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Article

Implementation of the floor impact noise monitoring system to the existing apartment buildings

Chan-Hoon Haan

Department of Architectural Engineering, Chungbuk National University, Cheongju 28644, Korea; chhaan@cbnu.ac.kr

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Abstract: Floor impact noise has been the prior social issue nowadays since most people are living in apartment buildings in Korea. Even though much research has been undertaken to reduce the floor impact noises architecturally and regulations were strengthened, the disputes concerning this matter have been increased. The present study is the first trial to solve this problem using ICT technologies called floor impact noise monitoring system. This system is to be operated all day long in the buildings monitoring real time all the noises for the reduction of the occurrence of floor impact noises. The system consists of sound and vibration sensors, a wireless communication gateway and the main server with analyzing software. In order to enhance the accuracy and durability of the system, the suitability tests for sensors were executed in an anechoic chamber using many current sound and vibration sensors, Also, the system was tested at the authority laboratory for the verification. The operating algorithm was first made satisfying with the current regulations in Korea, but it was modified several times with feedback procedures from the many tests. The systems were applied to the 300 dwelling units at three apartment complexes in Korea for three months. During the real-time implementations of the system, warning sound was rumbled to the dwelling units where excessive impact noise had occurred. Before and after the implementation, questionnaire surveys were undertaken to investigate the resident satisfaction measurement. As a result, it was found that the system can chase the floor impact noises well and localize the floor impact noise sources successfully. It was also revealed that the analyzed results of the system are in coincidence with the measured levels. Also, it was shown that excessive noise occurrence was reduced by 14% compared with the initial state. And residents replied that noise concerned stress was reduced by about 20% on average. Thus, it can be concluded that reliability of the floor impact noise monitoring system was verified, and the standard specification of the system was fixed for the system commercialization in future.

Keywords: Floor impact noise monitoring system; System algorithm; Sound & vibration sensor; Test-bed apartment; Sound source localization

1. Introduction

Korea has a high density of population, considering the size of the territory. Thus, high-rise residential buildings have been built during the last two decades in Korea. More than 75% of people are living in apartments. In addition, because of the improvement of the standard of living along with continuous national economic growth, the interest in well-being and the expectation of quiet life for comfortable and pleasant residential environment have also been increasing. Since Korean has the lifestyle of sitting on the floor with floor radiation heating system, floor impact sound has been occurring more and more frequently [1]. Eventually, unneighborly disputes have been a serious social problem. Even though the regulation and standards for floor impact noise have been strengthened, damage and disputes result from the noise between floors have been much more increasing [2]. Thus, it is obvious that existing noise management technologies are not very effective including thick concrete slab, multi-layer sound isolation materials, sound insulation filling in the air cavity [3].

So, it is required to prevent social conflict using some ICT facilities in living environment. The purpose of the present work is to reduce the number of disputes and to give secure aural environment in the multi-dwelling apartments. The present work was the first trial supported by the Korean government to reduce the dispute caused by floor impact noises using ICT facilities called floor impact noise monitoring system. This system can be applied to both new and existing apartment buildings. Especially for existing buildings, noise control and improvement can be acquired without any architectural remodeling works which result in great amount of financial expense [4].

2. System algorithm

The system consists of sound and vibration sensors, wireless communication gateway and the main server with analysis software. At least, one outlet which contains both a sound microphone and a vibration meter was installed on the ceiling of the living room.

The operation procedure of the monitoring system is displayed in **Figure 1**. When impact noises occur, the sensors catch the signals and transmit the signals to the server through the home gateway. Then, the server will analyze the signal and if the measured sound levels exceed the standard, it delivers alarm to the dwelling unit where impact noise was originally made.

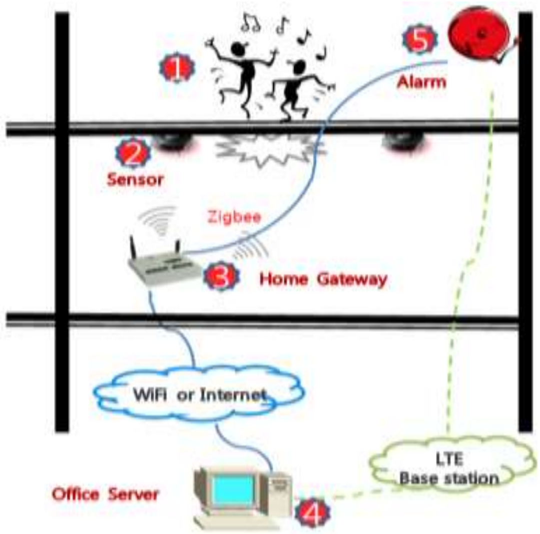


Figure 1. Operation procedure of the system.

