Evaluation of Impact Sound Insulation Properties of Light-Framed Floor with Radiant Floor Heating System*1

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ABSTRACT

In order to find out impact insulation properties, various types of current radiant floor heating systems and light-framed floors that are used in light-framed residential buildings were evaluated for two types of impact sources at the same time. Sound Pressure Level (SPL) was different from each impact sources for those spectrum patterns and peaks. In case of light-framed floor framework, the excitation position and the assumed effective vibrating area have effects on sound pressure level but it is not considerable, and Normalized SPL was reduced for each frequency by increasing the bending rigidity of joist. The mortar layer in the radiant heating system had relatively high density and high impedance, therefore, it distributed much of the impact power when it was excited, and reduced the Normalized SPL considerably. Nevertheless, Increasing a thickness of mortar layer had little influence on SPL. Ceiling components reduced the sound pressure level about 5~25 dB for each frequency. Namely, it had excellent sound insulation properties in a range from 200 to 4,000 Hz frequency for both heavy and lightweight impact sources. Also, there was a somewhat regular sound insulation pattern for each center frequency. The resilient channel reduced the SPL about 2~11 dB, irrelevant to impact source. Consequently, current radiant floor heating systems which were established in light-framed residential buildings have quite good impact sound insulation properties for both impact sources.

Keywords: sound pressure level (SPL), impact sound insulation properties, radiant floor heating system, heavy impact sound, lightweight impact sound

1. INTRODUCTION

Evaluating clauses for a residential environment are sound insulation, sound absorption, walkability, instant deflection, durability [14] and so on. Among them, sound insulation is the most discontented matter by occupants, in addition, it is a determinant factor of residential environmental assessment [6]. Impact noise generated by such behaviors as the walking of adults and the running of children causes many complaints from dwellers [25]. Namely, the occupants in multi-family buildings want to protect their privacy from adjacent neighbors. Therefore, the dwellers of multi-family buildings are very concerned about the impact

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sound insulation properties of floors.

In Korea, the construction of light-framed houses has increased rapidly. Notably, as one of the features of light-framed houses, same specification of radiant floor heating systems which were adopted on reinforced concrete floors are preferably installed [18]. Sound propagation properties or transmission patterns are different between light-framed floor and reinforced concrete slab [5,8,27], Nevertheless impact insulation properties of radiant floor heating systems have not been sufficiently evaluated yet [13,18, 27] and evaluations of impact insulation properties are progressed only with lightweight impact source [7,10,22-26]. Thus, there is an urgent need to assess the impact insulation properties of radiant heating systems on light-framed floors with both heavy and lightweight impact sources. Various types of radiant floor heating systems are currently used [18] : dry methods, wet methods, and hybrid methods. However, most light-framed structures have adopted a wet method which is composed of a cement-mortar layer within the radiant floor heating system.

Because light-framed floors have orthotropic characteristics in each coordinates [5,8,9,15,29], they have different structural properties from reinforced concrete floors which are isotropic. Due to the radiant floor heating systems being constituted of various laminations of various materials, the paths or characteristics of sound propagation in light-framed floors with radiant floor heating systems are different from light-framed floor frameworks analyzed in earlier studies. Furthermore, sound pressure level (SPL) spectrum patterns of light-framed floors generated by impact are different from those of reinforced concrete floors [5,8,27]. Behaviors of joints or influences of joint types have not been revealed yet. Radiant floor heating systems are composed of a covering layer, heating unit, damping layer, floor framework and ceiling layer. It is unable to predict the SPL patterns for the whole floor system by merely adding each layer's results together or small-scale specimen's evaluating results [27]. As a result, many types of radiant floor heating systems are needed in order to evaluate the impact sound insulation properties.

This paper aims to find out the characteristics of each impact sources, propagation of impact sound, and sound radiation distribution of SPL in a receiving room with experimental methods for light-framed floors and light-framed floors with radiant floor heating systems.

