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SUBJECTIVE EVALUATION OF HEAVY-WEIGHT IMPACT SOUNDS GENERATED BY AN IMPACT BALL

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Abstract

Subjective evaluations of heavy-weight impact sounds generated by an impact ball on reinforced concrete floors in apartment buildings were conducted in order to investigate the effect of loudness and annoyance of floor impact noise. The heavy-weight impact sounds were recorded through dummy heads and classified according to the frequency characteristics of the floor impact sounds. The characteristics of the floor impact noise were investigated by paired comparison tests and semantic differential tests. Sound sources for auditory experiment were selected based on the actual noise levels with perceptual level differences. Auditory experiments were also conducted to investigate the relationship between level indices and subjective responses. The results show that L_{Aeq} and L_{Amax} are highly correlated with subjective response to heavy-weight impact sounds.

1. INTRODUCTION

Heavy-weight impact sound is evaluated in terms of a maximum sound pressure level (SPL) known as $L_{iFmax,AW}$. However, even if $L_{iFmax,AW}$ is same, the subjective response to two impact sounds can be different. It has been recognized that objective parameters other than noise level may affect the perception of the noise source. As heavy-weight impact sound is important issue affecting apartment livability, it is needed to investigate the factors affecting the perception of heavy-weight impact sounds.

Jeon et al. [1] investigated the ACF and IACF factors of floor impact sound as well as the relationship between those factors and the perception of loudness. Sato et al. [2] conducted subjective tests to obtain scale value of annoyance of heavy-weight impact sounds and investigated the relationship between scale values and ACF/IACF parameters. These studies show that temporal and spatial fluctuation had an effect on annoyance as well as the SPL and its fluctuation. For SPL matrices in environmental noises, it has been suggested that L_{Aeq} shows better correlation with subjective responses than L_{Max} [3]. Zwicker's Loudness Level (LL_Z) and the arithmetic average of SPLs were recommended as an indicator of heavy-weight impact sounds [4].

Although impulsive sounds are often evaluated by the maximum levels, such as L_{max} and L_{Amax}, some studies showed that the L_{Aeq} of heavy-weight impact sounds is more highly correlated with subjective responses than the maximum sound level indices [3]. So far, there is a need for a valid indicator for perceived loudness and annoyance of heavy-weight impact sounds. The purpose of this study is to investigate the subjective responses to heavy-weight impact sounds. Measured heavy-weight impact sounds were classified into groups based on the frequency characteristics. Subjective tests were then conducted to investigate the characteristics of the groups. Finally, evaluation metrics of heavy-weight impact sounds, which were highly correlated with subjective response, were sought.

2. CLASSIFICATION OF HEAVY-WEIGHT IMPACT SOUNDS

2.1 Measurements of heavy-weight impact sounds

Heavy-weight impact sounds were generated in the centre of the upstairs room by an impact ball. Floor impact sounds were recorded in 31 box-frame type reinforced concrete apartment units using a binaural microphone (B&K Type 4100). The concrete slab thickness in the apartments varied from 150mm to 180mm. The majority of apartments tested had an area of around $100m^2$, which is the most common sized apartment in Korea.

An inverse A-weighted reference curve is used to determine $L_{i,Fmax,AW}$ which is prescribed in KS and JIS as a single number rating for heavy-weight impact sounds. When the measured maximum SPLs (L_{max}) were plotted against four-octave band frequencies from 63 to 500Hz, the fitting procedure allows for a total deviation of 8 dB above the inverse A-weighted reference curve in each of the four-octave bands. The $L_{i,Fmax,AW}$ is then the impact SPL at 500 Hz on the inverse A-weighted reference curve. Frequency characteristics of recorded sounds varied according to the floor structure, floor plan and finishing material as shown in Figure 1. The heavy-weight impact sound level, $L_{iFmax,AW}$, ranged from 43~66 dB and the light-weight impact sound level, L_{Aeq}, ranged from 39~61 dB. The frequency characteristics of averaged impact sound levels were similar to those of impact force exposure levels.