The most important features of the current system are to correct measure of the noise levels and to localize the exact location of floor impact noise occurrence. Also, separation of the floor impact noise from general interior noises is absolutely required. In order to satisfy these conditions, both sound and vibration sensors are needed to compare the measured data which can eventually localize the source location and differentiate the floor impact noise. Sound sensor is used for measurement of the floor impact noise while vibration sensor acts as a trigger to chase the floor impact noise and source location. In this case, a one-axis vibration sensor is enough to do these works since vibrating energy moving top and bottom is the object to measure.

The most floor impact noises occur at the low frequency range less than 125 Hz. So, frequency analysis of vibration sensor is required to measure the noise at 63 Hz and 125 Hz. Floor impact noises are intermittent and irregular noises. In this sense, LAeq is not good measure to evaluate floor impact noises. So, LAmax and LA_{10} are more suitable to detect floor impact noises.

The basic algorithm of the system was made following the regulation of the impact noise standards of Korea (43 dB during daytime). The sound and vibration levels are measured continuously with every 125 ms intervals. Two noise level parameters i.e., LAeq & LAmax, are recorded with every 60 seconds via A-filter while maximum vibration levels, VAL'max, are also recorded with every 60 seconds at frequencies from 20 Hz to 500 Hz. The reference limits applied to the first algorithm are displayed in **Table 1**. When three measures including LAeq, LAmax, VAL'max are exceeding reference limit, alarm shall be transferred to the dwelling unit where floor impact noises have occurred [5].

Table 1. Reference limits used for basic and modified algorithm of the system.

	Basic algorithm	**Modified algorithm**	
		source room	**receiving room**
LA_{eq}	≥ 43 dB (day)/38 dB (night)	≥ 53 dB	> 48 dB
LA_{max}	≥ 57 dB (day)/52 dB (night)	≥ 57 dB	stored
VAL'_{max}	≥ Linit 45 dB	-	-
VAL_{eq}	-	≥ 45 dB	≥ 48 dB
remark	more than 3 times occur per 1 hour		

The basic algorithm of the system has been modified several times with feedback procedures from the many tests. The major difference between the basic and modified algorithm is the application of reference limits to both sound source and receiving room respectively. Also, VALeq was used for modified algorithm instead of VAL'max. In modified algorithm, measured noise and vibration levels exceed both limits of source and receiving rooms, alarm is delivered to the source room location [5]. **Figures 2** and **3** show the basic and modified algorithm of the system.

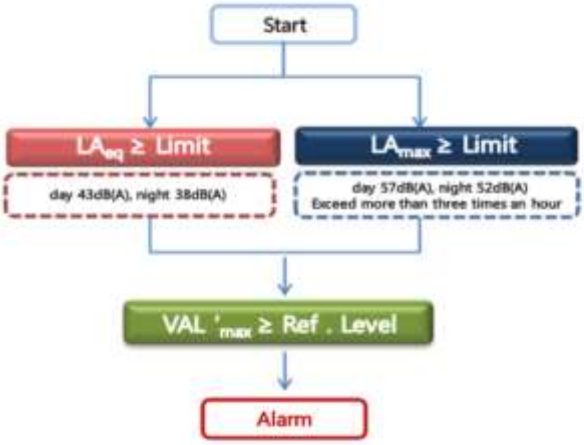


Figure 2. Basic algorithm of the system.

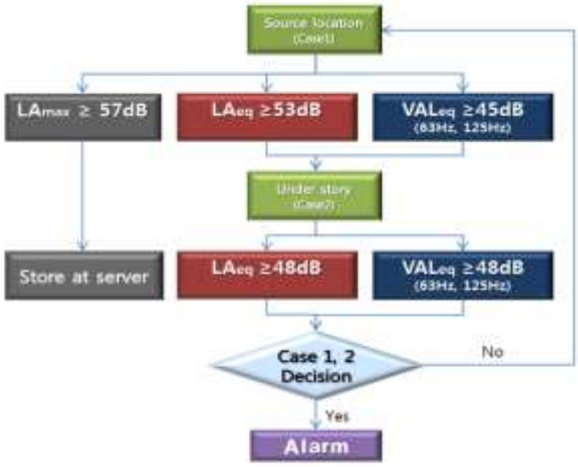


Figure 3. Modified algorithm of the system.

Figure 4 shows the sound and vibration signal path from the sensors to communication device. **Figure 5** shows the system configuration of a building with an example of the system outputs including date, time, measured sound and vibration level (LAeq, Lamax, VALeq) and the location.

