Selection of the standard impact sounds similar to the human impact sounds in reinforced concrete floors

실충격음과 표준충격원으로 발생된 바닥충격음의 비교

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Key Words : Standard floor impact sources, real impact sounds

ABSTRACT

This study investigates human floor impact sounds; not only the children's jumping and running represented by heavy-weight impact source such as bang machine and impact ball but also the high-heel walking and the light weight object dropping represented by tapping machine in the standard measurements. However, due to reliability problems as a standard impactor, bang machine has not been included in the new draft of ISO 10140 Part 3: Measurement of impact sound insulation. Therefore, the procedure to convert the floor impact sound level of the bang machine into that of the impact ball has been demanded because the bang machine has been only the standard heavy-weight standard impact source and much of its data has been collected, This study indicates that the use of impact ball is reliable and that the bang machine data can be successfully converted into the impact ball data in case of box-frame type reinforced concrete structures.

1. Introduction

Floor impact sounds, which are mainly caused by walking, running, and jumping, are regarded as the most irritating noise in apartment buildings. To simulate such human running and jumping, the standard heavy-weight floor impact sources, such as the bang machine (JIS A 1418-2; KS F 2810-2) and the impact ball (JIS A 1418-2; ISO CD 10140-3:2007) have been utilized.

Originally, the floor impact study started from the light-weight impact sound to mimic high heel tapping or the dropping of a lightweight object. In Germany, in 1932, a light-weight impact source called "tapping machine" was first developed and standardized in 1953. Laboratory and field measurements for floor impact sound insulation and a construction guide for a floating structure were standardized in the German standard DIN-52210 and later, in the ISO 140 series.

However, many studies have indicated that the floor impact noise evaluation using a tapping machine does not properly reflect the characteristics of human-made floor impact noise [1-6]. Furthermore, several publications have reported on the impedance levels of modified versions of the standard impact source for structure-borne noise [7-9]. These efforts have led to the proposal of a modified tapping machine (ISO 140-11). Although this modified tapping machine reasonably simulates adult's light walking, it is still insufficient to simulate the heavy-weight impact sources such as children running and jumping. Actually the impact sound pressure level generated by the modified tapping machine is much lower than real running and jumping in reinforced concrete buildings. Therefore, although ISO 717-2 suggests the use of additional weight to simulate the low-frequency of light-weight impact sounds, there are difficulties applying the spectrum adaptation term 'C_I'; namely, 1) there are large spectral variations in heavy-weight impact sound levels with different slabs, and 2) since the heavy-weight floor impact is impulsive, the impact sound pressure level should be evaluated by L_{max} not by L_{eq}.

In Japan, in 1973, "the experimental method for measuring floor impact noise (JIS A 1418)" was established. The measuring method for heavy-weight impact sound generated by a tire was developed for Japanese residential situations. For the past thirty years, floor impact sounds have been evaluated with the bang machine in Japan and Korea, however, the impact force of the bang machine is much above the range of the real impact forces especially at low frequencies and may damage the structural components of wooden frame houses. Therefore, a new standard impactor with a lower impact force was needed. The impact ball was specifically developed to reduce the potential damage to structural components in wooden frame houses [10].

Not only does the lower impact force of the impact ball reduce damage to structural components, it also enables the impact ball to better approximate real impacts. Tachibana *et al.* [11] examined the actual performance of impact balls in different Japanese residential buildings. When they measured the

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frequencies of four impact sources, they found that the characteristics of the impact ball were the most similar to the noise frequency characteristics of real impact noise. Jeon *et al*. [12] made a systematic comparison between the human impact sounds and impact ball and the bang machine objectively. The results of the impedance, impact force, and the impact sound level showed that the similarity of the impact ball sound to the real human impact sound. The impact force exposure level of the bang machine is higher than that of the impact ball below 63 Hz. On the other hand, the spectrum level of the impact ball is higher than that of the bang machine above 125 Hz. Not only physical characteristics of the floor impact sound but also properties which relate to subjective evaluation are needed to investigate. Nakazawa et al. [13] found that listeners judged that the impact ball sound is more similar than the bang machine to the real human-made impact sounds.

