Validity of Elevator Noise Measurement Method in International Standards on High-Rise Residential Buildings

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Abstract: Noise generated during elevator operation in high-rise residential buildings has a significant impact on the healthy and sustainable building environment of residents. However, there is still no clear standard for the measurement method. There are other international standards other than ISO 16032 on how to measurement elevator noise, but this standard relates to general construction equipment. In particular, it is not suitable as a method to measure elevator noise because it was proposed without considering the situation of modern high-rise residential buildings. In this study, by reflecting the characteristics of the elevator as a noise source and the structural characteristics of modern high-rise residential buildings, improvement measures were proposed for the elevator noise measurement conditions in ISO 16032, which are cited as their own standards in many countries including Korea. As an improvement plan, it contains information on elevator operating conditions, measurement frequency bands, evaluation unit, and measurement locations. As a result of applying these four improvement measures, it was verified that the elevator noise of modern high-rise residential buildings can be appropriately measured, unlike the existing partial elevator noise measurement method in ISO 16032.

Keywords: high-rise residential building; apartment; elevator noise; measurement method

1. Introduction

The increase in urban population is one of the main factors exacerbating the housing problem in cities. In many newly developing countries, including Korea, high-rise residential buildings are being adopted as an alternative to solving urban housing problems [1,2].

Although elevators are essential equipment [3,4] for the convenience of residents of high-rise residential buildings, noise [5,6] and vibration [7,8] generated during operation cause inconvenience in living [9,10], which is a problem for the healthy and sustainable construction environment of high-rise residential buildings. To solve this problem, most of the research on elevator noise so far has been focused on reduction measures [11,12] or standard setting [13,14].

However, there is a lack of research on how to measure and evaluate elevator noise, which should be the basis of research through experiments. Although the international standards, including ISO 16032, the noise measurement method for building equipment [15], deal with elevator noise measurement methods, these standards integrate and manage noise measurement methods of various equipment in buildings, including elevators. Additionally, they do not take into account recent high-rise residential buildings [16,17].

Considering these limitations, this paper intends to study a method for measuring elevator noise according to international standards for the realization of a healthy and sustainable building environment for residents of high-rise residential buildings.
2. Research and Methodology

This study was conducted to clearly suggest a method for measuring elevator noise. First, how the studies on elevator noise are conducted and what kind of elevator noise measurement methods are used in many studies were identified. Next, international standards or standards of various countries were investigated for the method of measuring elevator noise. As a result of the investigation, four research questions which address the important points of this study were derived.

The research hypothesis derived the problems of four items that need improvement in the international standard ISO 16032. They were “elevator operating conditions”, “measurement frequency band”, “microphone location selection”, and “elevator noise evaluation scale”. Hypotheses were established as solutions to each problem. To prove the research hypothesis, several experiments were conducted and analyzed at the site of high-rise residential buildings.

As a result, an improvement plan for each item was presented. In order to verify the validity of the finally proposed improvement plan, additional field experiments and result analysis were conducted. As a result, the validity of this study was presented as an improvement plan. The flow of the research methodology of this study problem seeking, hypotheses building, and proving is shown in Figure 1.

3. Literature Search of Elevator Noise Measurement

3.1. Advanced Research of Elevator Noise

Since elevators have been actively used in buildings, many studies have been conducted on elevator noise from the mid-1900s to the present. Research on elevator noise is mainly focused on finding the cause of noise and researching ways to reduce noise.
According to a study by Lee (1994) [18], the cause of elevator noise and vibration is the operation of the hoisting machine and motor in the machine room. It is mentioned that noise and vibration may be caused by elevator ropes and weights. Yang (2012) studied the control method [19] as a method of reducing noise and vibration generated during elevator operation along with the analysis of the cause, and Lee (2013) reported the reduction of elevator noise in elevator passageways and inside households. Methods were studied [20]. Recently, Oh (2021) studied a management plan to alleviate elevator noise in high-rise residential buildings [21].

As a result of examining previous studies on such elevator noise reduction measures, it is revealed that the measurement method is not clearly presented, or the researcher arbitrarily proceeds with the measurement and analyzes and interprets the results. These measured research results are relatively difficult to compare due to different measurement methods, and, above all, there are problems in the accuracy and reliability of the experiment. For research on elevator noise to have validity, research on the measurement method should precede all else.

