HEAVY-WEIGHT FLOOR IMPACT SOUND IN REINFORCED CONCRETE STRUCTURES

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Abstract

The purpose of this study was to evaluate the floor impact sound isolation systems in reinforced concrete constructions. The floor impact sounds were generated by the standard heavy-weight impact sources, a tyre drop tester[1] and an impact ball[2]. The noise and vibration from the impact sources were analyzed and the relationship between the sound levels and the subjective responses was investigated. From the different residential building structures, it was found that heavy-weight floor impact in a box frame-type concrete structure[3] readily transmits sound to the space below through the bearing walls, whereas the non-bearing walls of a rahmen structure[4] do not readily transmit sound. It was also observed that a linear relation exists between floor impact sound and vibration. In addition, when the noises were evaluated in in-situ conditions, the allowable sound levels were found to be 46dB for the tyre drop tester and 54dB for the impact ball.

Introduction

More than 50% of the housing in Korea consists of multi-storey reinforced concrete residential buildings having a radiant floor heating system called Ondol. And low frequency impact noise caused by foot traffic is a major complaint in indoor living.

However, in Korea, there were no regulations concerning sound isolation for buildings. The lack of restrictions on residents' living patterns has worsened the situation and frequent disputes occur among residents and between occupants and building contractors. In order to improve floor impact noise isolation performance and to increase the sound comfort of apartment building occupants, regulations based on an objective and easily understood measurement and evaluation method using standard impact sources which simulate well human actual impact are required.

In Korean and Japanese standards, both light-weight (tapping machine) and heavy-weight (bang machine or 'tyre drop tester') impact sources were utilized. Through the recent improvement of measuring and evaluating methods for floor impact noise, an impact ball was suggested as the second heavy impact source. Tachibana et al. [1] found that an impact ball has similar frequency characteristics to actual human impact noise for several floor structures. As a rating method of heavy-weight impact sound using bang machine, $L_{i,Fmax,AW}$ was regulated in KS. However, this method has different reference curve and single number calculation methods with ISO.

Very recently in Japan, the grades for floor impact noise were divided into five grades in the law for housing quality control [2]. In ISO, L'_{nw}, L'_{nw+CI} were regulated, $L'_{n,AW}$ is used to evaluate, measure, assess light-weight impact noise in Japan. However, these two methods have different reference curve and single number calculation method. Warnock [3, 4] emphasized the usefulness of a tapping machine, but also pointed out that low frequency noise was a common problem with Canadian joist floors and the IIC rating method, which uses a tapping machine and does not deal with low frequency [5].

Gösele [6] presented the reference curve for light-weight impact sound rating. Fasold [7] suggested a flat reference within frequency range 100-3150Hz. Olynyk and Northwood [8, 9] claimed that the FHA (U.S. Federal Housing Administration)'s evaluation curve [10] was different from the results of their loudness perception tests. Bodlund [11] proposed another straight reference curve with a positive slope of 1dB per 1/3-octave band from 50Hz to 1000Hz. Parmanen [12] discussed the results of Bodlund's study and mentioned that it was necessary to check the curve shape by studying living sounds.

In this study, the floor impact sound and vibration generated by standard heavy-weight impact sources in a box frame-type reinforced concrete structures were investigated and compared to heavy-weight impact noise in rahmen structures. In addition, subjective responses of the standard impact sources, impact ball and jumping were investigated. Finally allowable sound levels based on the subjective responses of heavy-weight impact sources were proposed.

Subjective/Objective Evaluation of Floor Impact Sound Isolation

Measurement of floor impact sound

[1] Tyre drop tester (Bang machine): Weight – 7.3±0.2kg; air-pressure level – $(2.4\pm0.2)\times10^5$Pa; drop height – 85cm (KS A 2810-2 & JIS A 1418-2)

[2] Impact ball: Weight – 2.5±0.1kg; drop height – 100cm (JIS A 1418-2)

[3] Box frame-type concrete structure: Structural system which is structurally supported by the reinforced concrete wall.

