Objective and Subjective Evaluation of Floor Impact Noise

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Floor impact noise has been evaluated by investigating the temporal and spectral characteristics of the noise. The noises generated by different impactors were analyzed to find out whether there is any correlation with the factors of ACF/IACF (Autocorrelation Function/Inter-aural Cross-correlation Function) [1] and Zwicker parameters [2]. Experiments were undertaken to compare the objective and subjective parameters of the floor impact noises generated by a bang/tapping machine, a rubber ball [3], and a walker. As a result, it was found that Φ(0) and IACC extracted from ACF/IACF, and Loudness, Unbiased Annoyance from Zwicker parameters showed high correlation with subjective evaluations of loudness concerning floor impact noises. In addition, it was revealed that jumping is similar to the ball.

Keywords: floor impact noise, subjective evaluation, ACF/IACF, Zwicker parameteres

1. INTRODUCTION

Floor impact noise has been regarded as the most irritating among the noises in multi-story residential buildings. With increasing demands from residential groups, it is likely that new regulations to control the impact of noise will be established. However, the general problem in evaluating the impact noise is the standard noise source; both the tapping and the bang machine have been widely used, but using a soft impactor known as a 'rubber ball' has not been standardized in ISO. Psychoacoustical characteristics of the noise, such as ACF/IACF (auto-correlation/interaural cross-correlation function) factors and Zwicker's parameters, have not been fully acknowledged.

In this paper, we analyzed the statistical sound pressure levels, the ACF/IACF factors and Zwicker's parameters extracted from floor impact noise generated by operating the tapping machine and the bang machine, and dropping a rubber ball together with a child's jumping. For the noise sources, auditory experiments were undertaken to evaluate people's loudness perception of floor impact noise. The main purpose of the experiments is to find out the physical and psychoacoustical parameters which have a high correlation with subjective loudness. At the same time, selecting a floor impact noise source, which has the highest correlation with subjective reaction among three floor impact noise sources, is also pursued.

Through the results of the experiments, we would like to choose a proper noise source, which is most similar to a children's jumping in points of objective and subjective evaluations, and to utilize it as a standard method to evaluate the reduction ability of floor impact noise in multi-story residential buildings. Also, the results could set the direction for actualizing the residential environment, which make inhabitants realize the acoustical improvement of the floor impact noise and to make use of them as floor impact reduction evaluations by evaluating psychoacoustical factors.

In Germany, in 1932, Reiher developed the evaluating method of floor impact noise using a tapping machine. In 1953, Germany industrially standardized the method for measuring floor impact noise from laboratory and in-situ experimentation (DIN-52211) and for the first time established a structure construction guide (DIN 4109) for floated floors. With these results, many countries have established their measuring method since 1950.

In 1965, Watters [4] reported the experimental results about the characteristics of floor impact noise in terms of the floor impact spectrum of the tapping machine and women's high-healed shoes. However, Olynyk and Northwood [5] reported that the noise evaluation using a tapping machine is difficult to replicate the real impact characteristics of a floor. In addition, they claimed that the FHA (U.S. Federal Housing Administration)'s evaluation curve is different from the results

Table 1. List of treatment of sound insulation for the original structure and nine other structures.

Component	Original	S1	S2	S3	S4	S5	S6	S7	S8	S9
Floor		●		●			●		●	
Ceiling		●	●		●		●	●		
Wall						●	●	●	●	●

of their loudness perception tests. Belmondo et al. [6] found that the ISO method using the tapping machine doesn't simulate inhabitant's walking on wood structured buildings. Similar experiments on the difference between the floor impact sound source and the real noise have been undertaken; Istvan [7] investigated a hard floor with elastic surface material, and evaluated the impact of noise in a floating floor. Shi et al. [8] revealed that the frequency characteristics of a falling a sand ball from a certain height is similar to the frequency characteristic of real impact noise after comparing the characteristics of the impact noise caused by the sources, such as walking, running, jumping, a sand bag, a sand ball, a tire and a tapping machine. Stewart et al. [9] suggested SEA (Statistical Energy Analysis) as a predicting method of floor impact noise. Recently, Warnock [10] of the NRC (National Research Council of Canada) confirmed that the loudness of real impact noise is similar to the loudness of lightweight impact (tapping) noise.