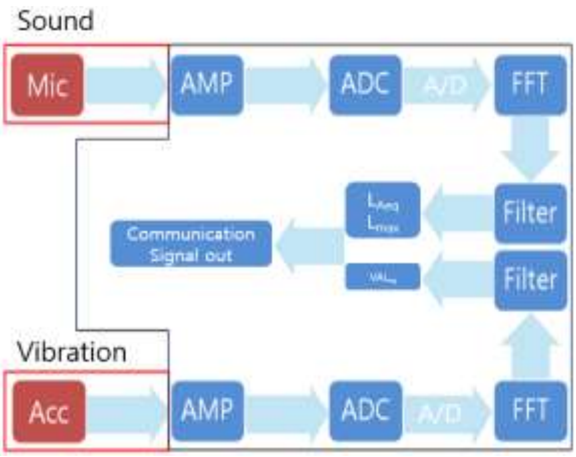


Figure 4. Sound and vibration signal manipulation chart.

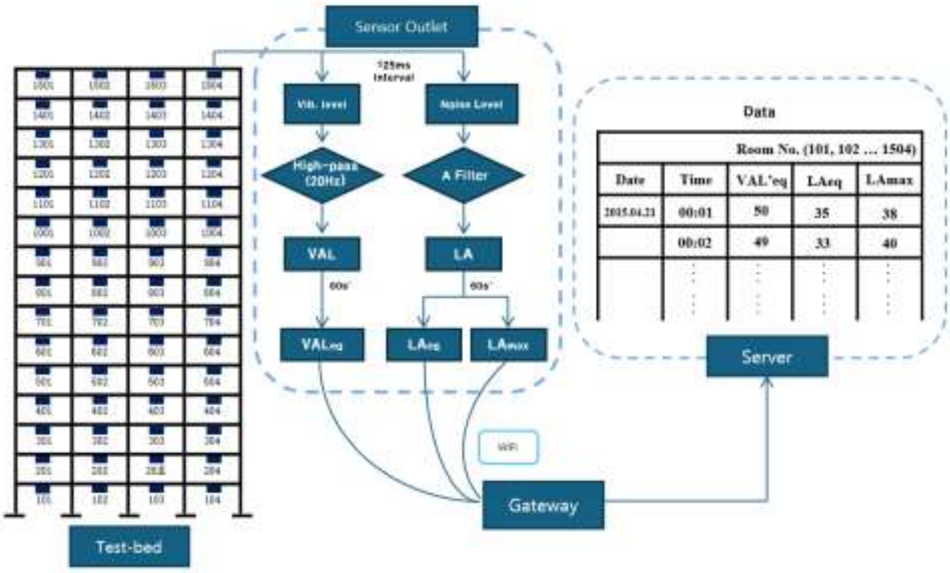


Figure 5. Example of system configuration in an apartment building.

3. System configuration

3.1. Suitability tests of current using sensors

The suitability tests for sensors were carried out using various current using sound and vibration sensors which can be eventually compatible with the floor impact noise monitoring system. For measurements of sound sensors, 7 sound microphones were used including 2 condenser types, 4 dynamic types and 1 electro condenser type. Also, 6 vibration meters were used including 2 MEMS types, 2 Piezo types and 2 spring types (refer to **Table 2**). Sound levels were measured in a semi-anechoic chamber with an average reverberation time of 0.1 s. The directional speaker and sensor were placed at a height of 1.5 m. White noise of 100 dB(A) was repeated five times for 10 seconds at a distance away from 1 m. SPL value was measured with a frequency range from 63 to 12.5k Hz at 1/3 octave bands (refer to **Table 3**).

A vibration sensor was attached to the corner of high-density wood plywood and was tested with a circle with an impact ball. Three repetitive free drops were made at a height of 1 m from the plywood center point. The vibration acceleration level (VAL) was measured with a frequency range from 16 to 4k Hz at 1/3 octave bands. Performance tests were conducted with the reference sensor S.1 for sound sensor and V.1 for vibration sensor. Round-robin tests were done to confirm the exact performances of all the sensors under the same condition.

As shown in **Figure 6** it was found that dynamic type microphones (S4) show the most similar frequency response sound level characterization in comparison with the reference condenser microphone especially in the air-borne sound frequency range from 250 Hz to 2K Hz. Regarding vibration sensor, it was found that spring-type (V4) vibration meter shows the most similar characteristics of vibration acceleration level (VAL) at 63 Hz, most critical structure-borne sound frequency. Thus, the results drawn from the round-robin tests were used for floor impact noise monitoring systems with the benefit of both economy and performance [6].

Table 2. Types of sensors tested for system.

Sound sensors							
Number	S1	S2	S3	S4	S5	S6	S7
Type	Condenser	Condenser	Dynamic	Dynamic	Dynamic	Dynamic	Electric condenser
Vibration sensors							
Number	V1	V2	V23	V4	V5	V6	
Type	MEMS	Piezo	Spring	Spring	MEMS	Piezo	

Table 3. Test information for sound and vibration sensors.