3.2. Standards of Elevator Noise Measurement

Elevator noise measurement method related standards were investigated. In the case of Germany, although it does not correspond to the national standard, the method of measuring elevator noise is covered in VDI 2566-1 and 2566-2 [22,23], presented by the German Engineering Federation. As the operating conditions, the arithmetic average value of the cycle of elevator operation start, normal speed operation (at least 5 s), deceleration, stop, and door operation is measured. In addition, for measurement related contents, the contents of the German national standard DIN EN 12354-5 [24] are to be used.

In the UK, BS 8233 [25] deals with elevator noise indoor standards and measurement methods. The operating conditions of the elevator are not clearly explained, and the value indicating the highest noise level during the operation of the elevator is measured. For other measurement related contents, the contents of BS EN 12354-5 [26] are to be used.

In the end, although elevator-related contents by country are dealt with based on BS EN 12354-5, it is difficult to see them as standards that closely reflect characteristics of elevator noise.

In the United States, ANSI and ASTM cannot find standards related to elevator noise measurement other than those related to elevator installation and safety management.

In the case of the International Organization for Standardization (ISO), most of the contents on elevator structure and safety [27,28] cannot find a standard that clearly suggests a method for measuring elevator noise. Even in the field of building or residential environment noise [29,30], there are no standards for measuring and evaluating elevator noise yet. Although ISO 16032 is the only method for measuring elevator noise in the field of building noise, this standard stipulates that the measurement procedure and test method of equipment installed in a building are the same, and only the operating conditions are specified and measured according to the equipment.

In the case of Korea, KS F ISO 16032 [31] was established and standardized by citing ISO as it is to harmonize with international standards.

In other words, most of the current national standards are treated in an integrated way by judging the elevator as a single equipment in the building. However, in high-rise residential buildings, elevators generate noise so high that they can be classified as a single source of noise, and residents are aware of annoyance. It can be said that the method of measuring elevator noise generated in high-rise residential buildings lacks validity and expertise. Among these international standards, this study was conducted to study the elevator noise measurement conditions targeting ISO 16032, which is the most widely cited international standard, deals relatively well with elevator noise, and is also selected as a target for consilience in Korea.
3.3. Research Question

Through the investigation of previous studies and the review of related standards, the most fundamental problem of this study can be divided into two.

(1) For elevators used in buildings, research on ride comfort, safety, noise source analysis, and noise reduction methods are continuously being conducted [27,28]. On the other hand, there is hardly any study on measurement methods for elevator noise transferred to the dwelling units. Instead, the measurement standards for indoor equipment (household alliances) are currently being applied.

(2) From the point of view of the measurement method of elevator noise transmitted to households, it is necessary to examine whether the current measurement standard is applicable to modern high-rise residential buildings.

4. Problems and Improvement Idea

4.1. Problems

Regarding the elevator noise measurement conditions of ISO 16032, a total of four problems were identified by reviewing the existing literature and reviewing standards.

(1) According to the previous study [16], it can be confirmed that the biggest problem of ISO 16032 is the operating conditions. The time required for more than 10 min and the influence of external noise or other noises decrease the accuracy of the experiment. In this regard, the validity of the method for measuring one-way sections was verified in a previous study [17]. In order to solve the problem of operating conditions, it is necessary to reduce the measurement time to minimize the influence of external noise and other noises, and to improve the operating conditions to effectively measure elevator noise on all floors of high-rise residential buildings.

(2) Measurement frequency band should closely reflect the characteristics of elevator noise, but ISO 16032 requires that elevator noise be integrated into the same noise as other building equipment and measured from 63 Hz to 8000 Hz. Regarding this content, the research literature [16,17] mentions that the frequency band below 500 Hz is important for the elevator noise. By collecting elevator noise measurement data from more variables, the characteristics and status of elevator noise in high-rise residential buildings should be closely understood through quantitative analysis and, based on this, the most suitable frequency band for elevator noise measurement should be proposed and verified.