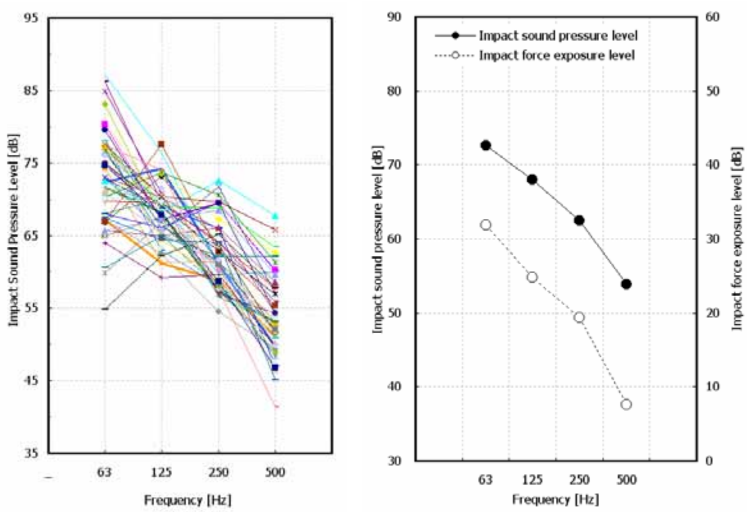

Figure 1. (a) Frequency characteristics of heavy-weight impact sounds, (b) Comparison of sound pressure levels with impact force exposure level

2.2 Classification of heavy-weight impact sounds

As shown in Figure 2, heavy-weight impact sounds were classified on the basis of their main frequency range determined with an inverse A-weighted reference curve and equal loudness contour. Heavy-weight impact sounds were categorized into three groups which indicated that deviation above the inverse A-weighted reference curve was the highest at 63, 125, and 250 Hz, respectively. Equal loudness contours also show the relationship between frequency and SPL for tones set at equal loudness. When the L_{max} values are plotted on the equal loudness contour, it is easily determined at which frequency bands the sound pressure level is heard loudly.

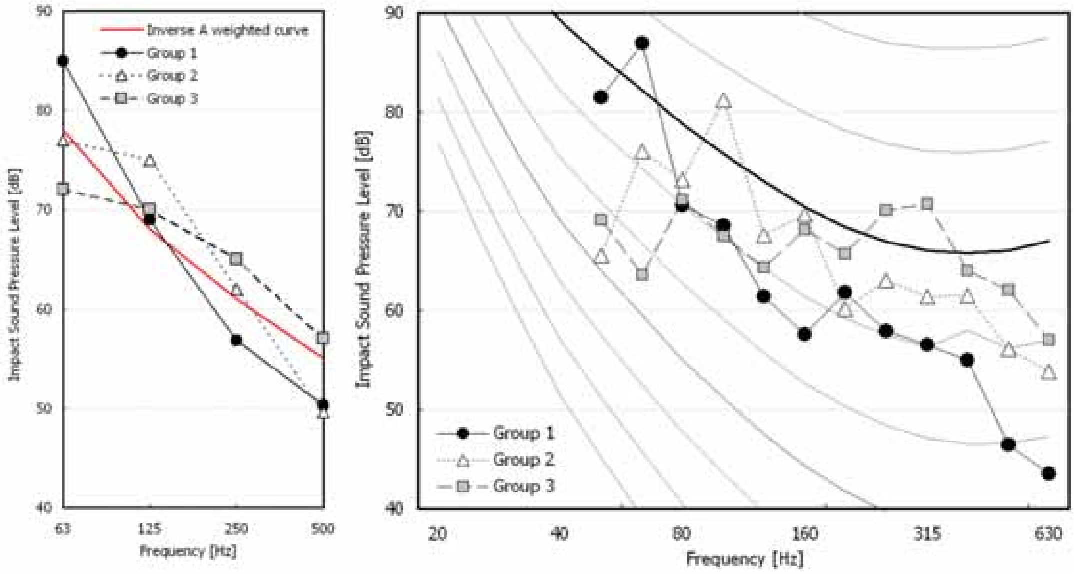

Figure 2. Classification method (a) inverse A-weighted reference curve, (b) equal loudness contour

When the classification was conducted using inverse A-weighted reference curve, Group 1~3 had 8, 48, and 15 sound sources, respectively. Classification result using equal loudness contour showed almost similar results. Frequency characteristics of each group are shown in Figure 3.

