlation coefficient.

In the magnitude scale, *MTVV* which is the maximum value evaluation, shows that the correlation is the strongest. In discomfort scale, *VDV* which considers the duration of the vibration in the 1/4 power, shows the strongest correlation. In any subjective responses, the evaluation of *AIJES* shows the strong correlation. On the other hand, *RMS* shows the weakest correlation among all the evaluated values.

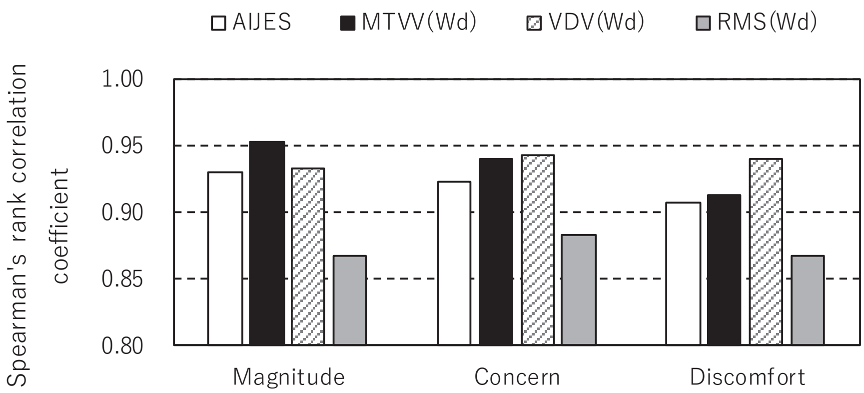
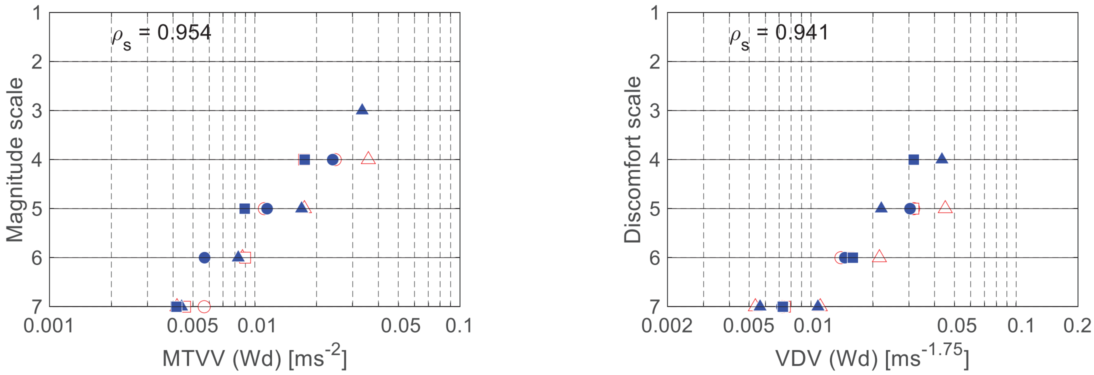


Figure 3 – Comparison of Spearman's rank correlation coefficients on sinusoidal vibration experiments

Figure 4 shows the correspondence between the subjective response and the evaluation value. As a representative, it shows the relationship between magnitude scale and *MTVV*, and discomfort scale and *VDV*. The evaluation values and subjective response are presented by the medians of 25 subjects. The figures show a tendency that the subjective response becomes stronger as the evaluation value increases, as expected. In addition, a similar tendency is observed in the results for 4 Hz and 8 Hz. This suggests that W_d frequency-weighting can adequately evaluate the subjective responses under consideration in this study for vibrations at two frequencies used.



(a) Maguitude scale (b) Discomfort scale

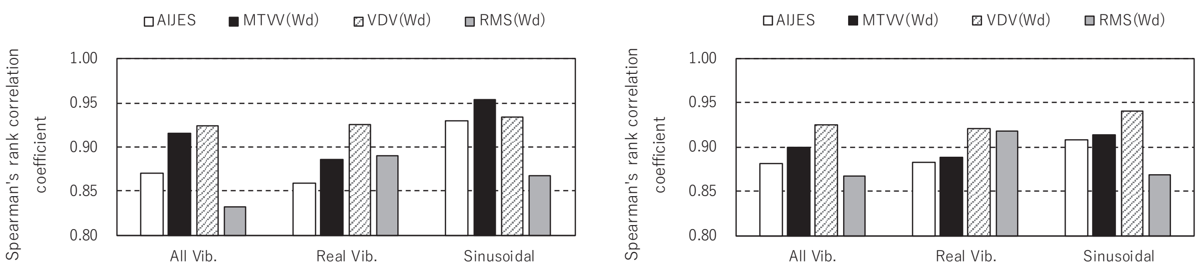
Figure 4 – Relation between subjective response and metrics of sinusoidal vibration

(○:4 Hz - 0.5 s, △ : 4 Hz - 2 s, □ : 4 Hz - 8 s, ● : 4 Hz - 0.5 s, ▲ : 8 Hz - 2 s, ■ : 8 Hz - 8 s)

3.2 Relation between subjective responses and all metrics

Figure 5 shows the Spearman's rank correlation coefficients between the subjective responses in this experiment and all the metrics for real vibrations only and all input stimuli. In addition, the results for sinusoidal vibrations, shown in Figure 4, are also shown for comparison.