(3) When measuring elevator noise in ISO 16032, the position of the microphone indicates that the experimenter directly measures the position of the microphone and selects a high point to measure it. These measurement methods may show different results depending on the experimenter. According to the research literature [32,33], it is mentioned that different values are shown for each frequency band depending on the location of the microphone. That is, an unspecified location of the microphone means that a problem may occur when comparing and analyzing measurement results. It is necessary to select the location of the microphone that can most sensitively pick up the mid-low range, which is the main frequency band of elevator noise.

(4) Finally, there is the issue of evaluation scale. It is divided into 1.2 maximum sound pressure level and 1.3 equivalent noise level in ISO 16032 Annex 2. Like the microphone position, it is selected and measured according to the operation and noise characteristics of the elevator. According to the results of previous studies, it can be seen that it is difficult to secure the signal-to-noise ratio in the case of elevator noise. In particular, when measured as an equivalent noise level, the difference with a single value was measured as 1 to 2 dB(A) compared to the background noise, but the difference in the maximum sound pressure level was measured to be 4 to 5 dB(A). The evaluation criteria should be selected when measuring the elevator noise by clearly understanding the characteristics of the elevator noise.
4.2. Improvement Proposal

(1) As the most important content to improve the elevator operating conditions, the measurement time should be minimized first. In addition, it should be possible to measure on any floor, and unnecessary movement should be excluded. In particular, noise generated when the elevator stops at the measurement floor and when the door is operated should be included. The following is a summary of the improvement plans focusing on these contents.

(2) When measuring the noise generated during the operation of an elevator in a high-rise residential building within a household, it is necessary to clearly measure the frequency band characteristics of the elevator noise. Although there are various factors, if we analyze the frequency characteristics of the elevator noise, measuring the 63–500 Hz band rather than the 63–8000 Hz band measurement suggested by ISO 16032 will measure the characteristics of the elevator noise more accurately even if all variables are considered.

(3) The low-mid frequency band below 500 Hz makes many people uncomfortable. According to previous studies [32,33], elevator noise is in the mid-low range, and the closer to the edge of the room, the higher the level according to the influence of the room-mode. It is reasonable to select and measure the most vulnerable point, not the position where the value of the noise source can be measured on average for the location of the microphone in the measurement space.

(4) A scale for measuring and evaluating elevator noise is selected according to the selection conditions of 1.2 maximum sound pressure level and 1.3 equivalent noise level of ISO 16032 Annex 2. Since elevator noise cannot maintain a high sound pressure level for a certain period of time, the equivalent noise level measurement is not valid. In addition, since it is difficult to secure the signal-to-noise ratio, it is accurate to measure the maximum sound pressure level.

Table 1 shows the four improvement measures.

| Measurement Method | Detailed Content |
|--------------------|-----------------|
| 1. Operating condition | Move 10 floors based on stopping at the measured floor for basic operating conditions. Measure up to the time of stopping after ascent from 10 floors below and opening/closing of elevator door when the measured floor is the highest floor. Be sure that the personnel aboard do not exceed 1 person required for elevator operation. |
| 2. Measurement frequency band | 1. Upon measurement according to the operating conditions, evaluate the band of 63–500 Hz for evaluation and frequency analysis while measuring the 1/3 Oct center frequency 31.5–2000 Hz for the frequency band of an analyzer. |
| 3. Microphone position | Conduct measurements in the elevator movement passage and the most adjacent space, and measure in a bedroom or a living room. For the position within the measurement space for microphone, measure 2 spots on the corners of both ends of the wall adjacent to the elevator movement passage and 1 spot at the corner excluding openings for a total of 3 spots. Exclude the center point. For the detailed position of microphone, have it positioned at the spot with separation from wall by 0.5 m and from floor by 0.75 m. Measure the openings allowing opening/closing in the close state. |
| 4. Evaluation unit | Measure characteristics-weighted maximum sound pressure levels. Use “Fast” for the time-weighted values. Mark the unit as L_A_max. |
5. Result and Verifications

5.1. Elevator Operating Condition

Field experiments were conducted to verify the proposed improvement plan. The experimental site is a 25-story, new high-rise residential building completed in 2020 located in Gyeonggi-do. They are two different flat types. Since it is not an experiment and analysis according to the plane type, no other explanation were added for the two planes. The elevator movement path is separated from the household, and the structure of the elevator is a structure without a machine room. Measurements were carried out in the bedroom closest to the elevator passage, and when moving the elevator, the minimum number of people required to move the elevator was one. As measurement equipment, 4 microphones (GRAS, Class0) and 4 channel analyzers (SINUS, Apollo) were used.

