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공학석사 학위논문

Influence of building components on heavy impact noise in residential buildings

공동주택 건물 구성요소 별
중량충격음에 미치는 영향

2017년 8월

서울대학교 대학원

건축학과

김 주 형

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지도 교수 박 홍 근

이 논문을 공학석사 학위논문으로 제출함

2017년 8월

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김주형의 공학석사 학위논문을 인준함

2017 년 8 월

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Abstract

Influence of building components on heavy impact noise in residential buildings

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Heavy floor impact noise generated by the occupant's footsteps is still a social problem occurring in residential buildings. Heavy impact noise is composed of low frequencies lower than 250Hz. The noise reduction level of heavy impact noise was not significant in floating floor system. Sometimes floating floor system even amplifies the noise level. Although various kinds of resilient materials have been developed and tested, the problem amplifying heavy impact noise has not been solved yet.

Even though the same resilient material is used, heavy impact noise level varies depending on the room dimension. Likewise, there are many variables affecting heavy impact noise in residential buildings. There are limitations in terms of time and cost in verifying the influence of various variables that determine heavy impact noise through experiments. If we can predict heavy impact noise using numerical analysis, it is expected to approach the heavy impact noise problem more effectively.

Many previous researchers have studied several methods for numerical modeling of bare slab system. On the other hand, little research has been done on numerical analysis of floating floor system including resilient materials. Since the performance of the heavy impact noise of the floating floor system cannot be verified through numerical analysis, the performance of the heavy impact noise in actual residential buidings cannot be predicted.

Therefore, this thesis focused on the proposal of heavy impact noise prediction of floating floor system. In order to develop the numerical model of floating floor system, four variables (room dimension, structure system, non-structural walls, and floating floor system) were analyzed based on field test results that are expected to influence heavy impact noise. Consequently, the numerical analysis result of the heavy impact noise proposed in this thesis were found to be in good agreement with the field measurement results.

This thesis proposed a numerical modeling method that can predict heavy impact noise of a floating floor system, and it is expected that it will be possible to evaluate the heavy impact noise level in design stage providing a basis for the plan design.

Keywords : Heavy impact noise, Floating floor, Resilient material, FE analysis

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Chapter 1. Introduction

1.1 Background

Floor impact noise in apartment building is a social issue, and it is required to predict floor imact noise in design stage. However, it is hard to predict floor impact noise because there are so many variables that affect the floor impact noise. It takes long time and costly to verify the influence of each variable through experiments. Therefore, it is necessary to predict floor impact noise through numerical analysis. So far, many studies have been done on the numerical modeling of bare slab system. However, after installation of floating floor system, the response of heavy impact noise is quite different from that of bare slab system. Although floating floor system effectively reduces both slab vibration and sound pressure level at high frequencies over 100Hz, amplified response is observed around 50-80Hz. As a result, after installation of floating floor system, sometimes the floor system even worse the noise performance. Table 1-1 shows a field test result of bare slab system and floating floor system.

Table 1-1 Single number quantities of bare slab and floating floor system

Floor system	Single number quantity ($L_{i,FMAX,AW}$, dB)					
	Site A	Site B	Site C	Site D	Site E	Site F
Bare slab	49	51	49	48	50	51
Floating floor	51	50	50	49	49	50
Reduction Level	**-2**	**1**	**-1**	**-1**	**1**	**1**

The result is opposite to the purpose of the floating floor system, and are not even consistent. This phenomenon makes us hard to predict heavy impact noise level. Thus, numerical modeling method of floating floor system needs to be developed. If the heavy impact noise level of floating floor system can be predicted accurately, it will be possible to evaluate the heavy impact noise in advance in design stage and to provide a basis for apartment design considering floor impact noise.

1.2 Scope and Objectives

The purpose of this thesis is to propose a numerical analysis method to predict the heavy impact noise of floating floor system. Great attention has been shown to the question of predicting heavy impact noise so far. Accordingly, much numerical works has been done on the topics of bare slab system. However, relatively few studies has been devoted to the modeling of floating floor system.

Central to this paper are two topics. Before formulate a numerical model of floating floor system, the paper examined four factors affecting heavy impact noise in floating floor system. Test result provided a basis of the modeling of floating floor system. As numerical analysis is performed using limited information, the paper does not attempt to provide every information related to heavy impact noise. While this paper does include topics of floor dimension, structural system, non-structural walls, and flooring system, it does not attempt to provide influence of windows, walls, finishing materials, etc.

Analysis results in the thesis are all examined by field experiment. In recent years, there have been many laboratory experiments, and it has been found that the results of laboratory test are different from those of field test. Therefore, it is expected that the test result of this paper can give convincing answers to the questions regarding heavy impact noise in real residential buildings. Consquently, the numerical model proposed in this study is expected to provide a basis for predicting the heavy imact noise of floating floor system.

1.3 Outline of the Master's Thesis

The thesis is divided into two main parts. To predict heavy impact noise of floating floor system numerically, several kinds of field experiments were preceded. Field experiment result provided a basis for numerical modeling. Numerical model of floating floor system showed reasonable prediction results. Figure 1-1 briefly summarizes the entire contents of this thesis.

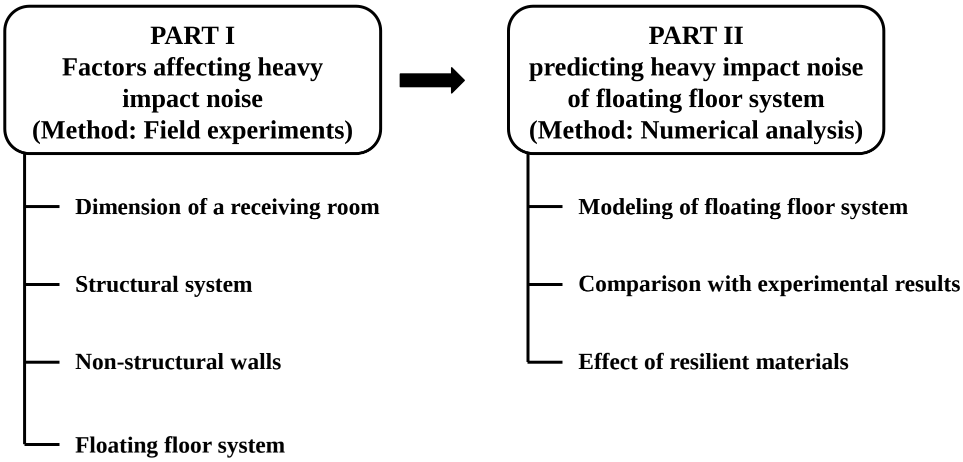


Figure 1-1 Outline of the master's thesis

PART I

In part I (chapter 3), four factors affecting heavy impact noise were analyzed. These factors are dimension of receiving room, structural system, non-structural walls, and floating floor system. These factors vary depending on the condition of apartments. The effect of each factor on heavy impact noise was verified through field experiments. Field test results of each factor provided a basis of numerical analysis model of floating floor system.

PART II

Based on the field test results in part I, a numerical modeling method of heavy impact noise of floating floor system is proposed. The numerical model is verified by comparing the analysis result to the field measurement data. Both slab acceleration and sound pressure level showed analogous result to the field test result. After that, the effect of resilient material in floating floor system is analyzed using the numerical model. The analysis showed consistent result with previous studies related to resilient materials.

Chapter 2. Literature Review

2.1 Code Review

2.1.1 Korean industrial standards

KS provides four standards related to heavy impact noise. Four standards specify measurement and rating method of heavy impact noise. However, there is no standard for design methods for reduction of heavy impact noise. Table 2-1 shows Korean standards related to heavy impact noise which are focused on measurement and rating of the noise.

Table 2-1 Korean standards related to heavy impact noise

Code number	Title
KS F 2810-2: 2012	Field measurements of floor impact noise insulation of bulidings – Part 2: Method using standard heavy impact sources
KS F 2863-2: 2007	Rating of floor impact noise insulation for impact source in buildings and of building elements – Part 2: Floor impact noise insulation against standard heavy impact source
KS F 2865: 2015	Laboratory measurements of the reduction of transmitted impact sound by floor covering materials using strandard light and heavy impact sources
KS F 2868: 2003	Determination of dynamic stiffness of materials used under floating floors in dwellings

2.1.2 ISO

ISO standards related to floor impact noise can be divided into two groups. There is one group pertaining to laboratory test of impact noise. The other group covers field test. Table 2-2 summarizes the ISO standards about building acoustics.

Table 2-2 ISO standards pertaining to building acoustics

	Building acoustics	Contents
Laboratory test	ISO 10140-1	Application rules
	ISO 10140-2	Measurement of airborne sound insulation
	ISO 10140-3	Measurement of impact sound insulation
	ISO 10140-4	Measurement procedures
	ISO 10140-5	Test facilities and equipment
Field test	ISO 16283-1	Airborne sound insulation
	ISO 16283-2	Impact sound insulation
	ISO 16283-3	Façade sound insulation

Detailed information of measurement equipments and procedures is provided. However, no definitive answer has been given to a design of impact noise as in Korean standards. Especially, because heavy impact noise is not a severe problem in other countries, research on insulation of heavy impact noise is still in early age. Accordingly, there is no specific standards related to the heavy impact noise. Current international standards does not provide standards related to the impact sound prediction in design stage.

2.1.3 Notice 2016-824 (MOLIT)

Amendment of ‘Approval and management standards for floor impact noise insulation in apartment buildings’ was noticed by the Ministry of land, infrastructure and transfort in 2016. If a floor system in wall type structure receive performance recognition, it can be applied to a flatplate or mixed structure. The minimum performance level determined by following the measurement procedure of KS F 2863-2 for heavy impact noise is 50dB. Table 2-3 shows the grading of floor impact noise level.

Table 2-3 Floor impact noise performance grade

Grade	Light impact sound (dB)	Heavy impact noise (dB)
1	$L_{n,aw} \leq 43$	$L_{i,Fmax,AW} \leq 40$
2	$43 < L_{n,aw} \leq 48$	$40 < L_{i,Fmax,AW} \leq 43$
3	$48 < L_{n,aw} \leq 53$	$43 < L_{i,Fmax,AW} \leq 47$
4	$53 < L_{n,aw} \leq 58$	$47 < L_{i,Fmax,AW} \leq 50$

Figure 2-1 shows the grades of heavy impact noise performance of actual residential buildings in Korea, when vibrated by standard heavy impact source I (bang machine). 66 among 135 numbers of apartment buildings couldn’t satisfy grade 4. Only 13 specimens showed grade 3 which is only 10% of the total residential buildings.

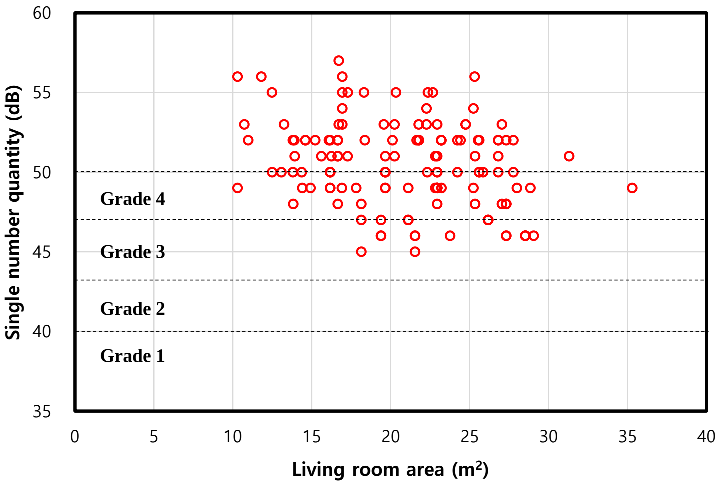


Figure 2-1 Heavy impact noise grades measured in apartment buildings

The notice also prescribes performance criteria of resilient material in flooring system. The dynamic stiffness and the loss factor are determined by the test method specified in KS F 2868. The dynamic stiffness should be less than 40MN/m^3 after 48 hours with the load plate mounted. As will be seen in chatper 2.2, low dynamic stiffness of a resilient material shows better floor impact noise performance, generally.

2.2 Literature Review

2.2.1 Stochastic signal (Shin et al.)

Fourier methods can be applied to deterministic phenomena. Floor vibration or floor impact noise is stochastic or random signal. In this case, it is hard to define the signal in frequency domain because the signal is not stationary (varies with time).

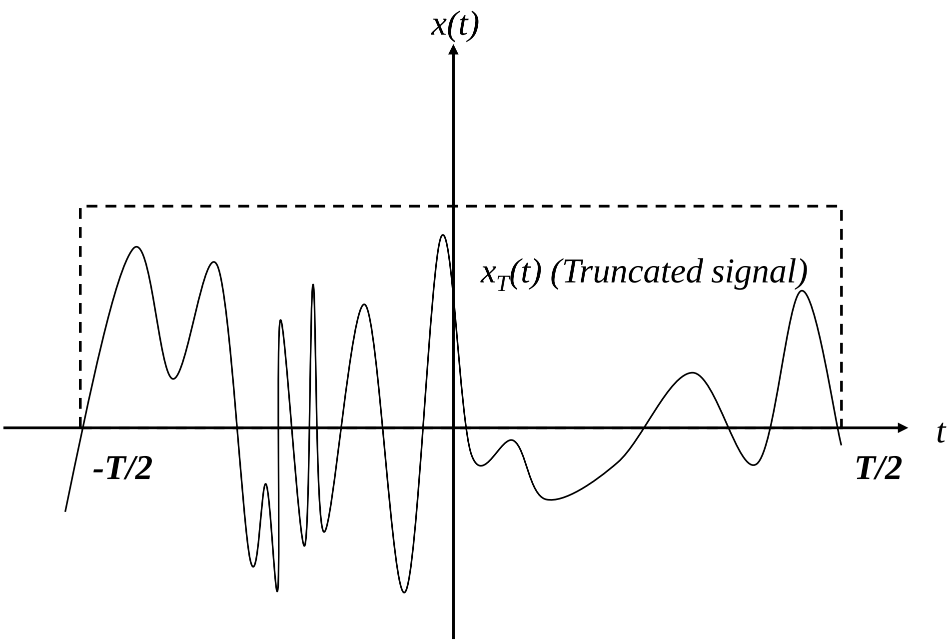


Figure 2-2 A truncated random signal (Length: T)

Figure 2-2 shows a sample of stochastic signal. Using the Parseval' theorem, the average power of the signal can be shown in frequency domain. Eq. (2.1)

$$\frac{1}{T}\int_{-T/2}^{T/2} x_T^2(t)dt = \frac{1}{T}\int_{-\infty}^{\infty} \left|x_T(f)\right|^2 df = \int_{-\infty}^{\infty} \frac{1}{T}\left|x_T(f)\right|^2 df \tag{2.1}$$

As, T → ∞, Eq. (2.1) can be written as

$$\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} x_T^2(t)dt = \int_{-\infty}^{\infty} \lim_{T\to\infty}\frac{\left|x_T(f)\right|^2}{T} df \tag{2.2}$$

Floor vibrations or floor impact noise is always buried in noise, i.e.,

$$x(t) = s(t) + n(t) \tag{2.3}$$

Where *s(t)* is the original signal, and *n(t)* is the noise. By averaging the raw signal, the erratic behavior (noise) can be removed.

$$E\left[\lim_{T\to\infty}\frac{1}{T}\int_{-T/2}^{T/2} x_T^2(t)dt\right] = E\left[\int_{-\infty}^{\infty} \lim_{T\to\infty}\frac{\left|x_T(f)\right|^2}{T} df\right] \tag{2.4}$$

Assuming zero mean values, the left hand side of Eq (2.4) is the variance of the signal, thus it can be written as

$$Var(x(t)) = \sigma_x^2 = E\left[\int_{-\infty}^{\infty} \lim_{T\to\infty}\frac{\left|x_T(f)\right|^2}{T} df\right] \tag{2.5}$$

Consequently, power spectral density shows statistical properties of the stochastic signal in frequency domain.

2.2.2 Prediction of heavy impact noise

Kim et al. [7] measured the vibration acceleration levels on the slab and predicted the sound pressure level by using them. According to the study, the result showed that the predicted value were in good agreement with the measured values within 5~10% in error rate. Eq. (2.6) is used to estimate the sound pressure level of structural-borne sound.

$$SPL = VAL + 10\log\sigma + 10\log(S/A) - 20\log f_m + 36 \qquad (2.6)$$

SPL is average sound pressure level, *VAL* is vibration acceleration level (dB, ref. $1\text{x}10^{-5}\text{m/s}^2$), *A* is interior total sound absorption (m^2), and f_m is center frequency (Hz). The result of this study showed that sound pressure level by the impact source is highly affected by the vibration level of the structure.

Mun et al. [8] predicted heavy impact noise using measured frequency response function for both bare slab system and floating floor system. According to his study, once frequency response function(FRF) can be acquired, it is possible to predict sound pressure for various impact sources. He derived frequency response function by conducting field measurement. Expected floor impact noise can be calculated using the Eq. (2.7)

$$G_{yy}(f) = |H(f)|^2 G_{xx}(f) \qquad (2.7)$$

$G_{xx}(f)$ is force spectrum, $H(f)$ is frequency response function, and $G_{yy}(f)$ is expected response. The test result showed that floor impact noise level can be predicted reasonably once FRF is generated. Using FRF function, responses induced by various kinds of impact sources can be estimated. However, field test must be preceded to get the frequency response function.

2.2.3 Numerical modeling of heavy impact noise (Bare slab)

Seo et al. [9] proposed simple FE analysis model with slab and boundary conditions corresponding to the concrete walls or windows. According to his study, slab thickness is the main factor that can reduce floor slab vibration effectively. Concrete strength, and density showed relatively small effect on the slab vibration. However, floor impact noise level is not included in this study. It is expected that the floor impact noise decreases as slab thickness increases, but there was no information about sound pressure level.

Mun et al. [10] performed numerical analysis of heavy-weight impact noise of bare slab system considering acoustic mode of a receiving room. He suggested material and structural properties related to floor impact noise specifically. According to his study, due to the effect of acoustic mode at a certain frequency, sound pressure level can be amplified as shown in Figure 2-3. Floor height of typcal residential building, 2.6m ~2.8m, caused 1^{st} vertical acoustic mode around 63Hz resulting in amplified sound pressure level at 63Hz.

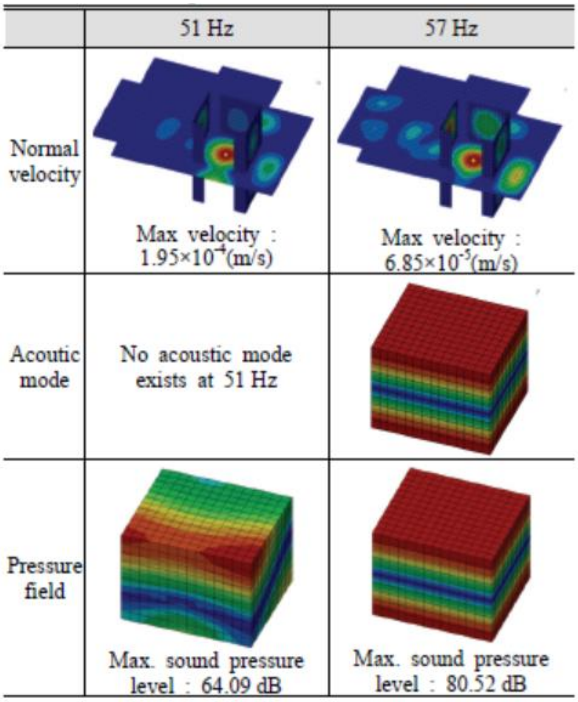


Figure 2-3 Surface normal velocity, acoustic modes, and acoustic pressure field (Mun et al. [10])

Hwang et al. [11] compared heavy impact noise of three different structural systems – wall structure, flatplate structure, and ramen structure by performing FE analysis.

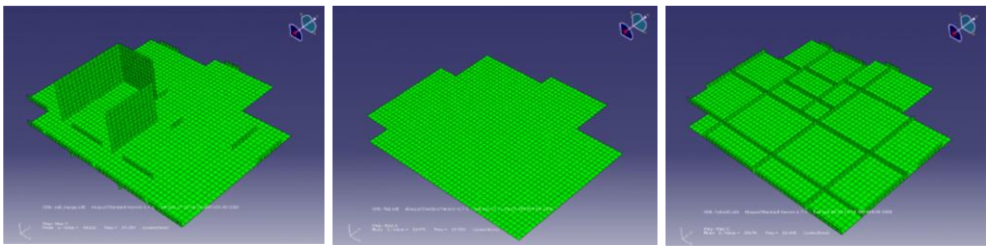


Figure 2-4 Analytical models of wall slab (left), flat slab (center), and RC slab (right) (Hwang et al. [11])

Figure 2-4 shows three analytical models of the study. According to the numerical analysis result, wall structure showed the largest floor impact noise level (51dB). Flatplate structure and ramen structure showed similar floor impact noise level (46dB). He explained that vibration of concrete wall caused larger floor impact noise. However, as studied in chapter 3.3 of this thesis, experimental result of a flatplate system showed larger floor impact noise level than a wall type structure. The reason why flatplate system showed worse noise condition than wall type structure, unlike general idea, is explained in chapter 3.3 in detail.

As summarized so far, many researches related to numerical modeling of floor impact noise has been proposed from various perspectives. The result showed reasonable prediction of the heavy impact noise level of bare slab system. However, there is little study related to a numerical modeling of floating floor system.

2.2.4 Resilient materials of floating floor system

Kim et al. [13] performed several tests with 51 different kinds of resilient materials to examine the relationship between dynamic stiffness and heavy impact noise level. Table 2-4 shows the relationship between the dynamic stiffness and reduction level($\varDelta L$) of the heavyweight impact sound.

Table 2-4 Heavy impact noise laboratory test results (Kim et al. [13])

Dynamic stiffness (MN/m^3)	Single number quantity ($L_{i,Fmax,AW}$, dB)	ΔL (dB)	Thickness of resilient material (mm)
- (Bare slab)	55	-	101
0.34	35	20	60
0.62	38	17	51
0.7	40	15	80
0.97	44	11	60
0.98	44	11	40
0.99	44	11	80
0.99	42	13	60
0.99	42	13	62
1.5	40	15	60
1.5	38	17	60
1.5	42	13	60
1.6	40	15	61
1.6	40	15	62
1.6	38	17	50
1.9	40	15	60
1.9	46	9	20
2	48	7	40
2	47	8	40
2	44	11	50
2.2	43	12	40
2.4	44	11	41
2.4	45	10	40
3	47	8	62
3.4	46	9	60
3.4	46	9	30
3.6	48	7	60
3.6	46	9	40
3.8	47	8	40
4	47	8	60
4.4	48	7	60
4.4	48	7	40
4.5	48	7	41
4.5	48	7	20
4.7	49	6	30
4.8	47	8	70
5.2	47	8	20
5.4	49	6	20

6.3	49	6	20
8.8	49	6	20
9.8	48	7	20
10.1	50	5	20
10.1	49	6	20
12	47	8	40
18.8	51	4	20
23	50	5	20
23	50	5	20
28.6	51	4	20
31	50	5	50
49	53	2	30
57	52	3	30
63	52	3	20

According to the study, floor impact noise reduction level increases as the dynamic stiffness of a resilient material decreases due to the large reduction level of high frequency range over 125Hz (1/1 Octave band level). In some cases where the dynamic stiffness of the resilient material is higher than 8MN/m^3, floor impact level of 63Hz is amplified due to the resilient material. This amplification deteriorated the heavy impact noise level of low frequency range. Consequently, he said the dynamic stiffness of the resilient material is highly related to the heavyweight impact sound, and it is recommended to apply resilient material of low dynamic stiffness lower than 8MN/m^3.

From a different point of view related to the resilient material, Cho's study [14] showed that the performance of resilient material varies when the measurement site is changed.

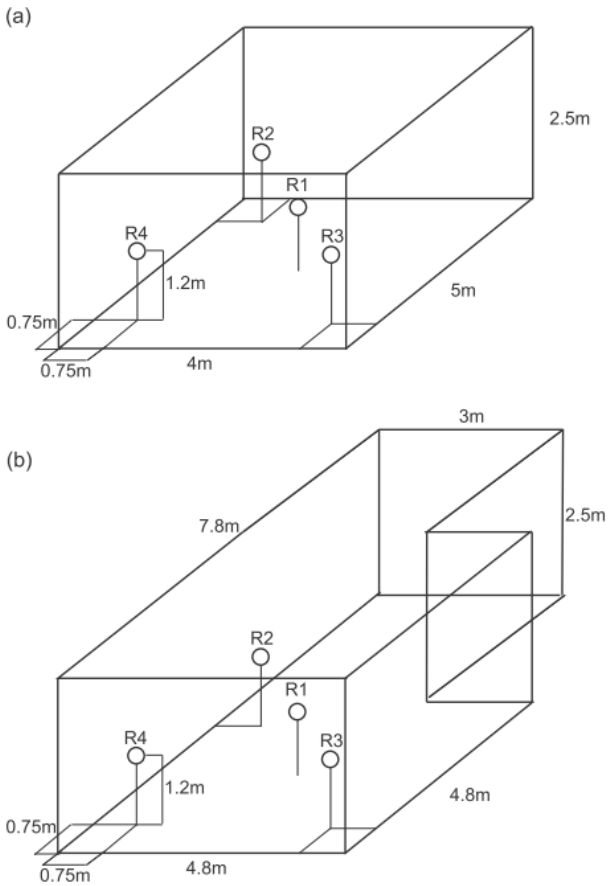


Figure 2-5 Laboratory and field test site (Cho [14])

Figure 2-5 shows floor impact noise measurement plan of the study. (a) The laboratory concrete building, (b) The real apartment building. R1 to R4 represents sound measurement points. Floor impact noise was measured for both system with bare slab, and floating floor. All conditions were same except the room dimension.

Table 2-5 Laboratory and field 63Hz octave band measurements (Cho [14]).

Building type	Bare slab					Resilient layer				
	R1	R2	R3	R4	Avg.	R1	R2	R3	R4	Avg.
Lab	81.1	79.1	79.1	81.4	**80.3**	68.2	68.6	68.5	72.1	**69.7**
Field 1	78.7	82.1	81.7	85.5	**82.7**	74.5	75.9	79.5	79.3	**77.8**
Field 2	78.9	78.2	81.9	83.8	**81.3**	76.9	84.5	83.5	81.1	**82.3**
Field 3	75.9	80.0	76.6	82.3	**79.5**	78.3	80.7	83.9	77.5	**80.9**
Field 4	76.0	79.3	79.0	83.5	**80.3**	77.0	77.7	81.8	74.5	**78.6**

As shown in Table 2-5, 63Hz octave band average response level of bare slab measured in lab is 80.3dB. 63Hz octave band average response level of field test varies from 79.5dB to 82.7dB. There are some variation, but still the laboratory value is located in field test value. On the other hand, the field measured impact sound level was significantly higher than the laboratory level for floating floor system. The only difference in this test is the dimension of the room. Accordingly, variations of heavy impact noise are due to the difference in room dimension. It means the performance of the resilient material tested in laboratory is not guaranteed when the resilient material is installed in real residential buildings. From the two previous studies related to the resilient material, it seems very hard to secure floor impact noise performance in actual residential buildings.

Chapter 3. Building Components Affecting Floor Impact Noise

3.1 Introduction

Many factors affect floor impact noise in residential buildings that make us hard to predict or reduce floor impact noise. Table 3-1 shows several variables and analysis methods this thesis have covered.