2. MATERIALS and METHODS

Floor frameworks are consisted of SPF 2× 10, 2×12, I-joist 2×10(PRI15), and I-joist 2× 12(PRI15) as the joists, structural OSB 23/32" for the sheathing panel, Cement-mortar (cement 1 : fine-aggregate 3) and commercial heating

Table 1. Specification of light-framed floor framework.

	Type I	Type II	Type III	Type IV	Type V
Framing	23/32" OSB	23/32" OSB	23/32" OSB	23/32" OSB	23/32" OSB
	2×10 Lumber	2×12 Lumber	I-joist 2×10 (PRI 15)	I-joist 2×12 (PRI 15)	I-joist 2×12 (PRI 15)
Spacing	12" O.C	16" O.C	12" O.C	16" O.C	24" O.C
Thickness (mm)	251	311	256	323	323
Actual size	4,150 mm × 2,950 mm				

unit for the radiant heating systems, 64 kg/m^3, 100 mm thick mineral wool, 16 mm Gypsum boards, and 8 mm thick resilient channels for ceiling components. The floor size was 4.2 m by 3.0 m and the test procedure was conformed to ISO 140-6 [Acoustics - Measurement of sound insulation in buildings and of building elements-part 6: Laboratory measurements of impact sound insulation of floors]. Impact sources were Heavy Impact Source (Tire) and Lightweight Impact Source (Standard Tapping Machine). SPL was measured for each 1/3 octave band center frequency in a range from 63 Hz to 4000 Hz [2-4,11,12,30,31].

Impact Sound Insulation tests were performed separately in two parts; 1) for only a light-framed floor framework with changing the joist material, spacing and the position of excitation, and 2) for whole floors with changing the components of the radiant heating system on the same light-framed floor framework.

At first, for detecting impact insulation properties, the floor framework consisted of only joists and sheathings, and five types of frameworks were composed with variant joist material and spacing. Secondly, four types of radiant floor heating systems on the same floor framework were constituted while the components of the laminated material were changed, and evaluated for their impact sound insulation properties. In particular, tests were proceeded within two ways - with and without ceiling components, in order to reveal the characteristics of ceiling components. Table 1 and 2 show a constitution of testing specimen, and the cross-sectional view of radiant floor heating systems are shown in Fig. 1.

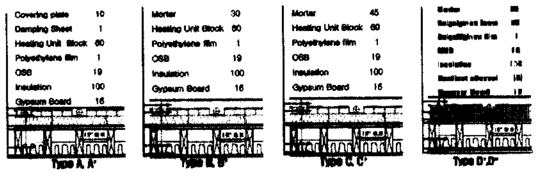


Fig. 1. Cross-sectional View of Test Specimens (unit : mm).

3. RESULTS and DISCUSSIONS

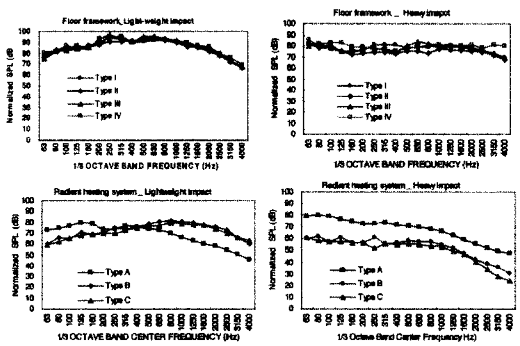
3.1. Characteristics of Impact Sources

As shown in Fig. 2, the heavy impact(tire) source made contact with the floor surface for about 20 ms [28], quite a long duration compared to contact made by the lightweight impact source (standard tapping machine). Sound power (impulse) and sound intensity were less in the case of heavy impact than in case of the lightweight impact source. Sound pressure propagation occurred mainly through flexural

Table 2. Specification of radiant floor heating system. (unit : mm)