The microphone was spaced 0.75 m from the wall and located at a height of 1.2 m from the floor, and a total of 4 points including the indoor center point were selected. Figure 2 shows the plane of the household to be tested, the position of the elevator, and the position of the measuring microphone. The verification experiment was performed in the same order as in Table 2.

Figure 2. Floor plan for Microphone Positions and Elevator Positions.

Table 2. Elevator Operating Conditions and Measurement Information.

| Measure No. | Receive | Microphone Position | Operate Conditions | Details |
|-------------|---------|---------------------|--------------------|---------|
| 1           | 25F     | 0.75 m near to wall | KS ISO 16032       | Each floor stop |
| 2           | 25F     |                     | 15F to 25F         | Move to 10 floors |
| 3           | 25F     |                     | 25F to 15F         |         |
| 4           | 13F     | Floor to high 1.2 m | 3F to 13F          | Move to 10 floors |
| 5           | 13F     | (Fixed)             | 23F to 13F         |         |
| 6           | 2F      |                     | 12F to 2F          | Move to 10 floors |
| 7           | 2F      |                     | 2F to 12F          |         |

Compared to the ISO 16032 elevator operation condition in which the elevator operation condition of the improvement plan stops at all floors, the measurement time was reduced by more than 90% as a result of experiment and analysis, and the correlation coefficient was found to be greater than 0.9 as a result of frequency analysis, confirming the validity of the improved operation condition. This verification result is an experiment and analysis result for verification of operation condition improvement plan only, and improvement plan for frequency band, noise evaluation scale, and microphone position was not applied. The results are shown in Table 3.
Table 3. Correlation coefficient between ISO measurement standard and operating conditions.

| Operate Condition | Running Time (s) | Correlation Coefficient |
|-------------------|------------------|-------------------------|
| 1                 | 624              | -                       |
| 2                 | 31               | 0.93                    |
| 3                 | 28               | 0.98                    |
| 4                 | 27               | 0.98                    |
| 5                 | 27               | 0.98                    |
| 6                 | 28               | 0.93                    |
| 7                 | 27               | 0.90                    |

5.2. Frequency Band of Measurement

To verify the validity of the measurement frequency band, 100 measurement data were collected considering all the major variables affecting the elevator noise transmitted from the high-rise residential buildings to the interior of the adjacent household. For the 100 data analysis, the improved operating conditions were applied for the operating conditions, and the noise scale and microphone position were measured and analyzed under the same conditions where the improvement plan was not applied. The experiment site was three apartment complexes, and the experiment was conducted in a room and living room within 8 households in each complex. The number of occupants of the elevator was limited to one required for operation, and the microphone was located 0.75 m away from the wall and 1.2 m high from the floor, and 4 points including the center of the room were selected. As the analysis equipment, APOLLO (4CH) of SINUS was used, and the microphone of 1/2 inch G.R.A.S (Class 0) was used. Table 4 shows the plane of the test site, the position of the elevator, and the position of the microphone.

Table 4. Measurement residential buildings floor plans and microphone locations.

| Mokpo, I Apartment, 7th floor (1 household) bedroom |
|----------------------------------------------------|

| Gwangju, W Apartment, 8th floor (1 household) bedroom |
|----------------------------------------------------------|

| Seoul, W Apartment, (3 households) living room |

As a result of frequency analysis of 100 data, it was confirmed that, overall, the measured value in the band below 500 Hz was higher than the average of the background noise of 17.6 dBA. In particular, the influence was higher in the 63 and 125 Hz bands than the average single numerical evaluation value of 28.8 dBA of 100 data. The lowest single numerical evaluation value was 21 dBA, and the highest single numerical evaluation value was 48 dBA. It can be confirmed that the elevator noise is 25–35 dBA on average when considering the deviation caused by the background noise and the external environment. As a result of this frequency analysis, the main noise source for elevator noise is the low-mid and low-frequency bands of 63 Hz and 125 Hz, and the noise level can be checked from the 500 Hz band compared to the background noise, which is 1/3 octave band center frequency 63 Hz. It was verified that the 500 Hz band is a measurement frequency band that can measure elevator noise more accurately. Shown in Figure 3.