Table 3-1 Factors covered in the thesis

Building components		Variables	Analysis method
1. Room dimension		59 Type / 84 Type	Statistical approach
2. Structural system		RC Shear wall / Flatplate	Field test
3. Non-structural walls	3-1. Masonry wall	Concrete brick wall	Field test / FEM Model
	3-2. Dry wall	Gypsum board	Field test / FEM Model
4. Floating Floor System	4-1. Resilient material	Dynamic stiffness	Field test / FEM model / equivalent SDOF model
	4-2. Contact condition	Adhesive/ Non adhesive	Field test

Dimension of a receiving room: Floor impact noise of a receiving room, especially a living room, is affected by the dimension of the room. It is generally acknowledged that larger room space provides reduced floor impact noise level. However, it is very hard to prove the phenomenon by an experimental approach. Instead, statistical approach could be a better way to analyze the effect of room dimension. In this paper, more than one-hundred field test data were collected and the result showed quite clear tendencies between a room dimension and heavy impact noise level.

Structural system: Most of the residential buildings are wall type structure or flatplate structure. Different structure type can cause different response of floor impact noise. Responses of slab acceleration and floor impact noise are analyzed for each structure system by performing field test. Of special interest is the heavy impact noise performance of flatplate structure is not better than that of wall type structure.

Non-structural walls: Concrete brick walls and dry walls composed of gypsum board and insulator are typical non-structural walls found in residential buildings. The impact of non-structural walls on floor impact noise is not fully studied yet. Several field tests have shown that existence of non-structural walls affect vibration and noise responses to some extent. From the field test data, reasonable numerical modeling method of non-structural walls is proposed.

Floating floor system: Floating floor system is a kind of layered floor system composed of concrete slab, resilient material, auto claved light-weight concrete (ALC), and mortar plate. Vibrational characteristics of the slab is significantly affected by the floating floor system when impact source is applied to the top of the mortar plate. The problem which is not solved yet is floating floor system amplifies the vibrational and noise response at a certain low frequency range, though high frequency responses are effectively reduced. In this thesis, the reason of the amplification is explained by both experimental data and an equivalent SDOF model. From the result, a numerical modeling method of floating floor system is proposed.

Neglected factors: finishing materials of ceiling and flooring, windows, doors also affect the floor impact noise. However, these factors were not covered in this thesis because these factors are generally regarded as relatively minor factors of floor impact noise. There are also very low possibility of changing material properties of these factors. Slab thickness is one of the most influencial factor on floor impact noise. However, slab thickness of most residential buildings is already fixed to 210mm. Furthermore, several studies have already been done on the topics of slab thickness. Therefore, the effect of slab thickness was not covered in this thesis.

3.2 Dimension of a Receiving Room

It is known that the response of low frequency components to vibration and sound pressure is influenced by the dimension of residential buildings. Therefore, it is necessary to analyze the influence of room dimension on heavy impact noise based on field measurement data. In particular, it should be analyzed by octave band response rather than single number quantity ($L_{i,FMAX,AW}$) to find the sensitive frequency range to the room dimension. Table 3-2 shows field test conditions.

Table 3-2 Field Test conditions

Impact source	Impact ball and bang machine
Impact points	4 points (KS F 2810-2)
Number of measured sites	125
Structural system	Wall type structure
Floor system	Floating floor
Slab thickness	210mm
Living room width	3000mm ~ 6000mm (usually 3600mm or 4500mm)
Living room depth	3000mm ~ 6500mm

Figure 3-1 shows a relationship between single number quantity ($L_{i,Fmax,AW}$, dB) and room area(including kitchen) when heavy impact sources (Bang machine and impact ball) are applied to the floating floor system. For both heavy impact sources, correlation coefficients showed negative value (-0.34 for impact ball and -0.27 for bang machine).

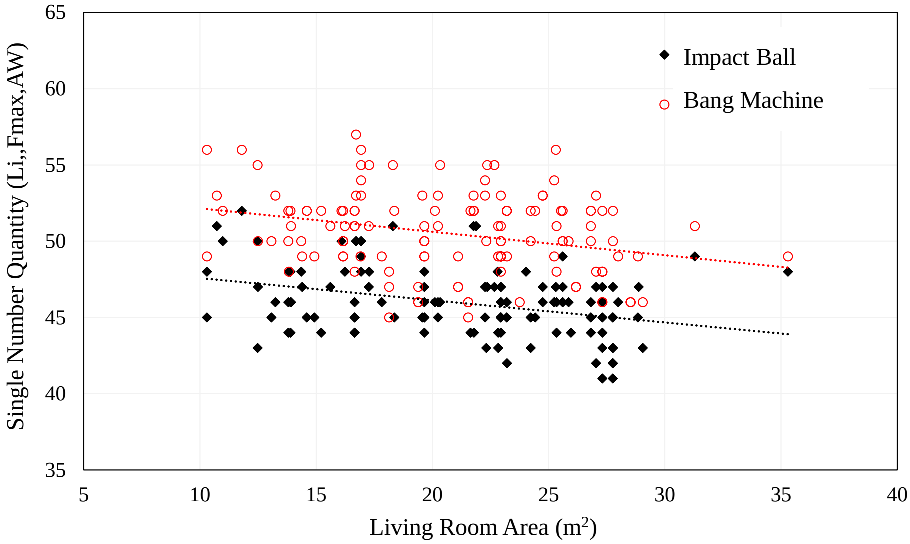


Figure 3-1 Relationship between living room area and floor impact noise

As has been noted by previous studies, floor impact noise level decreases as the room area increases. However, deviation for the same room area seems very large. For example, in case of room area 17m^2, single number quantity of bang machine distribute from 48dB to 57dB. It means sound pressure level cannot be explained only by the room area. It is necessary to analyze the result in more detail.

Table 3-3 Typical room dimension of two types of apartment

Apartment type	Living room width (w_1)	Living room depth (w_2)
59Type (small-sized)	3600mm	4000mm~5500mm
84Type (medium-sized)	4500mm	4500mm~6500mm

Most of collected field measurement have been mainly done at the medium

(84type) and small-sized (59type) apartment. Table 3-3 shows living room size of typical medium or small-sized apartment. Other types except 59type and 84types were excluded from the analysis due to the lack of specimens. In most of apartments, living room width of 59Type and 84Type were 3600mm and 4500mm, respectively. It allowed to analyze the floor impact noise with respect to floor depth while floor width is fixed.

Table 3-4 shows the tendency of sound pressure level with respect to room width and room depth for each 1/3octave band center frequency. In case of heavy impact noise, the sound pressure level over 80Hz is very small because the impact source is mainly composed of low frequency components. The responses are analyzed up to 315Hz, and the frequency components above that frequency are ignored.

Table 3-4 Slope and r^2 of 1/3 octave band responses – Impact ball

1/3 octave band center frequency	Impact source: impact ball			
	w_1=3.6m (59Type)		w_1=4.5m (84Type)	
	Slope	r^2	Slope	r^2
25Hz	-4.0554	0.3283	2.3767	0.1694
31.5Hz	-5.3165	0.5105	1.1684	0.0363
40Hz	-3.1808	0.6159	-4.0979	0.2890
50Hz	-1.8904	0.2618	-2.6234	0.2506
63Hz	-1.0369	0.1442	-2.2247	0.1472
80Hz	-0.7694	0.0139	-0.0711	0.0001
100Hz	-0.2995	0.0014	0.9062	0.0153
125Hz	0.7259	0.0106	-1.0052	0.0264
160Hz	3.5464	0.2474	-0.7951	0.0125
200Hz	1.3266	0.0446	-1.2573	0.0300
250Hz	1.8869	0.2074	-0.5570	0.0097
315Hz	1.3026	0.1224	-0.1413	0.0005

- 59Type: On condition of room width 3.6m, heavy impact noise of 25Hz, 31.5Hz, and 40Hz frequencies are mainly affected by changing of a room depth. r^2 value sharply decreases after 50Hz which means change of a room dimension rarely affects heavy impact noise of that frequency.

- 84Type: On condition of room width 4.5m, 40Hz, 50Hz, and 63Hz responses are main frequencies affected by changing of a room dimension. Comparing to 59Type with room width 3.6m, main frequencies were shifted slightly to higher frequency. As in the previous case, r^2 value sharply decreases as frequency increases. Heavy impact noise responses over 80Hz are rarely affected by a room dimension. Response of 25Hz and 31.5Hz is also not affected by a room dimension.

Table 3-5 Slope and r^2 of 1/3 octave band responses-bang machine

1/3 octave band center frequency	Impact source: bang machine			
	w_1=3.6m (59Type)		w_2=4.5m (84Type)	
	Slope	r^2	Slope	r^2
25Hz	-4.5119	0.3458	1.8774	0.0654
31.5Hz	-5.3531	0.4790	-0.5047	0.0074
40Hz	-3.6191	0.5188	-3.2023	0.2263
50Hz	-2.0699	0.2376	-3.2398	0.3185
63Hz	-1.9360	0.1343	-3.8232	0.3446
80Hz	-0.8825	0.0121	-2.1789	0.0981
100Hz	-0.9913	0.0112	-0.3434	0.0022
125Hz	0.1540	0.0006	1.4249	0.0468
160Hz	-0.8825	0.0121	-2.1789	0.0981
200Hz	-0.9913	0.0112	-0.3434	0.0022
250Hz	0.1540	0.0006	1.4249	0.0468
315Hz	1.4121	0.0639	1.7264	0.0964

As listed in Table 3-5, same phenomena observed when bang machine striked floor.

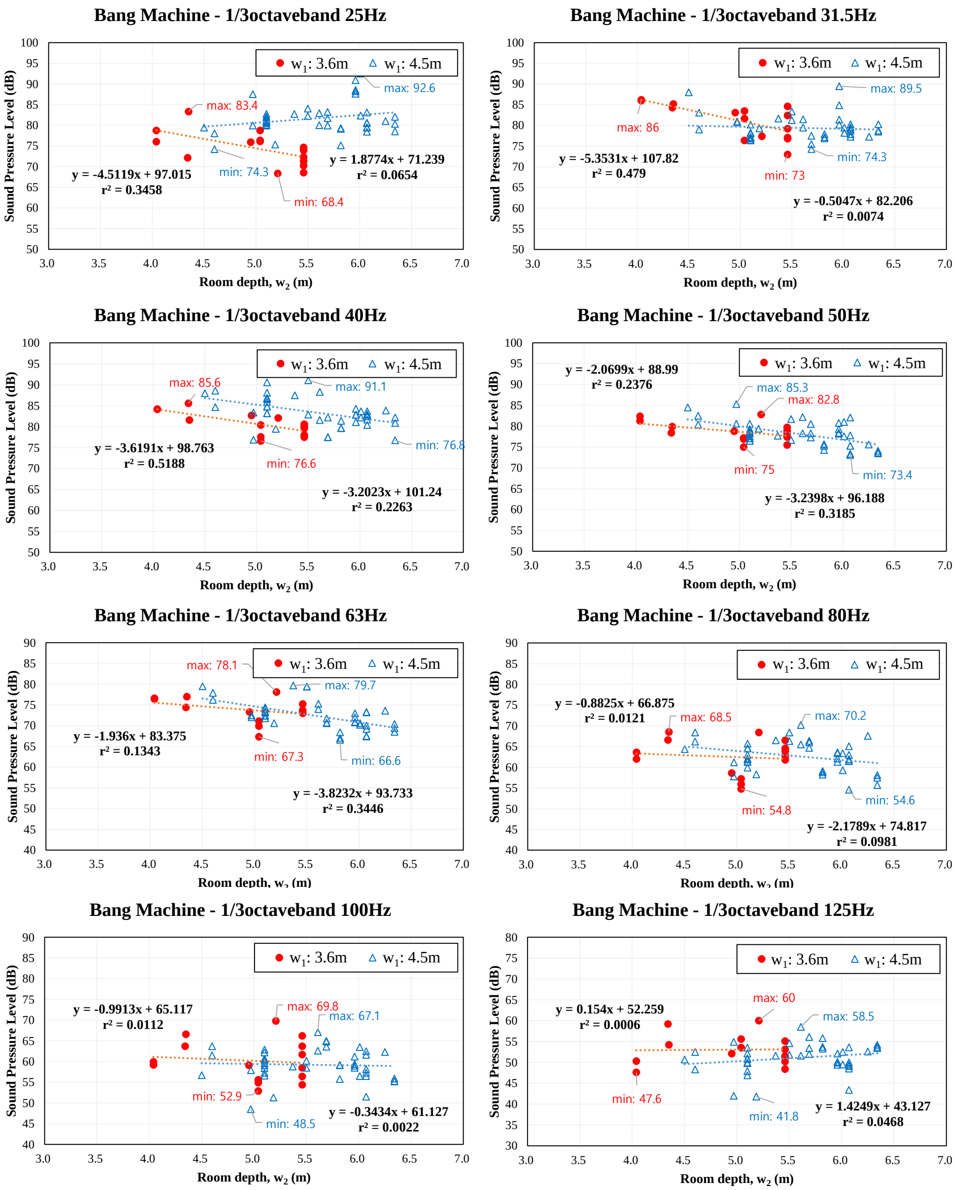


Figure 3-2 Relationships between room dimension and sound pressure level at each 1/3 octaveband center frequency (25Hz~ 125Hz)

Figure 3-2 shows the result of Table 3-5 in a graphical manner. The slope of each Figure become flat as frequency increases. Points were also scattered more randomly as frequency increases.

As a result, floor impact noise level decreases as room area increases. Responses lower than 80Hz were mainly affected by changing of the room dimension. On the other hand, Responses higher than 80Hz were rarely affected by changing of the room dimension. It is hard to reduce floor impact noise of 63Hz in 59Type apartment (room width 3.6m) by increasing the room depth. In case of 84Type apartment (room width 4.5m), floor impact noise of 63Hz can be effectively reduced by increasing room depth. Design plan to reduce floor impact noise can be applied differently depending on the area of the apartment.

From the field measurement data, simple estimation equation can be proposed. For simplicity, 1/3 octave band frequency response were converted into 1/1 octave band frequency response. Table 3-6 shows the proposed estimation formula.

Table 3-6 1/1 Octave band estimation formula of heavy impact noise

1/1 Octave Bands Center Frequency		Impact source	
		Impact ball	Bang machine
w_1=3.6m	31.5Hz	$SPL_{w_1=3.6}(dB)=-3.3w_2+93.9$ $r^2=0.388$	$SPL_{w_1=3.6}(dB)=-4.5w_2+107.0$ $r^2=0.623$
	63Hz	$SPL_{w_1=3.6}(dB)=-1.8w_2+81.3$ $r^2=0.310$	$SPL_{w_1=3.6}(dB)=-2.0w_2+90.0$ $r^2=0.219$
w_2=4.5m	31.5Hz	$SPL_{w_1=4.5}(dB)=-1.0w_2+85.3$ $r^2=0.047$	$SPL_{w_1=4.5}(dB)=-1.3w_2+94.5$ $r^2=0.054$
	63Hz	$SPL_{w_1=4.5}(dB)=-2.1w_2+83.7$ $r^2=0.257$	$SPL_{w_1=4.5}(dB)=-3.4w_2+98.1$ $r^2=0.366$

Using this formula, heavy impact noise of low frequency components of 31.5Hz, and 63Hz can be predicted simply. However, the formula can be applied to only two types of floor width due to lack of specimen. Still, the formula would give an idea to designer or engineer to consider the effect of a room dimension in a design stage.

3.3 Structural System

RC wall system is a typical structural system of residential buildings in Korea. Sometimes flatplate system also can be found. Generally, it is accepted that floor impact noise isolation performance of flatplate system is better than wall type system because flatplate system has no structural wall that transmits slab vibration. In this chapter, floor impact noise and slab vibration is compared between wall type system and flat plate system with similar floor dimension. Several experiments were conducted to investigate how floor vibration and floor impact noise vary depending on different structural system.

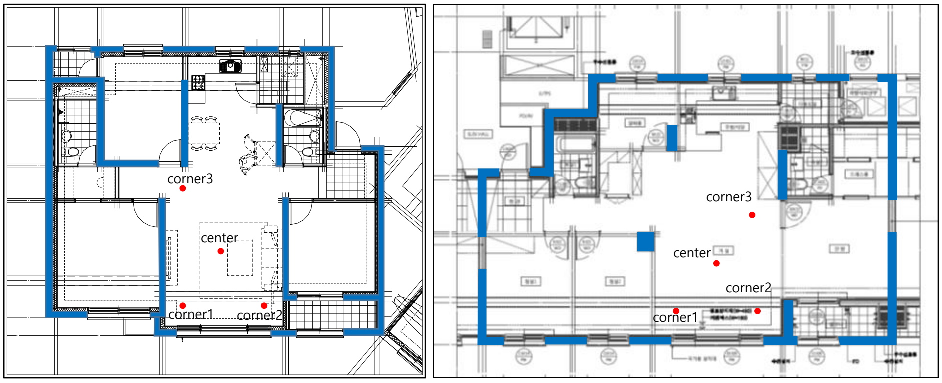


Figure 3-3 Floor plan of wall-type system (left) and flatplate system (right)

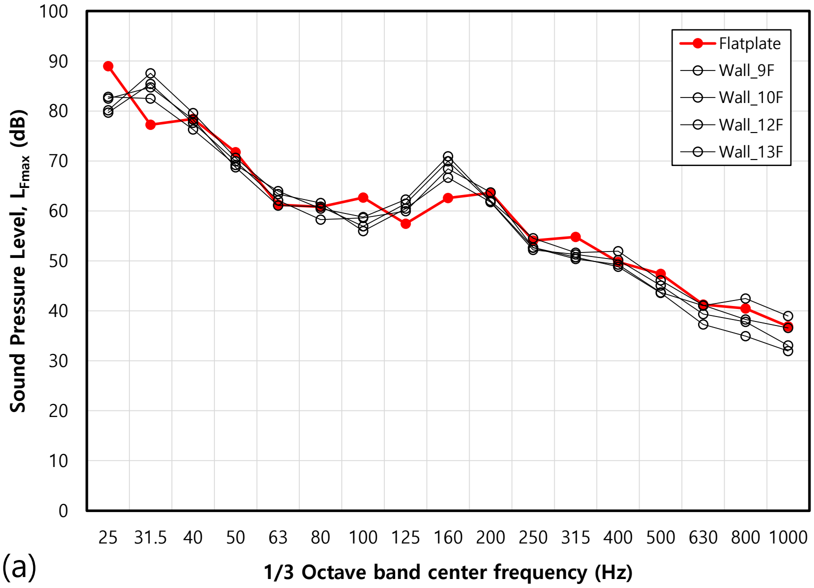
Figure 3-3 shows apartment plan of wall type system (left) and flatplate system (right) with similar room dimension. The blue solid line shows RC structures. Red dots show the position of impact and of measuring points. The width of the living room is 4.5m for both structural system while the depth of living room including kitchen is 10.6m and 9.2m, respectively. The experiment were performed for both construction sites following KS F 2810-2. Table 3-7 shows the test scheme.

Table 3-7 Test scheme of wall type system and flatplate system

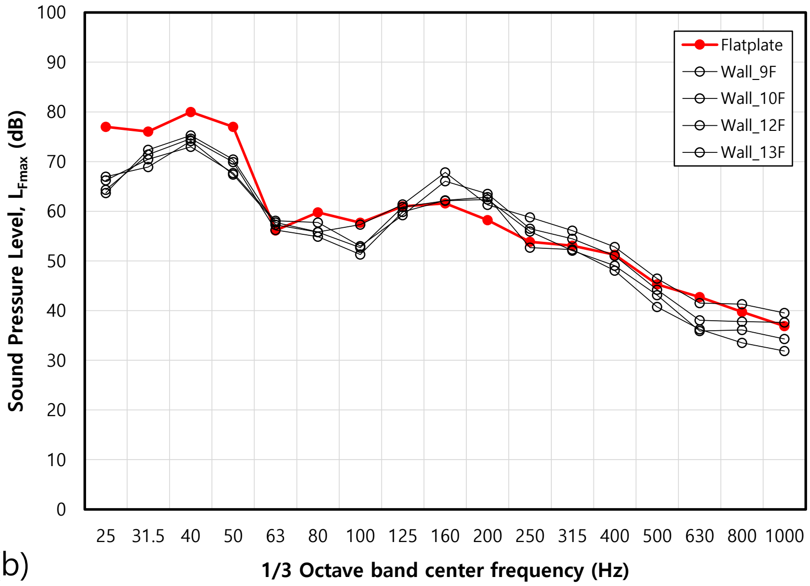
	Wall type structure	Flatplate structure
Living room width	4.5m	4.5m
Living room depth (including kitchen)	10.6m	9.2m
Slab thickness	210mm	210mm
Floor system	Bare slab	Bare slab
number of measured households	4 (9F, 10F, 12F, 13F)	1 (26F)
Impact source	Bang machine	Bang machine

It was assumed that the acoustic mode for both structural systems is the same and does not cause different responses because the dimension of the receiving room is almost identical. Generally, it is known that the flatplate structure improves the floor impact noise performance because there is no structural wall slab vibration transmitted. However, the test data showed different result.

Figure 3-4 shows average floor impact noise level of different impact points. When the impact ball hits the center of the living room (Figure 3-4 (a)), sound pressure level between 40Hz and 80Hz shows similar responses for both structure systems. Sound pressure level of 25Hz is larger for flatplate structure while sound pressure level of 35Hz is larger for shear wall structure. This is because the 1st mode of flatplate system is 22Hz, and the 1st mode of shear wall system is 29Hz.


Sound Pressure Level, L_{Fmax} (dB)
1/3 Octave band center frequency (Hz)
Flatplate
Wall_9F
Wall_10F
Wall_12F
Wall_13F
0
10
20
30
40
50
60
70
80
90
100
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000

(a)


Sound Pressure Level, L_{Fmax} (dB)
1/3 Octave band center frequency (Hz)
Flatplate
Wall_9F
Wall_10F
Wall_12F
Wall_13F
0
10
20
30
40
50
60
70
80
90
100
25
31.5
40
50
63
80
100
125
160
200
250
315
400
500
630
800
1000

(b)

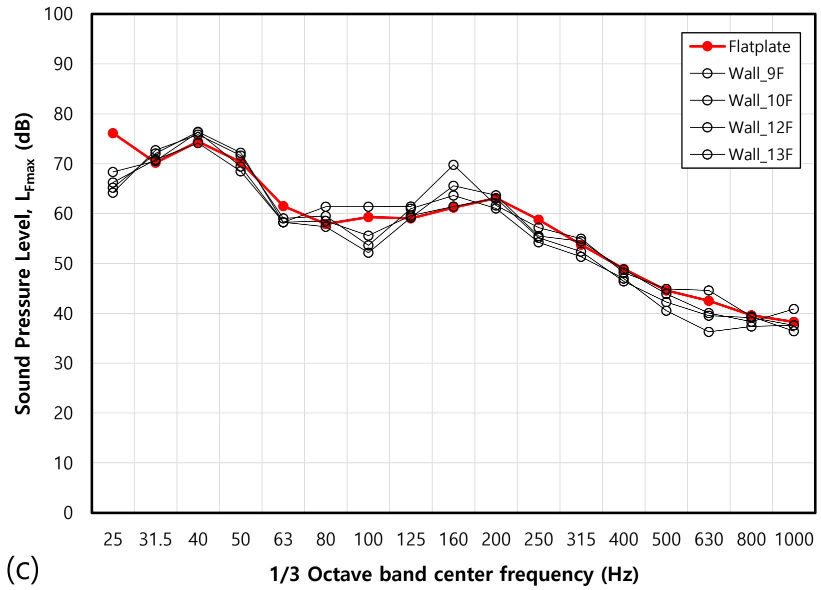


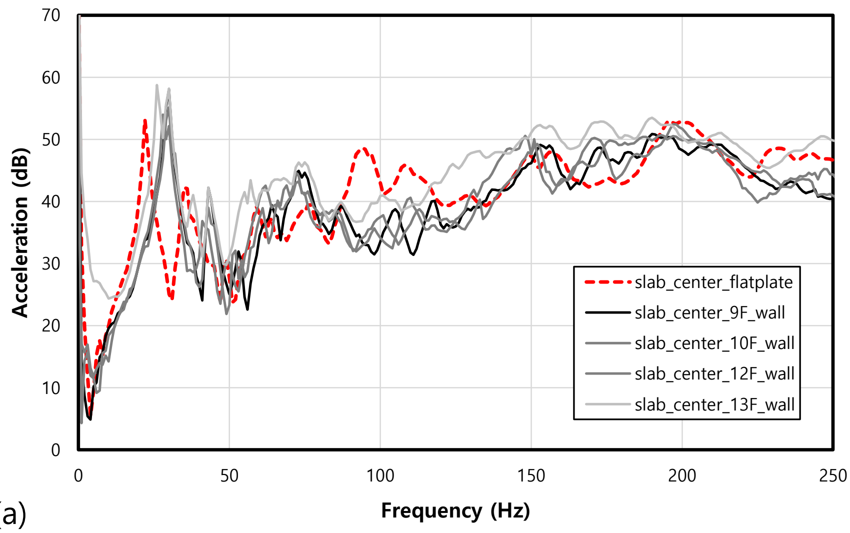
Figure 3-4 1/3 octaveband sound pressure level at each impact point - (a) Center impact, (b) Corner 1 impact, (c) Corner 2 impact

The most distinctive feature is, as shown in Figure 3-4 (b), the sound pressure level of flatplate structure is always larger than wall type system under 125Hz when impact ball hits the corner 1 (the corner faces non structural wall). The slab of the wall-type system is constrained in two directions by concrete walls, while the slab of the flat-plate structure is confined in one direction by the exterior RC wall. Therefore, it is expected that the slab vibration response at the corner 1 of flatplate system is larger than the slab vibration response of wall-type system causing increased floor impact noise level at the corner 1.

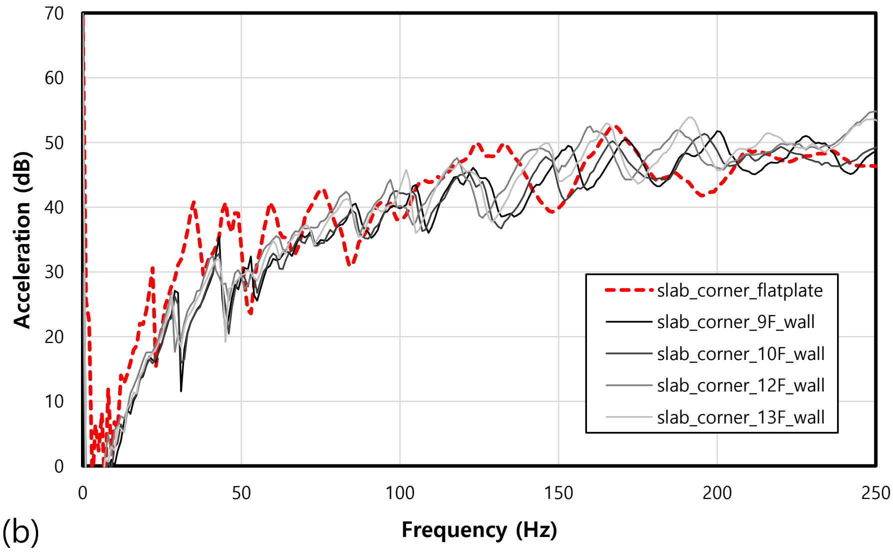
When impact source is applied to the corner 2, most of 1/3 octave band responses of flatplate system exist in the range of shear wall system except

25Hz response. Different impact sound level of 25Hz is induced by the 1st mode frequency difference between the wall type structure and flatplate structure. Boundary condition at corner 2 of flatplate system is similar with that of wall-type system resulting in similar impact noise level at 31.5Hz and above.

