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# Proposal of Evaluation Scale for Vibration Sense Targeting Impact Vibration on Floor of Building

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**ABSTRACT**

**The problem of environmental vibration is increasing in Japan due to the high density of cities and the large span of buildings floor. The purpose is to evaluate the insulation performance of buildings against vibration. This concept has been introduced in the field of floor impact sound, but it has not been introduced much in the field of environmental vibration. In order to evaluate the "vibration insulation performance of residential floor", it is necessary to consider the evaluation scale of corresponds to the vibration sense of human. In inter-noise 2018, we showed that it relates to the integral amount with respect to discomfort degree against impact vibration. Furthermore, when the experiment time was set to about 10 minutes, we reported that the evaluation scale of "$L_{Veq,h,Th}$+20log$_{10}$T$^{k}$" corresponded to the discomfort degree by changing k according to the vibration perception time. However, the value of k was a discontinuous value. Therefore, in this paper, we studied the evaluation scale which corresponded to the vibration sensation with the value of k as continuous value. In addition, we studied on the proposed evaluation scale not only for RC construction but also for the detached house with small mass / rigidity.**

**Keywords:** Vibration, Evaluation, Impact
**I-INCE Classification of Subject Number:** 49

## 1. INTRODUCTION

In inter-noise 2018[1)], we presented that uncomfortable sensations correspond to the integral quantity. For vibrations of approximately 10 min, Assuming the evaluation physical quantity is “$L_{Veq,h,Th}$ +20log$_{10}$(T$^{k}$)”, the correspondence with discomfort degree is improved by varying k for each vibration perception time.

However, because k is discontinuous, we have assigned it a continuous numerical value in this paper. From there, we conducted an experimental study that shows high correspondence between vibration sense and physical quantity, and reported the results herein. In addition, a similar experiment was undertaken in this study for detached houses

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having less mass and rigidity than reinforced concrete houses, and investigated the correspondence between the vibration response physical quantity and the amount of vibration sensation with regards to the rubber ball (ISO 10140-5:2010[2)]) drops and walking.

## 2. PROPOSAL OF EVALUATION SCALE WITH K AS CONTINUOUS FUNCTION

### 2.1 Study Method

The experiment was carried out in the building shown in Fig. 1. The building structure is made of reinforced concrete, with 15-cm thick, ordinary concrete floor having a surface damping ratio of about 1.5%. Fig. 1 shows the relationship between the excitation point and the receiving points, while Fig. 2 shows the response acceleration result of each receiving point. Experiments were conducted using the seven patterns shown in Table 1. A combination of experiment duration, impact interval, impact source, fall height, etc. varied for each pattern, and with all patterns except for Pattern 1, the fall heights of the rubber ball that were used as impact sources were randomized. An example of Pattern 7 is shown in Fig. 3. In the impact method, the rubber ball was allowed to fall freely at the excitation point. Subjects were asked to sit up in a position (ordinary sitting position with knees raised up) centered at the receiving point on the floor. The subjects consisted of 29 adults (15 males and 14 females) in their 20s. The total number of responses to the sensory evaluation experiment was 609, 579 of which were valid. The sensory evaluation items used in the experiments are shown in Fig. 4. The subjects wore earplugs during the experiment to avoid any influence of sound of the rubber ball impacts on their sensory evaluation. The subjects were also asked to read during the experiment in order to simulate a real-life situation.