In Japan, in 1965, the "Law for Housing Construction Plan" was announced, and also in 1973, "the experimental method for measuring floor impact noise (JIS A 1418)" was established. After that, the measuring method for heavyweight impact noise was developed for Japanese residential situations, and the sound isolation material such as "Rock wool shock-absorbing material for floated structure (JIS A 9321)" was classified. The national standards for sound isolation and the design guides of buildings were then proposed. In the early 1970's, the Japanese Housing Corporation regulated indoor noise criteria and noise control methods that stimulated the research (e.g., [11]) to prevent floor impact noise. In the mid 1980's, the research for predicting floor impact noise using Finite Element Method (FEM), Modal Analysis and Impedance Method has been actively undertaken. Lately, Tachibana et al. [12] suggested Zwicker's Loudness as an exact noise measure through auditory experiments on subjects who are exposed to low frequency noise, and they also proposed the arithmetic mean of sound pressure levels in octave bands as a single measure.

In Japanese standards, both lightweight (tapping machine) and heavyweight (bang machine – 'tire') impact sources are utilized. Through the recent improvement of measuring and

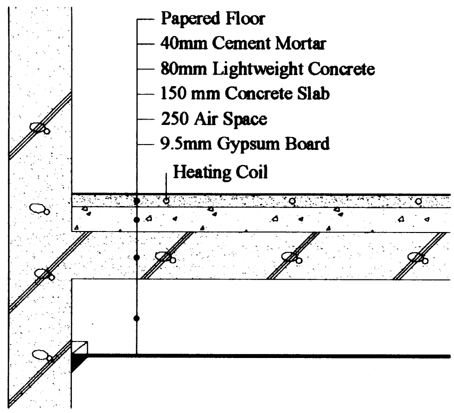


Fig. 1. A detailed section of an apartment floor.

evaluating methods for floor impact noise, a 'rubber ball' was suggested as the second heavy impact source. Tachibana [3] found that a rubber ball has similar frequency characteristics to real impact noise for several floor structures. Very recently in Japan, the grade for floor impact noise was divided into five grades in the law for housing quality control [13].

2. EXPERIMENTAL METHOD

2.1 Noise Stimuli

Measuring and recording were performed in a four-bedroom apartment (140m^2), which has a reinforced concrete structure. Ten suites of the apartment were selected for floor impact noise measurements. The measuring condition of the place was just before moving-in after completing construction. The floor structures of ten suites consist of one standard floor that was maintained as an original structure and nine other structures that were constructed under different conditions for reducing floor impact noise (see Table 1). The floor structure of a standard suite consists of floor finishing material (varnished paper) + mortar (50 mm) + lightweight concrete (80 mm) with heating pipe + reinforced concrete slab (150 mm) + air space (250 mm) + plaster board (10 mm) as shown in Fig. 1.

In measuring impact noise from the floors JIS A 1418 was applied. The newly regulated 'Ball' (JIS A 1418-2, 2000) was added to the present experiment. The floor impact was given at five points, and the noise was measured and recorded at the center point underneath.

A dummy head (B&K 4100) and DAT were used for binaural recording of the noise sources. For auditory experiments and psychoacoustical analysis, tapping machine (ISO 140-7:1998), bang machine (tire, JIS A 1418-2), rubber ball (JIS A 1418-2:2000) and jumping as real impact noise were recorded. Since jumping noise is the most frequently produced sound during an adult's walking and a child's playing in multi-story residential buildings, we reproduced the situation such that an adult (in 20s, 65–70kg) jumps on the spot.

Based on JIS A 1419, floor impact noise was analyzed from the ten floors. Figure 2 represents the comparison of average impact levels in each frequency obtained from the ten floors, which consists of real floor impact noise, a tapping machine, a bang machine and a rubber ball. As shown in Fig. 2, the frequency characteristics of jumping in the maximum sound pressure level is similar to those of the bang machine and the ball. Especially, the rubber ball seems closer to the jumping. The ranks of the floor impact noise shown in Fig. 2 were determined as Grade 4 in heavyweight and Grade 2 in lightweight according to the Japanese law for housing quality control [13].

2.2 Equipment for Auditory Perception Tests

There are two methods of presenting sound sources; an electrostatic headphone (Senheiser HD-600) was used for the binaural hearing experiment, and a loudspeaker (Bose-101) was used for the monaural hearing experiment. Both experiments were performed in a testing booth that has approximately 25 dBA of background noise. The size of the booth is 2.1 m x 2.6 m x 2.0 m and it has approximately 0.2 sec of reverberation time, and a window was installed in the booth. A desktop computer with MEDS (Musical Experiment Development System) was used to put the subjective reactions on record. A Korg 1212-I/O sound card with Crown CE-100 power amplifier was used to present sound sources.