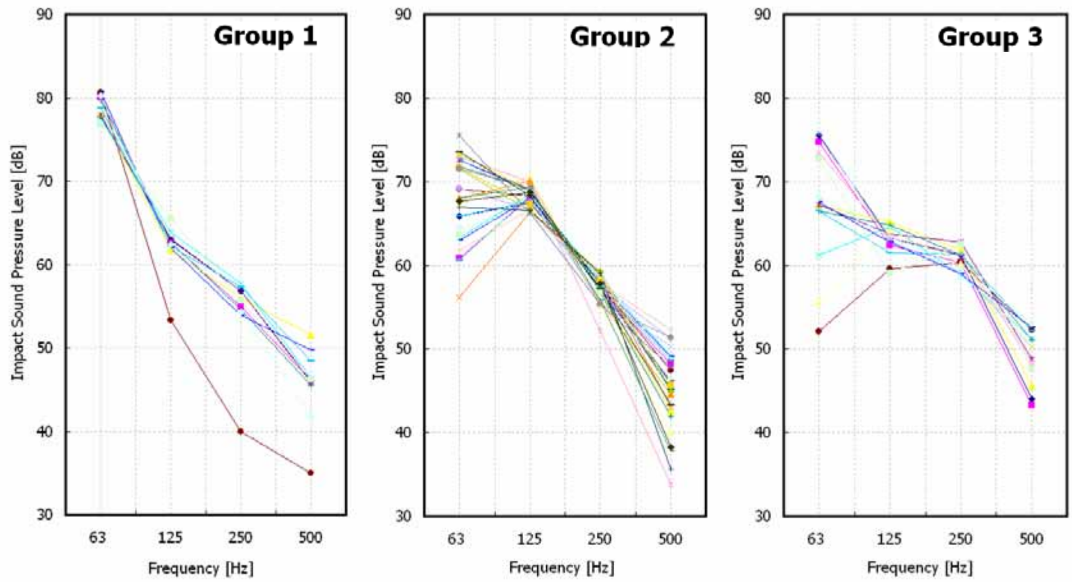

Figure 3. Frequency characteristics of each group

3. AUDITORY EXPERIMENT 1

3.1 Experiment set up

Auditory experiments were conducted to investigate the subjective responses to classified groups in a testing booth that has approximately 25 dBA of background noise. Three sound sources in each classified group (Group 1~3), total nine sound sources, were selected and sound pressure level was fixed at 50 dB ($L_{i,Fmax,AW}$). The signals were presented binaurally through headphones (Sennheiser HD600). Frequency characteristics of the sound sources used in this experiment are presented in Figure 4.

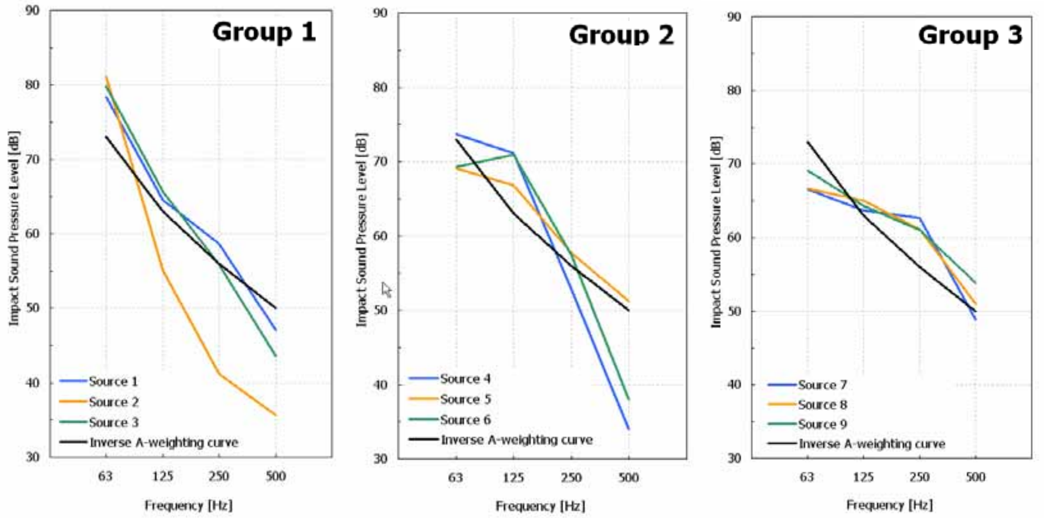

Figure 4. Frequency characteristics of sound sources used in the auditory experiment

3.2 Paired comparison test

Paired comparison tests were carried out to investigate the annoyance of each classified group. The duration of the stimuli, which consisted of two repeated noises, was about 6s, and the interstimulus interval (ISI) was 1s. Each pair of stimuli was presented in random order separated by an interval of 3s. A test session consisted of 36 pairs of stimuli. Twenty university students participated in the test. The subjects were asked to judge which of two stimuli was perceived as more annoying.