**Figure 3.** Frequency band analysis result of 100 data.
5.3. Microphone Location

An experiment was conducted to verify the above hypothesis. In the experiment, the position of the microphone was divided according to the distance from the wall and the height from the floor. The separation distance from the wall was 0.5 m, 0.75 m, and 1.0 m, and the height from the floor was divided into 0.5 m, 0.75 m, and 1.2 m. The operation section was measured on the 25th floor, which is the top floor, and two conditions were tested: the condition starting from the second floor and stopping at the 25th floor, and the condition starting from the 25th floor and stopping at the second floor. The reason is to compare the situation in which the opening and closing sound of the elevator door is sounded and the situation in which the opening and closing sound is not. The experimental site is a 25-story, new high-rise apartment building completed in 2020 located in Gyeonggi-do. A total of 24 data were obtained. The results are shown in Table 5. Each measured value is shaded to make it easier to recognize the influence of each frequency band.

As a result of the experiment, when the distance from the wall was 0.5 m and the height was 0.75 m, the measured values were high in the 63 Hz and 125 Hz bands, which are the main frequency bands of elevator noise. In particular, it showed a relatively high value in the 63 Hz band. This position is similar to the head position when the actual occupant is lying in bed. The values of 1ch, 2ch, and 4ch were high, and it can be seen that the value of the low frequency band decreases as the distance from the wall is increased. On the other hand, the measured value at the central point was lower than 10 dBA. In particular, there was a large deviation in the 63 Hz band, which is a major influencing factor. That is, it can be said that the measurement of the center point is a point where it is difficult to fully absorb the characteristics of the elevator noise. Judging from these results, when measuring elevator noise, it is reasonable to measure a total of three points (excluding the center point) at the other corners including the two corners of the wall (there should be no opening) adjacent to the elevator passage. As for the detailed location, the microphone should be placed 0.5 m from the wall and 0.75 m from the floor. It was verified that the measurement position of the microphone is the most sensitive point for measuring elevator noise, and it is the point at which the 63 Hz and 125 Hz bands, which are the main frequency bands of the elevator noise, can be best absorbed.
Table 5. Frequency analysis according to microphone position.