The factor causing difference in floor impact noise can be seen more clearly, when both the floor impact noise level and the vibration of the slab are compared together. As shown in Figure 3-5, it has been observed that the floor impact noise level is also large in the frequency where the slab vibration is large. Figure 3-5 (a) represents slab acceleration at the center of the slab when impact source is applied at the center of the slab. Figure 3-5 (b) represents slab acceleration at the corner 1 when impact source is applied at the corner of the slab. As mentioned earlier, comparing to the center slab vibration, amplified corner slab vibration for the flatplate system is observed.



(a)



(b)

Figure 3-5 Slab acceleration at each measurement point –

(a) center impact – center response, (b) corner 1 impact – corner 1 response

Looking more closely, when impact source is applied at the center of the slab (Figure 3-5 (a)), the acceleration amplitude between the wall type structure and flatplate structure is slightly different for each frequency. Peak accelerations for each structure system are determined by the natural frequency of the slab. Depending on the natural frequency of each system, the amplitude of acceleration changes. For example, at 22Hz, the flatplate vibration is larger than the vibration of wall type system because the frequency is the 1st natural frequency of the flatplate system. On the other hand, at 28Hz, the 1st natural frequency of the wall type system, the slab vibration of the wall type system is much larger than that of flatplate system.

However, as shown in Figure 3-5 (b), the corner slab vibration amplitude for each structure system shows different results. Regardless of the natural frequencies of each system, it always exhibits larger acceleration level in the flatplate system until 80Hz. The amplified vibration level at the corner of the slab caused amplified floor impact noise level at the corner in the flatplate system.

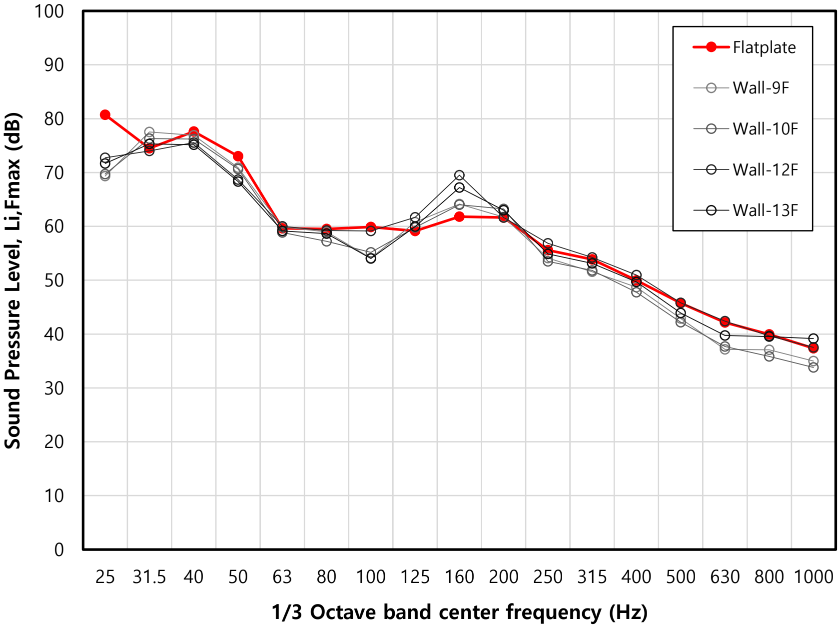


Figure 3-6 Average heavy impact nosie of flatplate system and wall-type system

Figure 3-6 shows average sound pressure level for the flatplate structure and the wall type structure. Generally, larger sound pressure level of the flatplate system is observed below 100Hz. Because the floor impact noise level is very large when impact source is applied to the corner 1 of the flatplate system, average floor impact noise level also shows a larger response for the flatplate system. As in Table 3-8, single number quantity ($L_{i,Fmax,AW}$) of the flatplate system is 1~2dB larger than wall type system.

Table 3-8 Measured single number quantity($L_{i,Fmax,AW}$, dB) for each floor

Structure type	Wall (9F)	Wall (10F)	Wall (12F)	Wall (13F)	Flatplate (26F)
SNQ ($L_{i,Fmax,AW}$)	49	49	50	49	**51**

Consequently, the performance of floor impact noise insulation is found to be more disadvantageous for the flatplate structure when the same floor plan and the same slab thickness are assumed. Increased floor impact noise level in flatplate system is mainly due to the amplified slab vibration at the corner of the slab.

3.4 Non-Structural Walls

In this chapter, two types of non-structural walls were covered. Drywalls composed of gypsum boards and concrete brick walls are typical partition walls. From several field test results, the effect of the non-structural walls to slab vibration and floor impact noise level was analyzed.

3.4.1 Dry walls (gypsum board)

Dry walls are common partition wall system in residential buildings because it is advantageous in construction and changing plan. Figure 3-7 shows the section of a typical dry wall system.

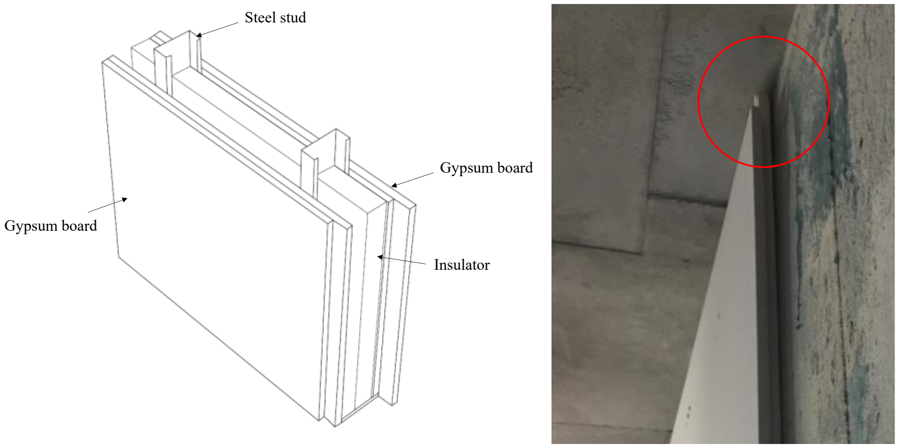


Figure 3-7 Components of typical drywall system

As shown in Figure 3-7, gypsum board is not fully constrained to upper slab. This condition allows the gypsum board free from bending caused by long-term slab deflection. However, it is still expected that when impact source is applied to the upper floor, the gypsum boards vibrate. Therefore, it should be verified what causes a vibration of gypsum board and how much the vibration of the gypsum boards affect floor impact noise.

Two kinds of field tests were performed to find the source that causes a gypsum board vibration (Table 3-9). Floor impact noise and dry wall vibration is measured simultaneously when each source is applied.

Table 3-9 Test scheme to evaluate dry wall vibration

Test purpose	Impact source	Measurements
1. Source of gypsum board vibration	Structureborne sound -Impact ball	Impact noise Slab vibration
2. Effect of gypsum board vibration to floor impact noise	Airborne sound -Balloon	Concrete wall vibration Gypsumboard vibration

Heavy impact source cause structureborne sound while balloon breaking cause airborne sound. By comparing the vibration induced by two different impact source, the vibrational characteristics of dry wall system is verified. Figure 3-8 shows the test plan of balloon popping and heavy impact source.

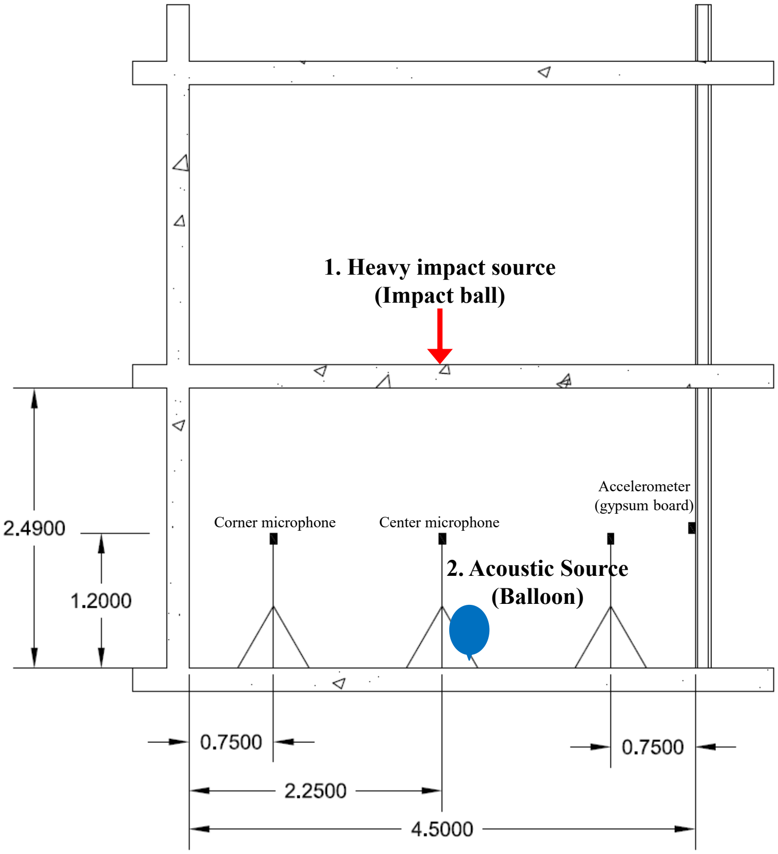


Figure 3-8 Test scheme to evaluate drywall vibration –

(a) applying heavy impact source, (b) Balloon popping

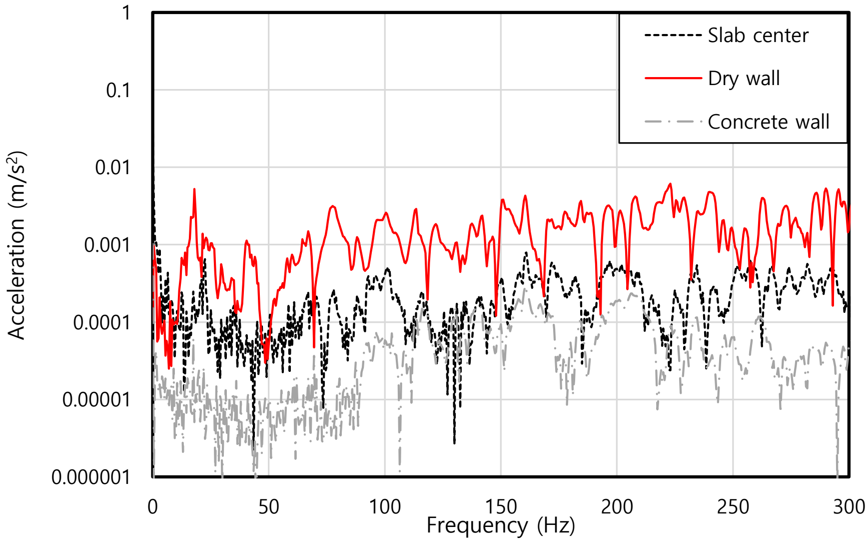


Figure 3-9 Vibration response when a balloon is breaked at the center of the living room

Figure 3-9 shows vibration responses of concrete slab, dry wall, and concrete wall when a balloon is popped at the center of the receiving room. The result shows that the vibration amplitude of dry wall is the largest. It means drywall vibration is affected by sound pressure relatively more than concrete structure.

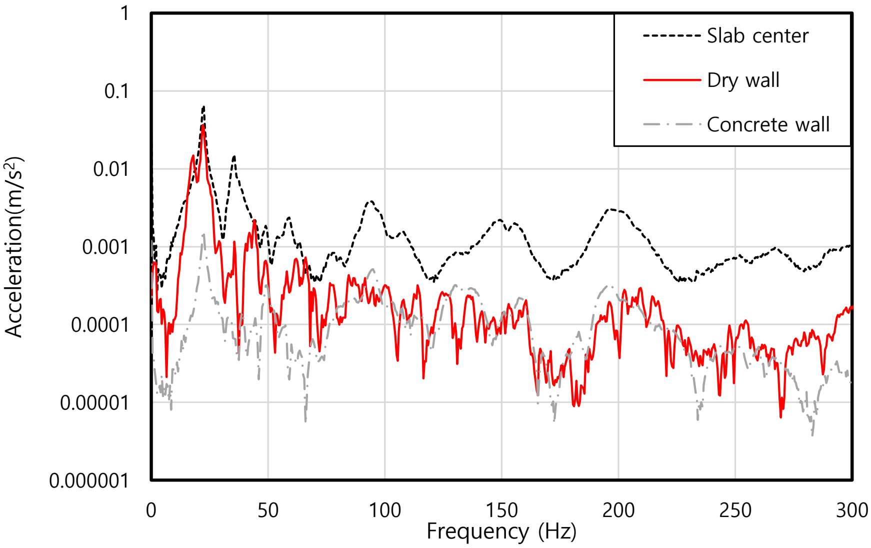


Figure 3-10 Vibration response when heavy impact source (impact ball) is applied at the center of the slab

Figure 3-10 shows vibration responses of concrete slab, dry wall, and concrete wall when an impact ball is applied at the top of the concrete slab. Different from balloon test, the result showed that the vibration amplitude of dry wall is much smaller than the slab vibration except certain frequencies (22Hz, 44Hz, and 66Hz). However, at certain frequencies the vibration of dry wall is bigger than the concrete wall while the vibration amplitude is similar over 100Hz. Table 3-10 summarizes the test results.

Table 3-10 Test results summary

Source	Vibration amplitude
Air borne sound (Balloon breaking)	Dry wall > Slab > RC wall
Structure borne sound (Heavy impact source)	- Near 1st mode: Slab ≒ Dry wall > RC wall - Under 100Hz: Slab > Dry wall > RC wall - Over 100Hz: Slab > Dry wall ≒ RC wall

A comparison between dry wall vibration and concrete wall vibration for different impact source is plotted in Figure 3-11. As shown in the figure when balloon is breaked (solid black line) assuming only air borne sound occurrence, fluid-drywall interaction is much larger than fluid-concrete wall interaction. It means dry walls are vibrated by air borne sound while concrete wall are rarely vibrated. On the other hand, when heavy impact source is applied, the ratio of dry wall vibration to the concrete vibration is much smaller than the case of balloon. The vibration level of the dry wall when heavy impact source is applied is a combined response of transmitted structure vibration and air vibration. Considering the interaction effect of fluid-dry wall is much larger than fluid-concrete interaction, it can be verified indirectly that transmission of slab vibration to the concrete wall is larger than dry walls. As a result, the vibration of a dry wall is mainly caused by air pressure rather than structure vibration, while vibration of concrete wall is caused by transmission of slab vibration.

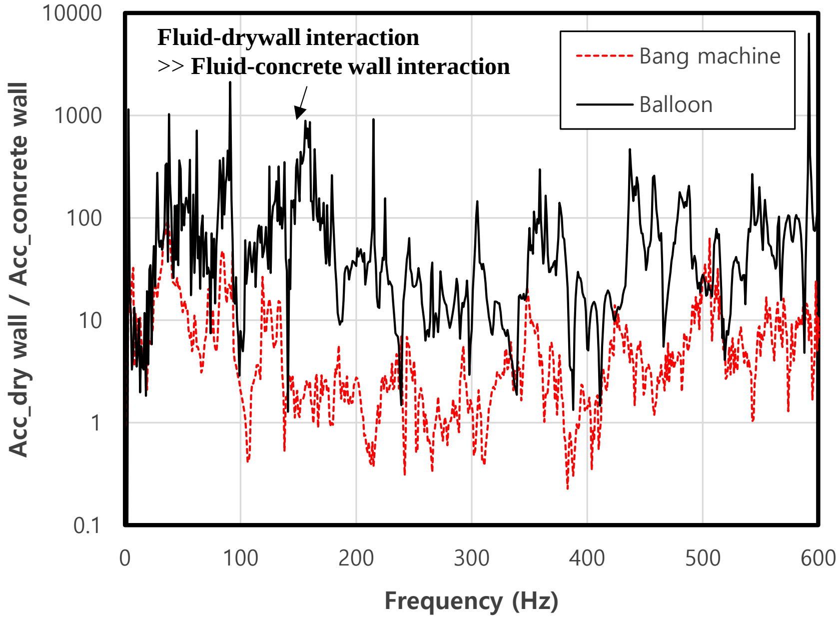


Figure 3-11 Ratio of dry wall vibration to concrete vibration when different impact source is applied

3.4.2 Masonry walls (brick walls)

In many cases, the portion of the masonry wall in apartment buildings is small because masonry walls are usually installed around bathrooms. As a result, vibration of masonry walls has little impact on floor impact noise. However, the mass of brick walls is not negligible. Density of brick wall is similar to concrete. Although vibration response of masonry wall is small, the presence of brick wall mass can change floor vibration response. The topic of masonry walls will be discussed in detail in the chapter 4 (numerical modeling).

3.5 Floating Floor System

Almost every residential buildings adopt floating floor system. Floating floor system is a kind of layered flooring system composed of concrete slab, resilient material, auto claved light weight concrete(ALC), and mortar plate. Figure 3-12 shows a typical section of floating floor system. Floating floor system effectively reduces impact noise of high frequency range over 100Hz comparing to bare slab system.

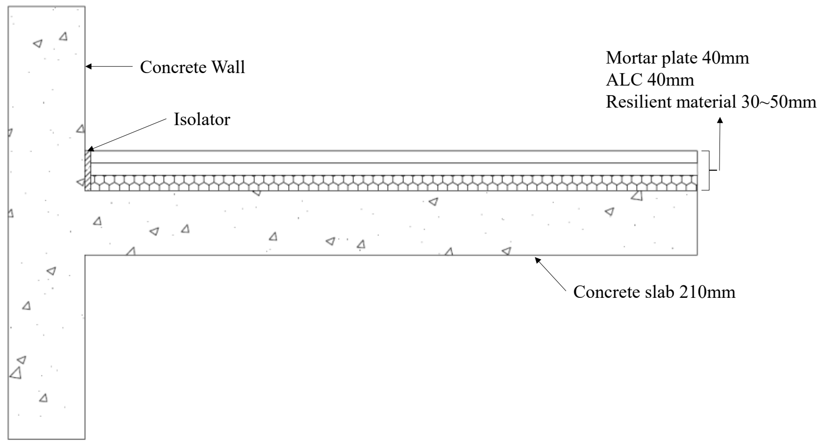


Figure 3-12 Composition of typical floating floor system

3.5.1 Vibrational characteristics of floating floor system

As shown in Figure 3-12, floating floor system is composed of concrete slab, resilient material, autoclaved light weight concrete (ALC), and mortar plate. As proven in many previous studies, floating floor system effectively reduces light impact noise while amplifying heavy impact noise in low frequency under 100Hz. The problem of low frequency amplification of slab vibration and impact noise is not solved yet. In this chapter, Vibrational characteristics of floating floor which cause amplification of heavy impact noise is analyzed.

In some previous studies, it has been revealed that heavy impact noise has not been improved after installing floating floor system. Floating floor system effectively reduces slab vibration of high frequency componenets over 100Hz. Accordingly, impact noise over 100Hz is reduced. However as in many cases, slab acceleration of relatively lower frequency range between 50~100Hz is amplified resulting in increased impact noise. As a result, floating floor system could even worse the heavy impact noise because heavy impact noise is mainly composed of low frequency components under 100Hz.

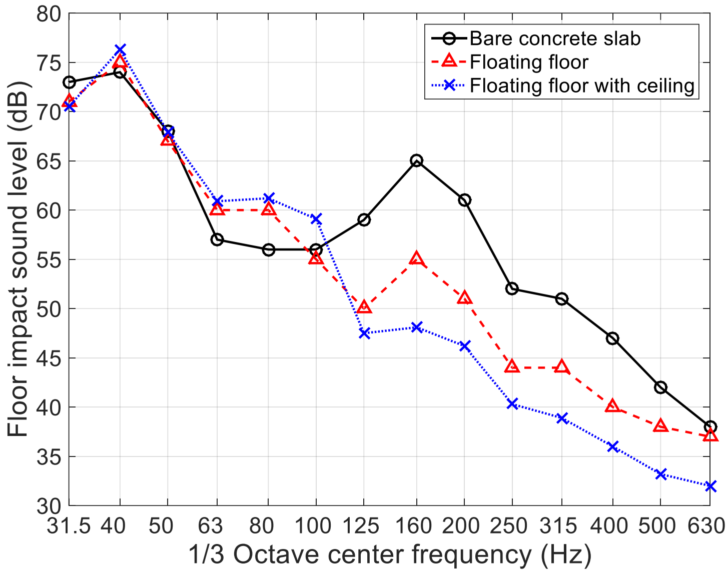


Figure 3-13 Floor impacat sound level for different site conditions

Figure 3-13 shows comparison of heavy impact noise level between bare slab and floating floor measured at the same site. The result also shows amplilfication of impact noise between 63-100Hz, and reduction after 100Hz. This phenomenon is originated by the slab vibration of floating floor system.

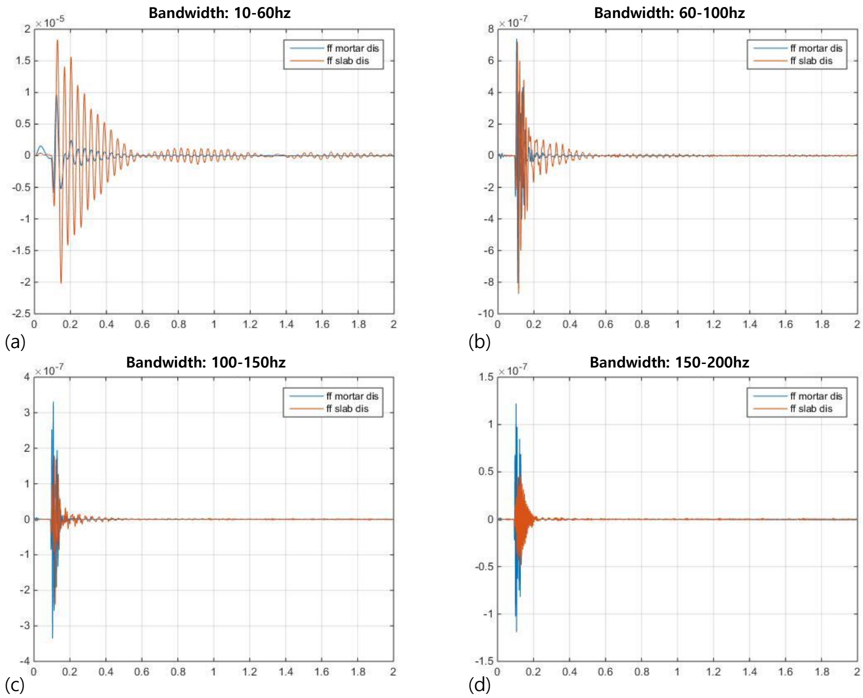


Figure 3-14 Slab and mortar acceleration in time domain for different frequency range (bandpass filtered data)

Figure 3-14 represents time domain data of slab and mortar plate vibration of floating floor system. Each figure is bandpass filtered data of different bandwidth. The bandwidth is 10-60Hz (a), 60-100Hz (b), 100-150Hz (c), 150-200Hz (d) each. Slab vibration is larger than mortar plate vibration when frequency is lower than 100Hz (Figure 3-14 (a), and (b)). As frequency increases, vibration of the mortar plate increases while slab vibration is decreased (Figure 3-14 (c), and (d)). Slab vibration is determined by the interaction between slab and mortar plate transmitted by the resilient material between them.

Comparison of slab vibration between bare slab and floating floor in frequency domain gives more clear result. Figur 3-14 shows the slab vibration of different flooring system measured at the same site. The slab vibration tendency is same as floor impact noise level of Figure 3-13. Amplified vibration of 50-100Hz caused amplified floor impact noise of 50-100Hz. Reduced vibration over 100Hz caused reduced floor impact noise over 100Hz. Additionally, 1st mode of floating floor is decreased by 2Hz due to the additional mass composed of ALC and mortar plate.

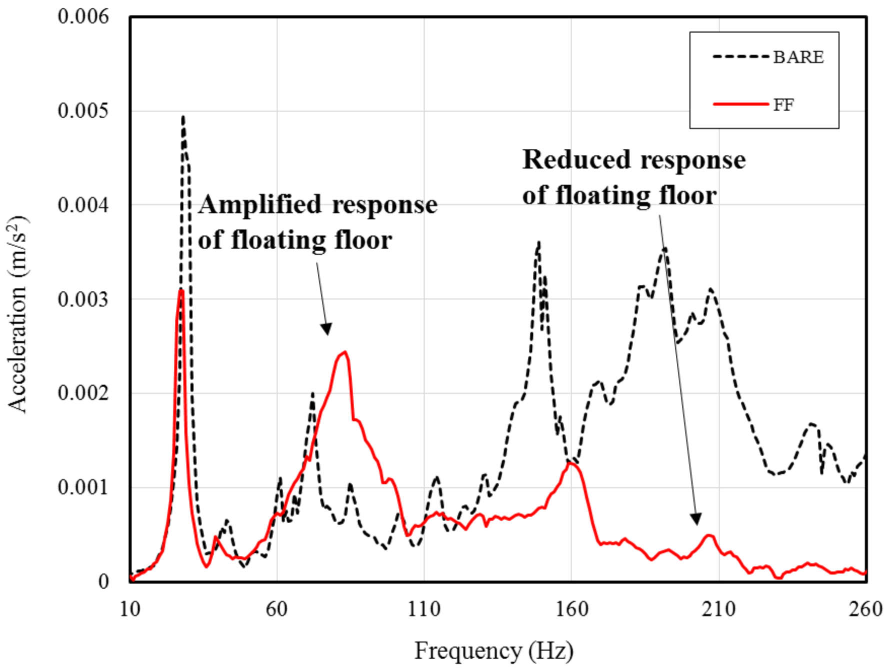


Figure 3-15 Comparison of slab vibration between bare slab and floating floor

Table 3-11 summarizes the vibrational characteristics of floating floor system.

Table 3-11 Vibrational characteristics of floating floor system

Frequency	Floating floor system
1^{st} mode	Decreased by 2Hz due to the additional mass of ALC and mortar plate
50~100Hz	Amplified slab vibration causes amplified floor impact noise level
Over 100Hz	Reduced slab vibration causes reduced floor impact noise level

3.5.2 Resilient material

Floating floor components cause the change of slab vibration as presented in the previous chapter. Among them, thickness and material properties of ALC and mortar plate rarely changes. Therefore, ALC and mortar plate values can be regarded as constant values. On the other hand, there are many kinds of resilient materials with various thickness and stiffness. Different resilient material can cause different response of slab vibration. There have been studies concerned specifically with the resilient material, but no definitive answer has been given to relation between impact noise and resilient material. In this chapter, it is verified how resilient materials affect slab vibration of floating floor system.

Impact sources do not directly hit the concrete slab but directly hit the mortar plate and the impact force is transmitted through mortar plate, ALC, and resilient material. Therefore, the force spectrum delivered to the slab would be different from the original force spectrum. However, it is difficult to measure the impact force spectrum transmitted to the concrete slab through field measurements. Instead, the transmitted force spectrum can be derived indirectly. Table 3-12 shows the indirect procedure of derivation of transmitted force spectrum.