[4] Rahmen structure: Structural system which is structurally supported by the reinforced concrete column and beam.

All measurements and recording were made in a reinforced concrete structure four-bedroom apartment (140m^2). Eight units of the apartment were selected for floor impact noise measurements. Measurements were made after the completion of construction and before occupants moved in. The floor structures of eight units consist of one standard floor that was maintained as an original structure and seven other structures that were constructed under different conditions for reducing floor impact noise.

Table 1 shows the structural components and details. For example, 'P' indicates a plain reference structure and the treatments in the structural components are indicated as 'F' for the construction of a floating floor, 'W' for the treatment in the walls and 'C' for the treatment in the ceiling. Thus, 'FWC' indicates a box frame type structure having all sound isolation treatments.

Field measurements and analyses of floor impact noise were conducted according to JIS A 1418. The light-weight impact (tapping machine) noise was analyzed at the overall equivalent sound pressure level (L_{eq}) and the heavy-weight impact (bang machine and impact ball) noise at the maximum sound pressure level (L_{max}). The test results shown in this paper comply with KS F 2863 & JIS A 1419; ($L'_{n,AW}$, the inverse A weighted normalized impact sound pressure level for light weight impact sound and $L_{i,Fmax,AW}$, the inverse A weighted impact sound pressure level for heavy-weight impact sound) which has a different curve of reference values for impact sound (Octave band). KS F 2863 & JIS A 1419 states that light-weight impact noise must not exceed an equivalent sound pressure level (L_{eq}) in the frequency range of 125-2,000Hz and heavy-weight impact noise must not exceed a maximum sound pressure level (L_{max}) in the frequency range of 63~500 Hz.

Table 1. Details of treated conditions with different sound isolations

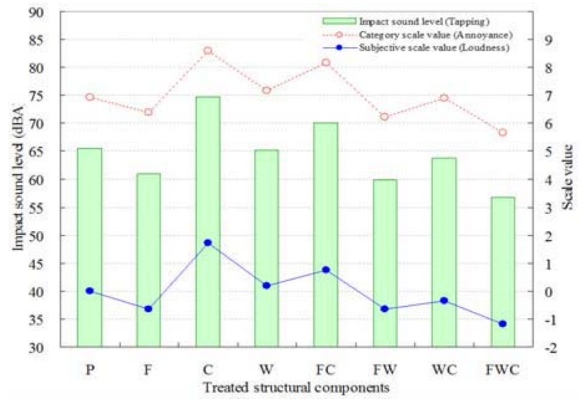
Structural components	Structural details (mm)
Floor (F)	Reinforced concrete slab150 + Impact Isolator 10 + Light-weight Concrete 80 + Cement Mortar 50 + Papered Floor*
Wall (W)	Concrete retaining wall 180 + Plaster bond (air gap) 5 + Sound Isolation (Rubber) Sheet 2 + Gypsum Board 9.5+ Wallpaper
Ceiling (C)	Reinforced concrete slab 150 + Vibration Absorbing Hanger & light-weight steel ceiling structure 230 + Sound Isolation (Rubber) Sheet 2 + Gypsum Board 9.5 + Wallpaper

* 2mm waxed paper covered as a traditional floor finish

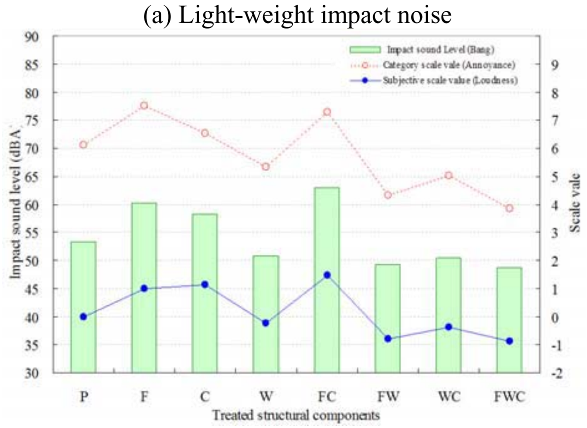
For auditory experiments and psychoacoustical analysis, the impact noises from a tapping machine, bang machine, impact ball and jumping children were recorded. It was found that the noise of running and jumping children and walking adult are the most frequently produced sound in multi-storey residential buildings [13] and that those real noises are very close to the noise generated by impact ball. We reproduced the situation such that an adult (in 20s, 65-70kg) walks on the spot instead of running and jumping children.