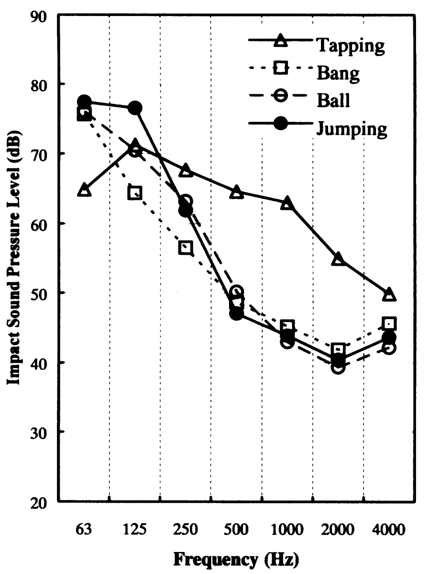


Fig. 2. Floor impact noise from different impact devices.

2.3 Experimental Design

A 1:1 comparison (pair comparison) method was used to investigate the subjective evaluation on the difference between physical data and psychoacoustical parameters. The noise source from the fundamental structure as shown in Figure 1 was used as standard stimulus (S), and nine comparison stimuli (C) were obtained from the floor impact noise sources recorded in different floor structures to reduce the floor impact noise. The presented impact noise levels to subjects were set up with the recorded sound pressure levels. The purpose of the comparison is to verify the auditory perception according to the small changes in the physical and psychoacoustical elements for the floor impact noise reduction. For the three noise sources (tapping, bang and ball), the standard floor was compared with the nine comparison floors by making the order as S-C, C-S to repeat twice each. The present auditory experiment provided a total of 108 comparisons. As shown in Figs. 3(a) and 3(b), there are two sound pairs in each comparison; the first pair is presented with 1.6 sec of stimuli having 0.5 sec of ISI (inter-stimulus interval) and, after 1 sec of interval, the second pair (0.8 sec each) was followed for subjects' confirmation of judgments. As shown in Fig. 3(b), in the case of heavyweight impact noise, two repeated noises are presented in the first pair and a single noise is followed in the second pair.

Loudness evaluation in a pair comparison was set up to respond on a five scale score (-1, -0.5, 0, +0.5, +1). Subjects were asked whether the first stimulus is much bigger (>>) or a little bit bigger (>), or both are equal (=), or the second

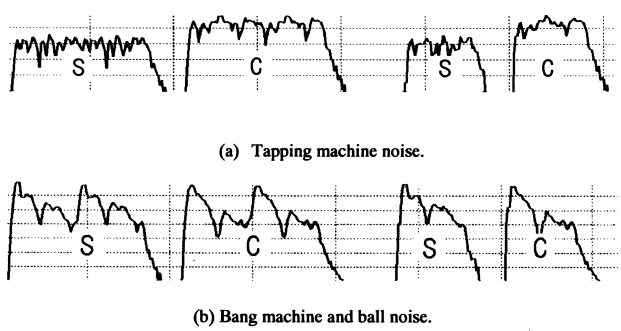


Fig. 3. Pair structures of noises for auditory experiments.

stimulus is a little bit bigger (<) or much bigger (<<). The order of sound stimuli varied in a pair and was presented randomly. If the loudness of comparison stimulus (C) from the modified floor structure is much smaller than the loudness of standard stimulus (S) from the basic floor structure, the scale score is -1. If vice versa, the scale score is +1. The evaluation task took approximately 15 min and the second experiment was undertaken for another 15 min after approximately five to ten min breaks. Before each test, subjects were trained to type their responses in keys for all kinds of sound sources and to respond to only the 'loudness' of given sound sources.

2.4 SUBJECT

Total numbers of subjects for the hearing experiments was 30 each for monaural and binaural signals. They were university students (both undergraduate and postgraduate) and researchers aged from 24 to 41 consisting of 27 males and 3 females. Almost half of the subjects had experienced similar auditory experiments previously and half from the total lived in a multi-story residential building.

3. PSYCHOACOUSTICAL EVAUATION

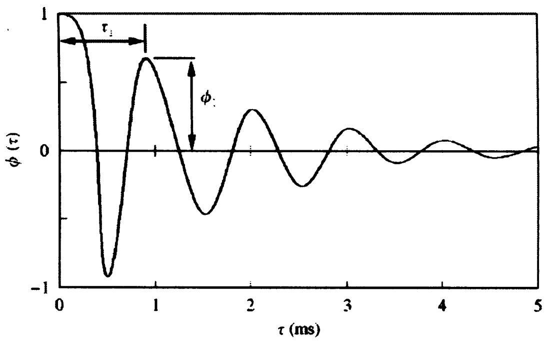
The impact noises were analyzed to find out whether there is any correlation with the ACF/IACF factors and Zwicker parameters. Ten concrete slabs with different acoustical treatments were tested to find out whether there is any correlation between the psychoacoustical parameters.