The present study further investigates the characteristics of the real floor impact sources and standard floor impact sources. In [12], the relationship between the bang machine and impact ball using an inverse A-weighted sound pressure level was also investigated. Tanaka and Murakami [14] also investigated the relationship between the bang machine and impact ball using the L-number. But conversion of a single number rating of the bang machine into that of the impact ball has not been available. Therefore, a method for converting the floor impact sound level of bang machine to that of the impact ball was also investigated to utilize the collected bang machine data.

2. Objective evaluations of floor impact sounds

The floor impact sounds were measured in units of the standard test building. Table 1 shows the summary of floor treatments for the floor impact sound measurements. In addition to the standard impact sources (impact ball, bang machine, and tapping machine), the real impact sounds including a dropping of a light-weight object (0.5 liter bottle), dragging a chair, high-heel tapping (53 kg), children's (33 and 40 kg) running, jumping on the floor, and jumping from a chair were generated. Interior surfaces of the units of the test building is the concrete, therefore, the absorbing materials were installed to adjust the reverberation time of the units (0.7 s) to that of a usual living room. Each impactor was used at the center of the driving room. Regarding the children's running, each child runs diagonally from a corner to another corner. The impact sound was recorded binaurally through a dummy head at the center of the receiving room representing the typical listening location of a tenant below.

Table 1. Room conditions of the standard test building for the floor impact sound measurements.

	Floor treatment	Slab thickness [mm]
180-1	20mm thick resilient isolator	180
180-2	10mm thick viscoelastic damping material	180
210-2	10mm thick viscoelastic damping material	210
210-3	Bare concrete slab	210

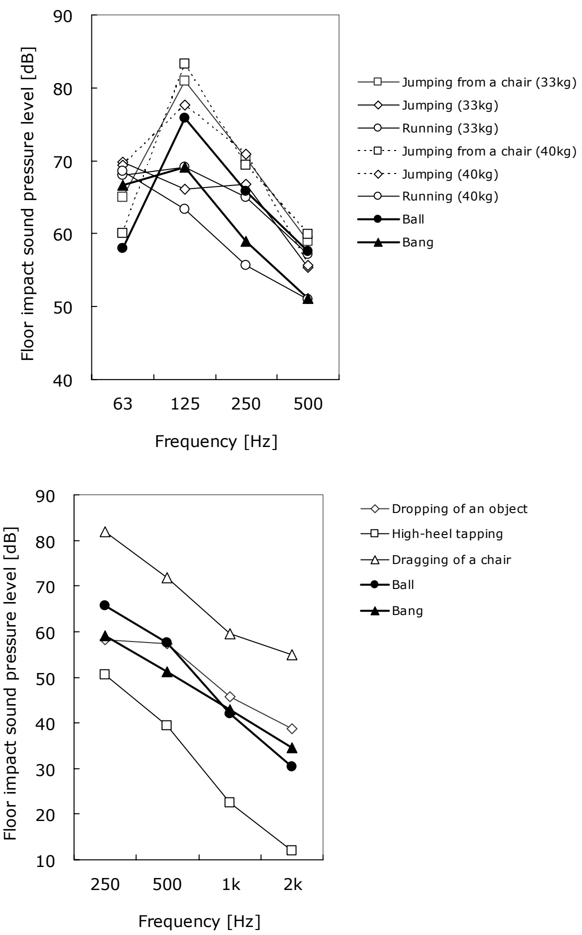


Figure 1. Frequency characteristics of floor impact sounds generated in unit 210-3 (bare concrete slab). (a) Heavy-weight impact sounds and (b) light-weight impact sounds.

