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SUBJECTIVE EVALUATION OF FLOOR IMPACT NOISE BASED ON THE MODEL OF ACF/IACF

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Floor impact noises generated by bang and tapping machines were measured through dual microphones on the ear of a human head. Matching and magnitude estimation techniques for noise evaluation were used to investigate the perceptual differences of the impact noises from apartment floors. Measurements of noise were also conducted by a diagnostic system based on the model of the human auditory–brain system [1]. Physical factors in the model were calculated by the use of the auto-correlation function (ACF) and interaural cross-correlation function (IACF) of binaural signals. From the results, it was found that perceived loudness of floor impact noise could be represented by the ACF/IACF factors. It became apparent that, at the beginning of each impact of intermittent noise ("bang noise"), the spatial impression of the sound field in an apartment bedroom corresponds to a high value of the IACC. Results also show that bang machine noise is perceived to be louder and noisier than that of a tapping machine.

1. INTRODUCTION

Although much work [2, 3] has been done in describing and quantifying the aspects that generate general sound annoyance, little research has been done investigating people's perception of noise within residential buildings. To efficiently and economically control noise, noise annoyance must be evaluated and explained as a comparable quantity. The purpose of this study is to provide a reliable method to subjectively evaluate floor impact noise.

The psychometric and psychophysical methods have been used to quantify the subjective responses to noise. Kuwano *et al.* [4] used magnitude estimation to investigate the effects of the steady state noise and the intermittent noise on noisiness. Berglund *et al.* [5] suggested a master scaling method to calibrate ratings of noise. After listening to several reference pink noises subjects were asked to evaluate the loudness of noise using magnitude estimation. Then, the differences between the loudness and the sound pressure level were used to calibrate the noises. So far, this method has been regarded as an efficient way to compare the individual differences in noise perception.

2. FLOOR IMPACT NOISE

Much of the population of major cities in Korea live in apartment buildings. Koreans have traditionally lived in buildings with subfloor heating slabs called "Ondol" and therefore without carpets, as these are thermal insulators. Most of the urban dwellers are therefore exposed to impact noise generated by the upper floor occupants. Figure 1 shows

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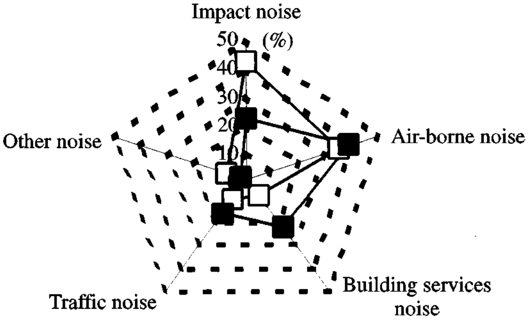

Figure 1. Responses that evaluated the various noises in residential buildings in major cities. (—□—), day; (—■—), night.

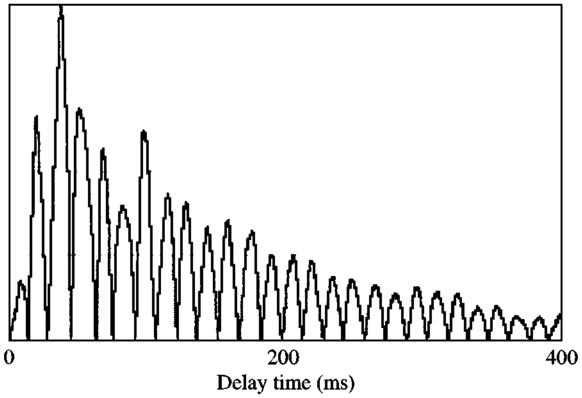

Figure 2. Energy curve of the impact noise caused by a bang machine.

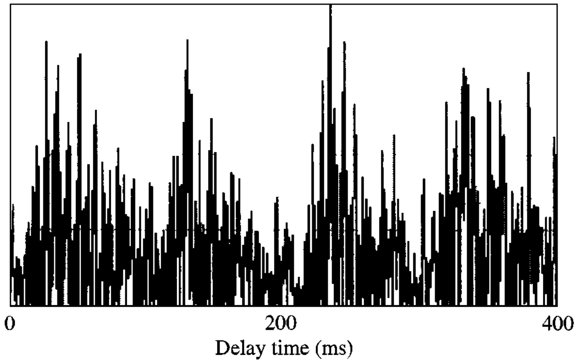

Figure 3. Energy curve of the impact noise caused by a tapping machine.

the responses of residents to various noises in residential buildings in major cities. A questionnaire was presented to 1200 residents, 20–50 years old, on their opinions of living environment. Results indicated that impact noise problems are directly related to residents' living standards.