Sound sensors						
Location	Source	Output level	Distance	Time	Repetition	Frequency
Semi-anechoic room (RT = 0.1 s)	White noise	100 dB (A)	1 m	10 s	5 times	63 Hz–12.5k Hz
Vibration sensors						
Floor	Source	Position of sensor	Drop point	Drop height	Repetition	Frequency
High-density plywood (1000 × 900 × 30)	Impact ball	Corner	Center	1 m	3 times	16 Hz–4000 Hz

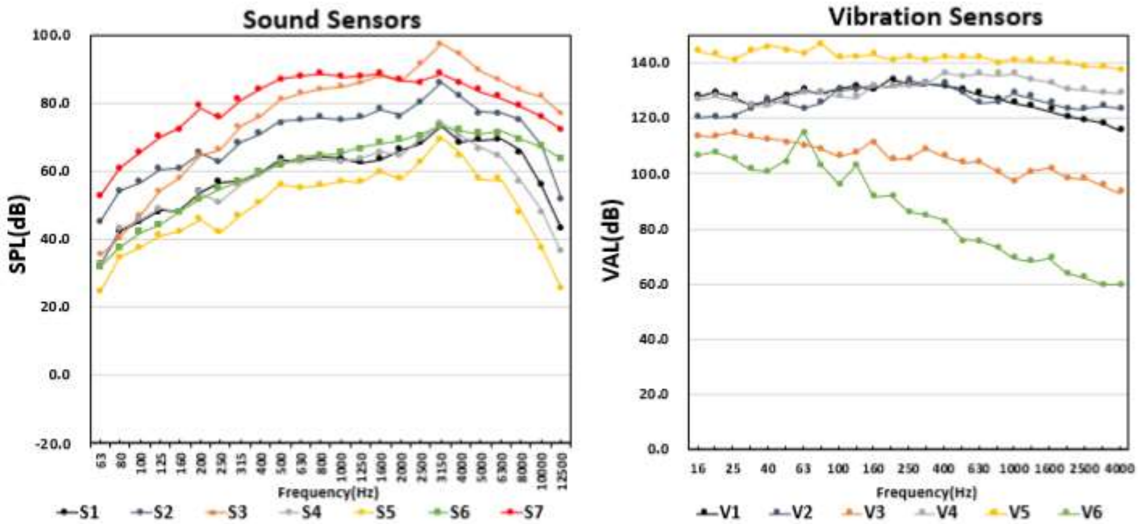


Figure 6. Measured sound level of sound and vibration sensors tested.

3.2. Performance standard of terminal unit

The performance of the terminal unit containing S4 and V4 sensors was tested in a laboratory. Standard specifications for sound and vibration sensors are listed in **Table 4** with frequency and error ranges. All the test results were analyzed, and the significance level of *T*-test was more than 0.05 in comparison with the measured level of the precise sensors in laboratory. The input power source was applied by electric supply port and linked to the terminal unit. The measured data are directly connected with the computer server via gateway.

Table 4. Standard specifications of terminal unit for sound and vibration sensors.

Feature	**Frequency range**	**Error range**	**Remark**
Sound	63 Hz–500 Hz	within ± 2 dB	*T*-test, $p \geq 0.05$
Vibration	63 Hz–500 Hz	within ± 3 dB	

Concerning gateway, Ethernet interface standard is more than 1 port concerning IEEE 802.3 10/100Mbps, RJ-45. **Table 5** shows the function and detail performance standard of gateway of the system.

Table 5. The function and performance standard of gateway.

Item	Specification
Transmission output level	Maximum 10 dBm
Data rate	More than 45 kbps
Antenna	More than 5 dBi

Concerning the linearity of vibration level, another test was done at mock-up rooms with 210 mm concrete slab using standard floor impact sound sources including bang-machine and rubber ball. A vibration sensor was installed at the ceiling center of the receiving room, and excitations were executed more than 8 times at the floor center of source room. Vibration levels at overall frequency ranges were measured, and acceleration levels (VALFmax) were analyzed at intervals of 125ms. In comparison with the measured level by precision vibration meter, statistically regardful correlation was obtained with correlation coefficient < 0.05. Also, maximum sound levels (SPLFmax) were measured at the center of the receiving room at intervals of 125ms. In comparison with the measured sound level by precision sound level meter, statistically regardful correlation was obtained with correlation coefficient < 0.05.

3.3. Calibration and correction of the terminal unit

Correction of the sensibility of sensors were undertaken using prototype terminal unit with standard calibrators. The gain of sound sensor was adjusted as 94 dB of sound level at 1k Hz in the prototype terminal unit when sound calibrator was operated. Also, the gain of vibration sensor was adjusted as 120 dB of vibration acceleration level at 159.15 Hz in the prototype terminal unit when vibration calibrator was operated [7].