3.1 ACF/IACF Factors

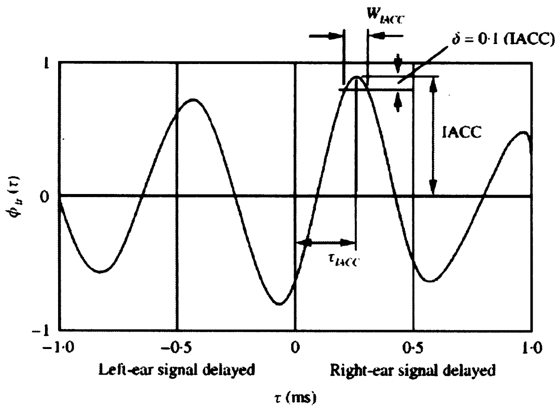
The ACF/IACF for identification and evaluation of environmental noise suggested by Ando [14] consist of 8 factors. The definition of each factor is shown in Fig. 4 and Table 2 [1].

In the previous analysis [15] on floor impact noise using ACF/IACF, it was found that the subjective evaluations of floor impact noise was related with Φ(0) and IACC. Based on the results, when the ACF/IACF factors for the three impact noise sources were analyzed as a function of time, supporting results were found as shown in Fig. 5. In Fig. 6(a), both impact noises from the bang machine and the ball produce similar variation in energy with time to jumping noise, whereas the bang machine produces more fluctuating values of IACC as shown in Fig. 5(b). The spatial effect of noise was discussed earlier [15] as an influential factor on loudness and noisiness perception. In this experiment, it was also revealed that, although the noises from the standard impactors show similar impact sound pressure level, neither bang noise nor tapping noise conforms to jumping noise in terms of spatial influence.

In addition to the result of the experiment, the relationships



(a) Definitions of τ_1 and ϕ_1 for the normalized ACF



(b) Definitions of the IACC, τ_{IACC}, W_{IACC} descriptors from IACF

Fig. 4. Definitions of ACF/IACF factors

Table 2. Descriptions of ACF/IACF factors.

Symbols	Descriptions
Φ(0)	Energy represented at the origin of the delay (dB)
τ_e	Effective duration of the envelope of the normalized ACF (ms)
τ_1	Delay time of the first peak (ms)
ϕ_1	Amplitude of the first peak
IACC	Magnitude the inter-aural cross-correlation
τ_{IACC}	Inter-aural delay time at which the IACC is defined (ms)
W_{IACC}	Width of the IACC at the τ_{IACC}

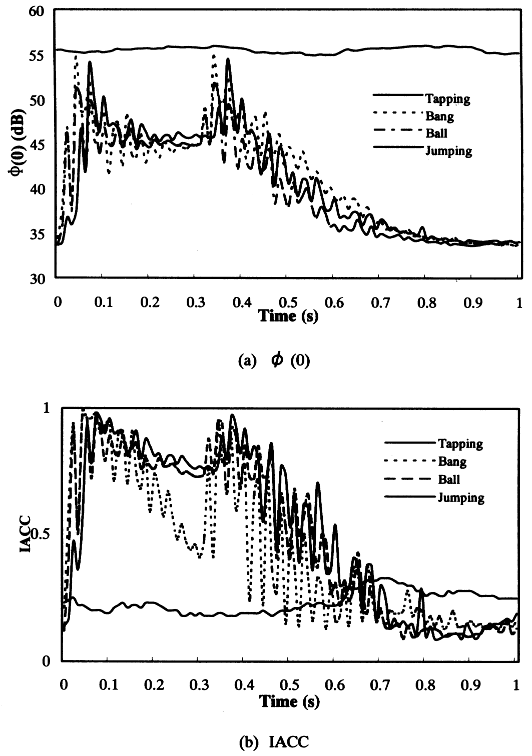


Fig. 5. Measures of related parameters for different impactors: (a) Φ(0), (b) IACC.