Figure 1 compares the impact sound pressure level from the standard impactors with those of the real impact sources generated in the unit with bare concrete slab. As shown in Figure 1(b), even the real impact sounds which are categorized into the light-weight impacts, the frequency characteristic is rather similar to those of the heavy-weight standard impact sources especially at high frequencies above 500 Hz. The correlation coefficient between the sound levels of the standard impact sources and each human impact sounds are listed in Table 2. The correlation coefficient for the tapping machine is much lower than those of the heavy-weight impact sources.

According to JIS A 1419-2 and KS F 2863-2, the measured data for the impact ball and the bang machine is evaluated in accordance with a single-number rating method using the inverse A-weighted impact sound pressure level, $L_{i,Fmax,AW}$. The impact sound pressure level from the tapping machine were calculated according to ISO 717-2 ($L_{n,W}$).

Table 2. Correlation coefficients between the sound levels (31.5-2000 Hz) of each real impact source and standard impactors (Average of 4 units).

	Impact ball	Bang machine	Tapping machine
Jumping (chair, 33kg)	0.90	0.91	0.07
Jumping (floor, 33 kg)	0.89	0.96	-0.14
Running (33 kg)	0.86	0.98	-0.34
Jumping (chair, 40 kg)	0.98	0.92	0.09
Jumping (floor, 40 kg)	0.91	0.95	-0.08
Running (40 kg)	0.86	0.97	-0.35
Dropping an object	0.83	0.82	0.23
High-heel tapping	0.91	0.98	-0.33
Dragging a chair	0.91	0.74	0.42

3. Similarity judgments

The floor impact sounds used in subjective tests were measured in a living room (125 m^2) of an apartment unit. The room was equipped with a set of furniture. The reverberation time in the room was 0.54 s at 500 Hz. Human-made impact sounds were generated by two children jumping on the floor and the jumping down from a sofa to the floor. The children were 5 and 10 years old and weighted 15 and 25 kg, respectively. The heavy-weight impact sound was generated with either the bang machine or the impact ball at the central position of upstairs room. The heavy-weight impact sounds were recorded binaurally through a dummy head (B&K 4100) positioned at the center of the room on the floor below representing the typical listening location of a tenant.

The floor impact sounds recorded were presented to the subjects through headphones in a sound proof chamber. The headphones have a frequency response of ±2 dB (32-500 Hz). Fifteen human-made impact sounds were compared with heavy-weight impact sounds by the impact ball and the bang machine. The sounds were presented in groups with same order. The human impact sound was presented first, and followed by the impact ball and then the bang machine. Fifteen subjects who have normal hearing participated in the experiment. The subjects were asked to judge whether the impact ball or the bang machine was more similar to the human-made impact sound. The session was repeated twice. Two of 15 subjects were excluded due to the inconsistencies of the responses for the two sessions. The result for each human impact sound is shown in Fig. 2. The percentage of the impact ball selection for all human-made 15 stimuli was more than 50 %. The sound jumping from a chair indicated higher percentage than the sound jumping on the floor.

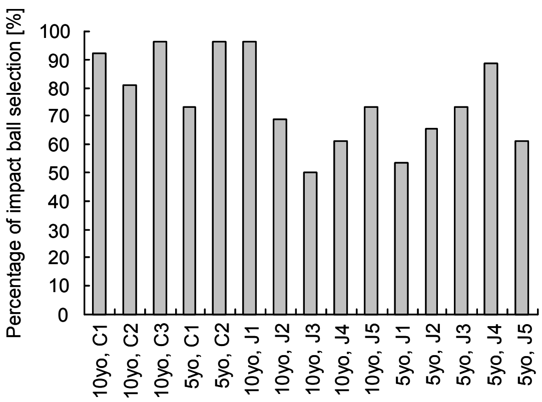


Figure. 2. Percentage of the impact ball selection of similarity judgments. 10yo: 10 years old child; 5yo: 5 years old child; C: Jumping from a chair to the floor; and J: Jumping on the floor.