| MIC Location | Ch | 63 Hz | 125 Hz | 250 Hz | 500 Hz | 1000 Hz |
|--------------|----|-------|--------|--------|--------|---------|
| 0.5 m/0.5 m  | 1  | 41.2  | 32.2   | 18     | 14.7   | 7       |
|              | 2  | 39.5  | 30.7   | 18.9   | 14.1   | 6.9     |
|              | 3  | 25.9  | 30     | 20.2   | 13     | 7.8     |
|              | 4  | 42    | 29     | 18.1   | 14.2   | 7       |
| 0.5 m/0.75 m | 1  | 41.8  | 24.2   | 14     | 17.2   | 12.5    |
|              | 2  | 42.3  | 23.6   | 13.9   | 16.2   | 10.8    |
|              | 3  | 21.7  | 22.8   | 18     | 15.8   | 11.8    |
|              | 4  | 41.6  | 20.4   | 13.9   | 17     | 12.4    |
| 0.5 m/1.2 m  | 1  | 38.9  | 31     | 14.8   | 15.8   | 7.3     |
|              | 2  | 39.9  | 30.8   | 13.9   | 16.9   | 7.6     |
|              | 3  | 22.9  | 30.3   | 20.5   | 12.7   | 8.7     |
|              | 4  | 41    | 30.6   | 14.7   | 16.2   | 7.2     |
| 0.75 m/0.5 m | 1  | 37    | 23.5   | 20.2   | 11.7   | 9.7     |
|              | 2  | 39.4  | 19.9   | 19.7   | 13.8   | 9       |
|              | 3  | 27.3  | 32.1   | 20.8   | 13.6   | 10.2    |
|              | 4  | 39.4  | 18.6   | 21     | 12.1   | 8.8     |
| 0.75 m/0.75 m| 1  | 41.5  | 25.8   | 17     | 16     | 7.2     |
|              | 2  | 37.7  | 12.5   | 17.2   | 10.7   | 6.2     |
|              | 3  | 21.4  | 27.3   | 18.7   | 9.6    | 6.1     |
|              | 4  | 42.4  | 20.4   | 17.5   | 15.3   | 6.8     |
| 0.75 m/1.2 m | 1  | 42    | 21.8   | 17.3   | 17.6   | 10.3    |
|              | 2  | 38.4  | 17     | 17.8   | 16.2   | 9.3     |
|              | 3  | 19.9  | 27.1   | 18.3   | 15.7   | 8.9     |
|              | 4  | 37.1  | 15.3   | 19.2   | 17.2   | 9.1     |
| 1.0 m/0.5 m  | 1  | 32.7  | 26.6   | 20.7   | 13.5   | 11      |
|              | 2  | 34.4  | 26     | 21.1   | 14.8   | 11.1    |
|              | 3  | 27.1  | 30.5   | 20     | 14.9   | 12.3    |
|              | 4  | 34.3  | 29.4   | 21.8   | 15.6   | 11.9    |
| 1.0 m/0.75 m | 1  | 32.4  | 27.2   | 17.1   | 15.8   | 11.7    |
|              | 2  | 30.3  | 24.4   | 21.7   | 14.1   | 12.3    |
|              | 3  | 25.7  | 31.8   | 20.7   | 13.7   | 11.8    |
|              | 4  | 37    | 28.3   | 22.5   | 13.9   | 11      |
| 1.0 m/1.2 m  | 1  | 36.5  | 28     | 19.1   | 14.9   | 10.5    |
|              | 2  | 32.6  | 23.9   | 21     | 15.8   | 13.1    |
|              | 3  | 22.3  | 31.9   | 21.3   | 13.8   | 11      |
|              | 4  | 31.4  | 26.2   | 20     | 13.6   | 12.5    |

5.4. Evaluation Unit of Elevator Noise

To verify the above hypothesis, the experimental results were analyzed. Figure 4 shows the effect of noise generated when the elevator door opens and closes and the point where the maximum sound pressure level occurs during elevator operation. The upper graph shows the case where the elevator door opening/closing noise appears the highest, and the lower graph shows the case where the elevator operating noise appears the highest. In the two situations, the point and cause of the maximum sound pressure level are different, and the inability to maintain the maximum sound pressure level for a certain period of time is a characteristic of elevator operation noise, so it is reasonable to measure the maximum sound pressure level rather than the equivalent noise level. In addition, as for the elevator noise, the mid-low frequency band is the main noise. In the case of the uppermost floor, the noise generated from the machine room is large, and in the case of the middle floor or the lowest floor, the effect of the noise generated from the hoist-way and the guide sound and the door operation sound are the main factors. Both noises show an effect in the band below 500 Hz, but the time of occurrence and time of occurrence are
different. Judging from this point, it is most appropriate to measure the maximum sound pressure level, not the equivalent noise level, for the elevator noise.

Figure 4. Characteristics of the maximum sound pressure level in the elevator operation section.

6. Discussions

A study was conducted to improve the elevator noise measurement method suggested by the international standard. There are two goals for improvement. The first is to improve the measurement method applicable to modern high-rise residential buildings, and the second is to accurately reflect the characteristics of elevator operation noise.