Table 3-12 A procedure to derive the transmitted force spectrum to concrete slab

	Indirect method
Purpose	Derivation of the transmitted force spectrum
Procedure	1. Generate transmissibility(TR) from vibration data 2. Multiply original force spectrum by TR
Assumptions	1. The slab vibration is dominant under 100Hz when impact force is applied to the floating floor. 2. ALC and mortar plate act as an additional mass.

Transmissibility of the floating floor can be derived from floating floor acceleration data devided by bare slab acceleration data. However, measured bare slab data cannot be used in this procedure because after floating floor has been installed, frequency shift occur. Peak frequencies are shifted due to the additional mass of floating floor system. Instead, numerical model of increased mass bare slab model can be used. Two assumptions were needed to use the increased mass bare slab model. As shown in the Figure 3-14, the slab vibration is dominant under 100Hz. In this case, ALC and mortar plate can be regarded as an additional mass. As frequency increases, mortar plate vibration become dominant, and the assumptions are no longer satisfied. As a result, the numerical model of increased slab mass can describe the frequency shift of floating floor up to 100Hz while the numerical model still cannot represent the interaction between floating floor layers as shown in Figure 3-16.

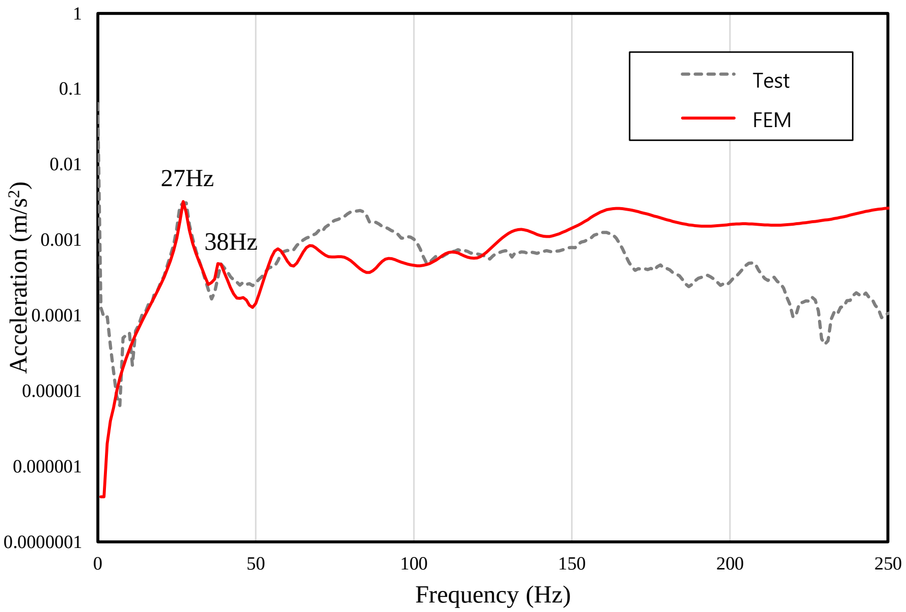


Figure 3-16 Frequeny response function (FRF) comparison between measured data and simplified FE model

Figure 3-17 shows transmissibilities of three floors derived by following Eq. (3-1).

$$Transmissibility = \frac{FRF_{FF}(f)}{FRF_{bare}(f)} \tag{3.1}$$

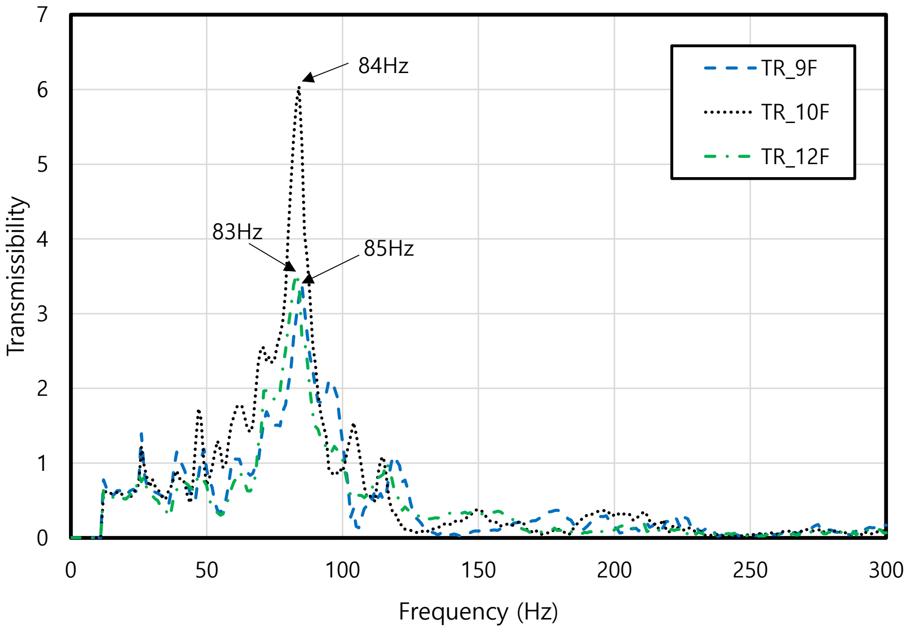


Figure 3-17 Derived transmissibility from field test result

Resonance frequency occured between 83Hz ~ 85Hz for different kinds of resilient materials. It seems that the gap of amplification is caused by different damping ratio of resilient material, or non-uniform impact force (impact ball) during the test. All of the three transmissibility functions show a value close to 1 at frequencies lower than the peak value, and increases until the peak value. After the peak frequency, the value decreases rapidly. The transmissibilities derived from the test seems structurally analogous to theoretical transmissbilitiy function of SDOF system. Figure 3-18 is an analytical model of SDOF system representing force transmission.

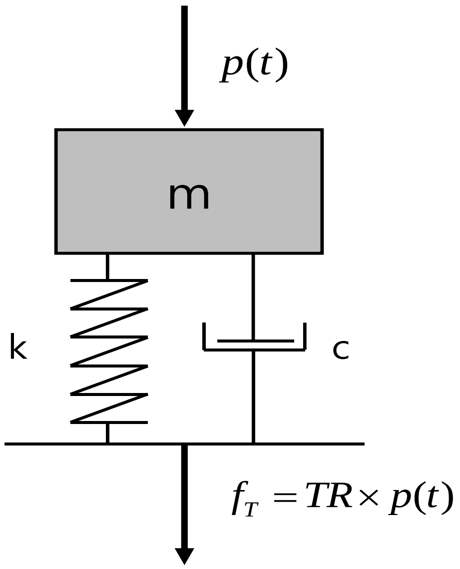


Figure 3-18 Transmissibility of SDOF system

Transmissibility of SDOF system is defined as Eq. (3.2).

$$TR = \left\{ \frac{1+\{2\zeta(\omega/\omega_n)\}^2}{\{1-(\omega/\omega_n)^2\}^2+\{2\zeta(\omega/\omega_n)\}^2} \right\}^{1/2} \tag{3.2}$$

ζ is damping ratio, ω is angular frequency of applied force, and ω_n is natural angular frequency of SDOF system. Transmissibility of SDOF system can be calculated from the derived natural frequency e.g., 84Hz. Figure 3-19 shows the comparison of transmissibility between measured data of 3 different sites and an equivalent SDOF system. Resonance frequency of measured data are 83Hz, 84Hz, and 85Hz, respectively. Resonance frequency of equivalent SDOF system is assumed to 84Hz. The exact value at each frequency is not the same, but the equivalent SDOF system gives reasonable result. Resonance between concrete slab and mortar plate cause amplification of vibration at a certain frequency range (in this case 84Hz), and reduction of vibration occur at certain frequency higher than natural frequency multiplied by √2, 119Hz.

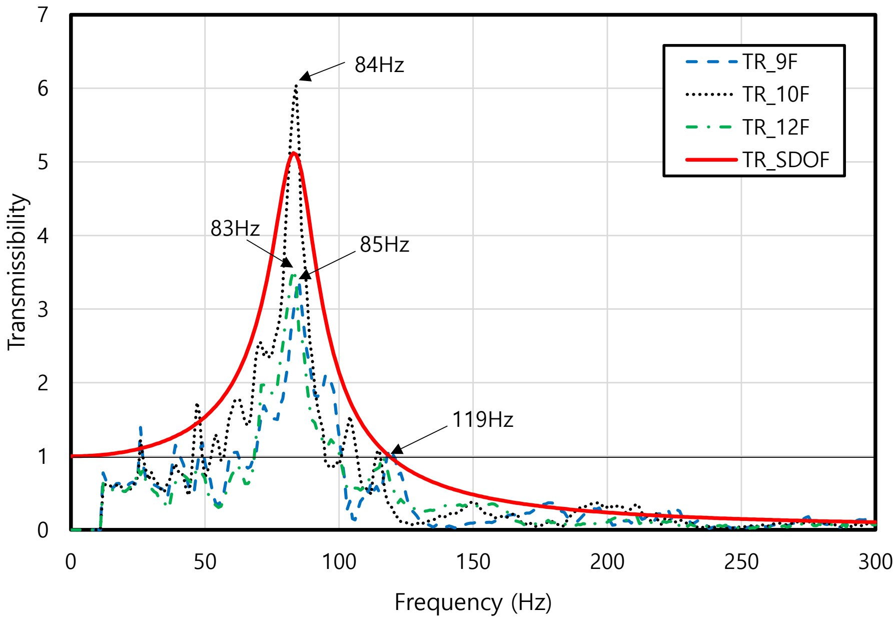


Figure 3-19 Transmissibilities of field test and SDOF system

From the generated transmissibility function, the impact force spectrum transmitted to the slab of floating floor system can be generated.

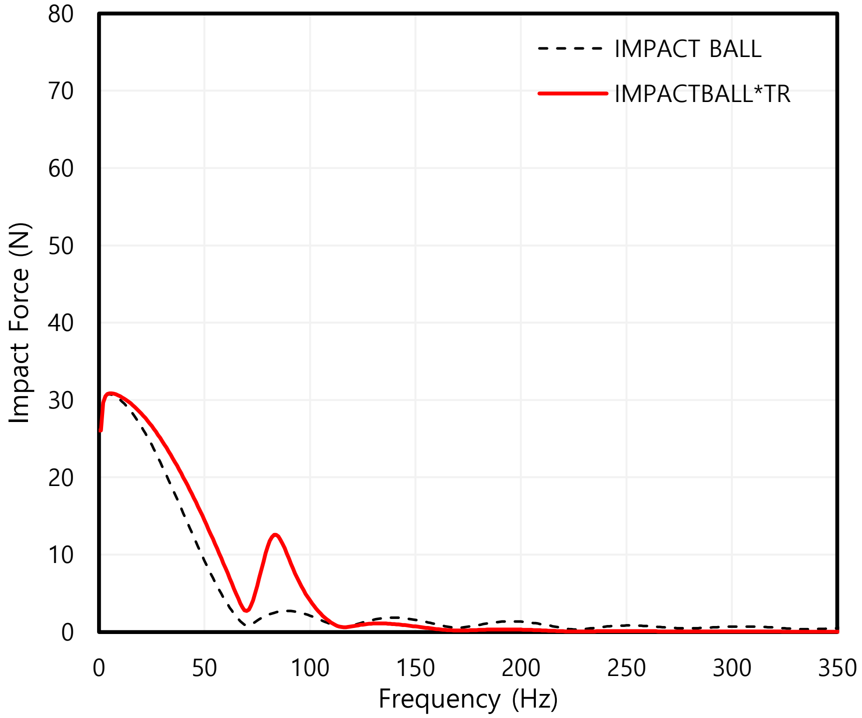


Figure 3-20 Derived force spectrum transmitted to concrete slab of floating floor system

Figure 3-20 shows original force spectrum of impact ball and foce spectrum multiplied by the transmissibility. The solid red line shows the force spectrum transmitted to the concrete slab. Foce spectrum is amplified around 84Hz and is reduced after 119Hz. Now the vibrational characteristics of floating floor system can be described using the transmitted force spectrum.

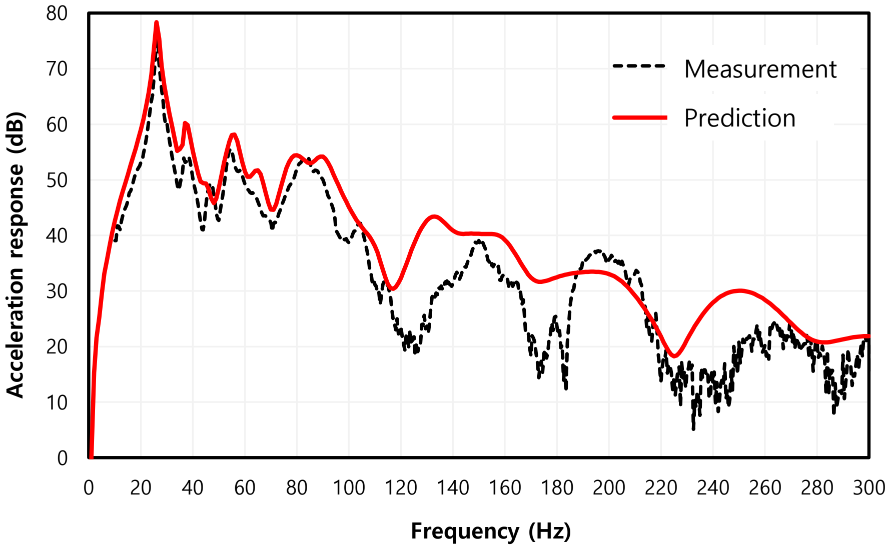


Figure 3-21 Predicted concrete slab vibration using transmitted force spectrum (center impact – center response)

Figure 3-21 shows a comparison of floating floor vibration measured at the center of the slab with predicted slab vibration using transmitted force spectrum. The SDOF model can describe the vibration of floating floor system. The predicted results slightly overestimated floor vibration.

However, there is a big limitation of this transmitted force spectrum method. The corresponding SDOF system cannot predict slab vibration when impact point and measurement point is not identical.

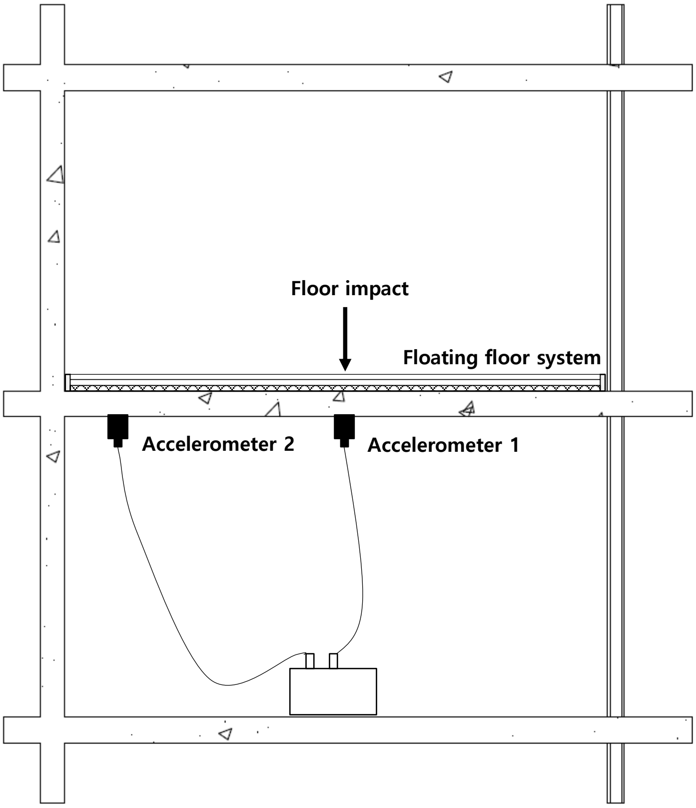


Figure 3-22 Measurement of slab vibration at each point of floating floor system

Figure 3-22 shows a test plan of slab vibration when floor impact is applied. Slab acceleration at the center (accelerometer 1) can be explained using equivalent SDOF model. On the other hand, slab acceleration at the corner (accelerometer 2) cannot be explained using equivalent SDOF model. When impact point is different from measurement point, idealized SDOF system no longer establish slab vibration of floating floor system. Figure 3-23 shows a comparsion measured slab vibration with predicted slab vibration for two measured points when imact is applied at the center of the slab.

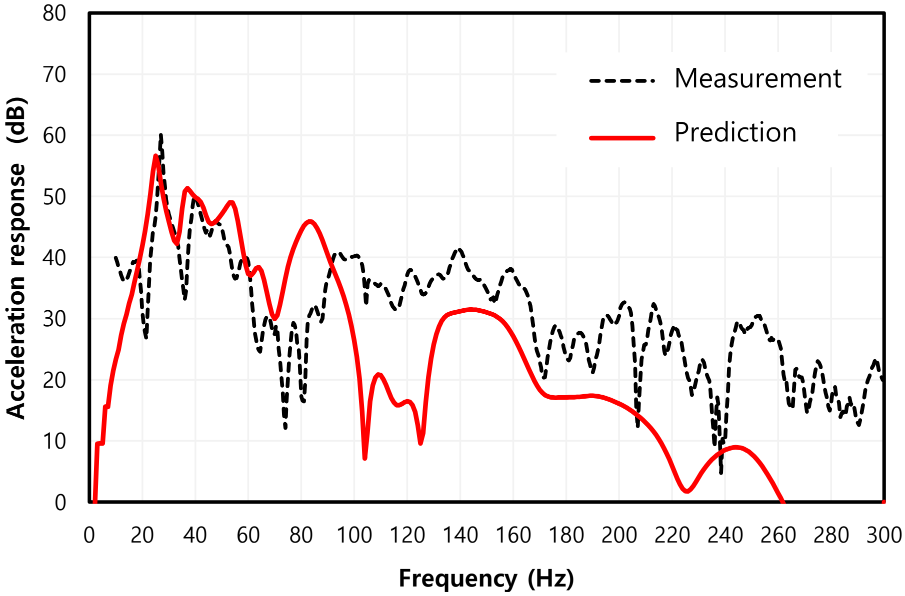


Figure 3-23 Predicted concrete slab vibration using transmitted force spectrum (center impact – corner response)

As expected, prediction error is relatively large when the measurement point is different to the impact point. The transmitted force spectrum method shows unnecessary amplification and reduction of slab vibration which was not observed in a field test. Accordingly, it is expected that the transmitted force spectrum cause overestimated floor impact noise around 80Hz, and underestimated floor impact noise over 100Hz. As a result, floor impact noise cannot be calculated from the transmitted force spectrum method because floor impact noise is not affected by certain points but affected by overall slab vibration.

<u>*Mortar vibration*</u>

Furthermore, the resonance frequency of the transmissibility function from the measured data cannot be determined simply by the material property of the resilient material. Flexural vibration of the ALC and mortar plate as well as resilient material affect the slab vibration of the floating floor system. Slab vibration of the floating floor system is determined by the interaction between the mortar plate and the concrete slab connected by the resilient material.

Figure 3-24 is the vibrating mortar shape at a certain time after an impact is applied at the center of the living room measured from a field test. From the figure 3-24, it can be found that the mortar plate and the concrete slab vibrate separately. At two edges connected to the concrete wall, concrete slab cannot vibrate vertically due to the fixed condition provided by the concrete wall. On the other hand, vertical deformation of the mortar plate is observed at the edge. It cannot be concluded that the two plates vibrate independently, but it can be seen that the slab and the mortar plate vibrate separately.

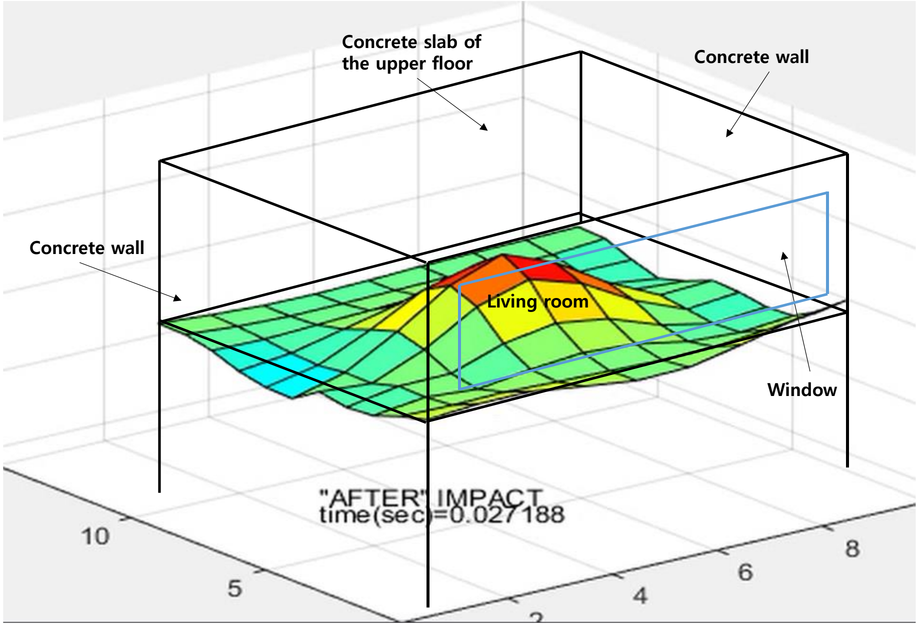


Figure 3-24 Deformed shape of mortar plate at certain time after heavy impact source is applied

Consequently, the resonance frequency of the transmissibility function (Figure 3-19) is not only determined by the resilient material property, but also determined by the overall mortar plate (including ALC) vibration. It means depending on the plan of the residential buildings, flexural vibration of the mortar plate can be changed resulting in changed slab vibration even though same resilient material is installed between them. This is corresponds to the test results done by Cho[14] in chapter 2, that the performance of the floating floor in field test is different from that in laboratory test. Although it is hard to determine the resonance frequency in transmissibility function exactly, the vibrational characteristics of floating floor system is explained using the transmissibility function.

3.5.3 Contact condition

In floating floor installation stage, lightweight concrete or mortar plate is poured on the resilient material. In this case, it is assumed that there is little adhesion between mortar plate and resilient material. It is not known that how much the vibration responses of floating floor slab is affected by the contact condition. A simple test was carried out to verify the effect of the contact condition on slab vibration.

Table 3-13 Test specimens with different contact condition

Properties	Test 1	Test 2	Test 3
Resilient material	PVC mat	PVC mat	PVC mat
Contact condition	No adhesive	Adhesive	Adhesive
Mortar plate	40mm	40mm	40mm
Measurement	Slab Acceleration	Slab Acceleration (2hrs later)	Slab Acceleration (22hrs later)

Table 3-13 shows the test plan to verify the effect of contact condition on slab vibration. Test 1 is a typical floating floor system, while adhesive is applied between resilient material and mortar plate in test2 and test3. In test 2, slab acceleration is measured two hours after application of the adhesive and in test 3, vibration is measured 22 hours later.

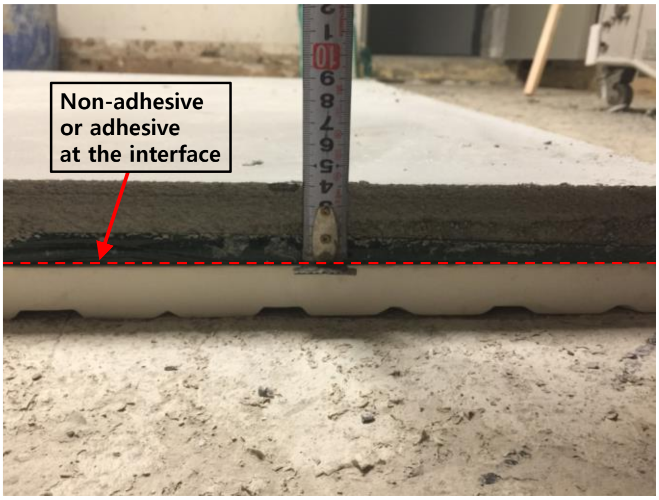


Figure 3-25 Contact condition between resilient material and mortar plate

Figure 3-26 shows slab vibration when heavy impact source is applied at the top of the mortar plate. There is little difference in acceleration amplitude at each frequency even though the contact condition is different. From the test result, it has been shown that the contact condition between mortar plate and resilient material rarely affects slab vibration. It means there is no separation during vibration due to the imposed weight of mortar plate. In real apartment, the weight of the mortar plate (80mm including ALC) is heavier than the test (40mm). As a result, the contact condition rarely affects slab vibration of floating floor system.

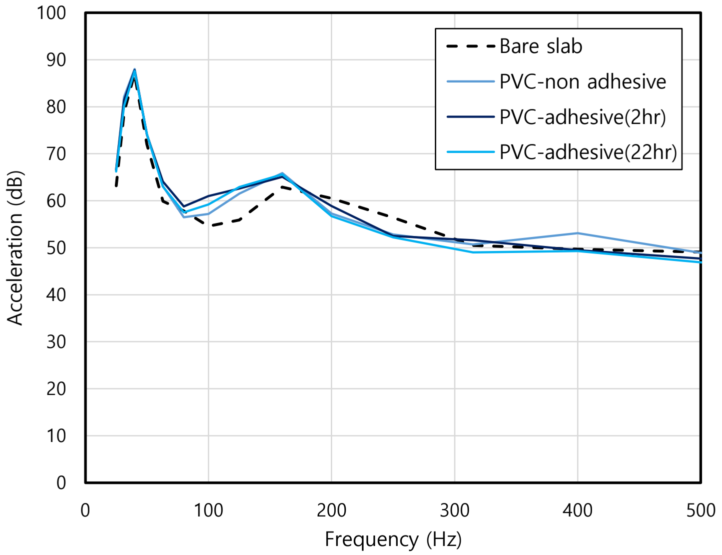


Figure 3-26 Acceleration responses of different contact conditions

3.6 Conclusion

In chapter 3, four factors affecting floor impact noise have been analyzed experimentally. The factors are room dimension, structural system, non-structural walls, resilient materials, and contact condition.

Dimension of a receiving room affects floor impact noise at low frequency range. In general, heavy impact noise decreases as the room area increases. According to the measured data, small sized apartment with room width 3.6m mainly affect 25Hz, 31.5Hz, and 40Hz responses, while medium sized apartment with room width 4.5m mainly affect 40Hz, 50Hz, 63Hz responses. Influence of room dimension on floor impact noise over 80Hz was relatively small. As a result, it is expected that the analysis result could provide a basis for planar design considering floor impact noise.

Depending on the structural system, floor impact noise can be changed. Floor impact noise of two different structural type was compared to evaluate the performance. Consequently, due to the amplified vibration at the corner of the flatplate structure, the average sound pressure level of flatplate was higher than wall type structure when other conditions are the same.

It was found that the influence of non-structural walls including dry walls and masonry walls on floor impact noise was relatively small. Except certain frequencies, vibration caused by the structural impact of dry walls is smaller than concrete wall. It means the vibration of drywall mainly affected by the air pressure. As a result, when heavy impact source is applied, the influence of dry wall on floor impact noise is smaller than the concrete wall. In case of masonry walls, usually the portion of the masonry wall is very small that the effect of masonry wall to the floor impact noise at the living room is negligible.

Floating floor system containing resilient material effectively reduces slab vibration at high frequencies, while amplifying slab vibration at certain low frequencies. In the chapter 3.5, the reason floating floor ampify slab vibration is verified. Transmissibility function was also derived to calculate the transmitted force spectrum to concrete slab. The corresponding transmissibility of SDOF system has shown similar slab acceleration response at the center of the slab. Resonance frequency of a transmissibility function is determined by dynamic properties of mortar plate as well as resilient material.