4. Conversion of floor impact sound levels for standard sources

It was shown that the impact ball sound was judged to be more similar to the real impact sounds. Thus, the impact ball is more appropriate to the standard heavy-weight impact source. As the floor impact noise has been evaluated with the bang machine for past thirty years, a conversion method from the floor impact sound level of the bang machine into that of the impact ball should be proposed to utilize the previously collected bang machine data. This section discusses the method of conversion of the floor impact sound level for the heavy-weight standard impact sources.

To obtain the floor impact sounds with variations in the structure and the sound insulation treatment, more floor impact sound measurements were conducted. Floor impact sounds were recorded in units of 101 reinforced concrete apartments. In every unit of apartments, floor impact sounds were generated at the center of the room upstairs by bang machine and impact ball. The floor impact sounds were recorded binaurally through a dummy head positioned at the center of the room below. The floor impact sound level showed a variation due to the sound insulation treatment, the floor area and the interior finishing, therefore, the idea of the classification of the impact ball sound was introduced. Floor impact sounds for the impact ball whose $L_{i,Fmax,AW}$ values are determined by the levels at 63, 125, and 250 or 500 are classified into Groups A, B, and C, respectively. The frequency characteristics of the floor impact sounds for the bang machine and the impact ball are shown in the Fig. 3. The average sound pressure level for the bang machine and the impact ball for each frequency are shown in Table 3.

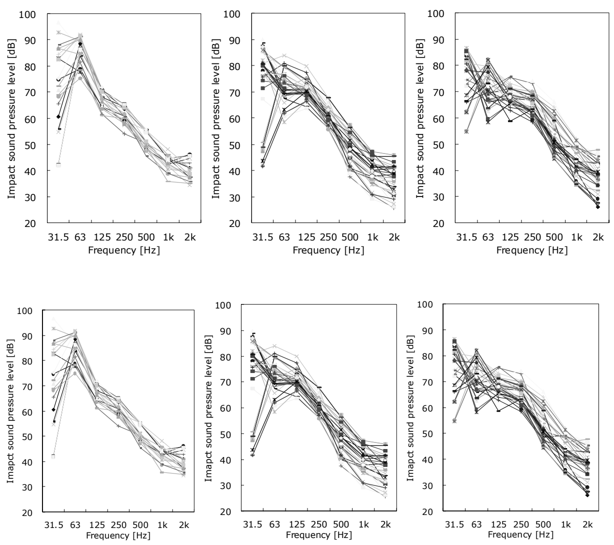


Figure 3. Frequency characteristics of the bang machine (above); and the impact ball (bottom). Group A (left), Group B (middle), and Group C (right).

Figure 4 shows the $L_{i,Fmax,AW}$ of floor impact noises generated by the bang machine and the impact ball. The $L_{i,Fmax,AW}$ of bang machine ranged from 41 to 63 dB where that of impact ball ranged from 45 to 66 dB. It was found that the $L_{i,Fmax,AW}$ of the impact ball could not be simply converted into those of the bang machine. Thus following two conversion methods were investigated.

Table 3. Classified groups of bang machine, tapping machine, and impact ball with different determining frequencies for single number index [dB].

	Frequency [Hz]			
	63	125	250	500
Bang machine				
Total	78.4	67.6	57.2	48.6
Group A	87.1	66.5	55.1	47.4
Group B	75.7	68.2	56.6	47.1
Group C	76.6	67.6	58.9	49.7
Tapping machine				
Total	66.1	69.1	67.8	64.3
Group A	70.5	65.6	66.5	68.1
Group B	66.5	71.2	67.1	61.7
Group C	62.4	68.8	69.5	64.5
Impact ball				
Total	74.7	69.3	62.9	51.3
Group A	85.2	66.9	60.8	51.1
Group B	72.3	71.3	61.4	48.3
Group C	71.2	68.6	65.5	53.2