Prevent malfunction caused by background vibration was tested in the Korean standard laboratory authority. The prototype terminal unit was installed on the center of ceiling at downstair room without any excitation of floor impact sound for more than 5 minutes. It was recorded that no regardful changes were found measuring the background vibration level.

4. Implementation of the system

The systems were applied to the 300 dwelling units at three apartment complexes in Korea for three months. First, current floor impact noises of the three Test-bed apartments were measured following ISO standard using standard noise sources (KS F 2863-1 & KS F 2863-2) [8,9]. The floor impact noise insulation performances were evaluated following the Korean standard regulations as listed in **Table 6**.

Table 6. Floor impact noise criteria and grades in Korea [10].

a) Standard for light-weight impact noise.		b) Standard for heavy-weight impact noise.	
Grade	**Grade Criteria (dB)**	**Grade**	**Grade Criteria (dB)**
1st	$L'_{n,AW} \leq 43$	1st	$L'_{i,Fmax,AW} \leq 40$
2nd	$43 < L'_{n,AW} \leq 48$	2nd	$40 \leq L'_{i,Fmax,AW} \leq 43$
3rd	$48 < L'_{n,AW} \leq 53$	3rd	$43 \leq L'_{i,Fmax,AW} \leq 47$
4th	$53 < L'_{n,AW} \leq 58$	4th	$47 \leq L'_{i,Fmax,AW} \leq 50$

Before the implementation, a series of several experiments were undertaken to investigate the performance verification including laboratory test for sensors, mock-up test for system operation and field test for system performance evaluation. The operating algorithm was made satisfying with the current regulations in Korea. During the real-time implementations of the system, warning sound was rumbled to the dwelling units where excessive impact noise had occurred. After the implementation, a questionnaire survey was executed to investigate the resident satisfaction measurement.

A terminal unit was installed at the ceiling center of every living room. A vibration sensor was attached to the ceiling surface and a microphone was installed in the terminal unit where it gets sound signal through many openings of the case of the terminal unit. Since a terminal unit is installed at every dwelling household, lots of sensors (microphone & vibration meter) measure the all the occurred noises in the building. **Figure 7** display the system diagram of the floor impact noise monitoring system installed at the test-bed apartments. Measured noise and vibration data were transferred to the application processors via wireless LAN which is located on every floor of the apartment building. Then the data were sent to the main computer server via internet LAN.

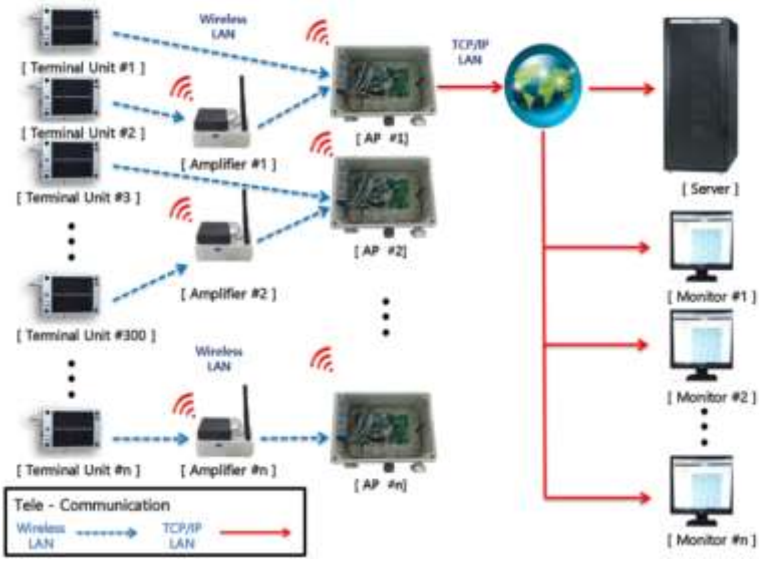


Figure 7. Diagram of the installed floor impact noise monitoring system.