A scale value of annoyance was obtained by applying the law of comparative judgment (Thurstone's case V). The scale values are shown in Table 1. The results showed that Group 1 and Group 3 were more annoying than Group 2. The test subjects indicated that Group 1 was annoying because it sounded heavy and dull. Those who found Group 3 the most annoying said that the sound was light and sharp.

Table 1. Scale values of each sound source

	Group 1			Group 2			Group 3		
	1	2	3	4	5	6	7	8	9
S.V.	0.43	0.11	-0.07	-1.12	0.35	-0.60	0.19	0.44	0.27

To investigate the reason why subjective responses to the each group were different, the psychoacoustic metrics (loudness, sharpness, roughness and fluctuation strength) were analysed. The subjective response was highly correlated with roughness and fluctuation strength as well as loudness.

3.3 Semantic differential test

16 adjectives were selected from 600 adjectives by 20 subjects as appropriate for evaluating floor impact noise conducting suitability and similarity tests. Each selected adjective was paired with an antonym and selected the adjectives which they thought appropriately expressed their impression of each stimulus. The presentation method was the same as that used in the paired comparison tests except each signal was presented continuously until the subjects finished the evaluation. All stimuli was also fixed at 50 dB ($L_{i,Fmax,AW}$).

The results of the semantic differential test on heavy-weight impact sounds are shown in Fig. 5. On the 7-point scale, larger numbers represent less desirable qualities. The 16 adjectives were grouped into three categories (Category 1– 'dull and reverberant', Category 2– 'loud' and Category 3– 'annoying') using factor analysis. As shown in Figure 5, Group 2 was better than Group 1 and Group 3 in terms of the Category 2 and Category 3. In addition, Group 1, which subjects said had a dull sound, was evaluated as the worst, particularly in terms of the Category 1 due to the effect of dominant sound pressure level at 63 Hz.

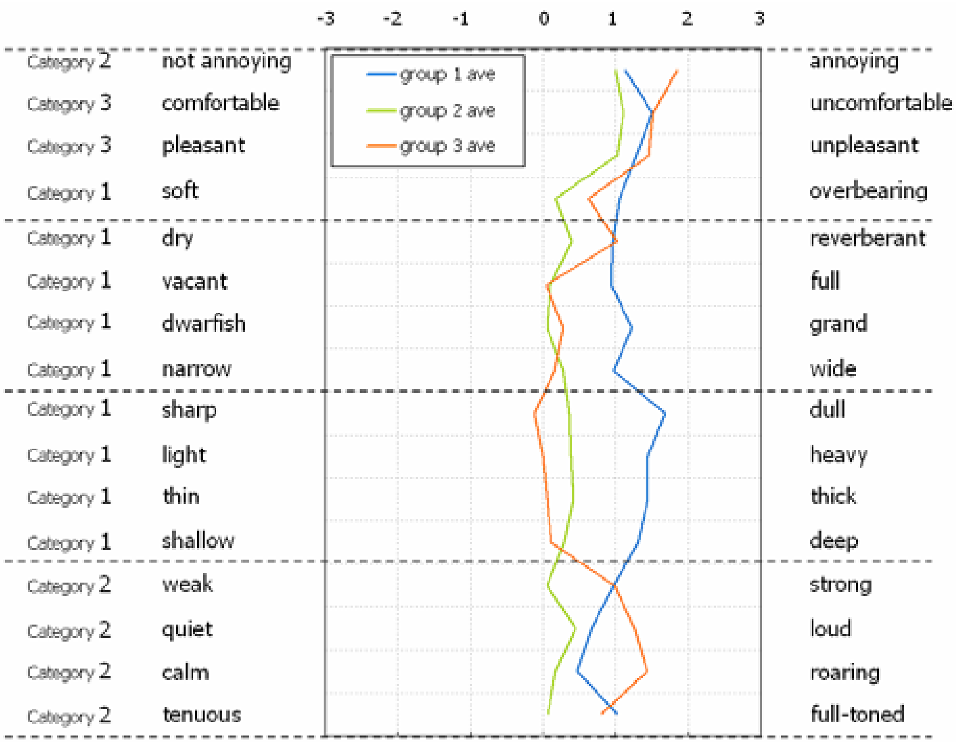

Figure 5. Semantic profiles for heavy-weight impact sound.