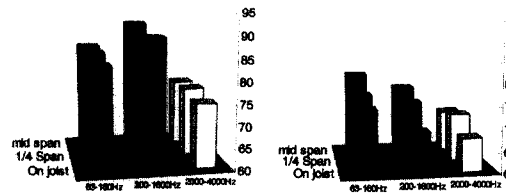
	Type A'	Type B'	Type C'	Type D'	Type A,B,C
Radiant Floor Heating System	Covering plate 10 damping sheet 1 Heating block 60 Polyethylene film 1	Mortar 30 Heating block 60 Polyethylene film 1	Mortar 45 Heating block 60 Polyethylene film 1	Mortar 45 Polystyrene-foam50 Polyethylene film 1	same with left except exclusion of Ceiling Components
Framework	Type IV	Type IV	Type IV	Type IV	
Ceiling	Mineral wool 100 + Gypsum Board 16				
Th. of heating system	73	91	106	95	
Total Th.	415 (399)	433 (417)	448 (432)	437 (445)	

Note) ( ) : Thickness of Type A,B,C,D



(a) (b)

Fig. 2. SPL spectrum of floor frames and radiant heating systems (a : Lightweight impact source, b: Heavy impact source).



(a) (b)

Fig. 3. Averaged SPL according to excitation position for each impact sources (a : Lightweight impact source, b: Heavy impact source).

vibration under the 500 Hz frequency range. Therefore, peak SPL is seen in a frequency range below 200 Hz.

On the other hand, the lightweight impact source is in contact with the floor surface for a shorter duration than that of the heavy impact source. This results in high intensity impact sound and high sound power. Therefore, it can be assumed that sound pressure propagation occurs mainly through a transverse wave with a peak SPL within the range of 500~2000 Hz. Nevertheless, sound pressure propagation in low frequency ranges is induced by longitudinal wave. These resulting patterns agree with those of reinforced concrete slabs or steel joist floors [13,14].

3.2. Light-framed Floor

3.2.1. Flexural Rigidity of Joist

For each of the heavy and lightweight impact source, the normalized SPL was generally decreased in the range of 63~1,250 Hz according to increases in the flexural rigidity of the joist [7,27]. In the range of 1,600~4,000 Hz, normalized SPL for each frequency range was not very constant, but almost the same or slightly greater than that of light-weight impact source. A pattern hegemony could not be found. Precisely speaking, SPL of heavy impact source was decreased more than that of lightweight impact.

In the case of heavy impact source, SPL was more decreased under the 1,600 Hz range. It can be inferred that increasing the flexural rigidity of a joist results in an increase of acoustical impedance, a decrease in the amplitude of floor vibration, or a reduction of the coincidence frequency. Naturally, SPL showed a decreased pattern of spectrum as the bending stiffness was increased.

From these results, it can be inferred that sound pressure is mainly generated and mainly radiated through flexural vibration in the range less than 200 Hz, and in the range between 250 ~4,000 Hz, in which sound pressure was radiated in the form of pseudo-steady-state radiation, surface deformation, and rigid body radiation through combined flexural and longitudinal vibration.

3.2.2. Excitation Position

In case of lightweight impact source (Fig. 3a), SPL was influenced by the flexural rigidity of the floor in the range between 63~160 Hz. In the case of the heavy impact sound(Fig. 3b), SPL was influenced more widely by the flexural rigidity of the floor at the range of 63~

Table 3. Deviation of normalized SPL with varying the flexural rigidity of joist.

Type of joist			Type I (L-10)	Type II (I-10)	$\Delta \overline{L_{n,W}}$	Type III (L-12)	Type IV (I-12)	$\Delta \overline{L_{n,W}}$
Flexural rigidity of joist (Nm^2)			428000	462225		715000	803548	
			Increasing Flexural rigidity 8.0%			Increasing Flexural Rigidity 12.4%		
SPL(dB) average	Heavy impact	63~160 Hz	79.3	77.2	- 2.1	77.8	76.6	- 1.2
		200~1,600 Hz	79.5	74.8	- 4.7	79.2	73.5	- 5.7
		2 K~4 KHz	73.7	72.2	- 1.5	74.4	74.9	+ 0.5
	Lightweight impact	63~160 Hz	84.2	83.6	- 0.6	81.7	81.7	0
		200~1,600 Hz	90.8	89.9	- 0.9	92.6	91.2	- 1.4
		2 K~4 KHz	74.7	74.7	0	75.7	76.7	+ 1.0

1,600 Hz. In other frequency ranges, regular patterns could not be detected.