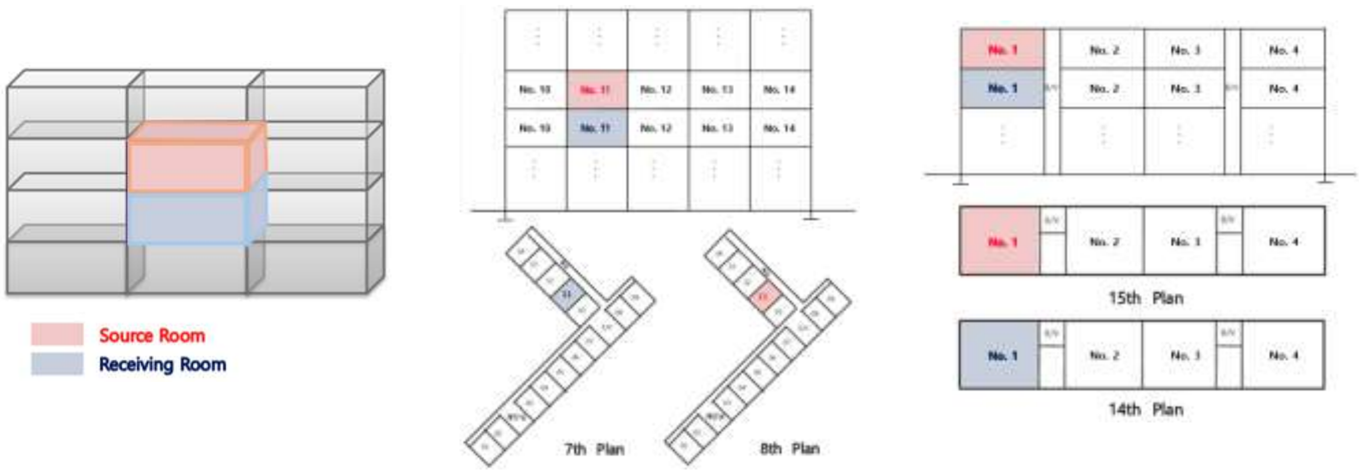
A total of 300 dwelling units were selected for the test-bed operation with 100 units at each three-apartment building (refer to **Table 7**). Among the 3 test-beds, S &

O apartments were built before 2004 with only 150 mm thickness of concrete slab while test-bed C is a university dormitory built in 2012 with 180 mm thickness of concrete slab. Plan and section of each test-bed apartments are displayed in **Figure 8** with the location of source and receiving rooms.

Table 7. Test-bed apartment information.

Test-Bed APT.	Name	No. of Units	Construction year
Test-bed A	S APT	100	1996.4
Test-bed B	O APT	100	2000.4
Test-bed C	U Dormitory	100	2012.9

Standard floor impact sound sources were used to measure both lightweight and heavy-weight floor impact noises including tapping and bang machine respectively. Background noise levels were measured, and the reverberation time was measured for the calculation of average sound absorption in rooms (refer to **Figure 9**). Floor impact noise levels were measured at the frequency range from 31.5 Hz to 4K Hz with 1/3 Octave bands. The measured level of each test-bed is listed in **Table 8**. As shown in **Table 8**, the floor impact noise insulation performance is getting better in accordance with the year of completion. It is revealed that both light and heavy-weight floor impact noise insulations of test-bed A are out of grades. It may be because of the aging effect of building and thin concrete slabs.



(a) Test-bed A. **(b)** Test-bed B. **(c)** Test-bed C (university dormitory).

Figure 8. Plan & section of each test-bed apartments.

(a) Microphones at receiving room **(b)** Source room excitation **(c)** Measuring RT

Figure 9. Floor impact noise measurements.

Table 8. The measured floor impact noise insulation performances of the three test-bed apartments.

Floor impact noise	Test-bed A		Test-bed B		Test-bed C	
	Noise level	**Grade**	**Noise level**	**Grade**	**Noise level**	**Grade**
Lightweight ($L'_{n,AW}$)	60dB	Below Grade	56dB	4	56dB	4
Heavy weight ($L_{i,Fmax,AW}$)	51dB	Below Grade	50dB	4	46dB	3

5. Results

5.1. Test results

Measured records of the test-bed apartment using the system were compared with the measured data of other residence in Seoul using precision devices. **Figure 10** shows the measured records of sound levels of two existent apartments in Seoul and the test-bed apartment in Ulsan using system devices during the same time. It shows that the noise patterns are similar with time. This means that the measurement devices used in the system is reliably working.

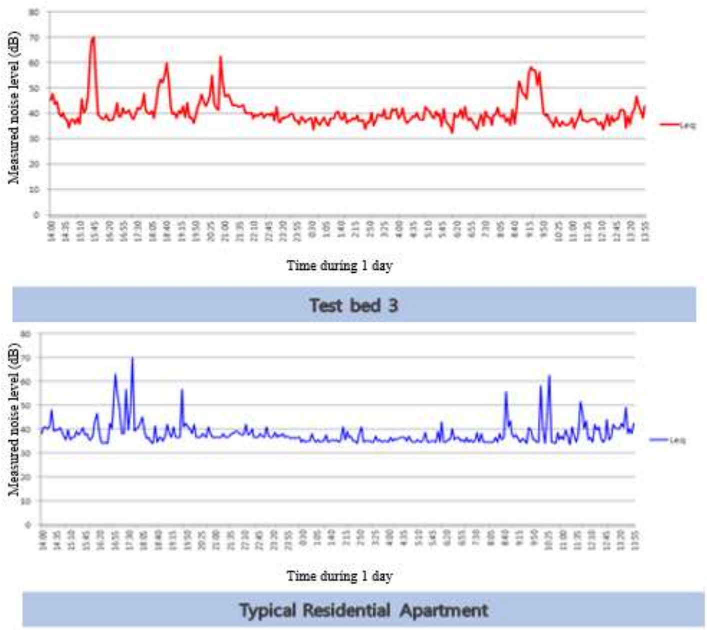


Figure 10. Comparison of the measured noise level in the test-bed apartment with the noise level measured in the apartment in Seoul for 1 day period.