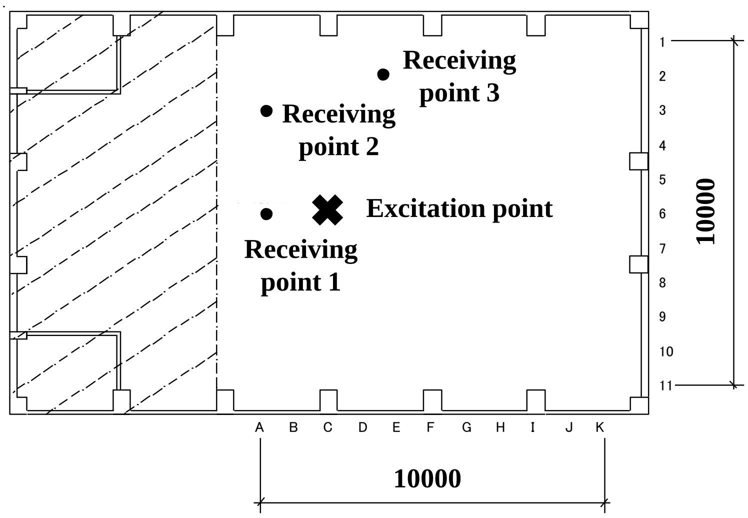



*Fig. 1 – Position of excitation point and receiving points.*

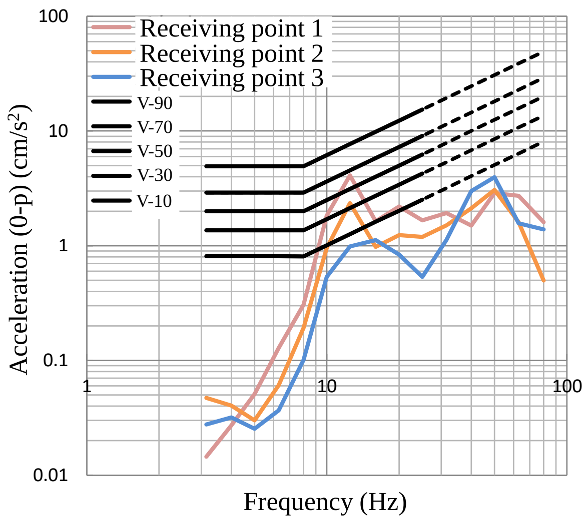



*Fig. 2 – Response acceleration of the receiving points.*

*Table 1 – Experiment Patterns.*

| Pattern | Number | Fall height of the rubber ball (number of times) | | | Impact Interval (s) | Experimental Time (s) |
|---|---|---|---|---|---|---|
| | | 100cm | 50cm | 25cm | | |
| Pattern1 | 7 | 7 | 0 | 0 | 2 | 15 s |
| Pattern2 | 16 | 5 | 3 | 8 | 2 | 30 s |
| Pattern3 | 20 | 2 | 4 | 14 | 1, 2, 4 | 30 s |
| Pattern4 | 10 | 1 | 2 | 7 | 1, 2 | 15 s |
| Pattern5 | 36 | 4 | 4 | 28 | 2 | 1 m |
| Pattern6 | 71 | 20 | 20 | 31 | 2, 4 | 3 m |
| Pattern7 | 40 | 8 | 8 | 24 | 1, 2, 4 | 1 m |

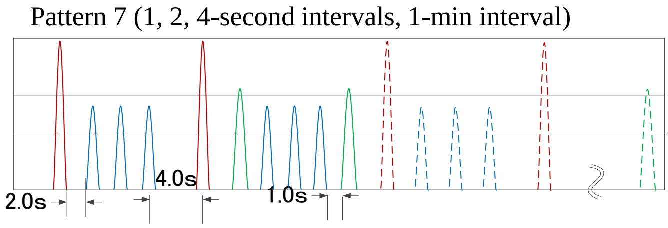



*Fig. 3 – Example of Pattern 7.*

Please circle the one that applies.
(1) Did you feel the vibration? (Yes / Not sure / No)
If you felt the vibration, how strong was it?
(Very Weak -3 -2 -1 0 +1 +2 +3 Very Strong)
If you answered "Yes" in (1), answer (2) and (3) as if you were relaxing in your own home.
(2) Did the vibration make you feel anxious?
I can't really say.
(Not at all. -3 -2 -1 0 +1 +2 +3 Yes, definitely.)
(3) Did the vibration cause you discomfort?
I can't really say.
(Not at all. -3 -2 -1 0 +1 +2 +3 Yes, definitely.)

*Fig. 4 – Sensory Evaluation Items.*

## 2.2 Investigation of the Sense of Vibration in Humans and their Corresponding Physical Quantity

Figure 5 shows an example of the $L_{V(10ms)}$ time waveform (vibration level analyzed for a time constant of 10 ms) at Receiving Point 1 of Pattern 1 in Table 1. Using the result from a previous paper[1], the sum total of the times when the vibration of $L_{V(10ms)} \geq 59$ dB is observed, is defined in this paper as "vibration perception time, $T_h$". Figure 6 shows an example of the temporal change of each physical quantity, with focus on integral quantity. Moreover, Fig. 7 shows the analysis results from that data with vibration of 59 dB or higher, as proposed in this research[1,3]. The terms and formulas utilized in this research are as follows:

$$L_{Veq} = 10\log_{10}\left\{\frac{1}{T}\sum_{i=1}^{N} 10^{\frac{Li}{10}} \cdot \Delta t\right\} \quad \cdots 1$$

$$L_{VE} = 10\log_{10}\left\{\sum_{i=1}^{N} 10^{\frac{Li}{10}} \cdot \Delta t\right\} \quad \cdots 2$$

$$L_{Veq} + 20\log_{10} T^{\frac{1}{4}} = L_{VE} - 10\log_{10} T + 20\log_{10} T^{\frac{1}{4}} = L_{VE} - 20\log_{10} T^{\frac{1}{4}} \quad \cdots 3$$

$$L_{Veq,h} = 10\log_{10}\left\{\frac{1}{T}\sum_{j=1}^{n}\sum_{i=1}^{M}(10^{\frac{L_{h,j,i}}{10}} \cdot \Delta t)\right\} \quad \cdots 4$$

$$L_{VE,h} = 10\log_{10}\left\{\sum_{j=1}^{n}\sum_{i=1}^{M}(10^{\frac{L_{h,j,i}}{10}} \cdot \Delta t)\right\} \quad \cdots 5$$

$$L_{Veq,h,T_h} = 10\log_{10}\left\{\frac{1}{T_h}\sum_{j=1}^{n}\sum_{i=1}^{M}(10^{\frac{L_{h,j,i}}{10}} \cdot \Delta t)\right\} \quad \cdots 6$$