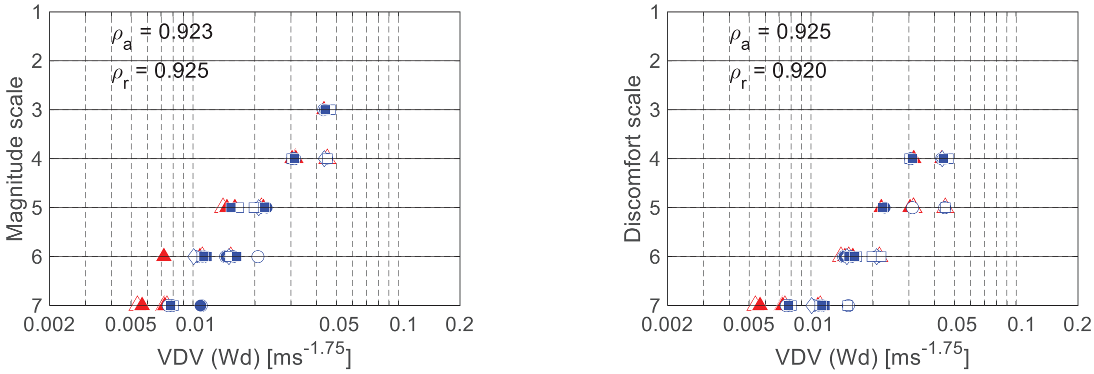
The correlation of *MTVV* is the strongest with the magnitude scale of the sinusoidal vibration, but the correlation is weak in the real vibration. *VDV* has a strong correlation with the subjective magnitude irrespective of the type of input stimulus. *VDV* also showed the strongest correlation with the discomfort scale for any input stimuli. Similar results were able to be observed even with concern scale. The above results suggest that *VDV* is the most appropriate evaluation value among the evaluation values examined in this study.



(a) Maguitude scale (b) Discomfort scale

Figure 5 – Comparison of Spearman's rank correlation coefficients on this experiment

Figure 6 shows the relationship between *VDV* with *Wd* frequency weighting and subjective responses in the magnitude scale and discomfort scale measured in this experiment. In the figure, ρ_a and ρ_r represent the Spearman's rank correlation coefficient for all input stimuli and real vibrations. It can be seen that the correspondence between *VDV* and the subjective response is good even for the actual vibration whose acceleration amplitude and frequency content change with time. In addition, it agrees well with the result of the sinusoidal vibration. It is, therefore, considered that *VDV* with *Wd* frequency weighting is appropriate as an evaluation for the subjective responses to horizontal building vibrations in small-scale residential building induced by road traffic and railways.



(a) Maguitude scale (b) Discomfort scale

Figure 6 – Relation between subjective response and metrics of all input stimuli

(○:Road, ● : Elevated road, □ : Conventional railway, ■ : Shinkansen, ◇ : Freight train, △ : 4 Hz, ▲ : 8 Hz)

4. CONCLUSIONS

This study examined the evaluation method of environmental vibration based on the subjective responses for magnitude, concern and discomfort to horizontal building vibration caused by external vibration source such as road traffic and railway. It was found that *VDV* considering the duration of vibration by 1⁄4 power evaluated the subjective response most appropriately for the sinusoidal vibration and various actual vibrations. It turned out that W_d frequency weighting was able to evaluate properly the vibration with different frequency components in horizontal vibrations.

ACKNOWLEDGEMENTS

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REFERENCES

1. ISO 2631-1 : 1997. Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-body Vibration – Part 1: General Requirements. International Standard.
2. ISO 2631-2 : 2003. Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-body Vibration – Part 2: Vibration in Buildings (1 Hz to 80 Hz).
3. Architectural Institute of Japan. Standard for the Evaluation of Habitability to Building Vibration. AIJES-V001-2018, 2018.11 (in Japanese).
4. Hayashi K, Matsumoto Y, Kano H. An Experimental Investigation of Applicability of Evaluation Methods Considering Duration for Subjective Responses to Horizontal Vibrations. Journal of Environmental Engineering (Transactions of AIJ), Vol.83, No.743, p.11-19, 2018. (in Japanese)