Consequently, in case of the lightweight impact source, the flexural vibration was a main factor of sound pressure under a 160 Hz frequency range, but it was not dominant one. In other frequency ranges, the distribution of SPL was scarcely affected by flexural rigidity and it could be assumed that SPL would be influenced prominently by the characteristics of floor covering. On the other hand, in the case of a heavy impact source, the frequency range of SPL, which was mainly influenced by flexural rigidity, was wider than that of lightweight impact source.

3.2.3. Joist Spacing and Depth

The flexural rigidity of Type II and IV (2× 12 16"O.C joist floor) was bigger than those of Type I and III (2×10 12"O.C joist floor) if excitation position was the same as on the joist, therefore SPL of Type II and IV should be smaller than that of Type I and III. Nevertheless, the SPL was not shown to have a regular pattern, which was expected.

Table 4 shows an averaged SPL for floor frameworks whose joist spacing and depth of joists were changed. Namely, each group of the normalized SPL, which was about same excitation position, was compared to find out the effect of an assumed vibrating area. For all,

Table 4. Averaged SPL with changing joist spacing and depth.

Type of joist			Type I (L-10)	Type III (L-12)	$\Delta \overline{L_{n,W}}$	Note	Type II (I-10)	Type IV (I-12)	$\Delta \overline{L_{n,W}}$	Note
Flexural rigidity of joist (Nm^2)			428000	715000		ΔEI= +67.1%	462225	803548		ΔEI= +73.8%
Assumed sound radiation efficient area (m^2)			1.5846	1.8274		ΔA= +15.3%	1.5846	1.8274		ΔA= +15.3%
SPL(dB) average	Heavy impact	63~160 Hz	79.3	77.8	-1.5		77.2	76.6	-0.6	
		200~1,600 Hz	79.5	79.2	-0.3		74.8	73.5	-1.3	
		2 K~4 KHz	73.7	74.4	+0.7		72.2	74.9	+2.5	
	Lightweight impact	63~160 Hz	84.2	81.7	-2.5		83.6	81.7	-1.9	
		200~1,600 Hz	90.8	92.6	+1.8		89.9	91.2	+1.3	
		2 K~4 KHz	74.7	75.7	+1.0		74.7	76.7	+2.0	

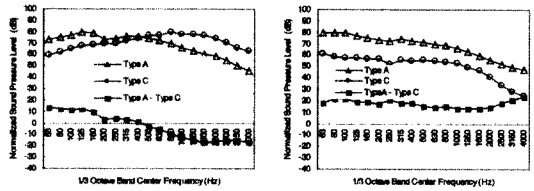
it can be concluded that the assumed vibrating area had more influence on the SPL spectrum than that of flexural rigidity.

3.3 Radiant Floor Heating System

3.3.1. Mortar Layer

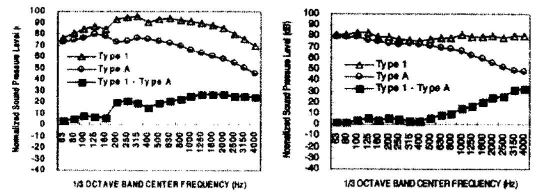
In the case of Type A, the covering plate was 800 mm×800 mm×10 mm, had low plane density, and caused 1~3 dB of reduced SPL for lightweight and heavy impact sound. Its impact insulation was quite small [8,9], so the impact insulation properties of the covering plate were neglected in order to find out a impact insulation properties of the mortar layer. It was assumed that the covering plate of Type A had no influence on SPL spectrum. Also, covering plate was assumed to have not influence on the reduced SPL of heating unit, and the reduced SPL of different covering material was the same. It was also assumed that the reduced SPL of each heating unit in Types A and C radiant floor heating system was not affected by covering material , and there was a uniform reduced SPL pattern.