T : Experiment time (s), $\Delta$t : sampling interval (s), $T = N \cdot \Delta t$

In Equation 4～6, $L_h \geq 59$, M is the sampling number of $L_h$ per impact, and n is the number of impacts.

In reference to Fig. 6, Equation 3, contains the proposed "$20\log_{10} T^{1/4}$", which is the average value of $L_{VE}$ and $L_{Veq}$, for the reason stated in the other paper[4] that physical quantities corresponded highly with the degree of anxiety for short vibrations during experiment times of up to around 30 seconds. In other words, for experiments up to around 30 seconds, although the degree of anxiety and its corresponding physical quantity also correspond to the integral quantity, they cannot intuitively be allowed to add up to $L_{VE}$. From Fig. 7, the proposed function $T_h^k$ is continuous function when the experimental time becomes longer (up to a maximum of 10 minutes), in which has been discussed in the previous paper[1]. Moreover, Fig. 8 shows the result when $k_2$ (= $-1/136 \cdot 10\log_{10}T_h + 1/4$) (The k in the previous report[1] is $k_1$ in this report). Note that $20\log_{10}T_h^k$ is constant when $Th \geq 50$ seconds.

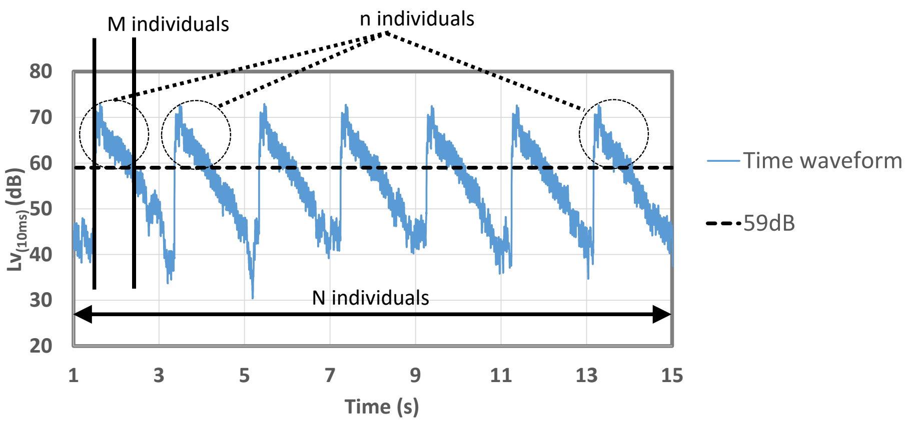



*Fig. 5 – Example of the time waveform of $L_{V(10\ ms)}$ (receiving point 1, pattern 1).*

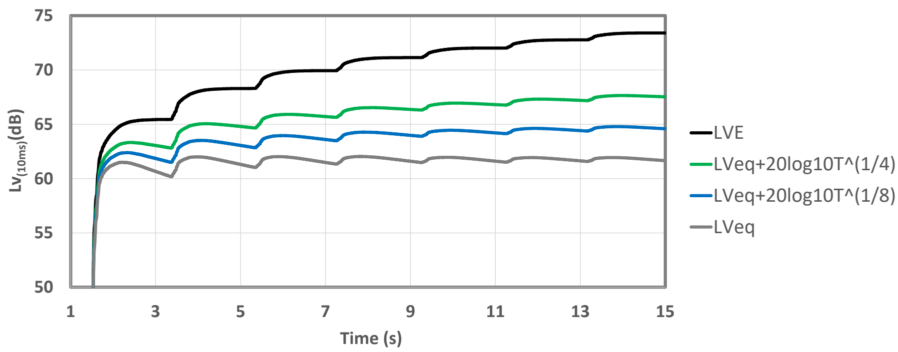



*Fig. 6 – Example of time waveforms with integral quantities (receiving point 1, pattern 1).*