The influence of contact condition in floating floor system on floor impact noise were verified experimentally. The result showed that the contact condition between resilient material and mortar plate rarely affects slab vibration or floor impact noise.

Chapter 4. Numerical Analysis of Heavy impact noise of Floating Floor

4.1 Introduction

In chapter 4, a numerical modeling of the floating floor system and evaluation of the floor impact noise is presented. Based on the analysis results of each building component affecting floor impact noise in chapter 3, a numerical modeling method is proposed. Factors considered in the numerical modeling are structural system, concrete structural walls, slab, non-structural walls, resilient materials, mortar plate, lightweight concrete, and boundary conditions of floating floor system.

In structural modeling and modal analysis, Abaqus/CAE is used. From the modal analysis data, floor vibration and sound pressure level of the acoustic room is calculated using, another FE software, Virtual Lab.

To check the validity of the numerical modeling of floating floor system, the FE analysis result was compared to the field measurement data. Both slab acceleration and sound pressure level were compared for each measurement points to check the validity of the numerical model. The limitations of the numerical modeling is explained. Still, the numerical modeling gives reasonable results.

Several numerical analyses were performed for some resilient materials with different dynamic stiffness. It was found that sound pressure level decreased generally, as the dynamic stiffness of the resilient material decreases. The numerical analysis results are consistent with previous studies.

Consequently, it is expected that designers or engineers can perform the numerical analysis of floating floor system in design stage to find effective system to the heavy impact noise.

4.2 Modeling of Floating Floor System

4.2.1 Assumptions

There are several assumptions in numercal modeling of floor impact noise. Table 4-1 shows the assumptions applied to the numerical model.

Table 4-1 Assumptions in numerical modeling

Type	Assumptions
Element type	Structural model: 4-node shell element Resilient material: 8-node solid element Acoustic model: 8-node solid element
Element size	150mm
Modeling range	One house hold with appropriate boundary conditions
Interaction	Fluid – structure interaction effect is neglected.

In the structural model, including concrete walls, concrete slab, and spandrels, 4-node shell elements were used because thickness-length ratio is very small, and flexural vibrations are main vibration modes. On the other hand, in case of the resilient material in floating floor system, 8-node solid elements were used. Unlike other structural elements, vibration modes of resilient material include axial deformation as well as flexural vibration. For the same reason, an acoustic model respresenting air is also composed of 8-node solid elements.

Element size of the numerical model is related to the accuracy of the analysis result. At least 6 elements are required to model the behavior of a vibration wave. Therefore, element size should be determined considering the main target frequency. 150mm rectangular shell element was used here to simulate frequency response under 380Hz. Frequency responses over 380Hz cannot be calculated exactly. However, considering that most of the frequency components of heavy impact noise is composed of low frequencies, 150mm element size gave reasonable results.

Modeling range is limited to one household with appropriate boundary conditions. As main object of numerical analysis is to calculate the sound pressure level of the living room, only one household is enough to simulate the vibration responses which cause sound pressure of the living room. Floating floor was modeled up to the continuous section of the mortar plate including the living room part. Figure 4-1 shows the modeling range of the structure model.

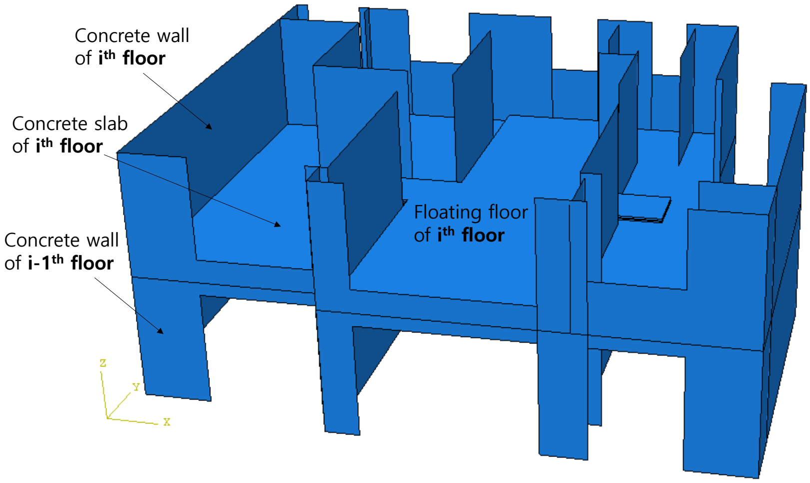


Figure 4-1 Modeling of floating floor system

Fluid – structure interaction effect is neglected in numerical modeling of floor impact noise. In the field test, it is observed that the effect of air pressure to the structure vibration when floor impact noise occured is negligible. Figure 4-2 shows the field test results of Figure 3-8 in chapter 3.

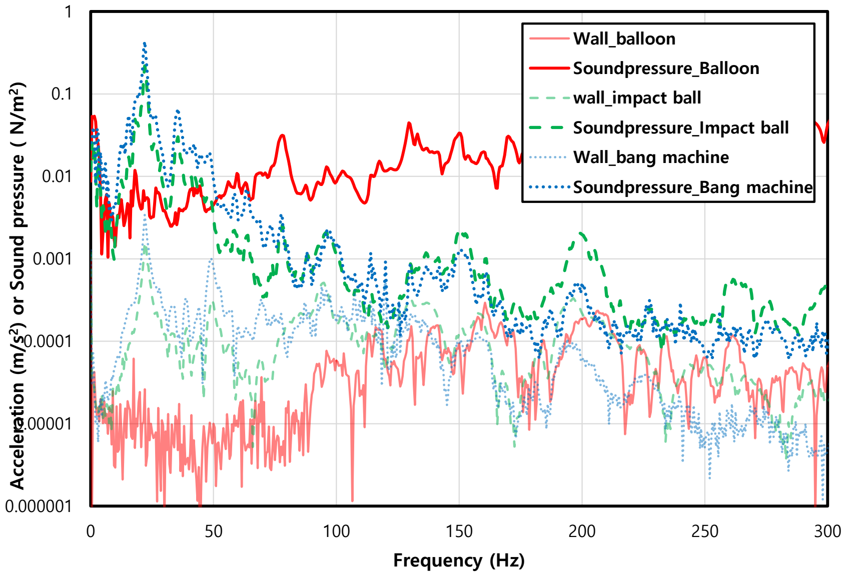


Figure 4-2 Sound pressure level and slab vibration response when different impact source is applied

Concrete wall vibration and sound pressure were measured simultaneously for each impact source. When a balloon was popped at the receiving room (solid red line), ratio of the structural vibration to the sound pressure for each frequency is very low comparing to other heavy impact sources. From the result, it was decided that the effect of air pressure to the structural wall vibration is so small that the effect is negligible. As a result, the effect of structural vibration to the sound pressure is the only concern and it makes easy to simulate the floor impact noise.

4.2.2 Structural system

Table 4-2 shows common structural properties of typical residential buildings. Architectural plan, floor height, floor system, and slab thickness are modeled same as the drawing. Modal damping ratio and Acoustic impedance values are determined by previous studies and field test result [10-15].

Table 4-2 Modeling information of floating floor

Structural property	Value
Architectural plan	Same as the drawing
Floor height	Same as the drawing (2.8m)
Floor system	Floating floor system
Non structural walls	Masonry wall: 0.5B or 1.0B brick wall
Slab thickness	Same as the drawing (210mm)
Concrete strength	24MPa
Young’s modulus	22GPa
Mass density of concrete	2450kg/m^3
Poisson’s ratio	0.167
Modal damping ratio (Floating floor system)	2-3% : 10-70Hz 4-5% : 70-120Hz 5% : over 120Hz
Boundary condition	Fixed support at the top and the bottom of the concrete wall
Sound speed	340m/s
Young’s modulus of air	0.14MPa
Mass density of air	1.225kg/m^3
Acoustic impedance	80,000kg/m^2/s for concrete surface
Boundary condition	Surface velocity of slab and wall

Damping ratio

Modal damping ratio of floating floor system was verified based on field measurement data. Because slab acceleration is governed by the 1st mode, band pass filter (butterworth filter, N=4, Sampling frequency=3200) is applied to the raw signal to check the damping ratio of different frequency range. Acceleration data were devided into 3 different frequency rage; 10-70Hz, 70-116Hz, 116-180Hz, respectively. Figure 4-3 provides a evidence of bandpass cutoff frequencies. Dips in force spectrum causes dips in slab acceleration. It is advantageous to select cutoff frequency as a dip frequency in filtering because governing peak frequencies could be found clearly. Once governing peak frequency is derived, corresponding damping ratio can be derived in time domain data.

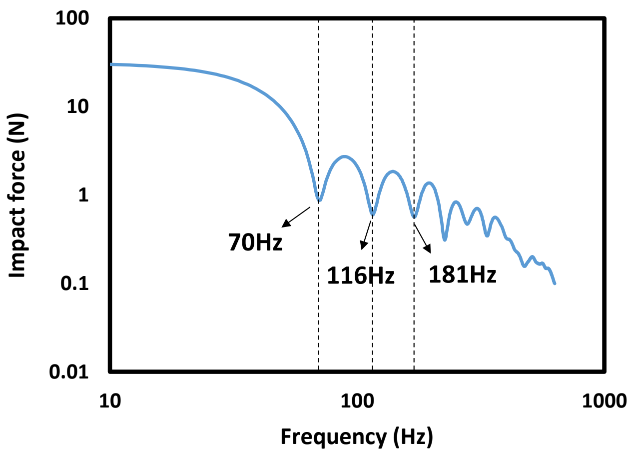
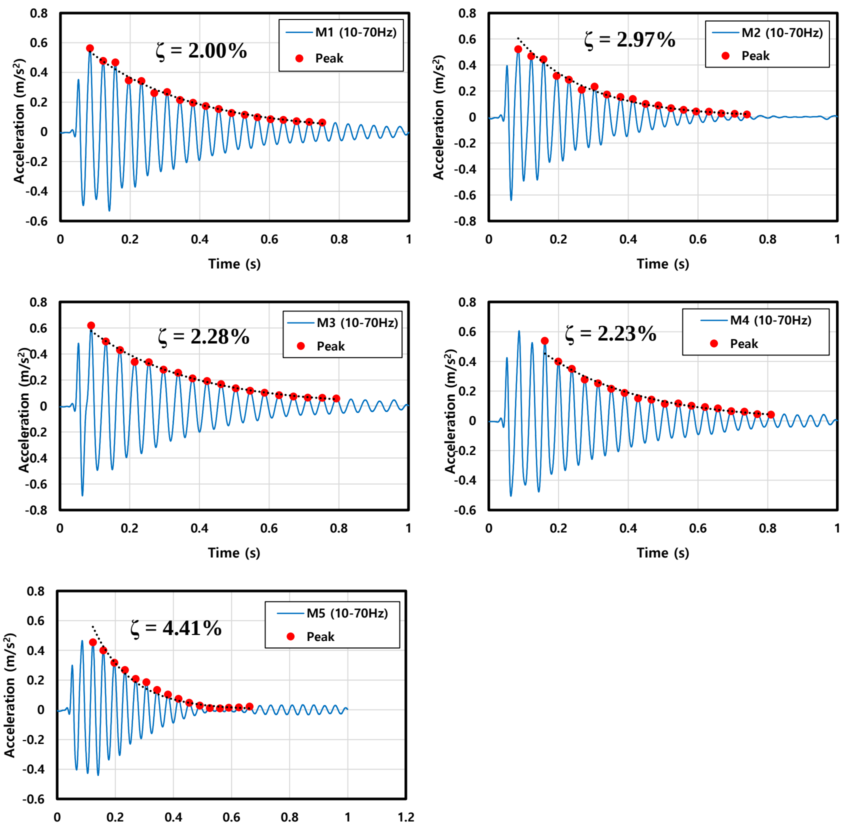
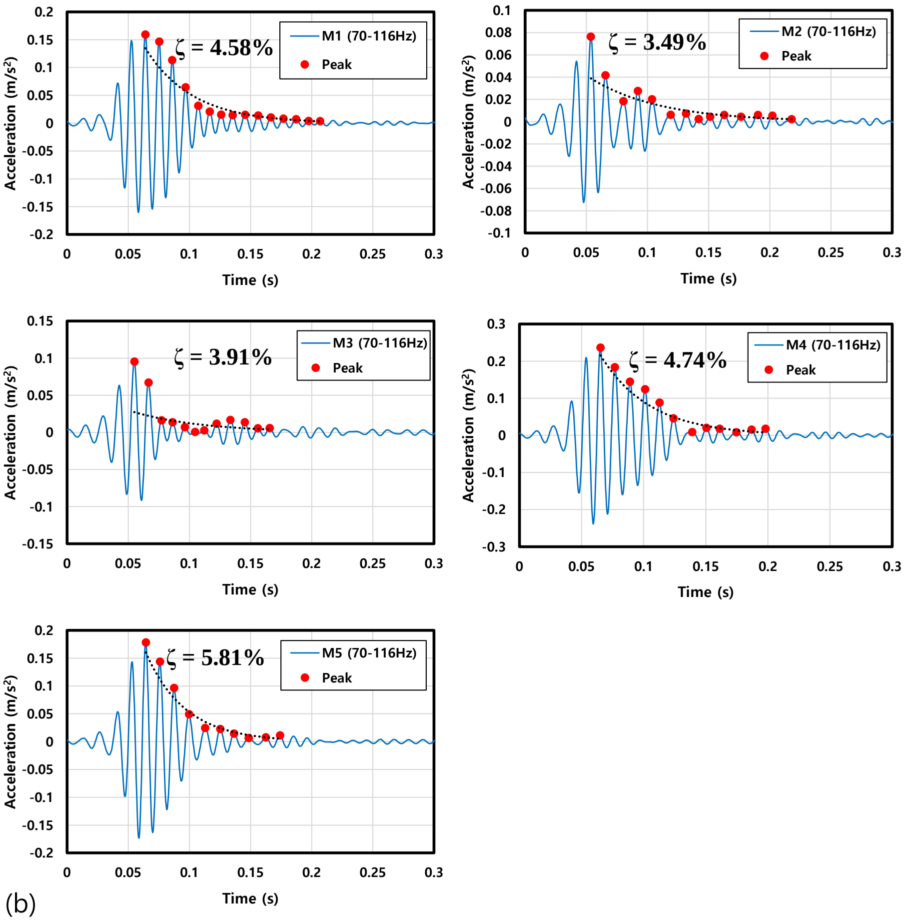


Figure 4-3 Impact force spectrum of impact ball (log scale) – selection of cutoff frequencies

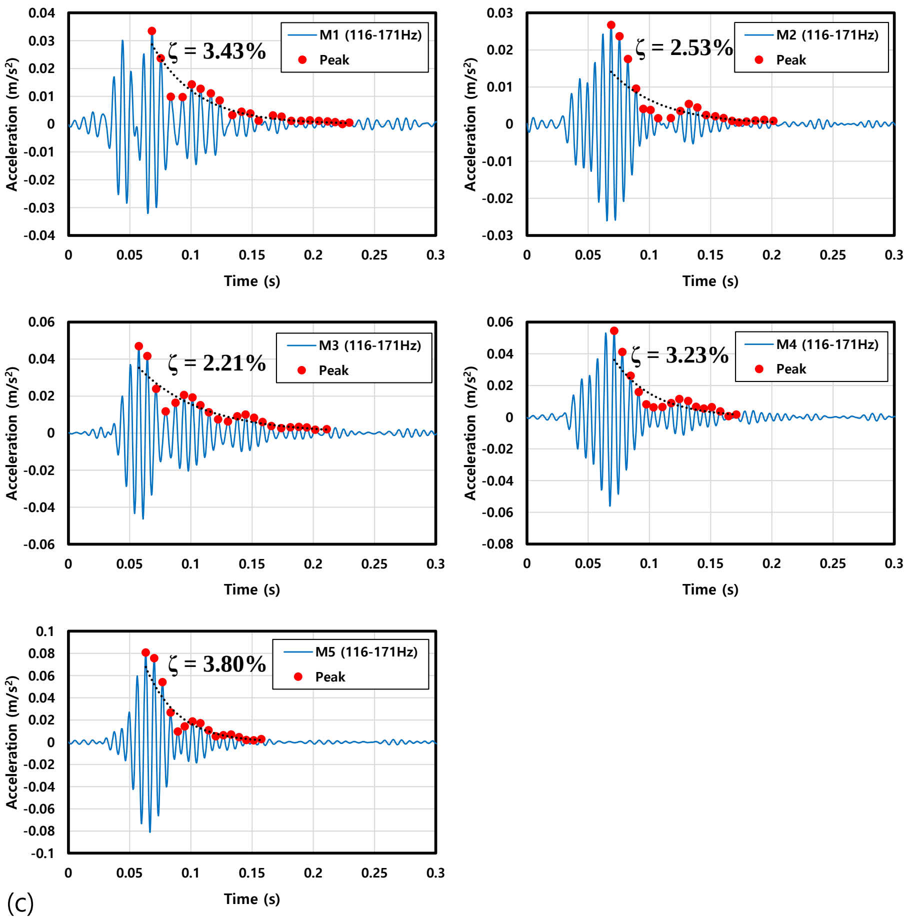
Responses over 180Hz were omitted because the influence of high frequencies on heavy impact noise is negligible. Slab acceleration was measured at 5 households with the same floor plan (Wall type, 84m^2) when heavy impact source (impact ball) is applied. When slab is in free vibration, damping ratio can be derived in time domain data. Figure 4-4 shows slab vibration responses in time domain. Envelope curves were drawn by connecting positive peak values in free vibration. From the evelope curve, damping ratio can be calculated because transient vibration is expressed as a function of damping ratio and natural frequency.



(a)


ζ = 4.58%
M1 (70-116Hz)
Peak
Acceleration (m/s²)
Time (s)
ζ = 3.49%
M2 (70-116Hz)
Peak
Acceleration (m/s²)
Time (s)
ζ = 3.91%
M3 (70-116Hz)
Peak
Acceleration (m/s²)
Time (s)
ζ = 4.74%
M4 (70-116Hz)
Peak
Acceleration (m/s²)
Time (s)
ζ = 5.81%
M5 (70-116Hz)
Peak
Acceleration (m/s²)
Time (s)

(b)



(c)

Figure 4-4 Damping ratio calculated from field measured data

(bandpass filtered, 10-70Hz(a), 70-116Hz(b), 116-171Hz(c))

Table 4-3 shows calculated damping ratio from the measured data. Generally, damping ratio of 10-70Hz is 2~3%. Damping ratio of 70-116Hz is 4~5%, showing slightly larger value than those of 10-70Hz responses. When heavy impact source is applied to floating floor, vibration amplitude decreases as frequency increases and there is no distinct governing peak frequencies in high frequency range. As a result, it is relatively hard to get clear damping ratio of 70-116Hz, and 161-171Hz.

Table 4-3 Damping ratio calculated from measured data (band pass filtered)

Slab acceleration		Curve fitting *(y=a·exp(-bx))*			
		a	*b*	r^2	Damping ratio, %
10-70Hz	M1	0.72	3.40	0.99	2.00
	M2	0.92	5.03	0.99	2.97
	M3	0.78	3.44	0.99	2.28
	M4	0.81	3.64	0.99	2.23
	M5	1.40	7.47	0.91	4.41
70-116Hz	M1	0.71	25.92	0.94	4.58
	M2	0.10	17.55	0.74	3.49
	M3	0.07	17.67	0.22	3.91
	M4	1.10	25.03	0.80	4.74
	M5	1.18	31.04	0.91	5.81
116-171Hz	M1	0.18	26.92	0.83	3.43
	M2	0.08	24.45	0.75	2.53
	M3	0.11	19.13	0.91	2.21
	M4	0.32	30.48	0.76	3.23
	M5	0.74	37.92	0.90	3.80

Table 4-4 shows arithmetic mean of damping ratio of 5 households at each frequency range.

Table 4-4 Avg. damping ratio of floating floor system

Frequency	10-70Hz	70-120H	Over 120Hz
Avg. damping ratio	2.78%	5.04%	3.15%

The average value showed that the damping ratio of main low frequency components between 10Hz and 70Hz is 2~3%. For higher frequencies of 70-120Hz, the derived damping ratio was 4~5%. For higher frequencies over 130Hz, damping ratios were distributed between 3% and 5%, and hard to determine average value. However, acceleration response over 120Hz is not a main components of both slab vibration and sound pressure level. Therefore 5% level of damping ratio is applied in numerical model for simplicity. Damping ratio measured in this thesis are based on the measured data of a certain apartment type; wall type, 84m^2. Therefore, the damping ratio obtained in this paper does not represent the damping ratio of all kinds of floating floor system.

4.2.3 Non-structural walls

Dry walls

In chapter 3, it has been shown that the interaction between drywalls and air pressure is negligible except certain frequencies, and most of residential buildings are wall type structure where the portion of the dry wall are relatively small. Furthermore, the stiffness and mass of dry walls are so small that overall vibrational response of the residential building is not affected by the presense of dry walls. Consequently, dry walls can be excluded from the numerical modeling. Following analysis result of excluded dry wall model (Figure 4-5) showed that the response of FE analysis and field test was quite close.

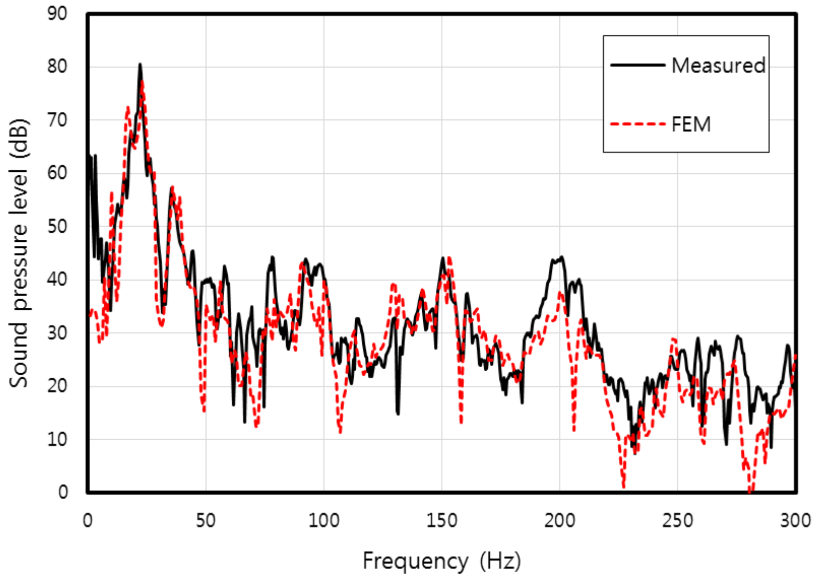


Figure 4-5 Sound pressure level of measured data and FE model without dry walls (bare slab system)

Masonry walls

The portion of masonry walls in residential buildings is also small as dry walls. Most of masonry walls are usually installed around bathrooms, resulting little impact on floor impact noise. However, the presence of masonry walls may affect the overall vibrational response because large mass is concentrated at certain area. Therefore, masonry walls were included in numerical modeling, but only for the upper floor. In many case masonry walls are not fixed to the upper slab. It can be assumed that brick walls are not supporting concrete slab. Therefore, masonry walls were modeled only at the upper floor imposing mass of the masonry walls to the concrete slab.

4.2.4 Contact condition

In modeling of floating floor system, the main issue is the contact condition where two different material meets. Table 4-5 shows contact conditions in floating floor system.

Table 4-5 Contact conditions in floating floor system

Contact condition	Interface materials
Vertical contact	Concrete slab – resilient material Resilient material – ALC ALC – mortar plate
Horizontal contact	Isolator – resilient material Isolator – ALC Isolator – mortar plate Concrete wall - isolator

In particular, Horizontal contact condition listed in Table 4-5 is hard to define. Figure 4-6 shows the isolator installed at a construction site. Isolators are installed to isolate mortar or ALC vibration from concrete wall. It is expected that the contact condition related to isolator can be defined by friction.

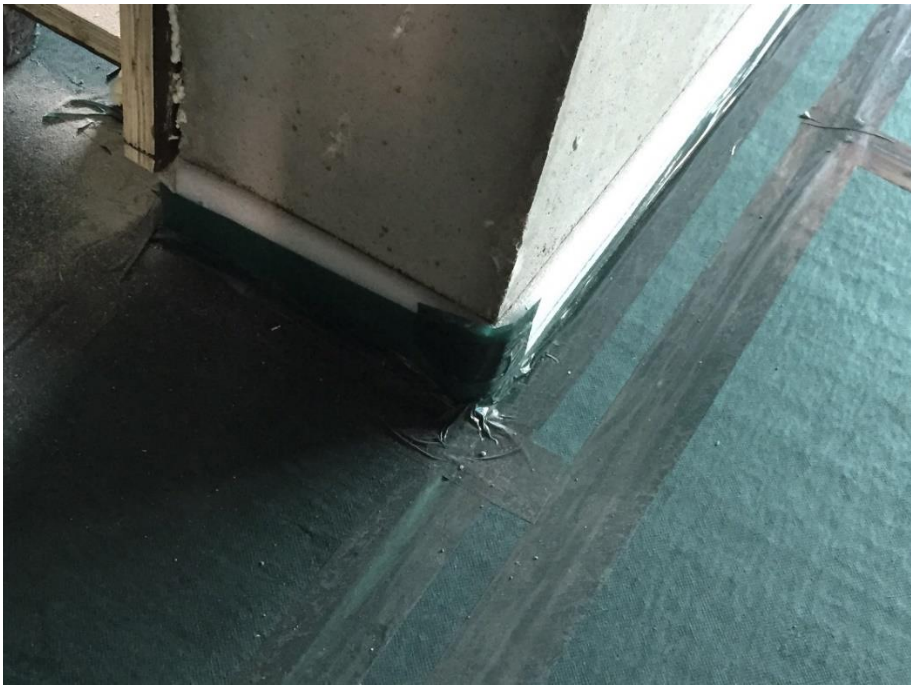


Figure 4-6 Isolator between concrete wall and floating floor system

(Before mortar pouring)

However, deriving frictional coefficient at the surface of isolator is hard to get experimentally. Instead, it is assumed that the isolator perfectly isolates mortar or ALC vibration to concrete wall to simplify numerical modeling. Figure 4-7 shows modeling method of isolators.