This study describes the work for developing an objective measurement of subjective responses to floor impact noise. It should be noted that the dynamic properties for impact noises are different from those of steady state noises. The floor impact noises generated by a bang machine (see Figure 2) and a tapping machine (see Figure 3) simulate the jumping of children and walking with high heels on the upper floor respectively. Binaural recordings used for evaluation were made through microphones attached to the ears of one subject.

3. SUBJECTIVE EVALUATION

3.1. FLOOR STRUCTURES

A plain floor and three sets of floors with different impact isolation materials (a rubber particle-type and two sheet-type resilient materials) were chosen for the perceptual evaluation. These isolators were placed in the slabs of the floors in the same apartment in order to reduce the noise (see Figure 4). Impact sound transmission levels for different floor structures are plotted in Figure 5. As shown in Figure 5, the impact noise from the upper floor provided various non-linear damping, thereby ensuring a broad range of stimuli.

Measurements and recordings were taken at night after building construction was completed. Sound insulation materials were put on the walls to adjust the reverberation times of the upper and lower rooms (4·2 m × 4·3 m) to 0·4 s.

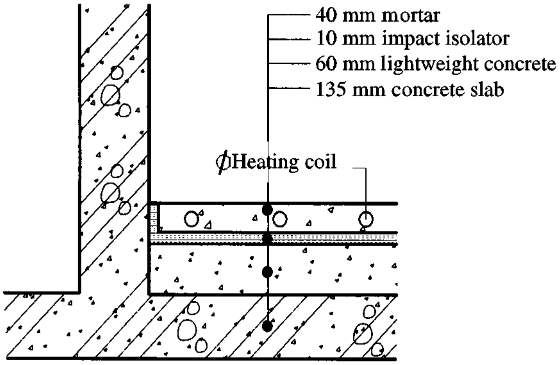

Figure 4. An apartment floor with an impact isolator.

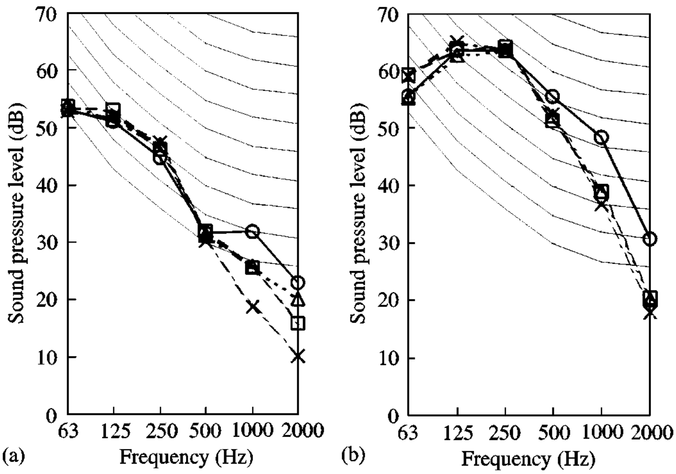

Figure 5. Floor impact noises generated by a bang machine (a) and a tapping machine (b). The web-featured lines, known as *L*-values, represent the grades of floor impact noise: (○), slab 1; (□), slab 2; (△), slab 3; (×), slab 4.

3.2. NOISE SOURCE AND EQUIPMENT

The noise sources placed in the master bedroom on the upper floor were a bang machine (T-TYPE, FI-02, RION) and a tapping machine (FI-01, RION) according to JIS A 1418 ("A method for the field measurement of floor impact sound levels"). Each machine was activated at the center of the upper floor bedroom and the transmitted noise level was measured and recorded using two-directional microphones at a subject's ear height of 1·3 m. The equipment used was a dual-channel real-time frequency analyzer (B&K, Type 2144), a DAT Recorder (PCD-D10, SONY) and headphones (Sennheiser HD-580).

3.3. PARTICIPANTS AND PROCEDURE

Twenty male and female subjects, 21–31 years old, heard impact sounds and pink noises through headphones. They were asked to match the bang/tapping noise with pink noise. All the standard stimulus sounds were recorded in wave files having duration of 5 s and were presented to subjects randomly. The levels were reduced in steps of 3–12 dB. The comparison stimuli were pink noises with sound pressure levels from 45 to 65 dB.