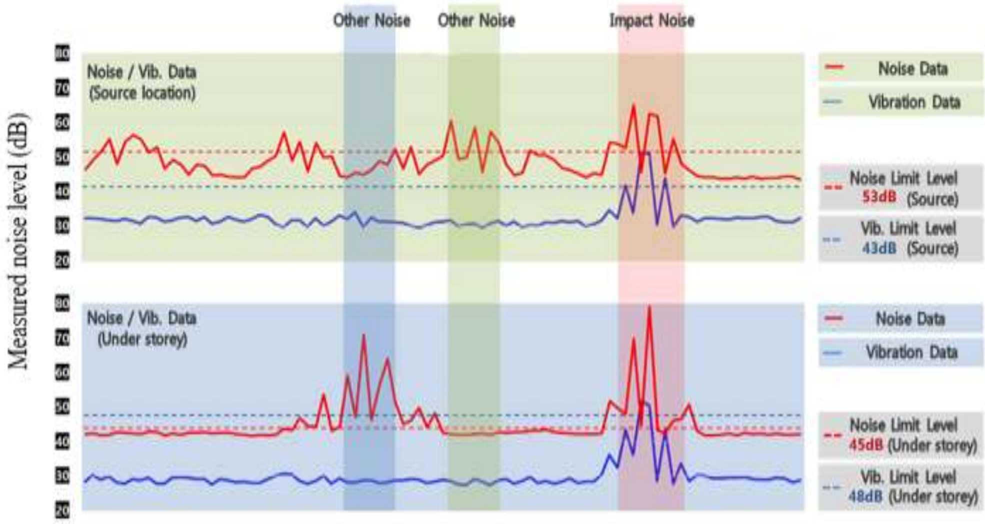


Figure 11. Example of the stored noise & vibration data including both impact noises and other general interior noises.

Figure 11 shows an example of the stored noise & vibration data including both floor impact and other noises in a vertically connected unit. There are two conditions to determine the occurrence of floor impact noises, only when noise and vibration levels exceed the reference level in the two units at the same time, the system decide that the floor impact noise occurs and recorded the data in the computer sever. The limit level of noise in source room is 53 dB and 43 dB for vibration level while the limit level of noise in receiving room is 45 dB and 48 dB for vibration. The vibration level of the under story is larger than the vibration level of upper story since the vibration meter is installed on the ceiling of room at under story. When other noises have occurred, the noise and vibration level do not make peak contour at the same time as shown in **Figure 11**. Also, floor impact noise can be distinguished using frequency analysis. With the satisfaction of two conditions written above, sound peaks at the range from 63 Hz to 125 Hz are recognized as the floor impact noises.

As a result, it was found that the system is operated well in real time pursuantly with the algorithm and regulation. It was also revealed that the analyzed results of the system are in coincidence with the real measured levels.

5.2. Verification of the tests

Also, the system was tested to verify the function of noise source localization since apprehension of the exact noise source and the correct alarm delivery to the noise source place are most important matters. In order to verify the conformation of the correct alarm delivery to the noise source place, tests were done twice in the Test-bed C using reference noise sources including tapping and bang machine and rubber ball [11]. At the 1st test, 12 rooms were randomly selected by an impactor. And the impactor recorded the time of impact and the room number. Also, the operator monitored the system and recorded the time of impact noise and the room number as well. However, among 12 trials, only 7 tests were in tune with noise sources and alarmed location at the 1st test. So, accuracy of correct localization was just 58.3%. **Table 9** shows the results of the 1st tests.

Table 9. 1st test result for system verification.

No.	Time	Source Room No.	Alarmed Room No.	Conformity
1	13:57	417	517	X
2	14:03	421	319	X
3	14:06	419	319	X
4	14:13	519	519	O
5	14:17	521	521	O
6	14:19	517	519	X
7	14:24	221	219	X
8	14:34	219	219	O
9	14:37	319	319	O
10	14:41	317	317	O
11	14:44	217	217	O
12	14:47	321	321	O

The 2nd Test was undertaken after modifying the source location tracing algorithm a few months later. At the 2nd test, 6 rooms were randomly selected by an impactor and the same procedures were executed as precisely as the 1st test. **Figure 12** shows the source room excitation using a rubber ball by the impactor. Totally 8 trials were done in 6 rooms and all the trials were in tune with noise source and alarmed location. This means 100% of, accuracy of correct localization. **Table 10** shows the results of the 2nd test for system verification.