In the case of a lightweight impact source (Fig. 4a), SPL was reduced by about 5~13 dB in the range from 63 to 500 Hz by adding a mortar layer. However, due to resonance of the mortar layer, SPL was increased in the range from 500 to 4,000 Hz. In the case of a heavy impact source (Fig. 4b), SPL was reduced about 16~26 dB in all of the frequency ranges. It is considered that the mortar layer reduce the sound power of heavy impact source because the mortar layer was quite massive and had a high acoustical impedance. After all, the mortar layer effectively reduced the heavy impact sound, such as an adult walking with bare feet, or the jumping and running of children.



(a) (b)

Fig. 4. SPL curves and SPL deviation by mortar layer (a : Lightweight impact source, b : Heavy impact source).



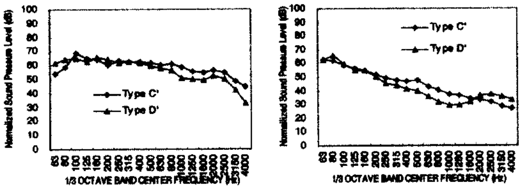
(a) (b)

Fig. 5. Normalized SPL & transmission loss of commercial heating block (a : Lightweight impact source, b : Heavy impact source).

3.3.2. Heating Components

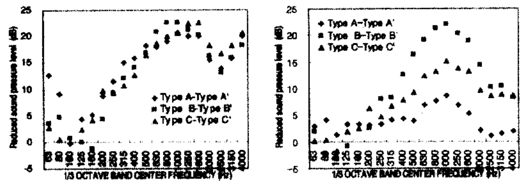
In case of lightweight impact source (Fig. 5a), reduced SPL was 3~5 dB in the frequency range of 63~160 Hz, and 18~26 dB in the frequency range of 200~4000 Hz. In case of heavy impact source (Fig. 5b), reduced SPL was 2~7 dB in the range of 63~500 Hz, and 11~33 dB in the range of 630~4,000 Hz.

Acoustic radiation of the impact sound occurred due to complicated floor vibration of floor members. Thus, SPL was influenced by flexural rigidity which is related to flexural vibration in the frequency range of 63~200 Hz for heavy impact source, and 63~500 Hz for lightweight impact source [7,26]. SPL was also influenced by the heating/resilient layer which reduces the sound power transmission above 200 Hz for lightweight impact source and above 500 Hz for heavy impact source. Namely, it can be concluded that heavy impact source has a wide range of rigidity determinant area and a



(a) (b)

Fig. 6. Comparison between heating block and polystyrene foam (a : Lightweight impact source, b : Heavy impact source).



(a) (b)

Fig. 7. Sound transmission loss by ceiling component for each radiant heating system (a : Lightweight impact source, b : Heavy impact source).

narrow range of mass law determinant area when compared to lightweight impact source.

3.3.3. Polystyrene foam vs. Commercial heating unit block

Fig. 6 shows a evaluating results of impact sound insulation of resilient layer. Fig. 6(a) shows the results of lightweight impact source and Fig. 6(b) shows that of heavy impact source. Polystyrene foam, despite it's low cost, has almost the same or better sound insulation properties compared with those of a heating unit block. The two layers have almost the same thickness and have similar heat insulation properties. Despite that impact insulation properties were not excellent [13] in the radiant floor heating system on the reinforced concrete slab, polystyrene foam is recommended as insulation in radiant floor heating systems on light-framed floors.

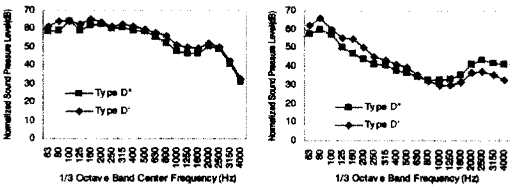
3.3.4. Ceiling Components

In the case of a lightweight impact source (Fig. 7a), notwithstanding the different radiant floor heating types, reduced SPL of ceiling components had a similar pattern. But, in case of a heavy impact source, somewhat variations were detected according to the types of radiant heating system.