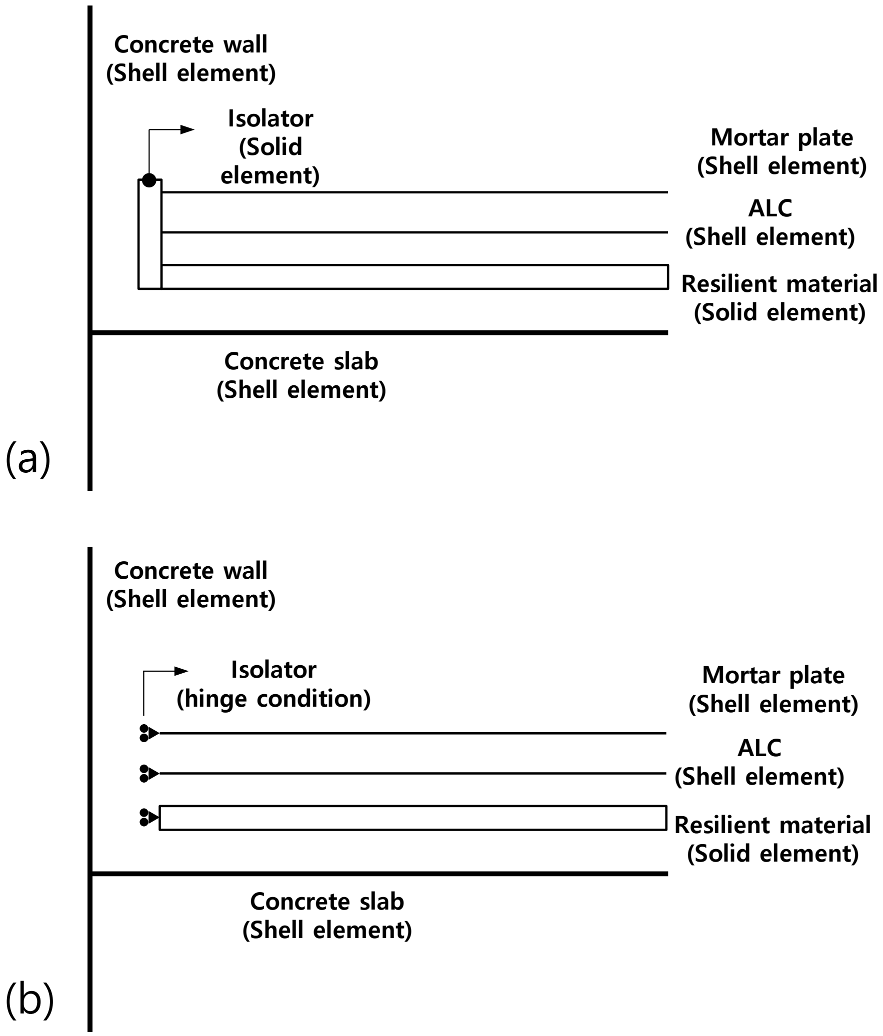


Figure 4-7 Modeling method of floating floor system –

(a) a model including isolator, (b) corresponding boundary condition model

Instead of defining every contact conditions in floating floor system (Figure 4-7 (a)), corresponding hinge boundary condition (Figure 4-7 (b)) is applied at the end of the floating floor system. The boundary condition allows vertical displacement while prohibiting horizontal displacement. Vibration of mortar plate or ALC is not directly transmitted to concrete walls. As a result, contact conditions to consider is reduced from seven to four. As verified in chapter 3.5.3, vertical contact conditions can be simply assumed as perfectly bonded condition.

4.3 Comparison with the Field Test Result

The numerical analysis result was compared to the field measurement result. To verify the accuracy of the numerical model, both slab acceleration and sound pressure level per every receiving point, specified in KS F 2810-2, are analyzed.

4.3.1 Test scheme

Figure 4-8 shows a test cheme of the measuured apartment. Slab acceleration and sound pressure level at each receiving point are recorded simultaneously for 4 impact points respectively. The numerical model was modeled to be identical to the field measurement condition such as slab thickness, dimension of the apartment, material properties of concrete and mortar plate, etc. Since the material properties of the resilient material was not known exactly, it was assumed that the dynamic stiffness of the resilient material is around 10~20MN/m^3.

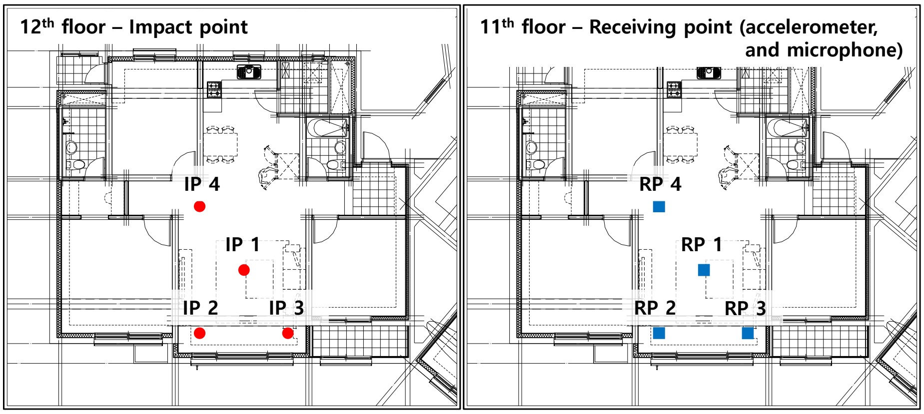
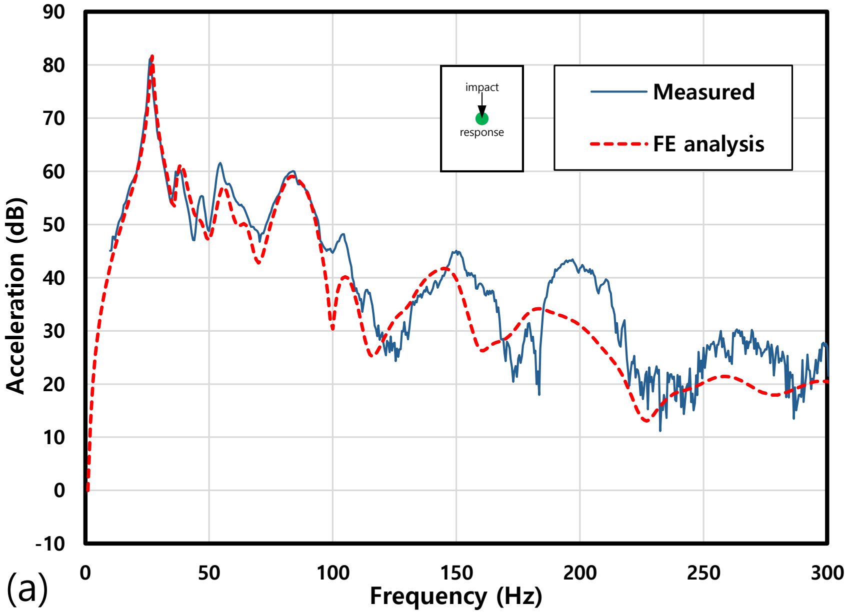
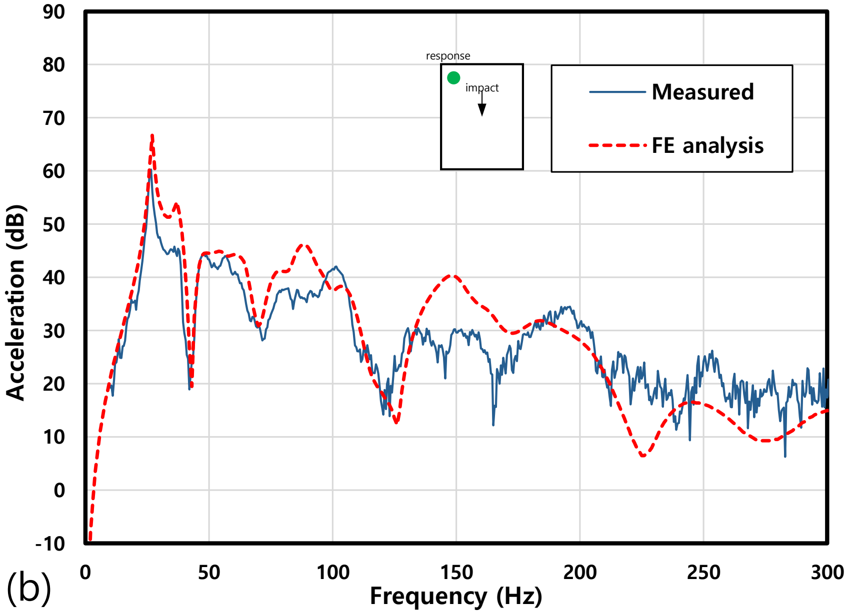


Figure 4-8 Impact points (left) and receiving points (right) in both field test and FE analysis

4.3.2 Slab vibration

Figure 4-9 shows comparison between the measured slab acceleration and the FE analysis results. Amplitude of the slab acceleration is the maximum at the center of the slab for both results. As shown in Figure 4-9 (a) clearly, vibration amplification around 80Hz is well described in numerical modeling. For each case, the numerical model generally shows similar responses to the measured acceleration until 100Hz. FE analysis results at RP4 (Figure 4-9 (c), and (d)) show larger amplitude at low frequency range. It seems that the overestimation is due to the difference of the accelerometer position between the field test and the numerical model. As frequency increases the acceleration of the numerical model considerably underestimates slab vibration. This phenomenon can cause underestimation of the floor impact noise because the floor impact noise is determined by the velocity of the slab vibration.


Acceleration (dB)
Frequency (Hz)
impact
response
Measured
FE analysis
(a)


Acceleration (dB)
Frequency (Hz)
response
impact
Measured
FE analysis
(b)

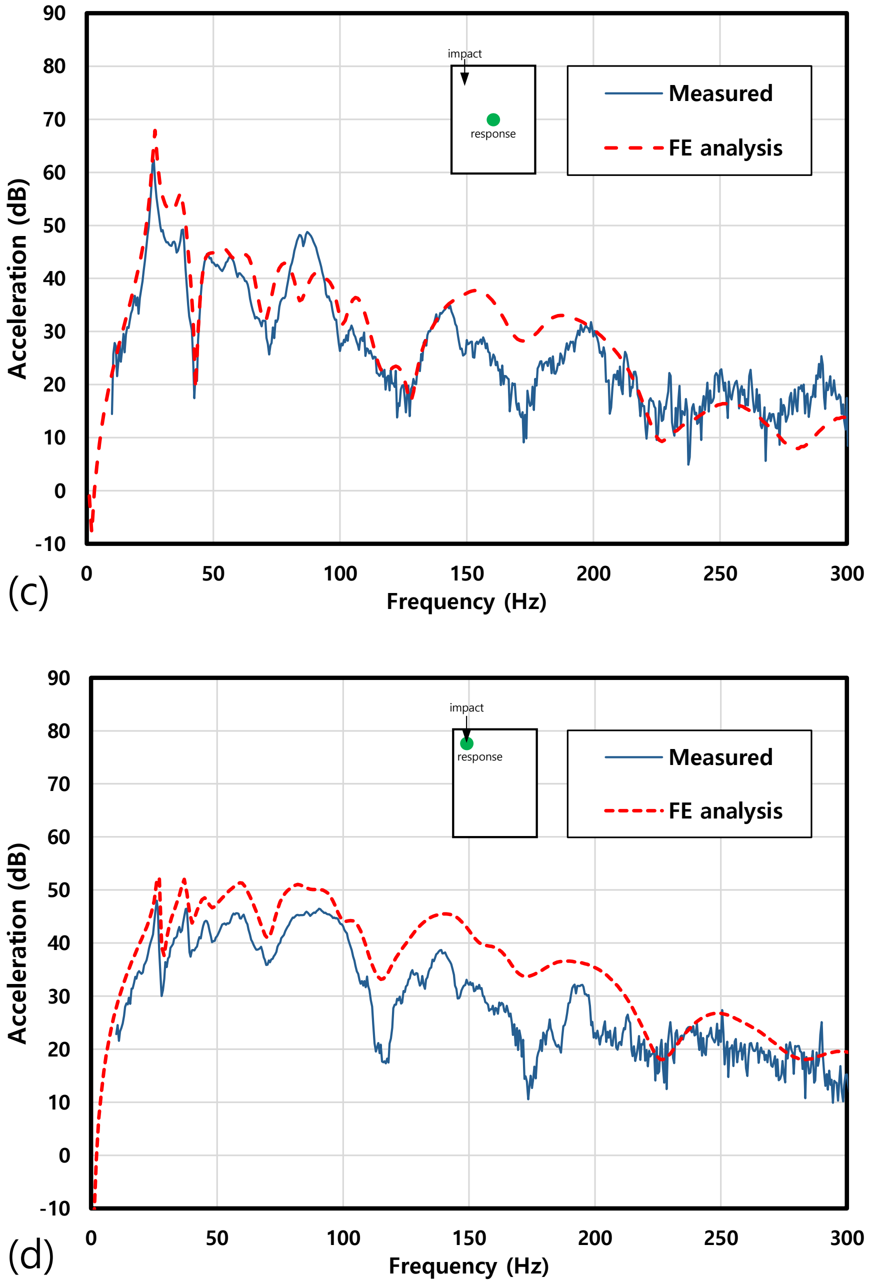


Figure 4-9 Comparsion of slab vibration between field measurement and FE analysis – (a) IP1 - RP1, (b) IP1 - RP4, (c) IP4 - RP1, (d)IP4 - RP4

To increase the accuracy of the numerical model, the background noise of the accelerometer is compared to the recorded acceleration generated by the heavy impact force. Figure 4-10 shows the acceleration comparison between when the heavy impact source is applied and when background acceleration is recorded (without an impact).

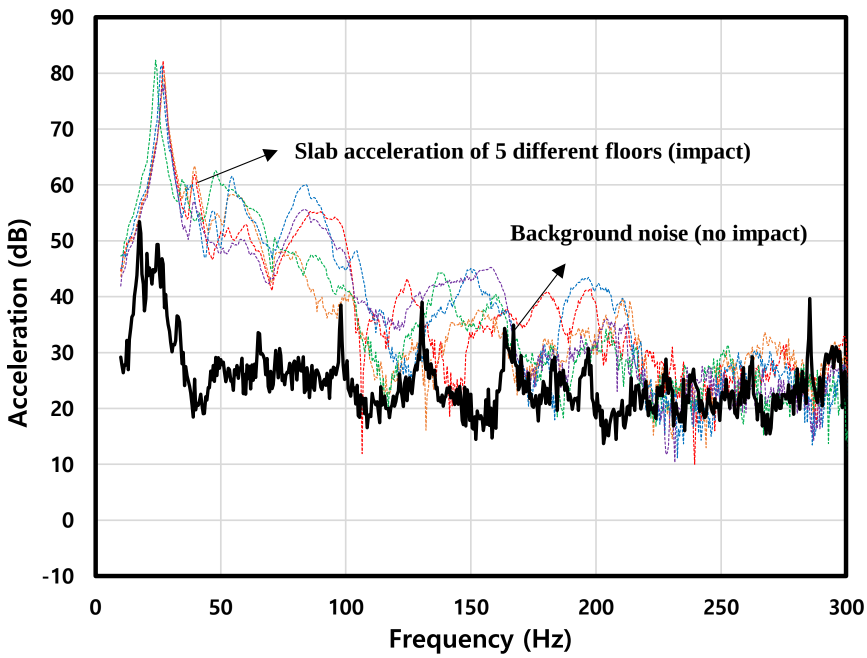


Figure 4-10 Slab vibration when heavy impact is applied and background acceleration without an impact

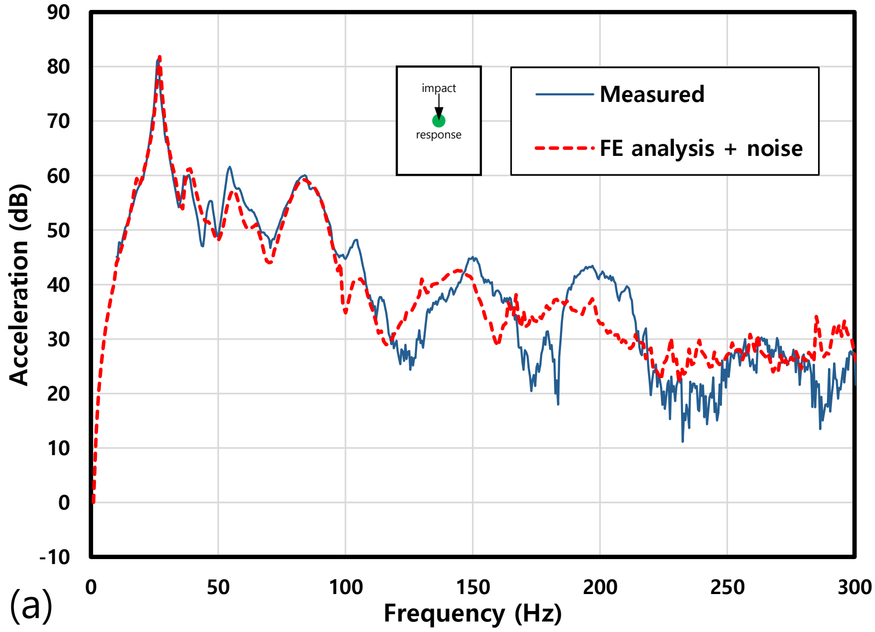
It has been observed in the field test that the vibration amplitude of the concrete slab over 230Hz is similar to the amplitude of the background noise. As shown in figure 4-10, the amplitude over 230Hz of 5 different floor shows quite similar value even though resilient materails are all different for each floor. It means that the slab vibration induced by the heavy impact source on the floating floor is very small over 230Hz, and the vibration amplitude is determined by the background noise. The measured background noise amplitude were gradually decreased from 20dB (230Hz) to 10dB (630Hz).

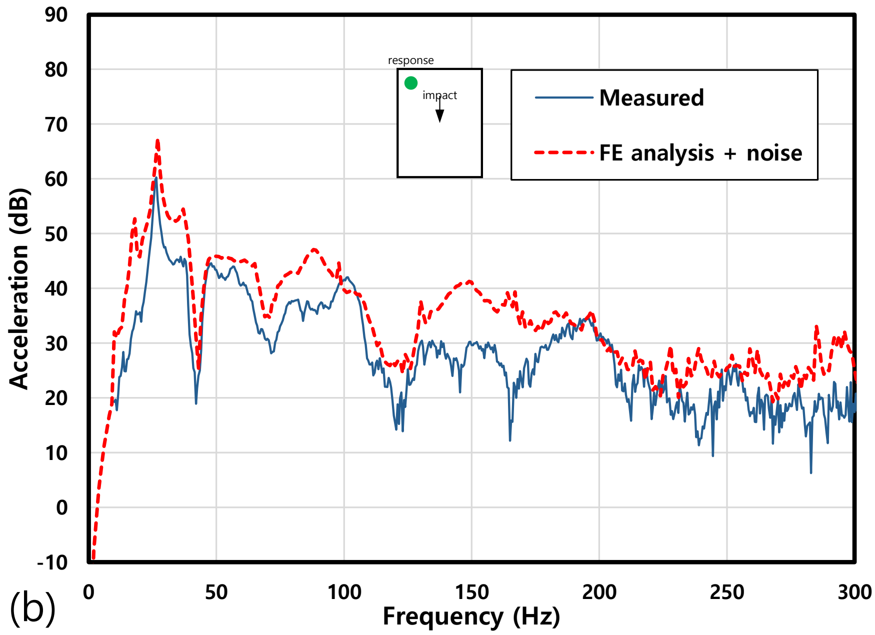
In numerical analysis, slab vibration occur only by an impact source. Namely, there is no background noise. As a result, the FE analysis results show very small vibration amplitude over 230Hz frequency components comparing to the measured data. Furthermore, predicting high frequency response is limited due to the element size. In case of the numerical model of this paper, element size for both structural and acoustic model were 150mm. Accordingly, Frequency response over 380Hz cannot be predicted correctly. It is not reasonable to make the element size small for high frequency analysis of heavy impact noise over 380Hz.

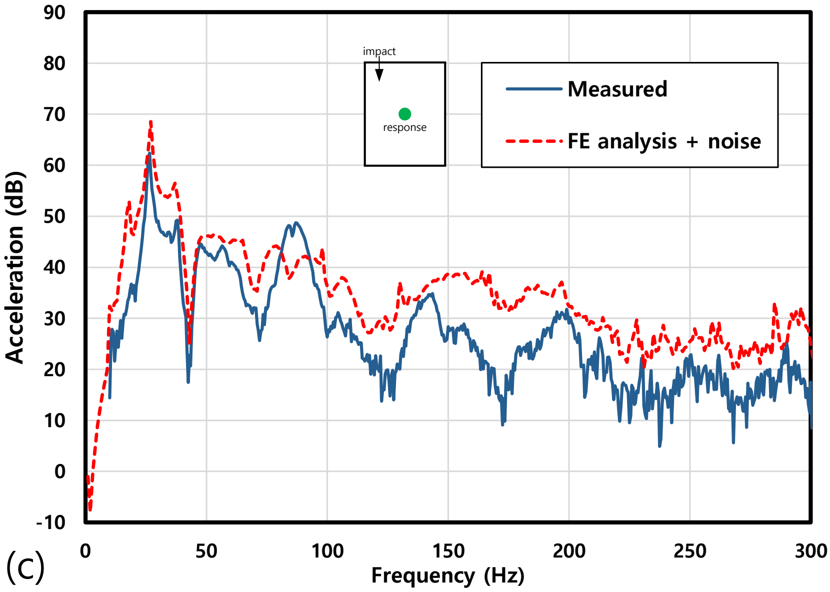
To minimize the variation between the measured data and FE analysis data, measured background acceleration is added to the numerical analysis results. i.e.

$$Acc(f) = Acc(f)_{FEM} + Noise(f)_{FIELD} \tag{4,1}$$

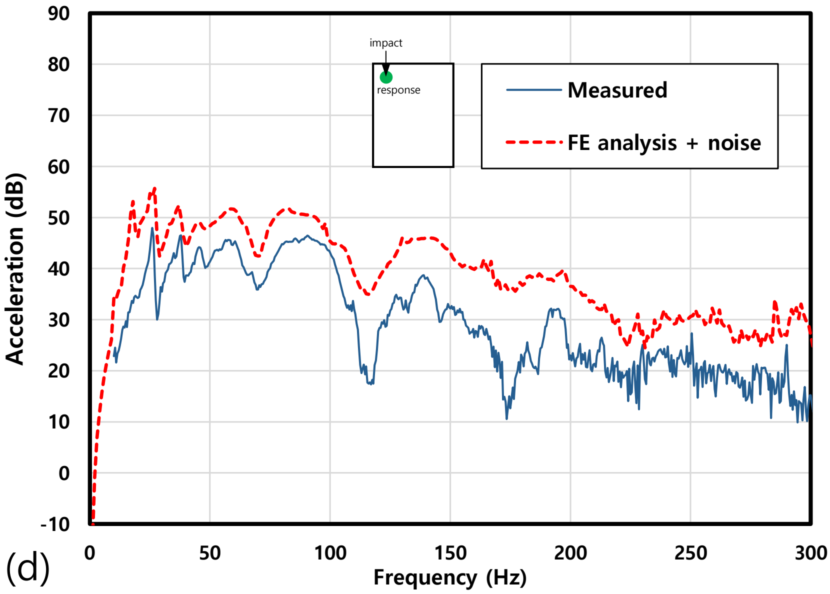
The following Figure 4-11 shows the results of the numerical analysis results containing background noise of the slab acceleration.


impact
response
Measured
FE analysis + noise
Acceleration (dB)
Frequency (Hz)
90
80
70
60
50
40
30
20
10
0
-10
0
50
100
150
200
250
300
(a)


response
impact
Measured
FE analysis + noise
Acceleration (dB)
Frequency (Hz)
90
80
70
60
50
40
30
20
10
0
-10
0
50
100
150
200
250
300
(b)



(c)



(d)

Figure 4-11 Comparsion of slab vibration between field measurement and FE analysis with background noise – (a) IP1 - RP1, (b) IP1 - RP4, (c) IP4 - RP1, (d)IP4 - RP4

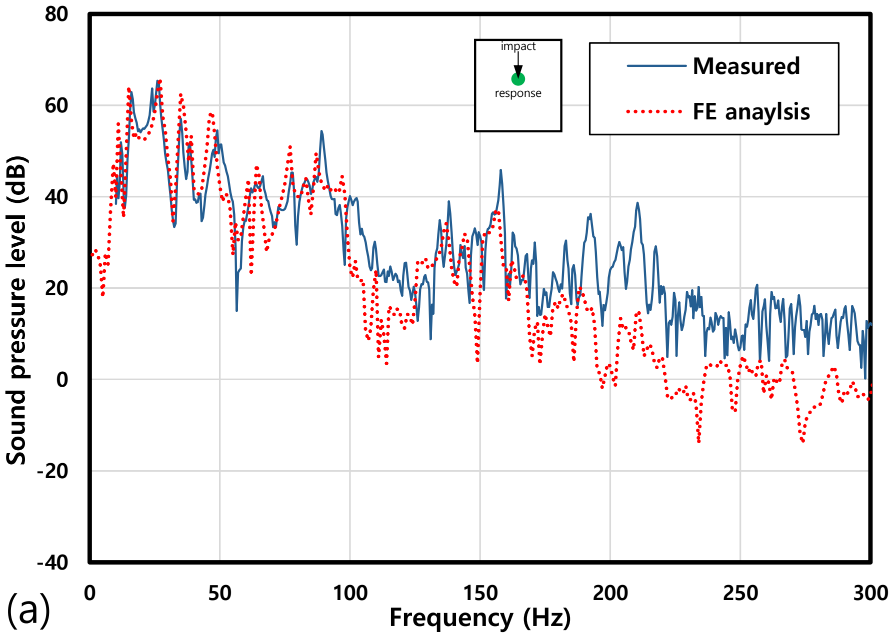
By including background vibration of the slab, numerical analysis results became more accurate. However, the response is not the exactly same although early low vibration modes of the FE model are correspond well to the measured acceleration. Response variation between 100Hz to 200Hz should be improved to get more accurate acceleration response.

4.3.3 Sound pressure level

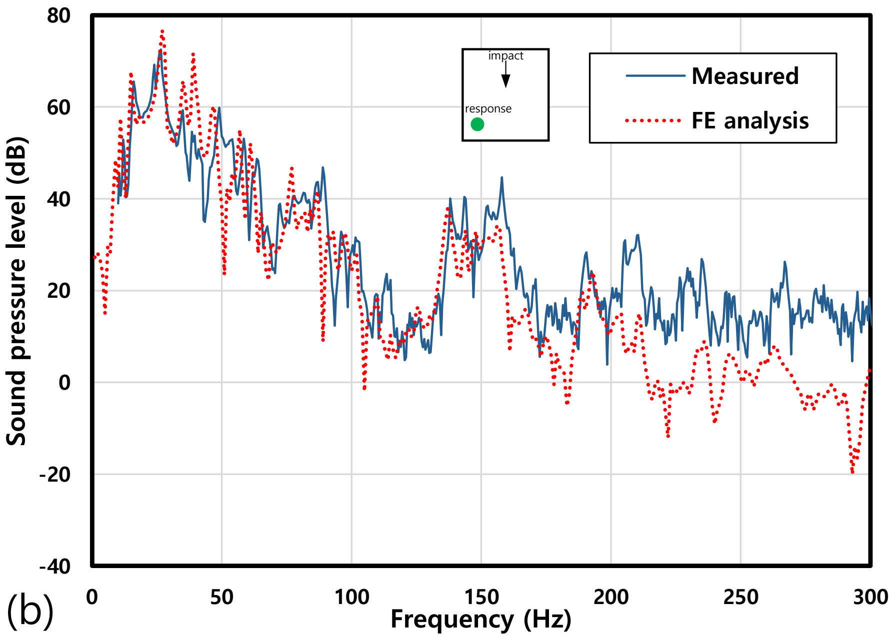
Floor impact noise is compared when impact is applied to IP1 and IP4. Each gragh of Figure 4-12 shows sound pressure level of the microphone at receiving point R1~R4. Until 150Hz, the numerical model gives reasonable responses comparing to the measured data. Although FE model slightly underestimates the floor impact noise from 50Hz, while overestimating floor impact noise under 50Hz, the tendency of the overall response seems similar.

As same in acceleration response case, floor impact noise of the numerical model underestimates the floor impact noise over 200Hz. To increase the accuracy of the numerical model, background noise of the receiving room is considered as in the acceleration response (Eq. (4.2)).