Table 10. 2nd test result for system verification.

No.	Time	Source Room No.	Response Time	Conformity
1	14:54	519	1 min. 12 sec.	O
2	15:00	521	2 min. 7 sec.	O
3	15:04	523	2 min. 49 sec.	O
4	15:15	421	42 sec.	O
5	15:19	423	1 min. 12 sec.	O
6	15:29	419	1 min. 26 sec.	O
7	15:34	421	1 min. 55 sec.	O
8	15:44	521	33 sec.	O

Figure 12. Floor impact noise measurement using rubber ball.

5.3. Results of questionnaire survey

In parallel with implementation of the floor impact noise monitoring system, questionnaire surveys were undertaken two times before and after operating monitoring system to the residents of the test-bed apartments. 250 residents of total 300 test-bed units were responded to the survey.

As shown in **Figure 13**, regarding the frequency of the impact noise occurrence, residents replied that excessive noise occurrence was reduced by approximately 14% compared with the initial state. Only for the ratio of excessive noise occurrence, 45.1 % of improved effect was obtained. It was presumed that the monitoring system is efficient for residents themselves to realize the noise. Also, it was replied that noise concerned stress was reduced by approx. 19% on average. This denotes that residents seem like feel freer for being concerned about generating noises after operating the system. There was also some effect on the alarming number of occurrences. After operating the system, the number of warning signals are reduced by 9% less than the number at the pre-survey.

(a) Ratio of impact noise occurrence. **(b)** Stress of noise assailant. **(c)** Alarmed experience.

Figure 13. Comparison of responded results from questionnaire survey before and after system operation.

6. Conclusion and discussions

The present work carried out the floor impact noise monitoring system using ICT technology with sensor-based devices to the real residential apartments. Implementation of the floor impact noise monitoring system was undertaken to 300 dwelling units for three months.

Through the implementation of the system, it was found that the system can differentiate the floor impact noises among many other interior noises in buildings. Also, it can localize the floor impact noise sources successfully. Thus, it was found that the system is operated well in real time pursuant with the algorithm and regulation. Also, residents replied that excessive noise occurrence and noise concerned stress was reduced much in comparison with the previous stage before the implementation of the system. As a conclusion, reliability of the floor impact noise monitoring system was verified, and the standard specification of the system was fixed for the system commercialization in the future.

However, for the universality and expandability of the current system, implementation of the system should be expanded to a larger number of buildings considering different floor structures, building ages, and different living environments. Also, further analysis of the tenant satisfaction survey should be required, including different households and tenant group.

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Conflict of interest: The author declares no conflict of interest.

References

1. Korean Ministry of Environment. Annual Statistical Report of Environment. Korean Ministry of Environment; 2008.
2. Korean Ministry of Environment. Survey Report of the National Poll for Noise Awareness. Korean Ministry of Environment; 2002.
3. Kim CH. A study on the propagation characteristics analysis for floor impact noise apartment houses [Master's thesis]. University of Yeungnam; 2006.
4. Haan CH. Implementation of the Floor Impact Noise Monitoring System through the Field Test-Bed Operation. Euro-noise, Crete; 2018.
5. Haan CH. New algorithm of the floor impact noise monitoring system implemented in the existing apartments. WESPAC, New Delhi; 2018.
6. Lee JK, Haan CH. Round-robin tests of the different types of sensors for floor impact sounds and vibration measurements. In: Proceedings of the Acoustics 2023; 2023; Sydney.
7. Yong JH, Ham JG, Cho HH. Comparison of Sensitivity of Sensors for Reducing Noise Between Stories in Buildings. In: Proceedings of the SAREK; 2020.
8. Korean Standards Association. KS F 2863-1, Method of Floor Impact Noise Measurement and Evaluation of the Performance of Noise Insulation: Standard Light-weight Impact Source (Korean). Korean Standards Association; 2022.
9. Korean Standards Association. KS F 2863-2, Method of Floor Impact Noise Measurement and Evaluation of the Performance of Noise Insulation: Standard Heavy-weight Impact Source (Korean). Korean Standards Association; 2022.
10. Korean Ministry of Traffics & Construction. National Standards for Sound Insulation and Floor Impact Noise of Apartments. Korean Ministry of Traffics & Construction; 2004.
11. Lee WH, Haan CH. Floor Impact Noise Characteristics Depending on the Experimental Conditions Using Impact Ball. The Journal of the Acoustical Society of Korea. 2011; 30(2): 92-99.