Auditory Experiments

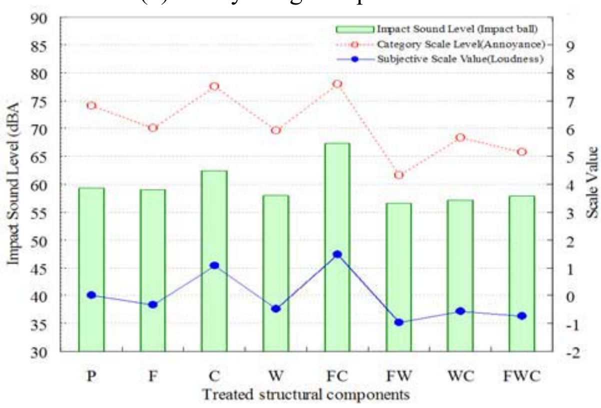
Electrostatic headphones were used for the binaural hearing experiment. Auditory experiments were performed in a testing booth that had approximately 25 dBA of background noise. Auditory experiments consisted of two experiments: one was on the loudness of the floor impact noises and the other was on the annoyance of the floor impact noise.



(a) Light-weight impact noise



(b) Heavy-weight impact noise



(c) Impact ball noise

Figure 1. Comparison of objective and subjective (loudness and annoyance) evaluation of impact noise isolation with different structural treatments.

The subjective and category scale values were calculated from the subjects' responses to loudness and annoyance differences. Figure 1 (a) illustrates that the loudness and annoyance of light-weight impact noise from F, FW and FWC treated structures were lower than that produced by C and FC treated structures. When F, FW and FWC were compared with P, they were evaluated on the subjective loudness scale at a value of about '-1', which means a 'clear difference in loudness'. Thus, the impact sound level of the floating slabs (F, FW and FWC) represented a reduction of more than 5dB. FWC showed the maximum improvement in both impact sound level and subjective and category scale values (loudness and annoyance).

In Figure 1 (b) and (c), W, FW, WC and FWC structures were found to be effective treatments for loudness and annoyance of heavy-weight impact noise. Although the reduction of the impact sound level of the structures was less than 5dB, the subjective and category scale values indicated that these treatments had a considerable effect on loudness and annoyance of heavy-weight impact noise. FW and FWC also showed considerable improvement in light-weight. Thus FW seems to be the most effective treatment. Therefore, for objective and subjective improvement of floor impact noise, box frame-type reinforced concrete buildings need sound isolation treatments in both floors and walls. An effective method of sound and vibration isolation for ceiling should be further developed.

The subjective responses of annoyance to both the light-weight and heavy-weight floor impact noise levels should be lower than a subjective magnitude '4' to avoid annoyance. However, as shown in Figure 1, the category scale value of annoyance is 5.8~8.6 for the light-weight impact noise and 3.8~7.6 for the heavy-weight impact noise. These results indicate that only FWC could satisfy the annoyance level of heavy-weight impact noise below the subjective magnitude '4'. Therefore, uncarpeted floors need better sound isolation treatments such as carpeting.

The Characteristics of Impact Sound and Vibration

In order to reduce the structure-born sound such as floor impact sound in a multi-storey reinforced concrete residential building, it is necessary to identify the relationship between floor impact sound and vibration. In this study, sound and vibration characteristics of a bang machine and an impact ball at various impact forces were measured. The slab consisted of a 150mm thick concrete slab, a 10mm thick resilient impact isolator, a 55 mm light-weight concrete layer and 45 mm thick layer of finishing mortar. The compressive strength of the concrete was 240kg/cm^2.