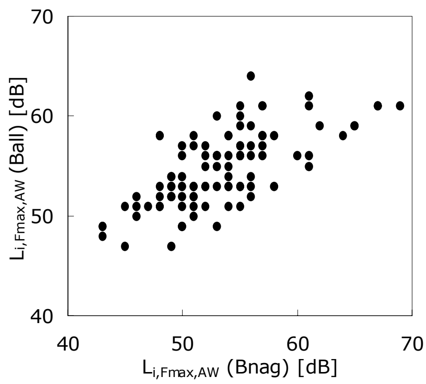


Figure 4. Relationship of the $L_{i,Fmax,AW}$ between the bang machine and the impact ball (r = 0.70).

Conversion method 1: The sound pressure level difference between the impact ball and the bang machine for each group listed in Table 3 was applied to the sound pressure level of the bang machine and then the $L_{i,Fmax,AW}$ was calculated. Figure 5(a) shows the relationship between the measured $L_{i,Fmax,AW}$ for the impact ball and the converted $L_{i,Fmax,AW}$ from the floor impact pressure levels of the bang machine (r = 0.91; p<0.01). In 45 of

101 units, the measured data of the tapping machine is also avairable, thus, the conversion of the sound level from the tapping machine to the bang machine was also investigated. Figure 5(b) shows the relationship between the measured $L_{i,Fmax,AW}$ for the impact ball and the converted $L_{i,Fmax,AW}$ from the floor impact pressure levels of the tapping machine ($r = 0.64$; $p<0.01$).

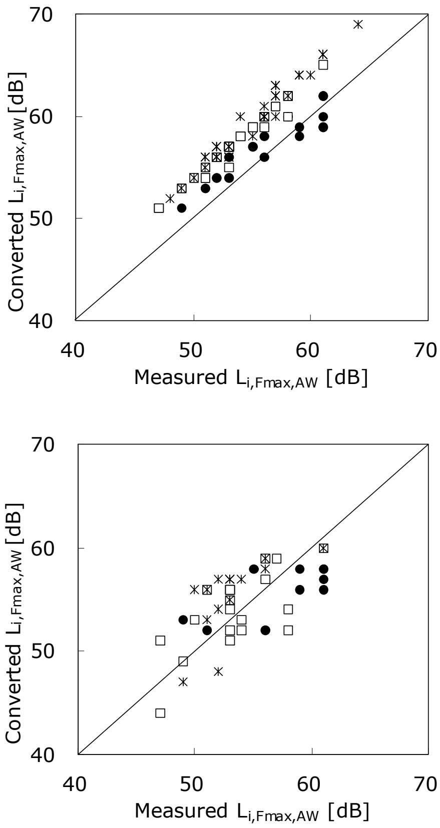


Figure 6. Relationship between the measured and calculated $L_{i,Fmax,AW}$ (method 1). (a) Bang machine, and (b) tapping machine.

Conversion method 2: Another conversion method by using a multiple regression analysis was investigated. The $L_{i,Fmax,AW}$ for the impact ball was calculated by the floor impact pressure level (31.5 to 2k Hz) for the bang machine and the tapping machine. The standardized partial regression coefficients of variables a_1 to a_7 in Eqs. (1) and (2) for each group are listed in Table 4. Figure 7 shows the relationship between the measured $L_{i,Fmax,AW}$ for the impact ball and the calculated $L_{i,Fmax,AW}$ by Eqs. (1) and (2) for each group ($r = 0.84$ and 0.91; $p<0.01$).