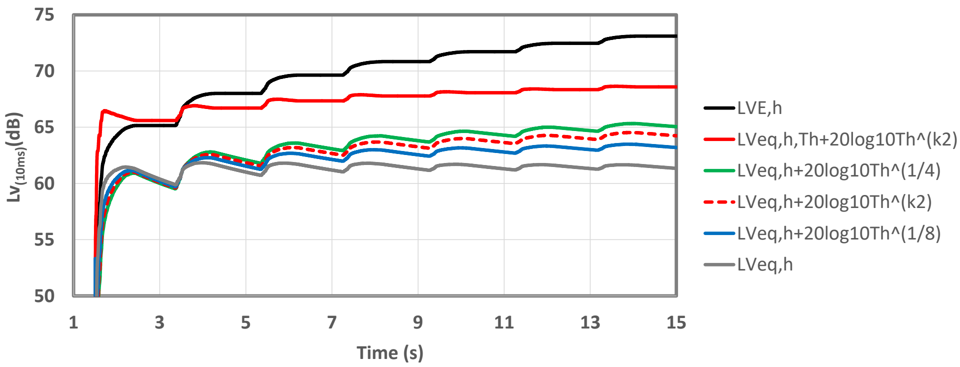



*Fig. 7 – Example of time waveforms with integral quantities (59 dB and above) (receiving point 1, pattern 1).*

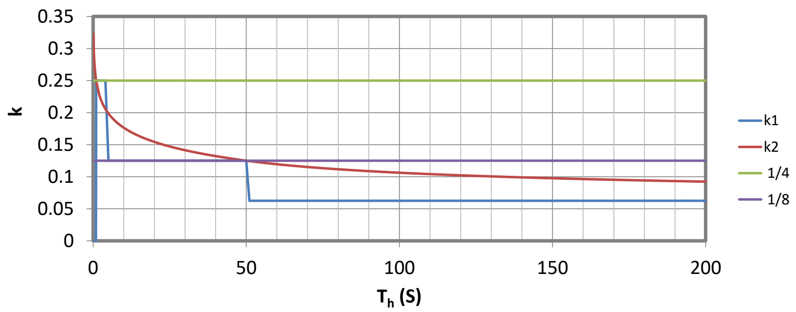



*Fig. 8 – Relationship between k and $T_h$ (vibration perception time).*

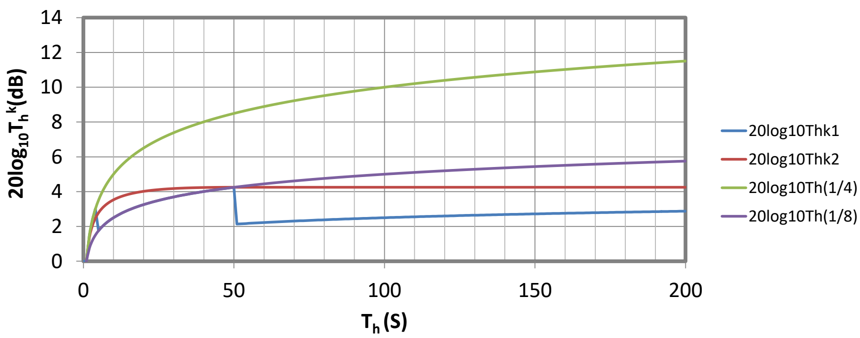



*Fig. 9 – Relationship between $20\log_{10}T_h^{\,k}$ and $T_h$ (vibration perception time).*

The correspondence between each physical quantity and the degree of anxiety is shown in Fig. 10. From ① and ②, we can see that the correspondence is high, which indicates the validity of the proposed $k^2$ as a continuous function in this report. On the other hand, $T_h$ is longer in ③ than in ① and ②, when using $T^{1/4}$, and the 4-50 second data lowers the correspondence. Furthermore, when $L_{Vmax(10ms)}$ is used in ④ instead of $L_{Veq,h,T_h}$, in the case of a constant impact force (blue circle) as in Pattern 1, there is a tendency for the degree of anxiety to increase. A similar tendency was also observed in the degree of discomfort.