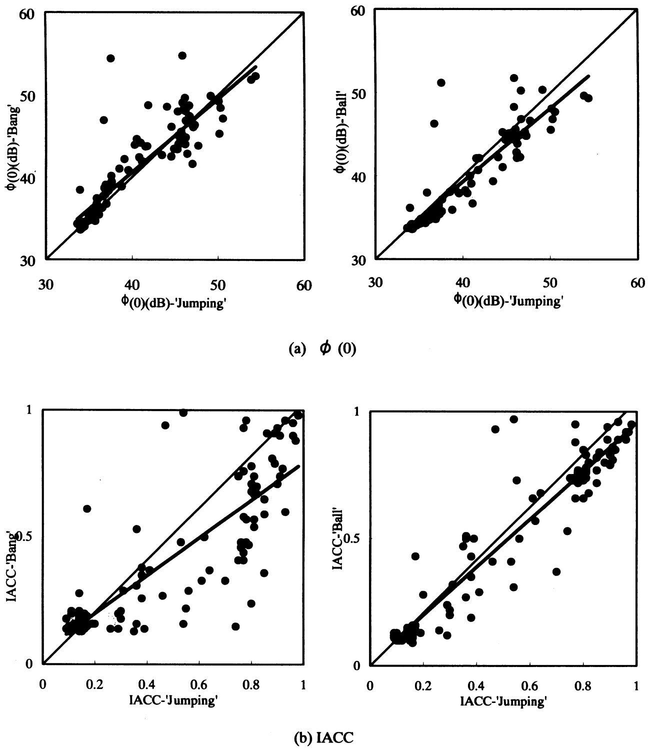
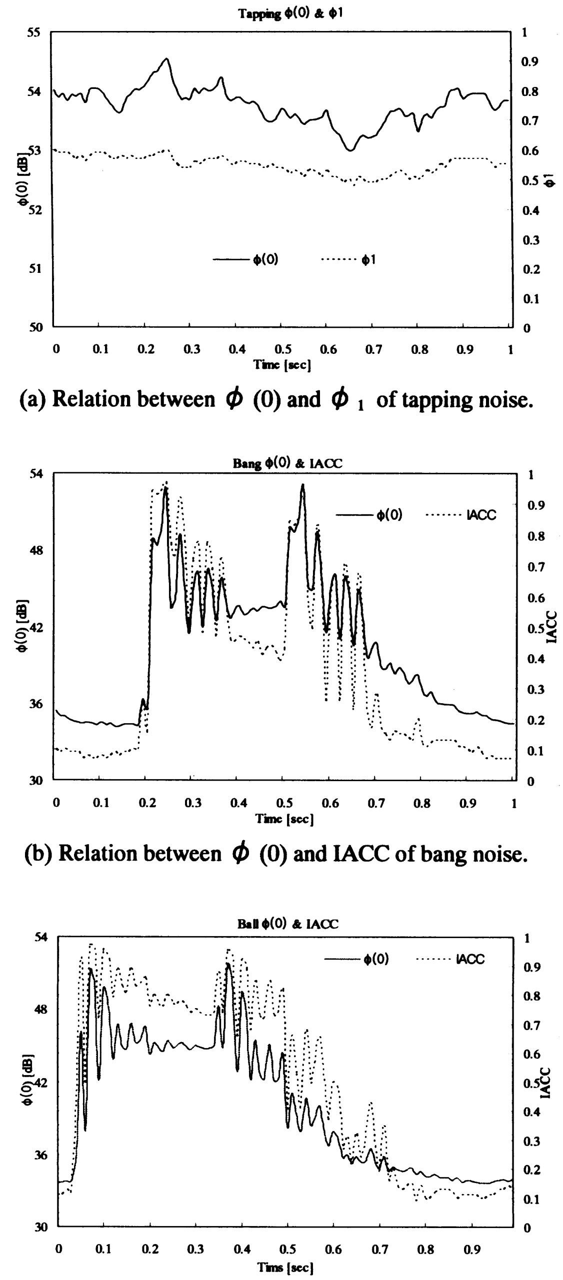


Fig. 6. Relation of different impactors: (a) Φ(0), (b) IACC.



(a) Relation between ϕ (0) and ϕ_1 of tapping noise.

(b) Relation between ϕ (0) and IACC of bang noise.

(c) Relation between ϕ (0) and IACC of ball noise.

Fig. 7. Relation of Φ(0) and other ACF/IACF factors.

between the impact noise sources and jumping in terms of Φ(0) and IACC are shown in Fig. 6. Figure 6 also shows the similarity of both bang noise (Φ(0) $r = 0.88$, $p < 0.01$; IACC $r = 0.82$, $p < 0.01$) and ball dropping noise (Φ(0) $r = 0.91$, $p < 0.01$; IACC $r = 0.943$, $p < 0.01$) with jumping noise. Consequently, ball noise is most similar to real impact noise (jumping) among the three standard impact noise sources.