Table 2 presents the correlation coefficients between the three categories and the psychoacoustic metrics. It was found that the Category 2 was highly correlated with both loudness and fluctuation strength, and the Category 3 was highly correlated with roughness. However, Category 1 was not correlated with any psychoacoustic metrics.

Table 2. Correlation coefficients between categories and psychoacoustic metrics

Category	Loudness	Sharpness	Roughness	Fluctuation Strength
1 (dull, reverberant)	0.18	0.41	-0.06	0.43
2 (loud)	0.73^{*}	0.08	0.58	0.72^{*}
3 (annoying)	0.51	0.35	0.81^{**}	-0.56

** $p<0.01$, * $p<0.05$

4. AUDITORY EXPERIMENT 2

4.1 Experiment set up

An auditory experiment was performed to determine a valid indicator for perceived loudness and annoyance of heavy-weight impact sounds. In the experiment, eight sound sources were selected from each classified group (Group 1~3) of heavy-weight impact sounds. A paired comparison method was adopted. The measured SPL was distributed at 39~61 and 32~62 dB in terms of $L_{iFmax,AW}$ and L_{Aeq}, respectively. 21 subjects participated in the experiment.

The level indices and psychoacoustic metrics regarding loudness were considered. L_{Aeq} is probably the most widely used noise index. It accounts for the sound duration, noise magnitude and subjective sensitivity at different frequencies [5]. The difference between A-weighted statistical levels, L_{A10}– L_{A90}, sometimes referred to as the noise climate, represents fluctuations of sound level. The Zwicker's Loudness Level (LL_Z) in phones [6] takes into account both the sensitivity of the ears to different frequencies and the reciprocal masking effect of complex sounds. In addition, it was found that the arithmetic average of the SPL in octave bands from 63 Hz to 4 kHz strongly correlates with the perception of loudness [4]. The arithmetic average of SPL in the octave bands from 63 to 500 Hz is denoted as $L_m$in this study.

4.2 Correlation between level indices and subjective response

The correlation coefficients between subjective responses from the auditory experiment and level indices are listed in Table 3. In the experiment, L_{Aeq} and LL_z were highly correlated with subjective responses in each group and the correlation coefficients of other level indices were also quite high.

Table 3. Correlation coefficients between scale value and level indices

	$L_{iFmax,AW}$	L_{Aeq}	L_{Amax}	L_m	LL_Z	L_{A10}-L_{A90}
Group 1	0.89^{*}	0.95^{*}	0.92^{*}	0.88^{*}	0.95^{**}	0.70^{*}
Group 2	0.91^{**}	0.96^{**}	0.94^{**}	0.93^{*}	0.96^{**}	0.68^{*}
Group 3	0.92^{**}	0.96^{**}	0.91^{**}	0.91^{**}	0.96^{**}	0.72^{*}

** $p<0.01$, * $p<0.05$

5. DISCUSSIONS AND CONCLUSIONS

Heavy-weight impact sounds generated by an impact ball in units in an apartment building were recorded and classified according to the frequency characteristics. The characteristics of the floor impact noise were investigated by paired comparison tests and semantic differential tests. It was found that Group 2, which had a dominant sound pressure level at 125 Hz, was perceived as less annoying than Group 1 and Group 3.

Subjective responses to the heavy-weight impact sounds were highly correlated with roughness and fluctuation strength as well as loudness. Semantic differential test results showed that the 16 adjectives describing heavy-weight impact sounds could be grouped into three categories: dull and reverberant (Category 1), loud (Category 2) and annoying (Category 3). In addition, it was found that the Category 2 was highly correlated with both loudness and fluctuation strength, and the Category 3 was correlated well with roughness. Therefore, improvement in the sound perception of heavy-weight impact sounds could be based on a comparative evaluation of the semantic differences of the noise.

For the valid metrics of the perceived loudness and annoyance of heavy-weight impact sounds, it was indicated that L_{Aeq} and L_{Amax} were highly correlated with subjective response to heavy-weight impact sounds. A-weighted maximum SPL, L_{Amax}, was more highly correlated with subjective responses than $L_{iFmax,AW}$. This indicates that it is better to use L_{Amax} as a single number rating value than to use $L_{iFmax,AW}$. The procedure to calculate $L_{iFmax,AW}$ is more complex. Consequently, LL_Z had the highest correlation coefficients in the experiment, but it is not practical to be used as an evaluation metric of heavy-weight impact sounds because the procedure to calculate LL_z is not simple.

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