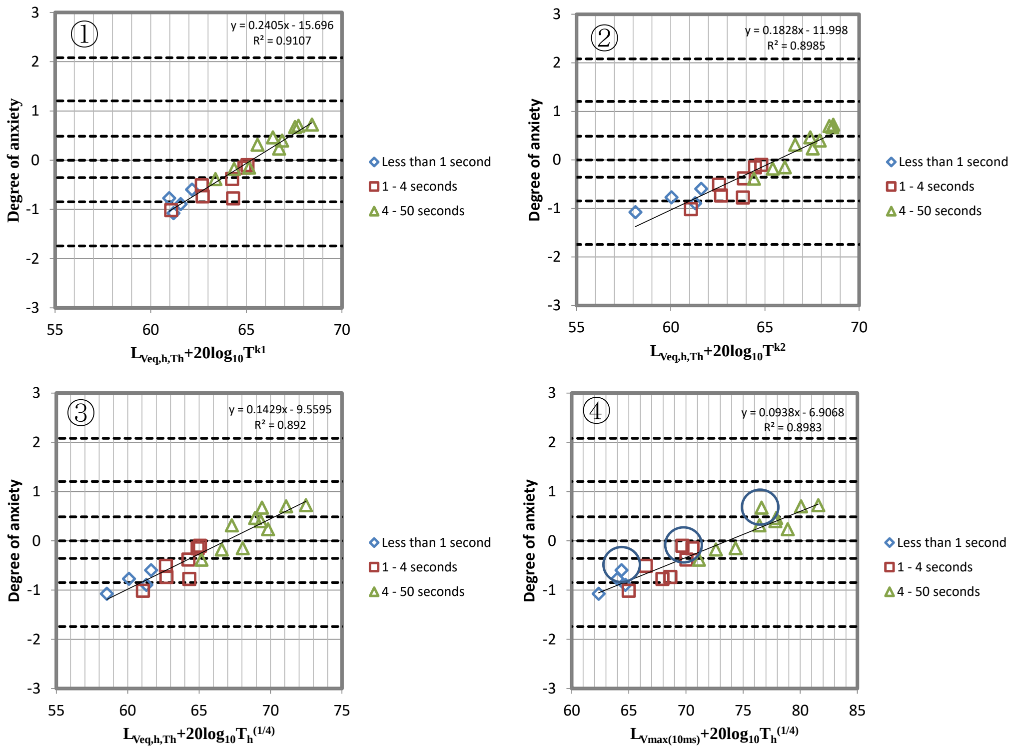



*Fig. 10 – Relationship between $20log_{10}T_h^k$ and $T_h$ (vibration perception time).*

## 2.3 Examination for Vibration Response Physical Quantity thru Extension of Vibration Exposure Time

The experiment was conducted in a building constructed of reinforced concrete, just like in 2.2. Figure 11 shows the relationship between the excitation point and the receiving points. Table 2 lists the conditions of the two types of experiment conducted. The data for Experiment 1 is identical to that in 2.2. In Experiment 2, the impact interval was set to 2 seconds, with the drop height of the impact source changed, and with the exposure time of the vibration going from 30 seconds to 10 minutes. For the vibrational excitation method, the rubber ball (ISO 10140-5:2010[2)]) used in the field of floor impact sound was allowed to fall freely, with sensory evaluation experiments carried out at the receiving point. The sensory evaluation items used and the state of the subjects were the same as in 2.2. There were a total of 807 responses in our sensory evaluation experiment, with the number of valid responses totalling 775. Note that in Experiment 2, sensory evaluations were conducted at different receiving points. As shown in Fig. 12, the response waveform of the 1/3 octave band analysis of each receiving point was ascertained to be nearly constant, so we treated all points as the same vibration response point and examined its correspondence with the sensory evaluation result.