The impact force of the bang machine was varied by varying the air pressure level of the bang machine tyre from 1.8 to 3.0kgf/cm^2 and by varying the free drop height of the bang machine tyre from 30-120cm. The impact force of the impact ball was varied by varying the free drop height from 20-200cm. As shown in the Figure 2, the center of the upper room was impacted by the bang machine and impact ball. The impact sound levels were measured at the center of the lower room at a height of 1.2m and the vibration acceleration levels were measured on the slab and beneath the slab. The vibration accelerometer on the slab was used for a trigger signal and sound and vibration acceleration levels were measured 5 times and averaged.

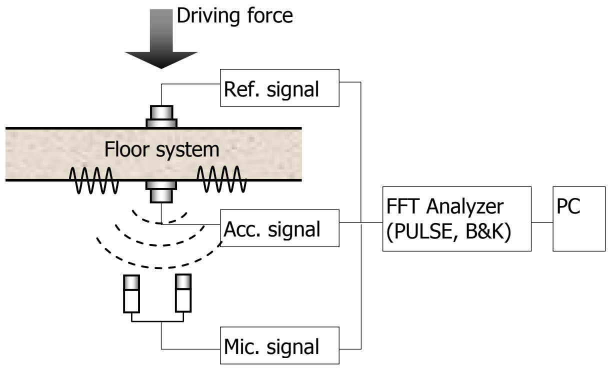


Figure 2. Experimental apparatus to measure the floor impact sound and vibration simultaneously.

In the bang machine experiment, the impact force of the bang machine varied with the air pressure level of the tyre and the height of drop. The impact force of the impact ball can be varied by the drop height. The relationship between impact sound pressure level and vibration acceleration level for the bang machine and the impact ball are shown in Figure 3.

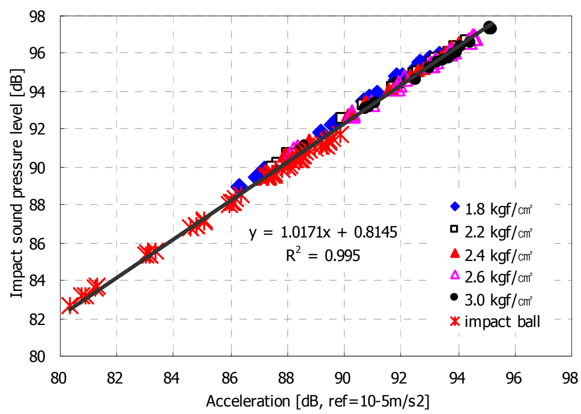


Figure 3. Relation between floor impact sound and vibration levels using bang machine and impact ball.

The experimental results show a linear relationship between overall floor impact sound level and vibration acceleration level despite the various floor impact forces. Therefore, a reduction of floor impact sound level can be achieved by reduction of the floor impact vibration acceleration level.

The Floor Impact Sound in Rahmen Structures

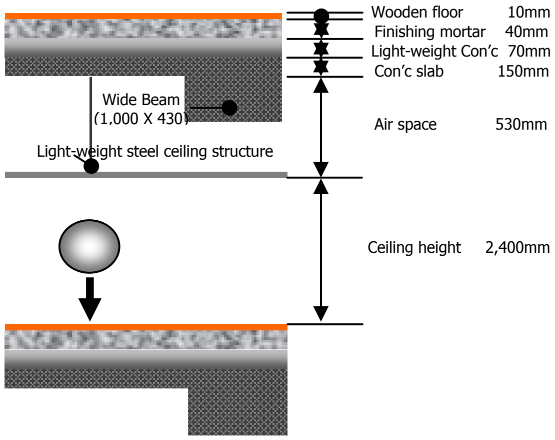
It has been reported that there is a limit for improving heavy-weight impact noise isolation performance of the box frame-type reinforced concrete residential buildings to meet the regulation of the Ministry of Construction and Transportation in Korea (MOCT). The floor impact sound levels in the regulation are shown in Table 2. In order to improve the heavy-weight impact noise isolation performance, improvement in structural systems such as increasing concrete slab thickness and application of rahmen structure have been proposed [14].