The experiments consisted of four blocks (Block 1: Loudness Matching, Block 2: Loudness Magnitude Estimation, Block 3: Noisiness Matching, Block 4: Noisiness Magnitude Estimation) of 15–20 min each. The subjects sat in a quiet room provided with a computer monitor and a keyboard. Background noise level was below 35 dB(A). A slide bar on the computer screen was used for magnitude estimation in Blocks 2 and 4.

3.4. RESULTS

The results of matching and magnitude estimation are shown in Table 1. The values of loudness matching and noisiness matching with pink noises have a high correlation ($r = 0{\cdot}916$, $P < 0{\cdot}01$). Magnitude evaluations were also conducted on rating scales. Table 1 shows that the subjects used the pink noise with 2–3 dB higher to match the noise generated by the bang machine and pink noise 3–4 dB lower to match the noise generated by the tapping machine. Bang noise seems to have been perceived 6–7 dB louder and noisier than tapping noise.

Figure 6 shows the magnitude estimation of loudness and noisiness for bang and tapping noise. As shown in Figure 6, within the tested range of noise levels (50–55 dB), bang machine noise was perceived to be louder and noisier than the tapping machine noise.

TABLE 1

Loudness and noisiness matching (LM/NM) *with magnitude estimation* (LME/NME)

	Bang noise					Tapping noise				
Slab	L_{max} (dB(A))	LM (dB(A))	LME	NM (dB(A))	NME	L_{max} (dB(A))	LM (dB(A))	LME	NM (dB(A)	NME
1	51·3	53·9	51	54·4	52	65·1	65·0	79	60·4	76
2	52·2	54·8	56	54·6	58	62·6	59·3	70	58·8	67
3	51·6	51·6	52	53·2	54	61·8	56·8	67	57·3	64
4	51·2	56·1	50	56·7	52	59·7	56·1	60	56·4	57
Average	51·6	54·1	52	54·7	54	62·3	59·3	69	58·2	66
Difference	0·0	+ 2·5		+ 3·1		0·0	− 3·0		− 4·1	

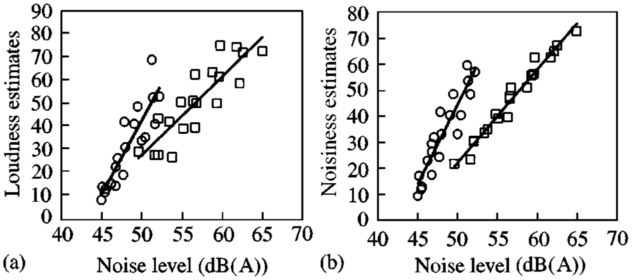

Figure 6. Magnitude estimation of loudness (a) and noisiness (b) for bang (○) and tapping (□) noise.

Table 2

Values of magnitude estimation of impact noise calculated from the regression lines shown in Figure 6

	Noise			
	Loudness		Noisiness	
Source	dB(A)	LME	dB(A)	NME
Bang	50	42	50	44
Tapping	50	**27**	50	22
Tapping	55	44	55	40
Tapping	60	**61**	60	58
Tapping	65	78	65	75

Table 3

Comparison of impact noise levels recalculated at the magnitude estimation of 30–60

	Loudness (dB(A))			Noisiness (dB(A))		
ME	Bang	Tapping	Difference	Bang	Tapping	Difference
30	48·1	56·2	8·1	47·7	52·2	4·5
40	49·7	56·6	6·9	49·3	55·0	5·7
50	51·2	57·1	5·9	50·9	57·8	6·9
60	52·8	57·5	4·7	52·6	60·7	8·1

Table 2 shows the equivalent noise levels of loudness and noisiness to magnitude estimation from the regression lines appearing in Figure 6. As shown in Table 2, when the noise levels generated by the tapping machine increased from 50 to 60 dB and also from 55 to 65 dB, the subjects tended to judge the 10 dB increases as twice as loud in their magnitude estimates. The fact has been known widely.