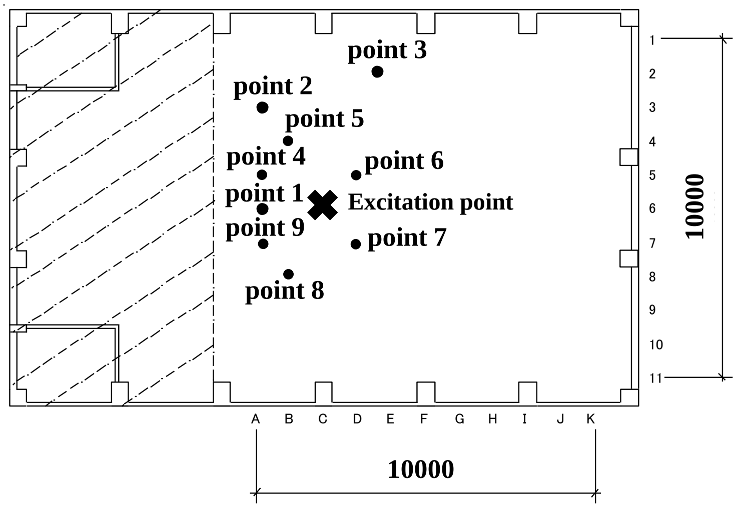



*Fig. 11 – Position of excitation point and receiving points.*

*Table 2 – Experimental conditions.*

| | Experiment 1: | | | | | Experiment 2: | | |
|---|---|---|---|---|---|---|---|---|
| | Pattern | Experiment Time (T) | Vibration perception time : $T_h$ | | | Pattern | Experiment Time (T) | Vibration perception time : Th |
| | | | Receiving point 1 | Receiving point 2 | Receiving point 3 | | | |
| Excitation conditions and impact time | 1 | 15s | 5.5s | 2.57s | 0.79s | 1 | 30s | 6.7s |
| | 2 | 30s | 9.5s | 3.46s | 0.89s | 2 | 30s | 6.98s |
| | 3 | 30s | 10.3s | 3.18s | 0.67s | 3 | 1m | 13.1s |
| | 4 | 15s | 4.8s | 1.47s | 0.29s | 4 | 1m | 13.6s |
| | 5 | 1m | 17.7s | 5.16s | 1.06s | 5 | 3m | 38.5s |
| | 6 | 3m | 41.3s | 14.62s | 3.71s | 6 | 3m | 40.7s |
| | 7 | 1m | 22.3s | 7.75s | 1.87s | 7 | 5m | 66.8s |
| | - | - | - | - | - | 8 | 5m | 65.8s |
| | - | - | - | - | - | 9 | 8m | 103.5s |
| | - | - | - | - | - | 10 | 8m | 102.2s |
| | - | - | - | - | - | 11 | 10m | 129.5s |
| Receiving point | 1, 2, 3 | | | | | 4, 5, 6, 7, 8, 9 | | |
| Number of test subjects | Adult men and women (15 men, 14 women) | | | | | Adult men and women (15 men, 15 women) | | |
| Valid response | 579 | | | | | 196 | | |

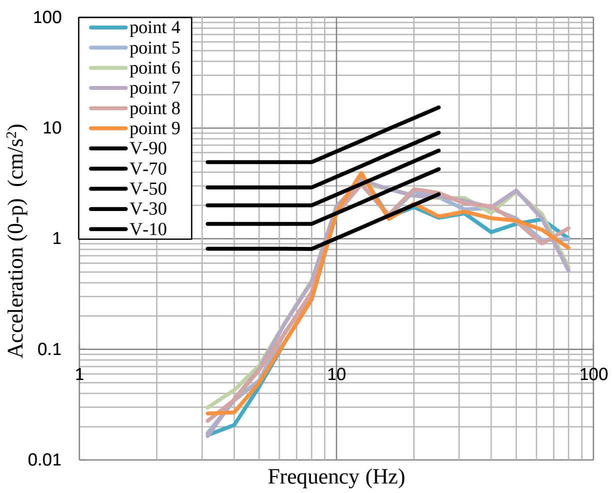
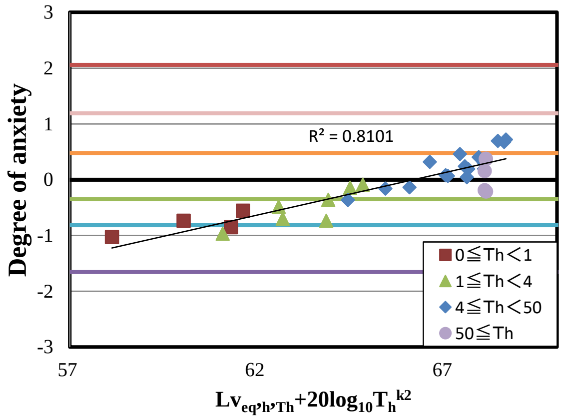



*Fig. 12 – Response waveform of each receiving point.*

Figure 13 shows the relationship between $L_{Veq,h,Th}$+20log$_{10}$$T_h^{k1}$, $L_{Veq,h,Th}$+20log$_{10}$$T_h^{k2}$ as proposed in 2.2 and the degree of anxiety, where it was revealed that $L_{Veq,h,Th}$ is the average energy level obtained by integrating the vibration level in the range of 59 dB or more and dividing it by the length of time in that range. $T_h$ is the duration of vibration perception, and is the sum of all the time in the ≥ 59 dB range. This shows that it corresponds highly to the sensory evaluation result regardless of $T_h$, and that the proposed $k_2$ corresponds well to data with long vibration exposure time of up to 10 minutes.



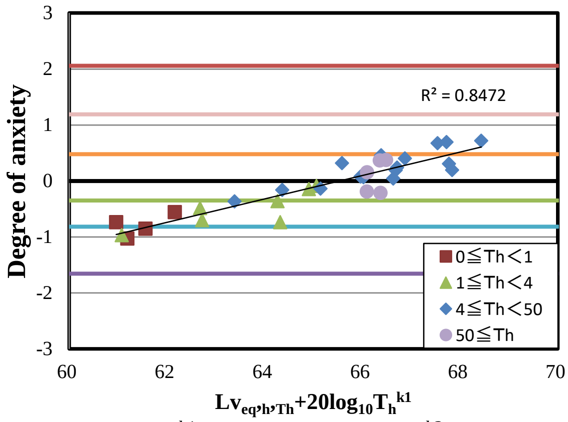




*Fig. 13 – $L_{Veq,h,Th}$+20log$_{10}$$T_h^{k1}$, $L_{Veq,h,Th}$+20log$_{10}$$T_h^{k2}$ and the degree of anxiety.*