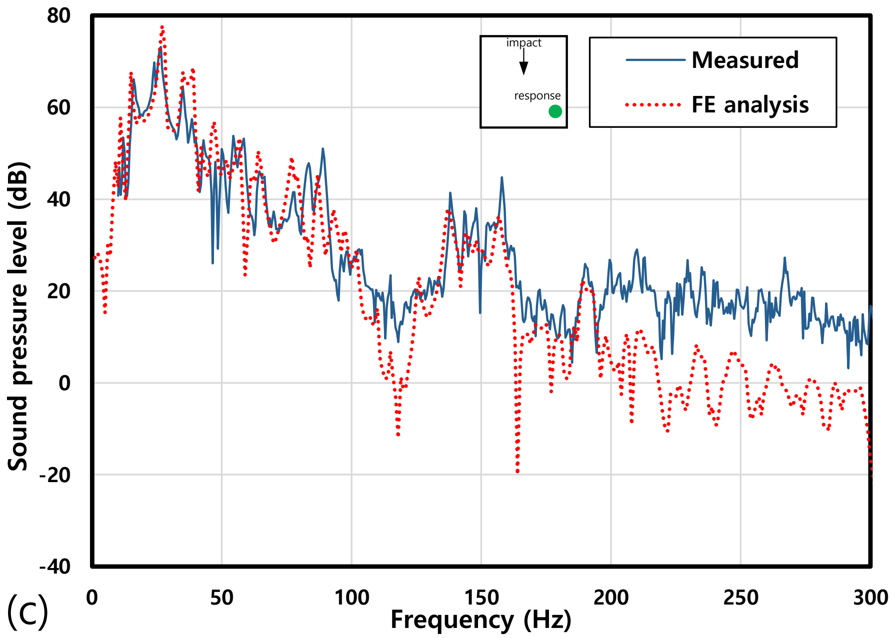
$$soundpressure(f) = soundpresure(f)_{FEM} + Noise(f)_{FIELD} \qquad (4,2)$$


80
60
40
20
0
-20
-40
Sound pressure level (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
Measured
FE anaylsis

(a)

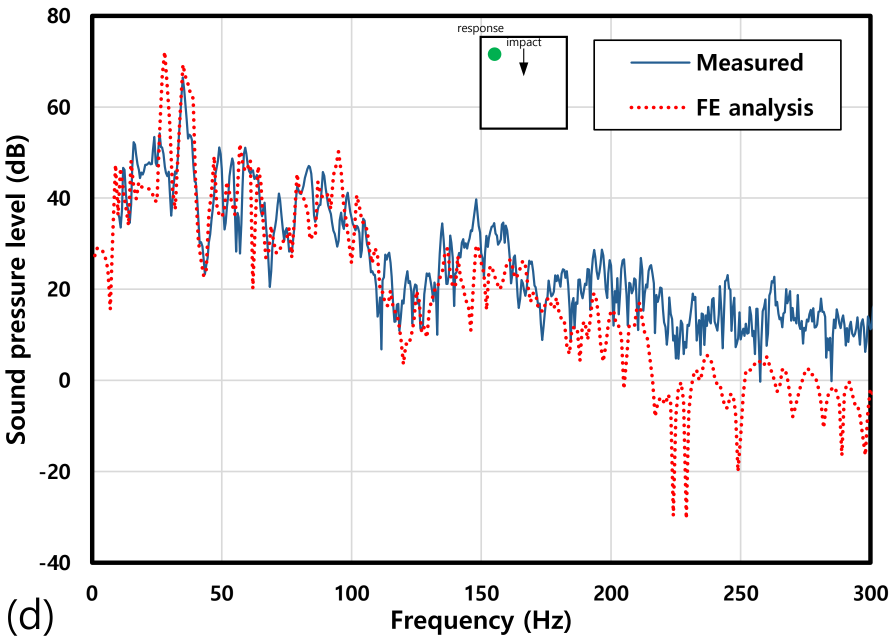

80
60
40
20
0
-20
-40
Sound pressure level (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
Measured
FE analysis

(b)



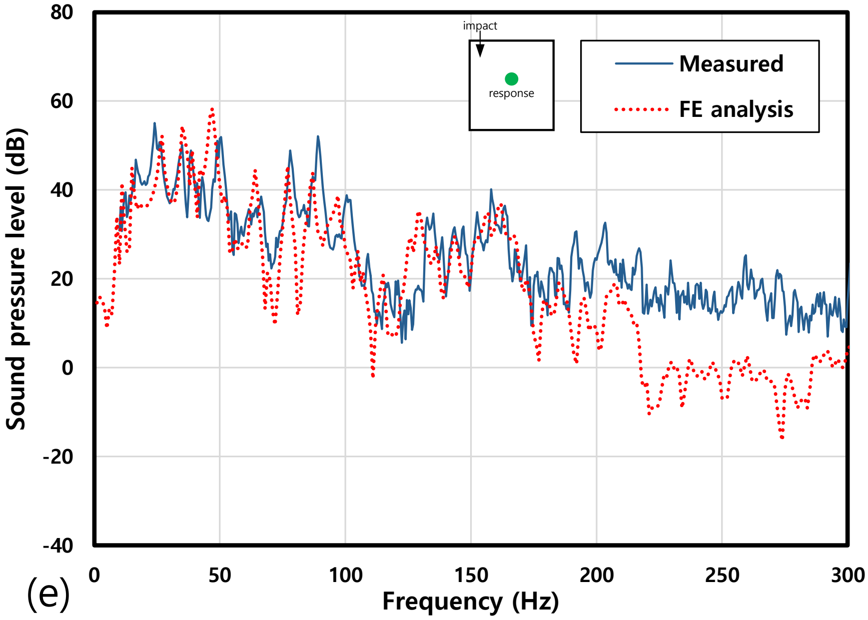
80
60
40
20
0
-20
-40
0
50
100
150
200
250
300
Sound pressure level (dB)
Frequency (Hz)
impact
response
Measured
FE analysis

(c)

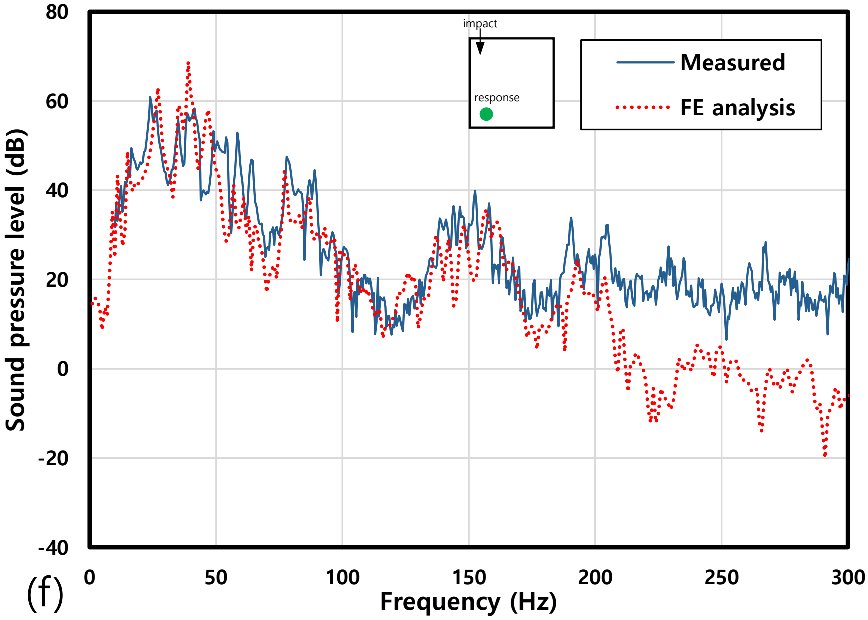


80
60
40
20
0
-20
-40
0
50
100
150
200
250
300
Sound pressure level (dB)
Frequency (Hz)
response
impact
Measured
FE analysis

(d)


80
60
40
20
0
-20
-40
Sound pressure level (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
Measured
FE analysis

(e)


80
60
40
20
0
-20
-40
Sound pressure level (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
Measured
FE analysis

(f)

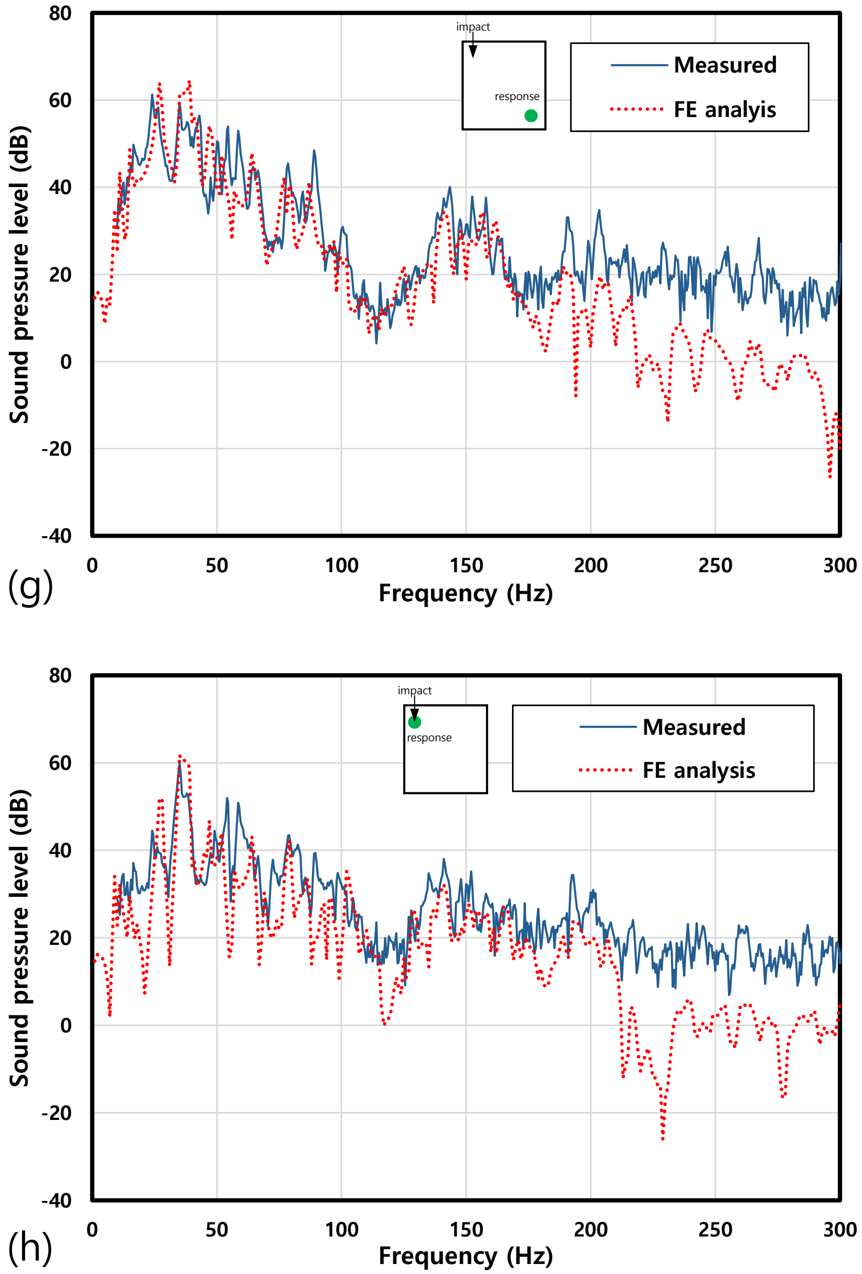


Figure 4-12 Comparsion of sound pressure level between field measurement and FE analysis at each impact and measurement point

Figure 4-13 shows the comparison between the heavy impact noise of 5 floors with different resilient materials and the background noise without an impact source. As same in the acceleration response, sound pressure level of the heavy impact source over 230Hz is quite similar to the background noise. It means that the response over 230Hz is rarely affected by the heavy impact noise.

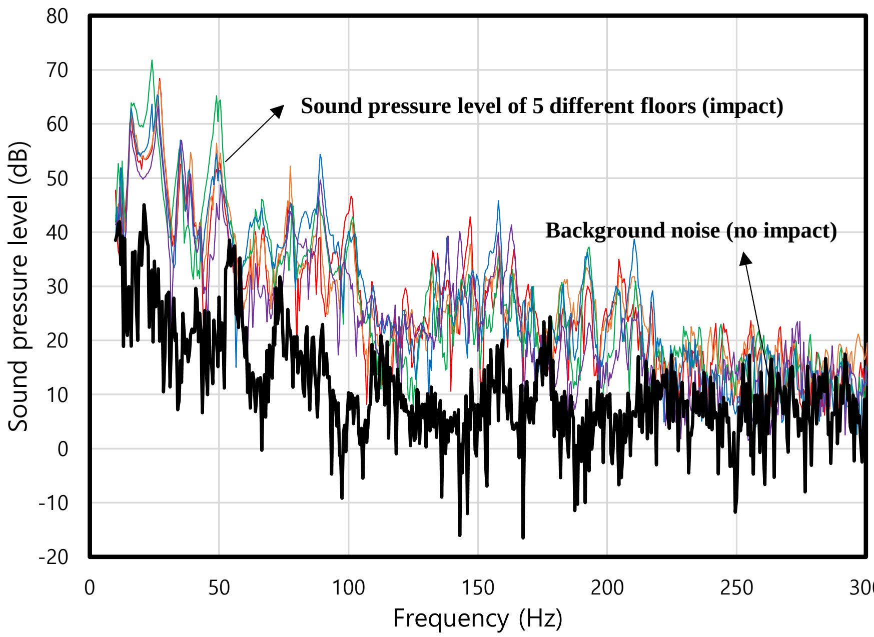
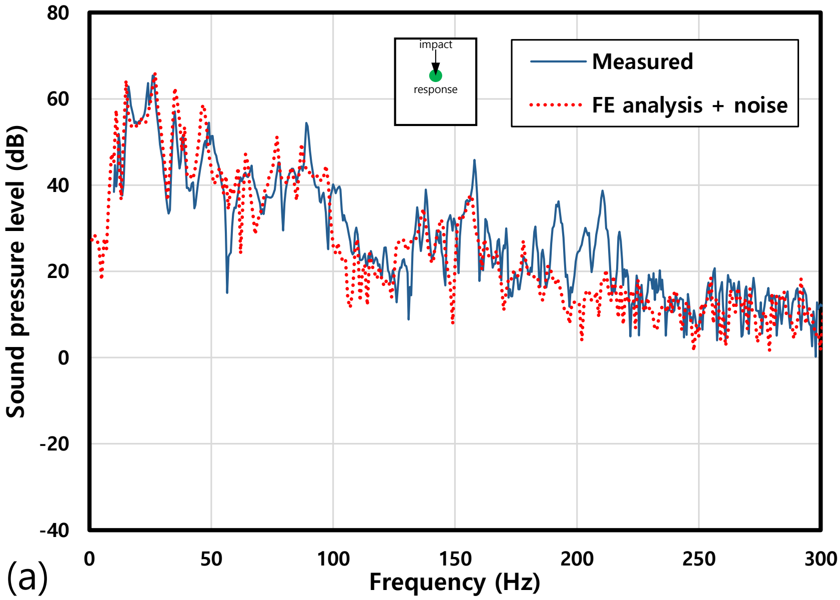
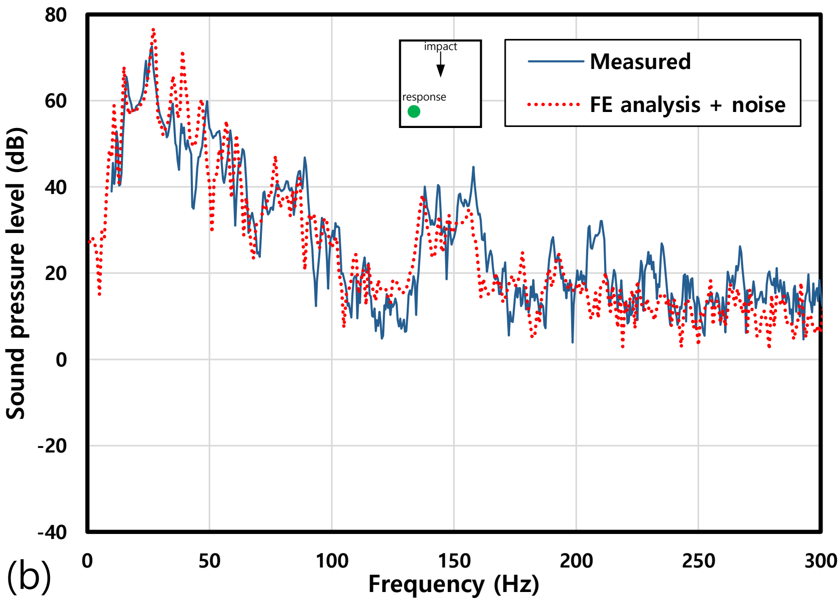


Figure 4-13 Sound pressure level when heavy impact is applied and background noise without an impact

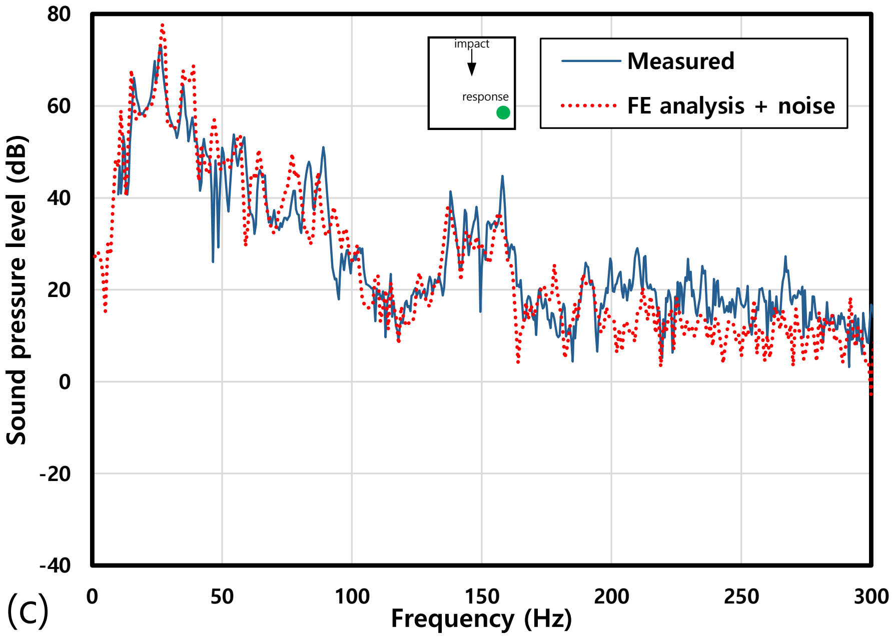
The following Figure 4-14 shows the improved numerical analysis results by considering the background noise of the receiving room. Still, the numerical model slightly underestimates sound pressure level between 50Hz to 300Hz at each receiving point.


impact
response
Measured
FE analysis + noise
Sound pressure level (dB)
Frequency (Hz)
80
60
40
20
0
-20
-40
0
50
100
150
200
250
300

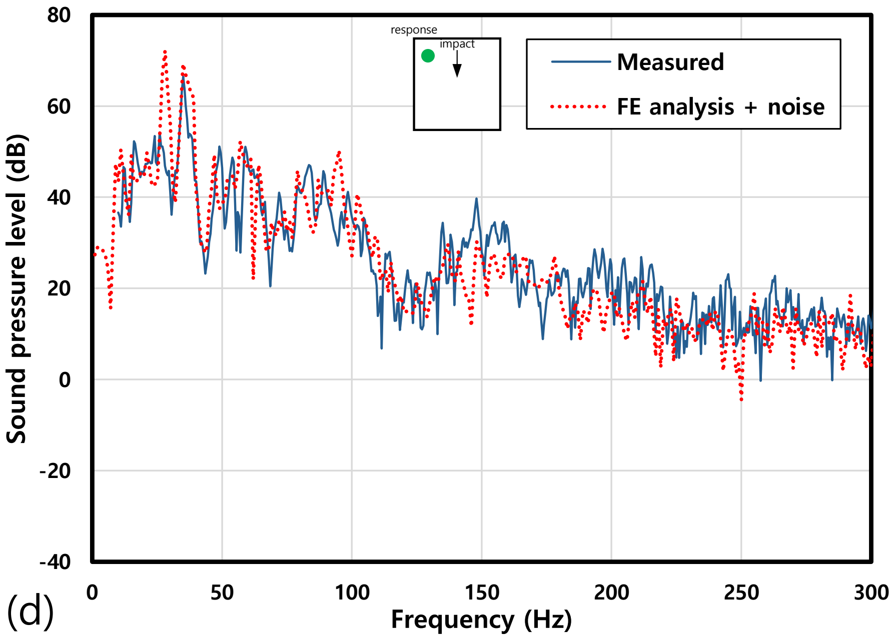
(a)


impact
response
Measured
FE analysis + noise
Sound pressure level (dB)
Frequency (Hz)
80
60
40
20
0
-20
-40
0
50
100
150
200
250
300

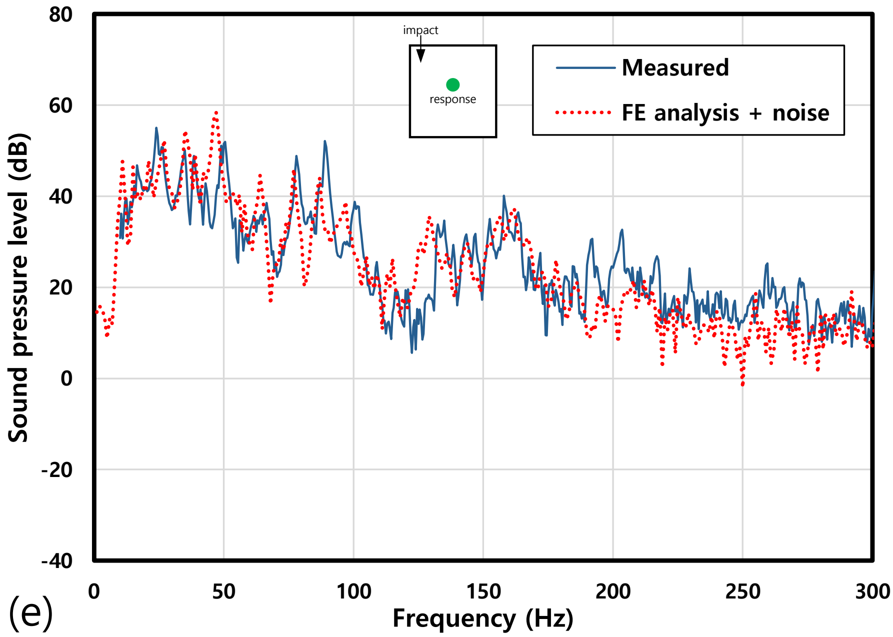
(b)


Measured
FE analysis + noise
impact
response
Sound pressure level (dB)
Frequency (Hz)

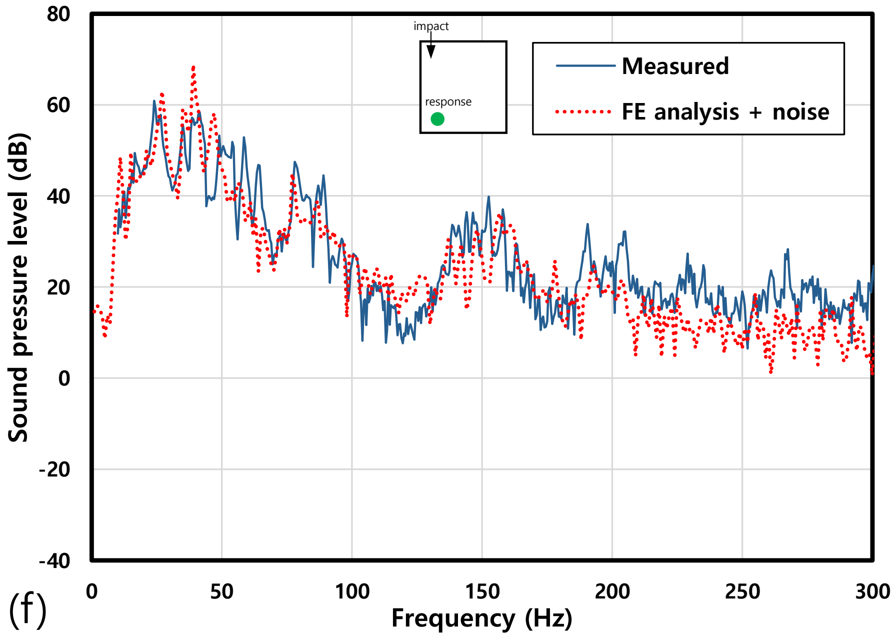
(c)


Measured
FE analysis + noise
response
impact
Sound pressure level (dB)
Frequency (Hz)

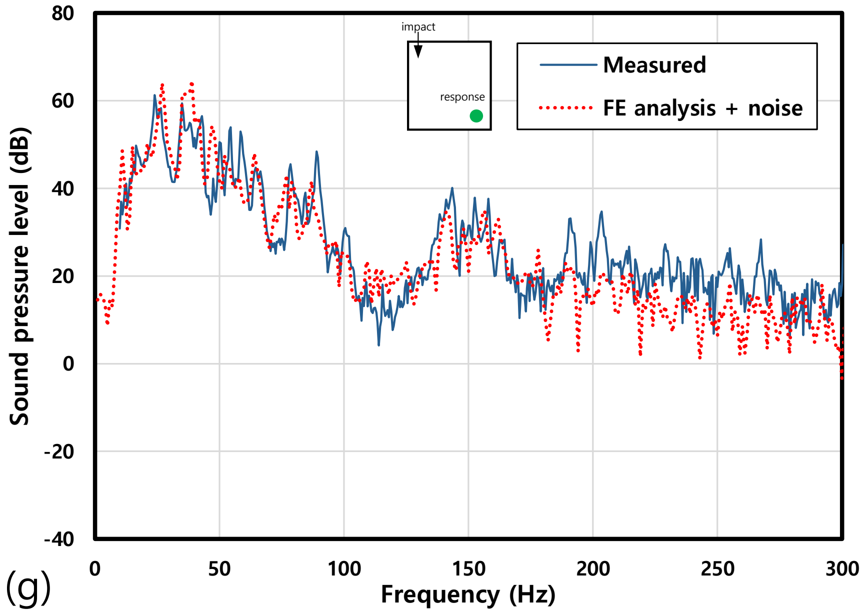
(d)


80
60
40
20
0
-20
-40
Sound pressure level (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
Measured
FE analysis + noise

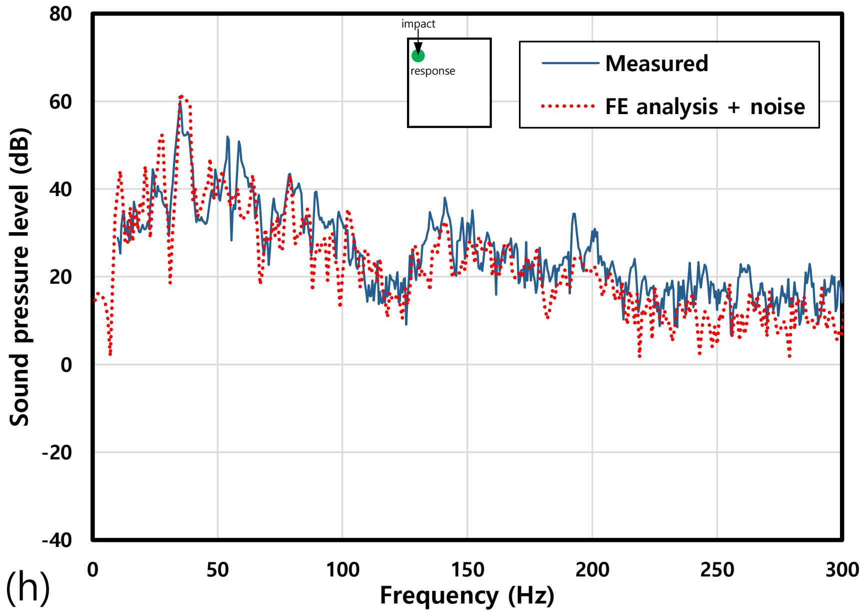
(e)


80
60
40
20
0
-20
-40
Sound pressure level (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
Measured
FE analysis + noise

(f)



(g)



(h)

Figure 4-14 Comparsion of sound pressure level between field measurement and FE analysis with noise at each impact and measurement point

The numerical model can simulate the floor impact noise measured in field test. However, the background noise should be added to the analysis result, because background noise cannot be considered in numerical modeling. The background noise of the microphone shows around 10dB sound pressure level even no impact is applied to the slab.