Table 2. The regulation on the floor impact sound levels in Korea

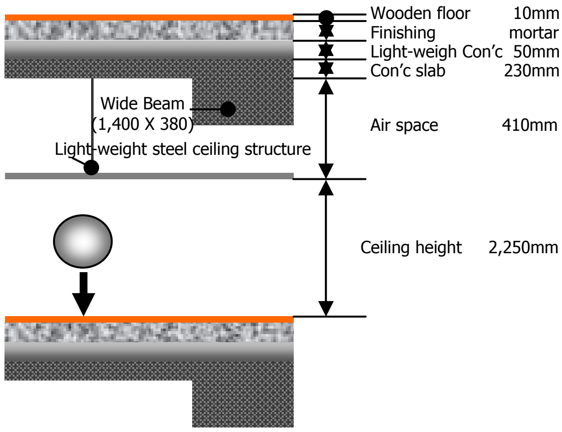
[dB]	Light-weight impact sound (Tapping machine)	Heavy-weight impact sound (Bang machine)
Regulation of MOCT	58 ($L'_{n,AW}$)	50 ($L_{i,Fmax,AW}$[5])

In this study, floor impact sound levels from ten apartments in two rahmen structure multi-storey residential buildings were measured prior to the tenants moving in. Figure 4 shows the structural section of two rahmen structure multi-storey residential buildings. In the rahmen structure residential building, the intra-tenancy walls were dry wall and the inter-tenancy walls were constructed as concrete walls. Measurements were made in the living room and two bedrooms at each apartment when the finishing treatments processes were finished.

Table 3 shows the floor impact sound levels in the rahmen structure residential buildings which were averaged values of sixteen and twelve rooms at each site. The average value of light-weight impact sound level from the two sites was 56dB ($L'_{n,AW}$). The heavy-weight impact sound level was 44dB ($L_{i,Fmax,AW}$) and the impact sound level of the impact ball was 41dB ($L_{i,Fmax,AW}$). The average impact sound pressure levels from the 89 box frame-type reinforced concrete residential buildings are also shown in Table 3. There are three reasons for the level difference between the reinforced concrete and rahmen residential buildings. The first is due to the construction of the walls. Heavy weight impact sound is easily transmitted to lower rooms through walls in the box frame-type residential buildings because the reinforced concrete walls between households were structurally coupled to the slab. However, the walls in rahmen residential buildings in Korea are usually constructed of dry wall which is not structurally coupled with slab. Even in the rahmen structure residential buildings, 2dB floor impact sound level differences between rooms which were constructed with dry walls and rooms which had a wall constructed with structurally coupled concrete wall were observed. The second and third reasons were the difference of structural system and air space in ceiling.



(a) Rahmen 1



(b) Rahmen 2

Figure 4. Section details of rahmen structure residential buildings.

[5]
$$L_{F\max} = 10 \log_{10}\left(\frac{1}{m}\sum_{j=1}^{m} 10^{L_{F\max,j}/10}\right)$$

$L_{F\max}$ = Maximum impact sound pressure level of each measurement point; $L_{i,Fmax,AW}$ is the weighted value of the reference curve in KS A 2810-2

Table 3. Floor impact sound levels in rahmen structure residential buildings

[dB]	Light-weight impact sound (Tapping machine, $L'_{n,AW}$)	Heavy-weight impact sound (Bang machine, $L_{i,Fmax,AW}$)	Impact ball ($L_{i,Fmax,AW}$)
Rahmen 1	58 (54-64)	44 (41-48)	42 (38-47)
Rahmen 2	55 (53-58)	43 (40-46)	40 (38-42)
Linear Average	**56**	**44**	**41**
Box frame-type	66	53	54

Classes of Floor Impact Sound Based on Subjective Responses

Auditory experiments on the annoyance of the floor impact noises were conducted. The purpose of the on-site experiment was to rate the floor impact sound level according to the annoyance felt by the subjects under real living conditions. Auditory experiments were conducted with 98 subjects in a living room of a multi-storey residential building. The subject group consisted of undergraduate and postgraduate students in their 20s. The impact sound pressure level of the bang machine and the impact ball were varied by varying the drop height of the bang machine tyre and the impact ball, and the impact sound pressure level of the tapping machine was varied by varying the floor-finishing materials.