## 3. EXAMINATION OF VIBRATION SENSE FOR DETACHED HOUSE THROUGH THE RUBBER BALL IMPACT AND WALKING

### 3.1 Experiment Methods

The experiments were conducted on a total of 8 detached houses, four of which were wooden-framed, and the other four were steel-framed (see Table 3). Figure 14 illustrates the location of the vibrational excitation point and receiving points. The experiment was conducted as follows. From Fig. 14, vibrational excitation was performed at the excitation point (motion behavior varied between walking around the room and walking in a straight line, as room sizes differed), while sensory evaluation was conducted at the receiving points. Two receiving points were set up while confirming the sites above the beam and between the beams. For the vibration experiment, we had a person walk and drop a ball freely from a height of 100 cm (except for cases where acceleration was too great for the excitation point to be measured by the vibration level meter, and the height had to be lowered to 50 cm). For the sensory evaluation experiment, we asked the participants to sit up in a position (ordinary sitting position with knees raised up) centered at the receiving point on the floor, and had them respond to sensory evaluation items shown in Fig. 4 (the same manner as in chapter 2). We asked the participants to wear earplugs, so as not to compromise the results of the evaluation due to the effects of sound.

*Table 3 – Outline of the experiment.*

| Detached house | Vibration source | Structure | Years since construction | Measured floors | Subjects (residents) | Subjects (non-residents) | floor measurements |
|---|---|---|---|---|---|---|---|
| J-residence | 50 cm, 100 cm ball, walking | wooden 2-story | 17 years | 1st floor, 2nd floor | 1 | 3 | 1st floor: 2,730×5,000<br>2nd floor: 3,640×3,640 |
| K-residence | 100 cm ball, walking | wooden 2-story | 36 years | 1st floor, 2nd floor | 1 | 3 | 1st floor: 2,600×3,200<br>2nd floor: 2,730×3,640 |
| L-residence | 50 cm ball, walking | wooden 2-story | 20 years | 1st floor, 2nd floor | 0 | 4 | 1st floor: 3,640×3,640<br>2nd floor: 3,640×3,640 |
| M-residence | 100 cm ball, walking | steel-frame 2-story | 17 years | 1st floor, 2nd floor | 1 | 3 | 1st floor: 4,550×5,000<br>2nd floor: 2,730×4,100 |
| N-residence | 100 cm ball, walking | wooden 3-story | 12 years | 1st floor, 2nd floor | 1 | 4 | 1st floor: 2,730×4,550<br>2nd floor: 2,730×4,550 |
| O-residence | 50 cm ball, walking | steel-frame 4-story | 30 years | 4th floor | 1 | 3 | 4th floor: 5,000×2,000 |
| P-residence | 100 cm ball, walking | steel-frame 2-story | 1 years | 2nd floor | 1 | 4 | 2nd floor: 3,200×7,480 |
| Q-residence | 100 cm ball, walking | steel-frame 3-story | 14 years | 2nd floor | 1 | 3 | 2nd floor: 4,700×5,500 |
| Receiving points | | | | ① between beam, ② above beam | | | |
| Number of resident responses | | | | 46 | | | |
| Number of non-resident responses | | | | 138 | | | |