For each of ten sound sources that were used for auditory experiments, ACF/IACF factors were analyzed. As a result, it was found that Φ(0) of lightweight impact noise has high correlation with ϕ_1 as shown in Fig. 7(a) ($r = 0.88$, $p < 0.05$). In addition, it was revealed that Φ(0) of heavyweight impact noise generated by Bang Machine and Rubber Ball has high

Table 3. Descriptions of Zwicker parameters.

Parameters	Descriptions
Loudness [sone]	Measure of sound energy
Sharpness [acum]	Description of the level of acuteness
Fluctuation **S**trength [vacil]	The sound models for frequencies fmod perceived to be less than 20 Hz
Roughness [asper]	Criteria to identify the perturbing effect of mid-frequency (20~300 Hz) modulation
Tonality [tu]	Quantity of tonal components in a spectrum of a signal
Unbiased **A**nnoyance [au]	Combination of the parameters (Sharpness, Fluctuation Strength, and Loudness 10%)

Table 4. Correlation coefficients for different noise impactors calculated from the results of measurements in Zwicker parameters (**Bold** > 0.70).

	Loudness				Unbaiased Annoyance			
	Jumping	Bang	Tapping	Ball	Jumping	Bang	Tapping	Ball
Jumping	1.00				1.00			
Bang	0.93	1.00			0.70	1.00		
Tapping	0.81	0.83	1.00		0.63	0.48	1.00	
Ball	0.84	0.81	0.86	1.00	0.74	0.46	0.85	1.00

correlation with IACC as shown in Figs. 7(b) and 7(c), respectively (Bang Machine r = 0.96, $p < 0.05$, Rubber Ball = 0.98, $p < 0.05$).

This result shows that, in case of lightweight impact noise, the change of sound energy accompanies the change of the pitch of tapping noise. On the other hand, in case of heavyweight impact noise, the change of the spatial factor of bang noise is followed by the change of sound energy.

3.2 Zwicker Parameters

Zwicker parameters, which have been defined in order to take account of the subjective nature of human perception and judgment of sound quality, reflect both frequency and temporal masking with application of equal loudness contours. In this study, six parameters as shown in Table 3 were analyzed for the noise sources.

The parameters that have high correlation are shown in Table 4. After analyzing six Zwicker parameters for ten different slabs, the correlation coefficients between floor impact noises were calculated. As shown in Table 4, loudness and unbiased annoyance of floor impact noise generated by the bang machine and the ball are correlated with those of jumping noise.

4. OBJECTIVE AND SUBJECTIVE EVALUATION

By analyzing the correlation among the subjective responses to the floor impact noises, the physical data and the psychoacoustical factors, the floor impact noise that is highly correlated with subjective evaluation was chosen. Figure 8 shows the scale values of loudness as a function of objective and subjective parameters that are highly correlated with subjective evaluations of floor impact noise. 9 plots for each impactors in Fig. 8 represent differences of loudness perception between the standard structure and nine other structures. The objective parameters out of ACF/IACF factors are calculated as the mean values for 1 sec of the noise.

Fig. 8(a) shows the relation between subjective response and $\Phi(0)$. It reveals that the subjects' evaluation of floor impact noise has high a correlation with $\Phi(0)$. The correlation coefficient of the scale values with tapping noise is 0.90 ($p < 0.01$), bang noise 0.92 ($p < 0.01$) and ball noise 0.93 ($p < 0.01$). Figure 8(b) shows the relation between subjective response and Leq. The correlation coefficient with tapping noise is 0.96 ($p < 0.01$), bang noise 0.98, ball noise 0.89 ($p<0.01$). Figure 8(c) shows the relation between subjective response and Lmax. The correlation coefficient with tapping noise is 0.96 ($p<0.01$), bang noise 0.94 ($p<0.01$) and ball noise 0.94 ($p<0.01$). All of three factors $\Phi(0)$, Leq, Lmax- have high correlations with loudness perceptions of floor impact noise.