Reciprocally, from the regression lines appeared in Figure 6, the values of magnitude estimation (ME 30–60) to bang and tapping machine noise are shown in Table 3. As shown in Table 3, when ME is 50, its equivalent noise level of bang machine noise is 51·2 dB, which is very close to the measured noise level (L_{max} = 51·2–52·2 dB). At this point, the difference

Table 4

Averaged results of tested ACF/IACF *factors obtained from the impact noise on four slab structures*

Slab	$10\log_{10}\Phi(0)$	τ_e	τ_1	Φ_1	SPL	IACC	τ_{IACC}	W_{IACC}	L_{eq}	L_{max}
Bang										
1	55·3	41·6	1·7	0·09	55·9	0·70	0·00	0·07	46·2	51·3
2	58·5	67·2	3·8	0·14	58·3	0·77	0·02	0·12	47·5	52·2
3	52·4	16·60	1·9	0·06	52·5	0·55	0·01	0·06	46·2	51·6
4	55·4	30·24	1·8	0·11	55·6	0·68	0·01	0·09	46·4	51·2
Average	55·4	38·9	2·3	0·10	55·6	0·67	0·01	0·08	46·6	51·7
Tapping										
1	58·0	18·3	2·3	0·07	58·2	0·24	0·23	0·29	64·1	65·1
2	56·0	37·2	1·8	0·11	56·1	0·42	0·03	0·50	61·0	62·6
3	53·6	19·3	4·1	0·17	54·4	0·47	− 0·06	0·45	60·2	61·8
4	53·2	17·4	3·8	0·12	53·2	0·50	− 0·03	0·44	58·3	59·7
Average	55·2	23·1	3·0	0·12	55·5	0·41	0·04	0·42	60·9	62·3

with the tapping machine noise is 5·9 dB, which is very similar to the result of pink noise matching of 5·5 dB. Therefore, it can be concluded that the method of evaluating subjective noise with matching pink noise is reliable. The results obtained for noisiness are definitely similar for the difference here being 6·9 dB, compared with 7·2 dB in Table 1.

4. THE ACF/IACF MODEL

As shown in Table 4, the average values of each factor of the ACF/IACF [6] were obtained from the beginning to the end of the noise. The average matched noise levels obtained from 20 subjects at four slab types are also listed in Table 4. For running ACF/IACF, an integration time of 0·1 s, with a running step of 0·01 s and a maximum delay time of 0·1 s was calculated. Eight significant parameters were obtained from each frame of running ACF/IACF and are represented in Table 4. The ACF/IACF factors were measured for 1 s where the impact noise recorded the highest (peak) value of $\Phi(0)$ both for the bang (only one intermittent noise was included) and the tapping noise.

The correlations among factors calculated in the ACF/IACF model of the impact noise levels (L_{Aeq}, L_{Amax}) are listed in Tables 5 and 6 with the matched pink noise levels. As shown in Table 6, the IACF factors are significantly correlated with the matched pink noise level for the tapping machine noise.

Values of $\Phi(0)$ and IACC for bang noise and tapping noise are shown in Figure 7. The spatial impression of the sound field generated by the bang machine (see Figure 7(a)) indicates a clear direction of sound at initial impact, followed by diffusion in direction for the remainder of the impact sound. On the other hand, as shown in Figure 7(b), the tapping noise does not seem to have a clear direction as impact noise as the tapping machine generated diffused sounds through the whole slab and the adjacent walls.

5. CONCLUSIONS

This study has been undertaken to measure loudness and noisiness of floor impact noise obtained from similar floor slab structures with three different impact isolators. Results

Table 5

Correlation coefficients among factors calculated in the ACF/IACF *model and the noise levels generated by the bang machine; pink means the pink noise levels for loudness matching of bang noise; the results obtained for the noisiness of bang noise are definitely similar; The significant correlations are in bold type*

	$10\log_{10}\Phi(0)$	τ_e	τ_1	Φ_1	SPL	IACC	τ_{IACC}	W_{IACC}	L_{eq}	L_{max}	Pink
$10\log_{10}\Phi(0)$	1·00										
τ_e	**0·96**	1·00									
τ_1	0·78	0·84	1·00								
Φ_1	**0·95**	0·83	0·69	1·00				**Bold** > 0·90			
SPL	**0·99**	**0·96**	0·71	**0·93**	1·00						
IACC	**0·97**	**0·93**	0·63	**0·92**	**0·99**	1·00					
τ_{IACC}	0·70	0·65	**0·91**	0·74	0·60	0·52	1·00				
W_{IACC}	**0·94**	0·87	0·88	**0·94**	0·89	0·84	0·90	1·00			
L_{eq}	0·86	0·87	**0·98**	0·81	0·80	0·73	**0·93**	**0·96**	1·00		
L_{max}	0·56	0·68	**0·95**	0·43	0·48	0·39	0·81	0·70	0·88	1·00	
Pink	0·69	0·47	0·19	0·84	0·71	0·74	0·36	0·63	0·37	− 0·13	1·00