In the case of heavy impact source (Fig. 7b), reduced SPL of ceiling components about Type A was small, as much as 2~9 dB. On the other hand, that of Type B' or C', which had a mortar layer substitution for a covering plate, as in Type A, was 2~22 dB according to frequency. But, because the mortar layer had large acoustical impedance due to its rigidity and effective mass, it distributed and decreased the sound power of the whole floor and therefore sound intensity in the receiving room was decreased. On the other hand, in case of Types B' and C', SPL increased unexpectedly in the frequency range of 80~160 Hz compared to SPL of type B and C which was absent from ceiling components. It is thought that harmonic vibration oriented by resonance in the vacancy between sheathing and gypsum board caused this result [27].

The resonance frequency of vacancy resulted in 61.46 Hz. This resonance effect of vacancy should be controlled by the thickness of the gypsum board, depth of the joist, and thickness of the insulation to a fundamental natural frequency 15~30 Hz [28], which is known to be the same as a general light-framed wooden joist floor, or it should be controlled to as low as possible.

Especially in the case of heavy impact source, Type A' has a relatively large reduced-SPL and transmission loss (TL) compared to Type B' or C' in the frequency range under 200 Hz. It also can be inferred that radiant heating systems that



(a) (b)

Fig. 8. SPL patterns for each case of with and without resilient channel (a : Lightweight impact source, b : Heavy impact source).

had low mass and plane density caused the reduction of resonance frequency of vacancy. In the other frequency ranges, Type B' and C' had relatively better impact insulation than in Type A', and the similar results also occurred when the result of a Type A to that of a Type B and C were compared.

3.3.5. Resilient Channel

The resilient channel reduced the SPL about 2～11 dB, irrelevant to impact source. In the case of a lightweight impact source (Fig. 8a), the resilient channel was effective in the low frequency range of 63～160 Hz. It also played a role as a separating layer, reducing the SPL 1～9 dB, and was thought to be effective and moreover, cheap [1]. In the case of heavy impact source (Fig. 8b), it reduced the SPL more effectively than that of lightweight impact source except in the range of 800～4,000 Hz, which experienced an unexpected increase of SPL as 3～5 dB.

Sound insulation at 100 Hz was considerably smaller than that of other frequencies for each of the impact sources, and the SPL increased unexpectedly, about 3～9 dB. Those were thought to be the effects of resonance from the floor or ceiling components but needed further study. Nevertheless, establishing a resilient channel is strongly recommended.

4. CONCLUSIONS

Sound Pressure propagation is induced by surface deformation, pseudo-steady-state radiation, and rigid body radiation. SPL was different for each impact source for those spectrum patterns and peaks. Peak SPL was shown in the frequency range of 200～2,000 Hz for lightweight impact source and 63～200 Hz for heavy impact source. Normalized SPL was reduced for each frequency by increasing the bending rigidity of joist or by increasing the joist depth and changing joist material from lumber to I-joist. In case of light-framed floor framework, the excitation position and the assumed effective vibrating area have effects on sound pressure level but it is not considerable. The mortar layer had relatively high density and high impedance, therefore, it distributed much of the impact power when it was excited. Thus, by adding a layer of mortar to the radiant floor heating system, Normalized SPL was reduced considerably. By increasing the thickness of mortar from 30 mm to 45 mm, SPL was decreased slightly, but it was not very constant for every center frequency. Ceiling components reduced the sound pressure level about 5～25 dB for each frequency. Namely, it had excellent sound insulation properties in a range from 200 to 4,000 Hz frequency for both heavy and lightweight impact sources. Also, ceiling components had a somewhat regular impact sound insulation pattern for each center frequency. The resilient channel reduced the SPL about 2～11 dB, irrelevant to impact source.

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