From Zwicker parameters, Loudness and Unbiased Annoyance of the floor impact noises are highly correlated with loudness perception. Figs. 8(d) and 8(e) show the relation among Loudness, Unbiased Annoyance and subjective evaluation. The correlation coefficient of the scale values with Loudness in tapping noise is 0.94 ($p < 0.01$); bang noise 0.74 ($p < 0.01$) and ball noise 0.94 ($p < 0.01$). In addition, the correlation coefficient with Unbiased Annoyance in tapping noise is 0.92 ($p < 0.01$); bang noise 0.72 ($p < 0.01$) and ball noise 0.76 ($p < 0.01$). The results also show that Loudness

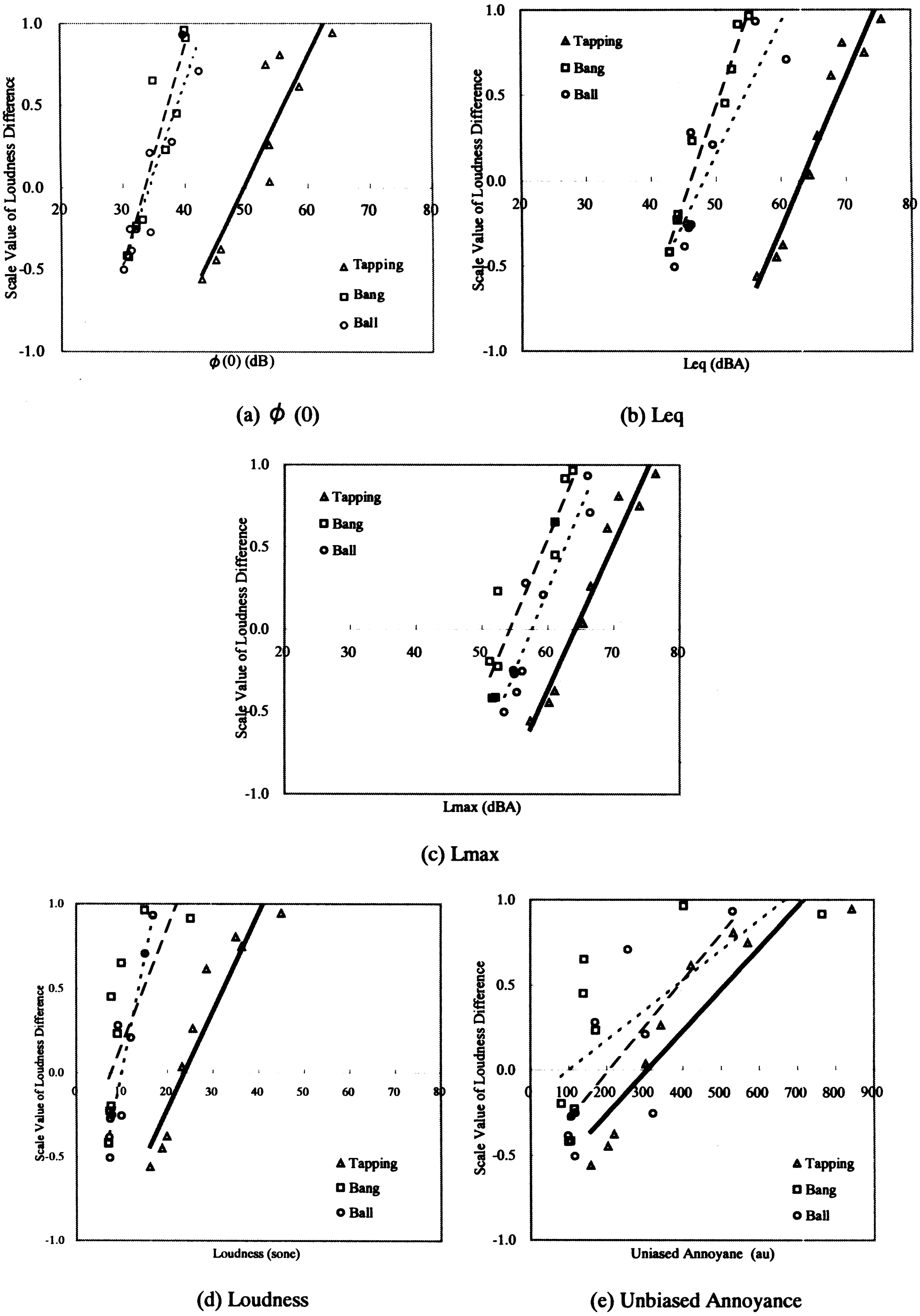


Fig. 8. 10 Subjective evaluations of floor impact noises in relation to objective parameters.

and Unbiased Annoyance are highly correlated each other.