According to the results of Tables 2, 3, and 6, the improvement of operating conditions is a new measurement method applicable to modern high-rise residential buildings. As a result of the analysis in Table 5, the location of the microphone is suggested when measuring elevator noise, where the sound pressure level is low and the mid-low frequency band is important. The reason why the low-mid frequency band is important here can be seen from the analysis in Figure 3, which suggests that the elevator noise should be measured at the maximum sound pressure level.

| Household Number | Operate Method | Time (s) | $L_{Aeq}$ (dBA) | $L_{Amax}$ (dBA) |
|------------------|----------------|---------|-----------------|-----------------|
| 201-2602         | BGN            | 10      | 17.0            | 20.3            |
|                  | ISO 16032      | 818     | 20.6            | 35.0            |
|                  | 16F to 26F     | 61      | 19.9            | 28.0            |
| 201-1403         | ISO 16032      | 806     | 22.8            | 37.9            |
|                  | 4F to 14F      | 44      | 21.3            | 26.3            |
|                  | 24F to 14F     | 40      | 19.9            | 25.6            |
| 201-102          | ISO 16032      | 803     | 20.8            | 41.3            |
|                  | 11F to 1F      | 57      | 18.6            | 24.1            |
| 201-2605         | ISO 16032      | 791     | 22.1            | 47.1            |
|                  | 16F to 26F     | 54      | 22.6            | 41.6            |
| 201-1505         | ISO 16032      | 795     | 19.3            | 31.8            |
|                  | 5F to 15F      | 46      | 18.7            | 21.5            |
|                  | 25F to 5F      | 49      | 20.3            | 35.2            |
| 201-205          | ISO 16032      | 762     | 20.5            | 35.6            |
|                  | 12F to 2F      | 58      | 17.5            | 22.8            |
| 211-2708         | ISO 16032      | 783     | 22.2            | 29.4            |
|                  | 17F to 27F     | 41      | 22.9            | 26.2            |
| 211-703          | ISO 16032      | 857     | 15.9            | 26.6            |
|                  | 17F to 7F      | 53      | 16.3            | 26.8            |
| 211-105          | ISO 16032      | 823     | 18.0            | 28.9            |
|                  | 11F to 1F      | 50      | 17.2            | 21.4            |
In this study, two important problems were solved. The results of this study will enable more accurate elevator noise measurement in high-rise residential buildings where elevators are used.

7. Case Study; Application of the Improvement Proposal

By comparing and analyzing the experimental results, the validity of the improvement proposals was comprehensively verified. The experimental site is a new high-rise residential building located in Busan Metropolitan City, and 20 data were collected from a total of nine households in three buildings.

Measurements were made in the bedroom closest to the elevator hoist-way, and the equipment used for the measurement was a CLASS0 1/2-inch microphone from G.R.A.S and an Apollo 4CH analyzer from SINUS. The location of the microphone was 0.5 m away from the wall and 0.75 m high from the floor. The center point of the experiment was additionally located for the measurement of the control group. Background noise was measured for 10 s under the same experimental conditions. The experimental site is shown in Figure 5 below.

![Figure 5. Field measurements and microphone positions.](image)

Table 6 below shows the operating conditions of each floor stopping order of ISO 16032 in all measured households, and the time required for the 10th floor moving operation conditions presented in this study and the result values. The operating condition of ISO 16032 takes about 780 s to 800 s, but the time when only the movement of 10 floors was measured was found to be around 40 to 60 s. Looking at the result of the maximum sound pressure level, in the case of the ISO operating condition, the deviation was 21 dBA from the low 26 dBA to the high 47 dBA. This is because external noise that can occur during a long measurement time of about 800 s affects the elevator noise measurement. On the other hand, as a result of the operation condition test for moving 10 floors, it was found to be as low as 21 dBA to as high as 35 dBA, and the deviation was 14 dBA, confirming that the deviation of 7 dBA compared to the ISO 16032 standard could be reduced.

Such a long measurement time is highly influenced by external noise (traffic noise). If these noises are measured at the equivalent noise level, it is difficult to accurately measure the elevator noise, and even if it is measured, it cannot be said that the elevator noise has been absorbed well. This can be seen from the equivalent noise level measurement results. If you look at the test results of the ISO 16032 measurement method and the test results under the operating conditions of 10 floors, the deviation does not exceed 7 dBA. Additionally, when compared with the background noise, it was found that the equivalent noise level did not deviate from the background noise. It was confirmed that when measured at the maximum sound pressure level, it could be clearly distinguished from the background noise. Here, the elevator noise measurement is a result that can further verify that the maximum sound pressure level is reasonable.