Consequently, the accuracy of the numerical model is verified. The numerical model can generally describe the overall floor impact noise response, but it tends to underestimates the floor impact noise between 50Hz and 300Hz while overestimating the floor impact noise under 50Hz. There are so many factors that can cause the variation between the measured data and the numerical model. For example, different impact point, receiving point, slab thickness, measurement error, etc. In the thesis, the result is compared only at the one household. To increase the accuracy of the numerical model, more field measurement should be made.

4.4 Effect of Resilient Materials

In chapter 4.3, the validity of predicting floor impact noise is verified. There are many tries to reduce heavy impact noise by changing resilient materials in floating floor system. In this chapter, the effect of resilient material in residential building is analyzed by performing numerical analysis.

4.4.1 Resilient materials in FE model

For six kinds of resilient materials with different dynamic stiffness, numerical analysis was performed. Resilient material varies from 5MN/m^3 to 30MN/m^3. Table 4-6 shows the material properties of resilient materials.

Table 4-6 Six modelings with different resilient materials

Resilient material	Floating floor RM5	RM10	RM15	RM20	RM25	RM30
Dynamic stiffness (MN/m^3)	5	10	15	20	25	30
Thickness (mm)	30	30	30	30	30	30
Elastic modulus (MPa)	0.15	0.3	0.45	0.60	0.75	0.90

For numerical simplicity, the thickness of the resilient material is assumed to have same thickness, 30mm. Thus, elastic modulus of each resilient material is different. The target floor plan is selected to the plan in Figure 4-8, which is a typical wall type medium sized residential building.

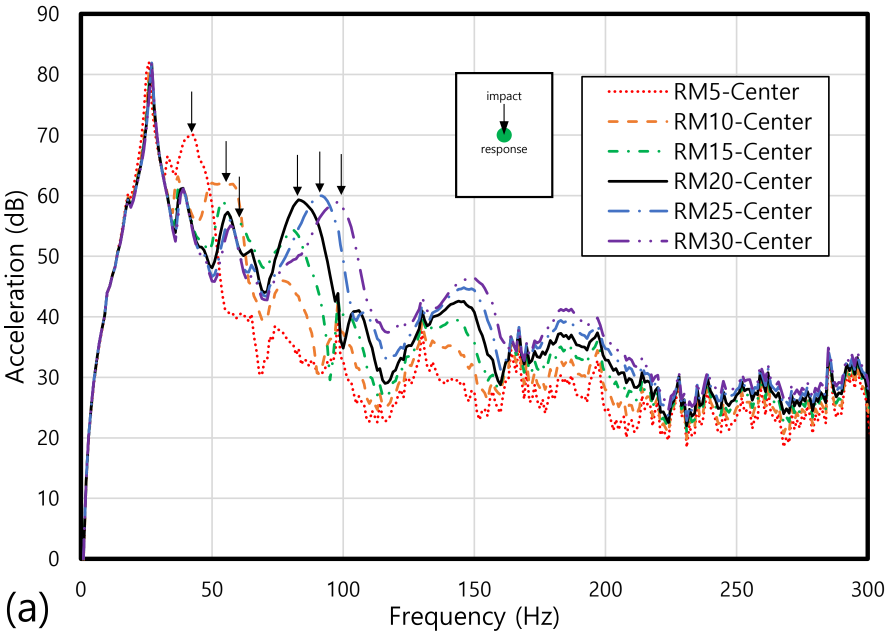
Table 4-7 shows the modal analysis result for each floating floor system. As expected, frequency of each mode increases as the stiffness of the resilient material increases.

Table 4-7 Modal analysis results of each FE model

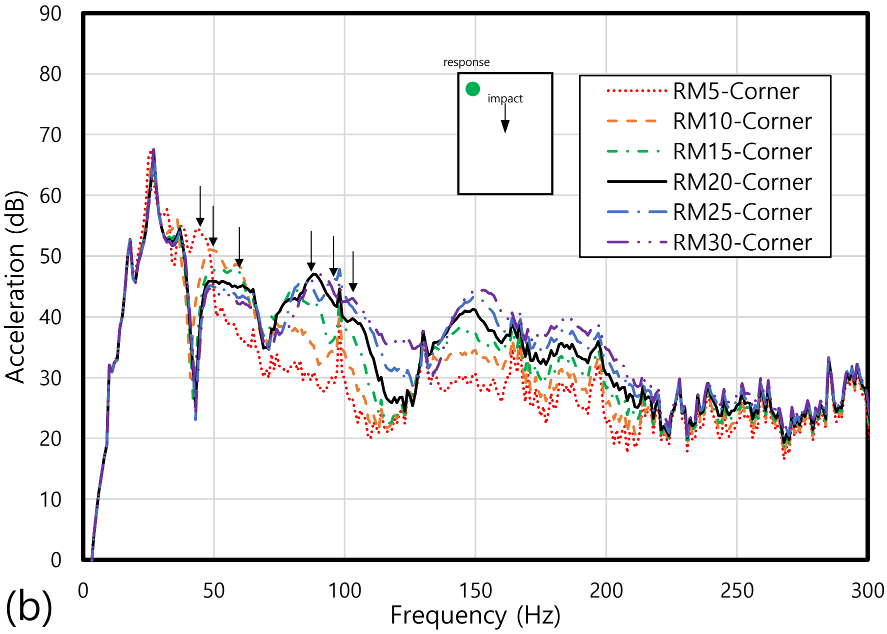
Frequency	Floating floor					
	RM5	RM10	RM15	RM20	RM25	RM30
1st mode	25.6	26.4	26.7	26.8	26.9	27.0
2nd mode	32.7	36.2	37.1	37.4	37.6	37.7
3rd mode	35.4	42.4	44.6	45.3	45.6	45.7

4.4.2 Slab vibration

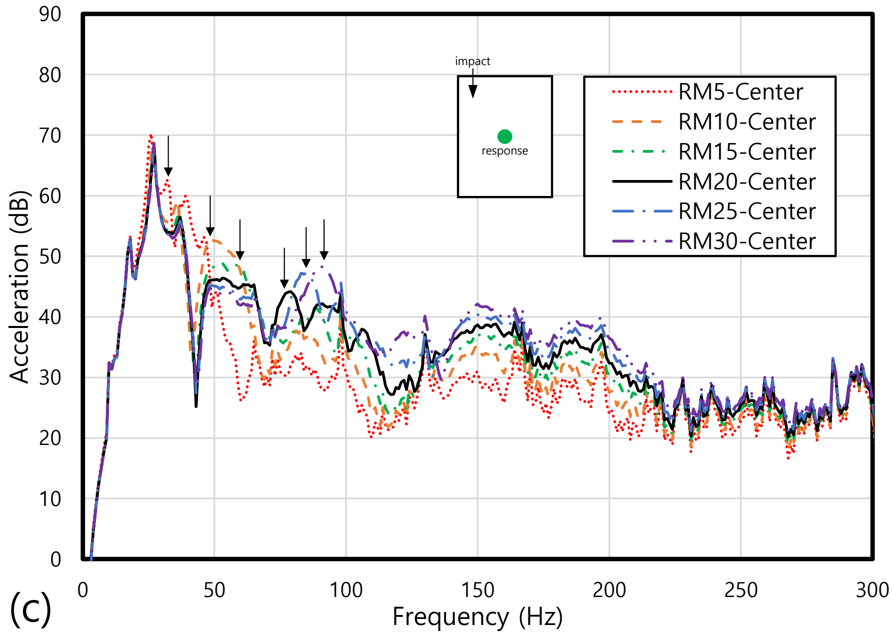
Figure 4-15 shows the slab vibration for each floating floor system, RM5 ~ RM30. As analyzed in chapter 3.5, resonance frequencies are determined by the dynamic stiffness of the resilient material. Lower dynamic stiffness results in lower resonance frequency. For example, RM5 shows amplified response around 40Hz, while RM 30 shows amplified response around 100Hz. Also, considering transmissibility function, early amplification cause early reduced response. Thus, lower dynamic stiffness shows more reduced slab vibration at high frequencies.


90
80
70
60
50
40
30
20
10
0
Acceleration (dB)
0
50
100
150
200
250
300
Frequency (Hz)
impact
response
RM5-Center
RM10-Center
RM15-Center
RM20-Center
RM25-Center
RM30-Center

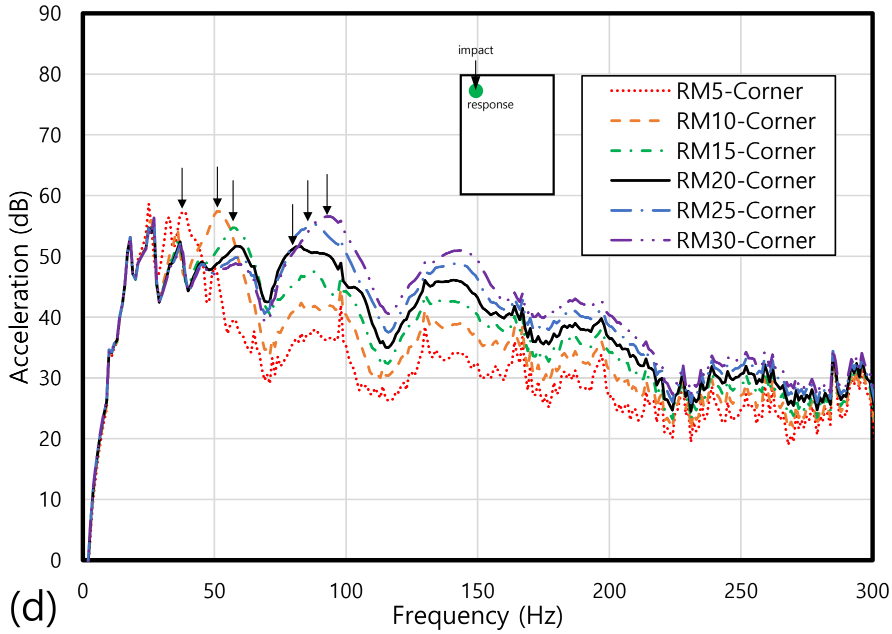
(a)


90
80
70
60
50
40
30
20
10
0
Acceleration (dB)
0
50
100
150
200
250
300
Frequency (Hz)
response
impact
RM5-Corner
RM10-Corner
RM15-Corner
RM20-Corner
RM25-Corner
RM30-Corner

(b)



(c)



(d)

Figure 4-15 Slab vibration responses of FE models

4.4.3 Sound pressure level

Based on the analysis result of slab acceleration, average sound pressure level ($L_{i,Fmax}$) of the receiving room (living room) is calculated. Table 4-8 shows reduction level of each model compared to the RM20 model ($L_{i,Fmax}$(RMi) – $L_{i,Fmax}$(RM20), i=5,10,15,20,25,30). Similar to the acceleration response, the numerical model of lower dynamic stiffness shows amplified sound pressure level at lower frequency range, while effectively reducing sound pressure level at higher frequency range. On the other hand, models with higher dynamic stiffness than RM20 shows reduced floor impact noise at lower frequency range, while amplifying the floor impact noise at higher frequencies. Figure 4-16 shows the tendency more clearly. RM5, RM10, and RM15 which has lower dynamic stiffness of resilient matrial show amplified sound pressure level under 40Hz comparing to the RM20 model, and show reduced sound pressure level over 80Hz comparing to the RM20 model. In case of RM25, and RM30 which has higher dynamic stiffness of resilient material than RM20 shows the opposite result.

Generally, lower dynamic stiffness of resilient material shows reduced single number quantity ($L_{i,Fmax,AW}$). This means low dynamic stiffness is advantageous in floor impact noise because the reduced frequency range increases as the dynamic stiffness decreases in transmissibility function.

Table 4-8 Sound pressure reduction level at each 1/3 octaveband center frequency ($L_{i,Fmax}$(RMi) – $L_{i,Fmax}$(RM20), i=5, 10, 15, 20, 25, 30)

1/3 Octaveband	RM5	RM10	RM15	RM20	RM25	RM30
16	1.40	0.42	0.13	-	-0.08	-0.13
20	2.16	0.60	0.19	-	-0.11	-0.19
25	2.76	0.41	0.02	-	0.00	-0.01
31.5	5.23	3.76	0.94	-	-0.42	-0.64
40	3.12	2.43	0.60	-	-0.26	-0.40
50	-2.63	1.97	0.04	-	-0.14	-0.28
63	-7.69	0.33	1.57	-	-1.51	-2.41
80	-13.07	-7.02	-2.74	-	1.65	1.44
100	-13.07	-7.32	-3.02	-	2.36	4.38
125	-10.77	-6.52	-2.98	-	2.63	4.87
160	-11.04	-6.51	-2.95	-	2.48	4.62
200	-4.86	-3.28	-1.64	-	1.62	3.21
250	-2.05	-1.38	-0.69	-	0.69	1.38
315	-1.12	-0.75	-0.38	-	0.38	0.77
400	-0.27	-0.18	-0.09	-	0.09	0.19
500	-0.07	-0.05	-0.02	-	0.02	0.05
SNQ reduction	**3**	**0**	**1**	**0**	**-1**	**-1**

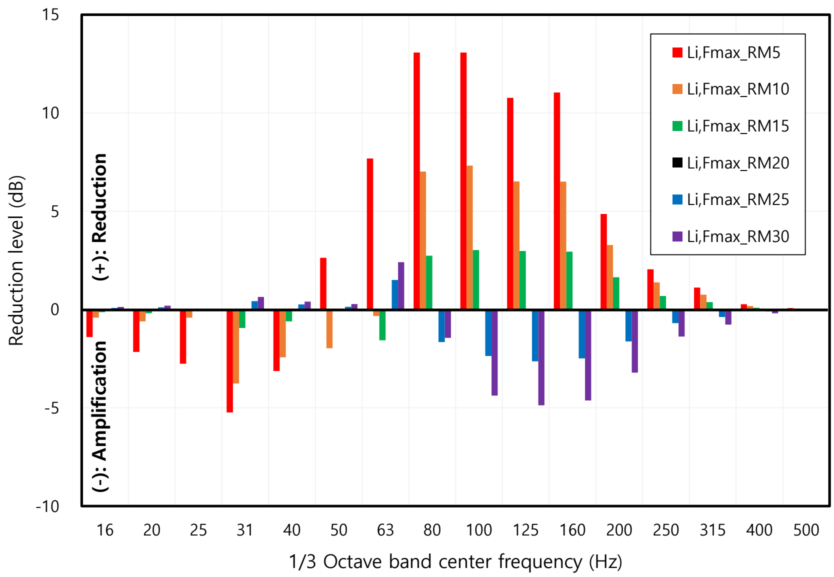


Figure 4-16 Sound pressure reduction level at each 1/3 octaveband center frequency

The analysis result is analogous to the previous research [13] performed laboratory test with different resilient materials. Figure 4-17 shows the test result. At 25Hz, and 40Hz amplification occur for most of resilient materials except very high dynamic stiffness. Between 63Hz and 315Hz, the relation between dynamic stiffness and sound reduction level is clear for both numerical and experimental results. Over 315Hz, the difference of sound pressure level for different resilient material is small. The previous laboratory test results cannot be directly compared to the numerical analysis data because the performance of the field test data is different from that measured by laboratory test. However, it is possible to explain the phenomenon observed in laboratory test or field test using the numerical analysis result.

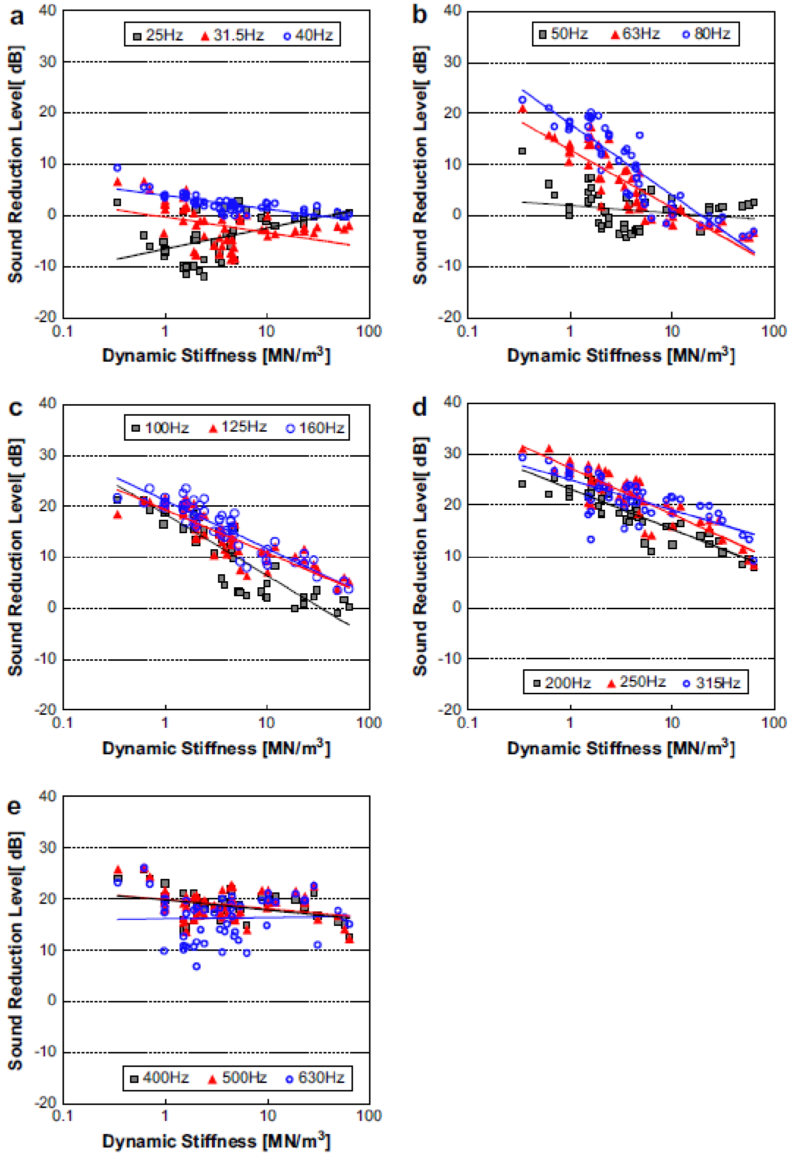


Figure 4-17 Correlation expression involving the dynamic stiffness and heavyweight impact sound reduction level(1/3 Octave band): (a) 25-40Hz; (b) 50-80Hz; (c) 100-160Hz; (d) 200-315Hz; (e)400-630Hz (Kim et al. [13])

Amplified or reduced response at a certain frequency is determined by the resonance frequency of the transmissibility function of the floating floor system. As studied in chapter 3, the resonance frequency cannot be simply determined by the material property of the resilient material. The resonance frequency is determined by not only resilient material but also by motar plate (including ALC). Consequently, the performance of the floating floor system cannot be controlled by the resilient material only, because dynamic properties of the mortar plate varies depending on the room dimension resulting in different performance for different size of the apartment building.

4.5 Conclusion

In this chapter, FE modeling method of floating floor system is proposed to simulate heavy impact noise in residential buildings. Concrete structures including concrete slab, concrete wall and concrete brick wall are included in numerical model while neglecting dry walls. Modeling of flooring system is composed of concrete slab, resilient material, ALC, and mortar plate. It is assumed that nodes at the interface between different materials are tied and there is no separation between different layers. As studied in chapter 3.5, the contact condition rarely affects floor vibration, the numerical modeling assuming perfect bond condition gave reasonable results.

The FE analysis result is compared to field measured data for both slab acceleration of the slab and sound pressure level at the living room. The results have shown that FE model predicted both slab vibration and sound pressure level well until 100Hz. However, as frequency increases the FE model considerably underestimated both slab vibration and sound pressure level for two reasons. Later, it has been found to be the influence of background noise and element size. In FE analysis, background noise doesn’t exist, while there are background noise in real situation to some extent. In field test data, it has been shown that the background noise over 230Hz governs the response of slab vibration and sound pressure level. Therefore, the background noise should be included in numerical modeling to get an accurate result. In chapter 4.3, the FE analysis result including background noise showed that the accuracy of the FE model has been improved. However, FE model still slightly underestimated the floor impact noise and the model should be improved to solve the problem.

Based on the analysis result, the effect of resilient materials with different dynamic stiffness to the floor impact noise has been verified. It has been found that as with previous studies, the performance of floor impact noise tends to be improved as dynamic stiffness of resilient material is decreased. Although the FE model couldn't predict exact level of floor impact noise, it presented the influence of resilient material on heavy impact noise as in previous studies.

Chapter 5. Concluding Remarks

5.1 Summary

To predict heavy impact noise of floating floor system numerically, several kinds of field experiments were preceded. Field experiment result provided the basis for numerical modeling. The numerical model of floating floor system showed reasonable prediction results.

In chapter 3, four factors expected to affect heavy impact noise level were studied experimentally. To evaluate the effect of each factor to heavy impact noise, corresponding field tests were performed. Comprehensive field test data provided here would be helpful for understanding the charateristics of floor impact noise in residential buildings. The effect of each building components are summarized below.

- Room dimension: Room dimension affect heavy impact noise level under 80Hz for small or medium sized apartments

- Structural system: Flatplate structure could amplify heavy impact noise level due to the larger vibration at the corner of the slab than wall type structure.

- Non-structural walls: The effect of non-structural walls including dry walls and masonry walls can be neglected in numerical modeling

- Floating floor system: Force spectrum transmitted to concrete slab is derived from experimental data. It has been shown that the characteristics of floating floor system is determined not only by the resilient material but also by the properties of mortar plate including ALC.

In chapter 4, based on the analysis results in chapter 3, a numerical modeling method of floating floor system has been proposed. The numerical analysis result was compared to the field test data. Both slab vibration level, and sound pressure level reasonably predicted field test data. Especially, it is meaningful that the numerical model can express amplified responses of floating floor system around 50Hz-100Hz. The accuracy of the numerical model was increased when background noise is considered. In numerical modeling of floating floor system, background noise should be considered for two reasons. First, element size applied in this modeling was 150mm, and the element cannot represent responses over 380Hz, resulting in reduced responses. Second, due to the transmitted force spectrum, as analyzed in chapter 3.5, slab vibration level of high frequency range become very small. In numerical modeling, small responses of high frequency range can be chaptured, while in field test condition, the response is buried by background noise. In other words, it can be interpreted that there is almost no high frequency component in the floor impact noise of floating floor system. Sound pressure level of high frequency component is governed by background noise at the site.

5.2 Discussion

Experimental results covered in this thesis can provide basis for residential building design considering floor impact noise. According to a room dimension of an apartment, heavy impact noise under 80Hz can be controlled. It is expected that designers or engineers can determine which plan or structure system is better for floor impact noise. Based on experimental results of this thesis, it is difficult to expect a fundamental change in heavy impact noise of floating floor system. However, the response of the floating floor system is not often analyzed through field measurement data so far. Thus it is meaningful that the basis understanding characteristics of floor impact noise based on field measurement data is presented.

This paper also suggested numerical model of floating floor system which has not been studied yet. The numerical analysis result of floating floor system explained the vibrational characteristics of floating floor system which has been observed by various studies so far. However, the accuracy of the numerical model is still a problem to be solved. Small differences in sound pressure level at a certain frequency can cause large difference when the narrow band response is converted to the octave band level. Also, the model must be supplemented through field experiments because numerical analysis necessarily involves many assumptions. There are still many factors not covered in this paper. The accuracy of the numerical analysis should be improved through continuous field experiments and data accumulation.

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초 록

공동주택 건물 구성요소 별 중량충격음에 미치는 영향

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주로 거주자의 걸음에 의해 발생하는 중량충격음은 여전히 우리나라 공동주택에서 발생하고 있는 사회적 문제이다. 중량충격음은 약 250Hz 이하의 저주파 대역으로 이루어진 소음으로 경량충격음과는 달리 뜬 바닥 구조에서 소음 저감 효과가 크지 않은 것으로 나타났다. 이러한 문제를 해결하기 위해 다양한 종류의 완충재가 개발 및 시험되고 있지만 저주파 대역의 소음이 저감되지 않는 문제는 여전히 해결되지 않고 있다.

동일한 완충재를 사용했음에도 바닥충격음 저감 성능이 평면 구성에 따라 다르게 나타나는 등 실제 거주 환경에서 중량충격음에 영향을 미치는 변수는 매우 다양하다. 중량충격음을 결정하는 다양한 변수들의 영향을 실험을 통해서 확인하는 데에는 시간 및 비용 측면에서 한계가 있다. 수치해석을 통해 중량충격음을 유사하게 예측할 수 있다면, 중량충격음 문제를 더욱 효과적으로 접근할 수 있을 것으로 기대된다.

초 록

기존 많은 연구자에 의해 바닥 완충재 및 바닥 마감재가 포함되지 않은 맨바닥 구조의 수치해석 모델링에 대한 방법이 연구되었다. 반면, 완충재와 마감재가 포함된 뜬 바닥 구조의 수치해석 모델에 대한 연구는 거의 이루어지지 않았다. 뜬 바닥 구조의 중량충격음 성능을 수치해석을 통해 검증할 수 없으므로, 실제 거주 환경에서의 중량충격음 성능을 예측하지 못한다.

따라서 본 연구에서는 뜬 바닥 구조의 바닥충격음 예측 기법을 제안하는 것에 초점을 두었다. 뜬바닥 구조의 수치 해석 모델 개발을 위하여 중량충격음에 영향을 미칠 것으로 예상되는 4가지 변수(수음실의 평면 구성, 구조 시스템, 비구조 벽체, 뜬 바닥 구조)를 현장 실험 결과를 바탕으로 분석하였다. 결론적으로 본 연구에서 제안된 뜬 바닥 구조 수치해석 모델의 중량충격음 해석 결과는 현장 측정 결과와 비교적 잘 일치하는 것으로 나타났다.

본 연구는 뜬바닥 구조의 바닥충격음을 예측 할 수 있는 수치해석 모델링 방법을 제안함으로써 설계 단계에서 미리 바닥충격음을 평가하고 최적 평면 설계를 할 수 있는 근거를 제공할 수 있을 것으로 기대된다.

주요어 : 뜬바닥구조, 완충재, 바닥충격음, 유한요소해석

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