Table 4. Nine category scales for evaluating annoyance levels of floor impact noise

Annoyance Group & Subjective magnitude		Scale 1 Noisiness	Scale 2 Disturbance	Scale 3 Amenity
Not Annoying	1	Hardly perceivable	At ease	Excellent
	2	Far-off noise	Not affected	Very fine
	3	Unconcerned	Undisturbed	Good
Annoying	4	Slightly heard	Detectable	Controllable
	5	Heard	Noticeable	Endurable
	6	Clearly heard	Discernable	Yielding
Very Annoying	7	Noisy	Obviously	Unbearable
	8	Very noisy	Undoubtedly	Intolerable
	9	Extremely noisy	Seriously	Let's move OUT!

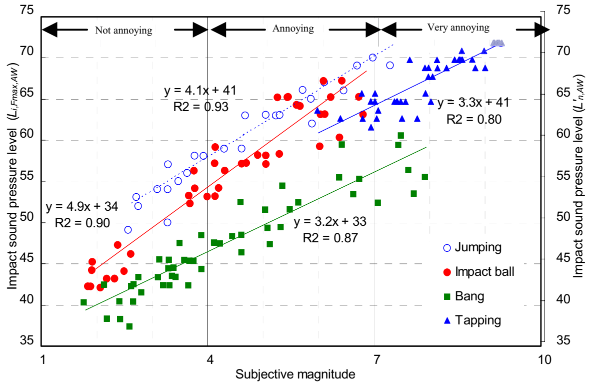


Figure 5. Relationship between floor impact sound and subjective magnitude.

Subjects responded on three questionnaire sheets on the floor directly below the points of impact. Three questionnaire forms, originally developed in 1997 by the Architectural Institute of Japan, were modified and used for the evaluation of the floor impact noise. As shown in Table 4, these forms evaluated the sound sources for 'Noisiness', 'Disturbance' and 'Amenity'. In addition, after careful consideration of the borders of the groups, the upper and lower limits were intentionally set up as follows: the upper limit - Evaluation Point 7, where noise bothers people greatly, and the lower limit - Evaluation Point 4, where the noise started to bother people.

The relationship between subjective response and floor impact noise level (inverse A-weighted impact sound pressure level), which as corresponds to the evaluation scales, appears as a linear equation as shown in Figure 5. The upper and lower floor impact sound levels ($L_{i,Fmax,AW}$, $L'_{n,AW}$) were established from the regression line of the subjective response. The floor impact sound level of upper limits (average value of evaluation point 7) for heavy, light-weight and impact ball noise, were 56dB ($L_{i,Fmax,AW}$), 66dB ($L'_{n,AW}$) and 68dB ($L_{i,Fmax,AW}$), and the floor impact sound level of lower limits (evaluation Point 4) were 46dB ($L_{i,Fmax,AW}$), 56dB ($L'_{n,AW}$) and 54dB ($L_{i,Fmax,AW}$) respectively. Similarly, Jeon [16] found that people feel that heavy-weight impact noise is louder than light-weight impact noise when the two types of noises are compared on the basis of L_{eq} values.

Conclusions

The floor impact sounds and vibrations generated by the standard heavy-weight impact sources in a box frame-type reinforced concrete structures were investigated and compared to heavy-weight impact noise in rahmen structures. In addition, the frequency characteristics of and subjective responses to the tapping machine, bang machine, impact ball and running and jumping children were compared. Finally, allowable sound levels based on the subjective responses of heavy-weight impact sources were proposed.

In this study eight floor impact noise isolation structures were evaluated objectively and subjectively. The results show that the objective and subjective improvement of floor impact noise in box frame-type reinforced concrete buildings need sound isolation treatments in both floors and walls. In addition spatial factors of the floor impact noise should be taken into consideration for the subjective improvement of floor impact noise [17].