Figure 6 is a frequency analysis of the measurement results of the ISO 16032 operating conditions and the movement measurement results of 10 floors measured in the 201-
2602 generation in Table 6. What is clearly evident is that the effect of elevator noise is not absorbed at all at the pickup point of the central point (ch3). The impact of these extreme results can be confirmed only by a simple comparative analysis. The effect of elevator noise in the 63 Hz band shown in both graphs is hardly absorbed at the center point. In short, it is the result of verifying that the center point measurement is not a sound pickup point that has a great influence on the elevator noise measurement. In addition, in the graph of the ISO 16032 measurement standard, the 250 Hz band showed a high sound pressure level at all receiving points. This is a frequency characteristic that cannot be confirmed in the 10-story moving operation condition graph, and it was confirmed that it was external traffic noise (bus) generated during ISO 16032 measurement. That is, in Figure 6 above, it was revealed that the long-time measurement of ISO 16032 has a big problem in measurement accuracy, and at the same time, it was confirmed that the short-time measurement of the 10-floor movement measurement section is more advantageous for measuring elevator noise.

![Figure 6](image_url). Frequency analysis according to operating conditions.

All measured data were excluded for other variables such as measurement time and interval. It was analyzed using the measured values for each frequency band of the equivalent noise level and the maximum sound pressure level. The average value of the equivalent noise level of the background noise is about 26 dBA. On the other hand, the average value of the equivalent noise level of the elevator noise was about 30 dBA. Considering that the elevator noise is at a very low level, the 4 dBA difference was judged to be sufficiently problematic due to the influence of external noise or other environmental noises. On the other hand, the average value of the maximum sound pressure level of the elevator noise was about 40 dBA, showing a difference of 14 dBA from the background noise. This was judged to be a sufficiently significant difference even considering the influence of external noise. Shown in Figure 7. This result is the result of verifying that it is appropriate to measure the elevator noise at the maximum sound pressure level.
Judging from these on-site measurement and comprehensive analysis results it was verified that the improvement measures for the four conditions could be improved to a measurement condition suitable for application to high-rise residential buildings rather than the ISO 16032 measurement condition.

8. Conclusions

The noise generated from the elevator, the most important equipment in high-rise residential buildings, is unpleasant for residents. This is a problematic factor for a healthy and sustainable built environment. Research so far has focused on elevator noise reduction measures and standard setting, but research on the most basic measurement method is lacking. Although international standards other than ISO 16032 deal with elevator noise measurement methods, they remain at the level of integrating and managing building equipment.

Therefore, in this study, problems were identified in the ISO 16032 elevator noise measurement condition, which is an international standard, and improvement was confirmed.

First, the long measurement time was the biggest problem for the operating conditions suggested by ISO 16032. It was verified that the operating conditions for the movement of 10 floors suggested in this study can be measured within 1 min, and since the measurement time is short, the influence of external noise can be effectively reduced, and the characteristics of elevator noise can be more accurately captured.

Second, as for elevator noise, 63 Hz and 125 Hz bands are the main low-mid frequency noise, and it is reasonable to measure the 1/3 octave band center frequency band 63 Hz to 500 Hz. Frequency characteristics of elevator noise by analyzing more than 100 data was verified by careful analysis.

Third, the location of the microphone was selected from two viewpoints. The first was to fully consider the situation when the resident actually rests or sleeps, and the other, the mid-low frequency band was selected as the best point for sound collection. As a result, it was confirmed that the mid-low frequency band was best absorbed at the corner points except for the center point 0.5 m from the wall and 0.75 m from the floor.

Fourth, since the point and cause of the maximum sound pressure level are different for elevator noise, and the inability to maintain the maximum sound pressure level for a certain period of time is a characteristic of elevator operation noise, it was verified that it is reasonable to measure the maximum sound pressure level rather than the equivalent noise level.
A high-rise residential building field experiment and analysis were conducted to verify the feasibility of the measurement condition integrating all four conditions above. As a result, it was verified that the improvement plan can solve all the problems raised in ISO 16032 and reflects the characteristics of elevator noise better.

This study is a partial improvement of the elevator noise measurement conditions presented in ISO 16032. In future research, it is necessary to prepare a method to measure and evaluate elevator noise more professionally through the study of the evaluation method for the band below 500 Hz, which is suggested as the measurement frequency band.

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