Table 6

Correlation coefficients among factors calculated in the ACF/IACF *model and the noise levels generated by the tapping machine; pink means the pink noise levels for loudness matching of tapping noise; the results obtained for the noisiness of tapping noise are definitely similar; The significant correlations are in* ***bold*** *type*

	$10\log_{10}\Phi(0)$	τ_e	τ_1	Φ_1	SPL	IACC	τ_{IACC}	W_{IACC}	L_{eq}	L_{max}	Pink
$10\log_{10}\Phi(0)$	1·00										
τ_e	0·24	1·00									
τ_1	− 0·85	− 0·68	1·00								
Φ_1	− 0·83	− 0·08	0·75	1·00				**Bold** > 0·90			
SPL	**0·99**	0·21	− 0·79	− 0·73	1·00						
IACC	− 0·95	0·07	0·65	0·79	− 0·96	1·00					
τ_{IACC}	**0·94**	− 0·08	− 0·68	− 0·89	**0·91**	− 0·98	1·00				
W_{IACC}	− 0·63	0·59	0·17	0·64	− 0·64	0·84	− 0·84	1·00			
L_{eq}	**0·94**	0·05	− 0·66	− 0·66	**0·98**	− 0·97	**0·91**	− 0·73	1·00		
L_{max}	**0·93**	0·12	− 0·68	− 0·61	**0·98**	− 0·95	0·87	− 0·67	**1·00**	1·00	
Pink	**0·97**	0·00	− 0·70	− 0·82	**0·97**	− 1·00	**0·98**	− 0·80	**0·97**	**0·94**	1·00

presented in this paper on noise levels are based on the difference of noisiness between steady state noise and intermittent noise [4]. This study shows a 3 dB level increase within a 5 s intermittent noise signal with three impact sources in the signal. However, the tapping noise seems not to have the same effect because it was perceived as steady state noise, 4 dB lower on average.

From the correlations among the ACF/IACF factors, it is apparent that $\Phi(0)$ is highly correlated to the perceived noise levels for the tapping machine noise. The IACF model seems to be related with the initial noise impact. The spatial impression of the sound field at the point of initial impact corresponds to a high value of the IACC. The duration of the initial impact seems to be perceived as a directional source. If the noise peak is repeated

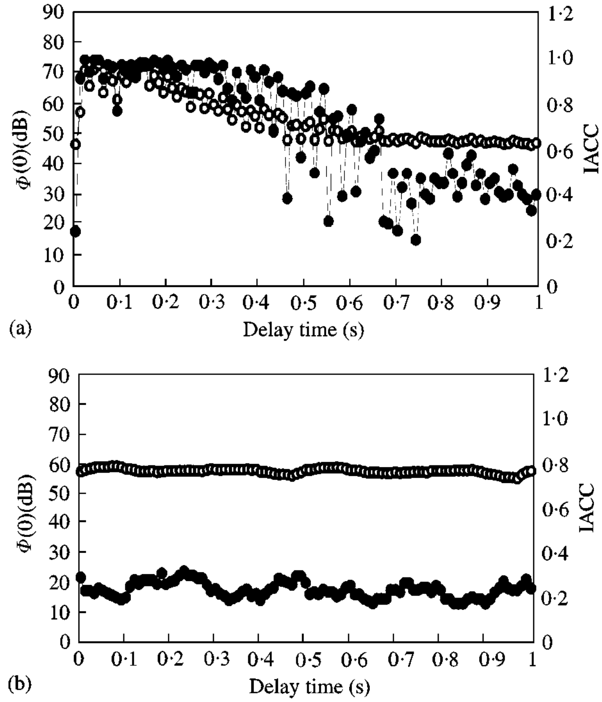

Figure 7. Values of *Φ*(0) and IACC for bang (a) and tapping (b) noise: (○), *Φ*(0); (●), IACC.

within a short period of time (around 0·1 s as in the tapping noise), the noise seems to be diffused. Thus, the perceived loudness and noisiness of the floor impact noise can be explained by the ACF model and also the directivity of noise peak by the IACF model.

From the results of the experiments, the matching and magnitude estimation techniques are considered as a reliable method to subjectively evaluate noise. It is also recognized that the IACF of binaural signals differentiates early perception of loudness and noisiness of bang machine noise from that of tapping machine noise. Although a proper interval for the intermittent noise for loudness or noisiness is unknown at the present stage, the spatial impression of the sound field seems to correspond to its intermittency of noise.

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