The results of the floor impact sound and vibration measurement results show that a linear relationship exists between overall floor impact sound and vibration regardless of the various floor impact forces. From the different structures, it was found that heavy-weight floor impact in a box frame-type concrete structure is readily transmitted to the space below through the bearing walls, whereas the non-bearing walls of a rahmen structure do not readily transmit impact.

From the recent study on the comparison of frequency characteristics and subjective responses of the three standard impact sources and actual human impact, it was revealed that the noise from the impact ball was similar to the noise of running and jumping children [18]. When the noises were evaluated in in-situ conditions, the allowable sound levels were found to be 46dB for the bang machine and 54dB for the impact ball.

Acknowledgement

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References

[1] H. Tachibana, H. Tanaka, M. Yasuoka, and S. Kimura, “Development of new heavy and soft impact source for the assessment of floor impact sound insulation of buildings,” Proc of Inter-noise 98, 1998.

[2] H. Fukusima, A. Hattori, J. Yosimura, K. Inoue and M. Yasuoka, “Introduction to sound insulation regulations in the Japanese new law concerning the labeling system and the system for quality securing about newly-built house, -Part:2-,” Proc of Journal of the Acoustical Society of Japan, pp.753-754, 2000.

[3] A. Warnock, “Low frequency impact sound transmission through floor systems,” Proc of Inter-noise 92, 1992.

[4] A. Warnock, “Low frequency impact sound transmission through floor systems,” Proc of Inter-noise 2000, 2000.

[5] A. Wornock, “Low-frequency impact sound rating of floor systems,” Proc of Noise-Control Engineering Journal, 2000, p.2611, 2000.

[6] K. Gösele, “Zur bewertung der schalldämmung von bauteilen nach sollkurven, ” Acustica **15**, pp.264-270, 1965.

[7] W. Fasold. "Untersuchungen über den verlauf der sollkurve für den trittschallschutz im wohnungsbau," Acustica 15, pp.271-284, 1965.

[8] D. Olynyk and T. D. Northwood, “Subjective judgments of footstep-noise transmission through floors,” J. Acoust. Soc. Am., 37, pp.1035-1039, 1965.

[9] D. Olynyk and T. D. Northwood “Assessment of footstep noise through wood-joist and concrete floors,” J. Acoust. Soc. Am., 43, pp.730-733, 1967.

[10] Federal Housing Admin, “Impact noise control in multifamily dwellings,” FHA No,750, 1963.

[11] K. Bodlund, “Alternative reference curves for evaluation of the impact sound insulation between dwellings,” Journal of Sound and Vibration, 102(3), pp.381-402, 1985

[12] J. Parmanen, Comments and conclusions based on "Alternative reference curves for evaluation of the impact sound insulation between dwellings," Journal of Sound and Vibration, 213(4), pp.763-773, 1998.

[13] J. Y. Jeon and J. H. Jeong, “Measurements of floor impact noise using a new impact ball,” Proc of Noise-Con 2003, 2003.

[14] S. H. Seo and J. Y. Jeon, “Noise and vibration characteristics of the reinforced concrete slab impacted by heavy-weight source in an apartment building,” ICA 2004, Japan: 2401-2402. 2004.

[15] J. Y. Jeon, J. H. Jeong, M. Vorläder and R. Thaden, “Evaluation of floor impact sound insulation in reinforced concrete buildings,” Acta Acustica Vol. 90:313-318, 2004.

[16] J. Y. Jeon, “Subjective evaluation of floor impact noise based on the model of ACF/IACF,” Journal of Sound and Vibration, 241(1): 147-155, 2001.

[17] J. Y. Jeon, J. H. Jeong, and Y. Ando, "Objective and subjective evaluation of floor impact noise," Journal of Temporal Design in Architectural and the Environment, 2(1):25-33, 2002.

[18] J. Y. Jeon, J. H. Jeong, "The use of the impact ball in evaluating floor impact sound, " Proc of Inter-noise 2004, 2004.