From the result of the high correlation coefficients with tapping noise, it seems that Zwicker parameters are more consistent with lightweight impact noise that is continuous noise than heavyweight impact noise, which is intermittent noise. It was also found that loudness perception of tapping noise is highly correlated with $\Phi(0)$ ($r = 0.90$; $p < 0.01$), τ_e ($r = 0.66$; $p < 0.01$) and τ_1 ($r = 0.84$; $p < 0.01$) among ACF factors, whereas, in the case of heavyweight impact noise (bang or ball noise) which is occasional, only $\Phi(0)$ affects on the perception of loudness.

To calculate the subjective loudness from each impact source, multiple regression analyses were examined for six Zwicker parameters and the mean of the ACF/IACF factors except SPL (SPL was excluded due to multi-colinearity with Φ(0)). All possible combinations were examined to obtain an optimal model. The regression equations of subjective loudness for lightweight impact noise were shown as Eqs. (1-1) and (1-2);

$$SV_{\text{Loudness Tapping}} = -17.761 + 0.065\Phi(0) + 11.51\tau_1 - 1.45\phi_1 \quad (1\text{-}1)$$

$$SV_{\text{Loudness Tapping}} = -5.731 + 0.25\text{L} + 2.23\text{FS} + 1.16\text{T} - 0.0076\text{UA} \quad (1\text{-}2)$$

Using these tentative values for Eqs. (1-1) and (1-2), the total correlation coefficients 0.94 and 0.98, respectively, were obtained with the significance level $p < 0.05$. These results show that the change of sound pitch as well as sound energy is the important factor for subjective evaluation of loudness of lightweight impact noise.

The regression equations of subjective loudness for heavyweight impact noise caused by bang machine and rubber ball were shown as Eqs. (2) and (3), respectively;

$$SV_{\text{Loudness Bang}} = -3.691 + 0.147\Phi(0) - 0.251\tau_e - 3.83W_{\text{IACC}} \quad (2\text{-}1)$$

$$SV_{\text{Loudness Bang}} = -0.534 + 0.22\text{L} \quad (2\text{-}2)$$

$$SV_{\text{Loudness Ball}} = -4.754 + 0.121\Phi(0) - 0.2021\tau_e - 1.01\text{IACC} + 0.992\tau_{\text{IACC}} \quad (3\text{-}1)$$

$$SV_{\text{Loudness Bang}} = -1.431 + 0.177\text{L} + 0.24\text{FS} - 0.0012\text{UA} \quad (3\text{-}2)$$

Using these tentative values for Eqs. (2-1), (2-2), (3-1) and (3-2) the total correlation coefficients 0.96, 0.74, 0.98 and 0.95, respectively, were obtained with the significance level $p < 0.05$. These results show that the change of spatial factors as well as sound energy is the important factor for subjective evaluation of loudness of heavyweight impact noise.

5. CONCLUSIONS

Floor impact noise with a tapping machine, a bang machine and a rubber ball which are regulated by ISO and JIS were analyzed by the method of JIS A 1419 and the psychoacoustical factors of the noises from ten slabs that have different structures and frequency characteristics were compared with loudness evaluations of subjects. As a result, real sound source implemented with jumping noise on upper floor has similar perceptual characteristics to heavyweight impact noise, especially the noise generated by the rubber ball.

After analyzing correlations of the ACF/IACF factors obtained from ten different floor structures as a function of time, it was found that the correlation between ACF factor Φ(0) and IACF factor IACC was high for heavyweight impact noise, especially ball noise. Lightweight impact noise has high correlation between Φ(0) and ϕ_1. Therefore, it can be concluded that, in the case of heavyweight impact noise, loudness is related with IACC and, in the case of lightweight impact noise, it is related with ϕ_1.

The relation between loudness perception and physical and psychoacoustical factors for the three noise sources were analyzed. Results showed that subjective evaluations are mostly affected by Φ(0), Leq, Lmax, and Zwicker Loudness and Unbiased Annoyance. Among these, especially Φ(0) and IACC had high correlation with heavyweight impact noise, and, therefore, loudness of heavy weight noise seems to be realized both with sound pressure level and spatial information of the noise. Zwicker Loudness was highly correlated with lightweight impact noise. It was revealed that loudness perception of constant noise generated by tapping machine is affected by Φ(0), τ_e and ϕ_1. Through these results, we can find that the loudness of lightweight impact noise can be easily perceived by variation of sound pressure level with time. It can be concluded that loudness perception of heavyweight impact noise can be expressed by the loudness factors extracted from ACF/IACF and lightweight impact noise can be expressed by the ACF factors, Loudness and Unbiased Annoyance.

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