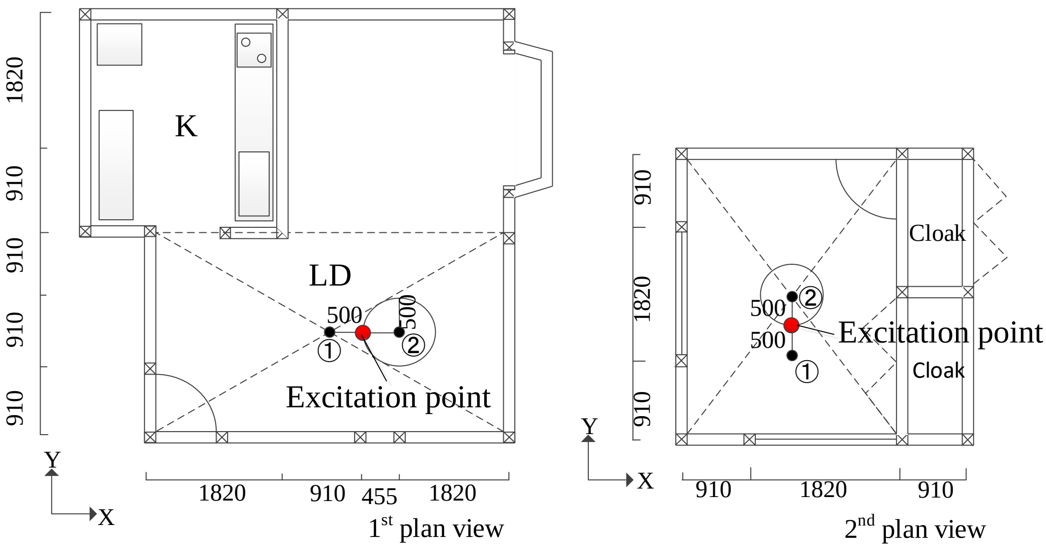



*Fig. 14 – Excitation point and receiving points (J-residence).*

### 3.2 Consideration of Physical Quantity and Sensory Evaluation in Detached Houses

Figure 15 shows the relationship between various physical quantities and the degree of anxiety in the subject detached houses. The physical quantities were calculated in reference to chapter 2. In addition, to carry out our study in the same way as in the laboratory experiments in chapter2, this report presented the analysis results only for non-residents. The values of the various physical quantities at the time of each person's motion and rubber ball impacts were counted in increments of 2 dB, while the sensory evaluation result for each impact source and structure was calculated using the successive category method. However, we targeted three or more responses in that range. Looking at the figure, the trend seems to suggest correspondence between the physical quantities of $L_{Veq,h,Th}+20\log_{10}T_h^{k2}$ of chapter2 with the degree of anxiety, as well as in the degree of discomfort.

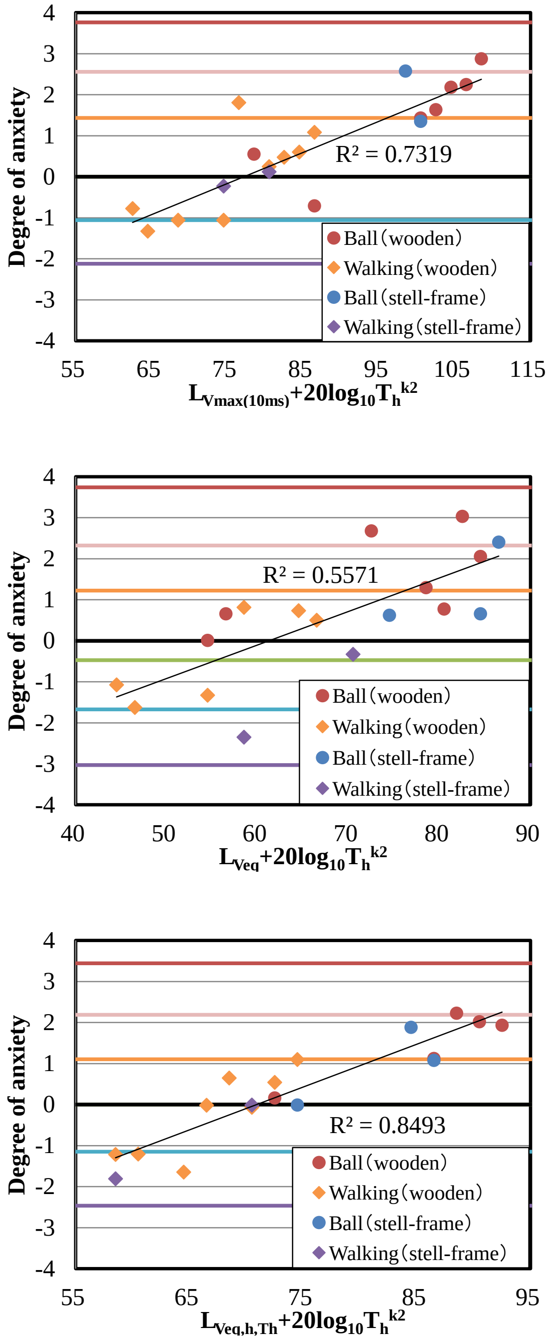



*Fig. 15 – Relationship between various physical quantities and degree of anxiety for detached houses.*

## 4. CONCLUSIONS

In this report, we conducted the vibration sense of human and floor vibration response that occurs on the floor slab with the rubber ball (ISO 10140-5:2010[2)]) used in the field of floor impact sound. We obtained the following results:

(1) For vibrations of approximately 10 min, Assuming the evaluation physical quantity is “$L_{Veq,h,Th}$ +$20\log_{10}T_h^{k2}$”, the correspondence with degree of anxiety is improved by varying k2 for each vibration perception time.

(2) Moreover, we were able to define k2 as a continuous function.

(3) Even in examination for detached houses having less mass and rigidity than reinforced concrete houses, we showed that the correspondence between " $L_{Veq,h,Th}$ $+20\log_{10}T_h^{k2}$" and degree of anxiety is good.

To investigate the validity of this claim, future studies involving experiments on variable traffic vibrations, aside from the impact variations, are advisable. Furthermore, we would also like to conduct experiments on residential properties to examine the physical quantities that take into account the long-term reactions of residents, and establish a standard vibration performance evaluation method for buildings.

## 5. ACKNOWLEDGEMENTS

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