$$\begin{aligned} L_{i,Fmax,AW}(\text{ball}) &= a_1L_{max}(\text{bang, 31.5Hz})+a_2L_{max}(\text{bang, 63Hz}) \\ &+a_3L_{max}(\text{bang, 125Hz})+a_4L_{max}(\text{bang, 250Hz}) \\ &+a_5L_{max}(\text{bang, 500Hz})+a_6L_{max}(\text{bang, 1kHz}) \\ &+a_7L_{max}(\text{bang, 2kHz})+c \qquad (1) \end{aligned}$$

$$\begin{aligned} L_{i,Fmax,AW}(\text{ball}) &= a_1L_{eq}(\text{Tapping, 31.5Hz})+a_2L_{eq}(\text{Tapping, 63Hz}) \\ &+a_3L_{eq}(\text{Tapping, 125Hz})+a_4L_{eq}(\text{Tapping, 250Hz}) \\ &+a_5L_{eq}(\text{Tapping, 500Hz})+a_6L_{eq}(\text{Tapping, 1kHz}) \\ &+a_7L_{eq}(\text{Tapping, 2kHz})+c \qquad (2) \end{aligned}$$

Table 4. Standardized regression coefficients of variables a_1, a_2, a_3 and a_4 in Eq. (1) for each group.

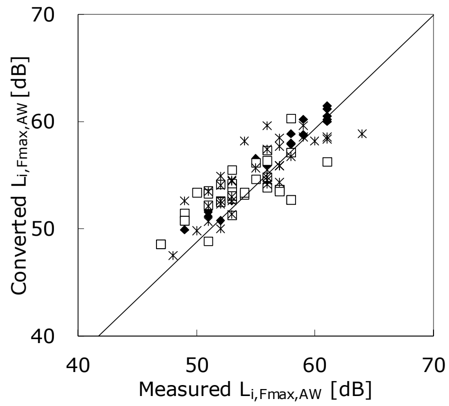
	a_1	a_2	a_3	a_4	a_5	a_6	a_7
Bang							
Total	0.05	0.36	0.23	0.31	0.18	-0.12	0.21
A	-0.43	1.02	0.42	0.21	-0.27	-0.02	-0.01
B	-0.01	0.16	0.23	0.51	-0.35	-0.05	0.42
C	-0.19	-0.03	0.25	0.21	0.56	-0.08	-0.03
Tapping							
Total	0.38	0.30	0.13	0.41	-0.05	-0.82	0.98
A	0.32	0.65	0.27	-0.26	0.08	-0.05	0.09
B	-0.01	0.13	0.39	0.69	0.23	-2.40	2.22
C	0.13	0.33	0.62	0.11	0.06	-0.44	0.28

**: $p<0.01$

4. Remarks

Objective and subjective evaluations of the real floor impact sources and standard floor impact sources were conducted. The results of the subjective tests showed that the floor impact sound generated by the impact ball is a more similar human-made impact sound than that of the bang machine. Thus, the impact ball is more appropriate to the standard heavy weight impact source both for subjective and objective evaluation.

The floor impact sounds by the impact ball, the bang machine, and the tapping machine were measured in various types of units. The $L_{i,Fmax,AW}$ of the impact ball and the bang machine did not correlated well, therefore two the methods of conversion of the floor impact sound level generated the bang machine to that of the impact ball were investigated. The conversion method by multiple regressions gave more reliable results.



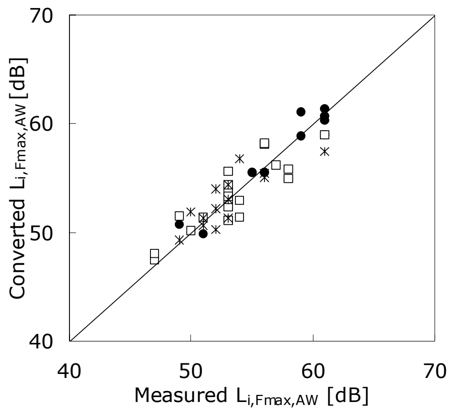


Figure 7. Relationship between the measured and calculated $L_{i,Fmax,AW}$ (method 2). (a) Bang machine, and (b) tapping machine.

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