

Article

Construction Management Solutions to Mitigate Elevator Noise and Vibration of High-Rise Residential Buildings

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Abstract: In high-rise residential buildings (HRBs), elevators run at a high speed, which causes problems such as change of atmospheric pressure, noise, and vibration. Elevator noise and vibration (ENV) of HRBs causes both mental anxiety and a consistently negative effect for promoting a comfortable residential area. Therefore, a solution for alleviating the ENV of HRBs is essential. To date, studies related to ENV have been mostly conducted in the approach of mechanical and electric aspects. There have been few cases conducted from the perspective of construction management (CM), which integrates design and construction. Therefore, the aim of this study is to propose CM solutions to mitigate the ENV of HRB. For this study, the CM solution is presented after identifying the ENV problems of HRBs through documented research and case measurement. By measuring the noise of HRB that the solution was applied to, the noise level, especially in a range of >125 Hz, was extensively reduced. The result of this study will be used as sustainable guidelines that alleviate ENV problems in the process of design and construction of HRB elevators. It is expected that studies for improving ENV problems that occur in high-rise elevators will increase on the basis of the results of this study.

Keywords: elevator; noise; vibration; construction management; high-rise residential building

1. Introduction

A high-rise residential building (HRB) is a type of housing that has multi-dwelling units built on the same land. This housing has become popular in urban areas because of the increase in land cost [1]. Efficient vertical mobility is a critical component of developing and constructing tall buildings [2]. Advances in elevators over the past 20 years are probably the greatest advances we have seen in tall buildings [3].

However, the elevators of HRB operated at a high-speed cause problems such as changes in atmospheric pressure inside and outside a lift car, noise, and vibration [4–13]. In particular, elevator noise and vibration (ENV) cause both mental anxiety for passengers and a consistent negative effect on promoting a comfortable residential area close to the elevator shaft [11,14–21]. To secure a sustainable living environment, the impacts can be significant issues related to sound quality, sleeping conditions, and enjoyment within residences [14,16–20,22–25].

To solve these problems, multiple studies have been conducted, which mostly focused on mechanical and electric aspects [6,7,10,26–36]. However, it is not easy to solve ENV problems only with machinery solutions for HRB elevators that run at a speed of >90 m/min [21,37–39]. The reason is

that not only do noise and vibrations occur in the elevating machinery itself, but there are architectural problems of elevator shafts or air turbulence because HRB elevators run at a high speed [4,14,37–39]. Thus, identifying solutions after analyzing such causes is necessary. Solutions for ENV problems should be provided in detail in the design phase primarily, and construction should be followed according to the design details. However, we have confirmed that ENV problems continue to occur due to errors or mistakes in the design and construction phase through research and site surveys over the past several years.

This is because there is no CM solution that integrates design and construction for ENV problems. As shown in routines (1) and (2) in Figure 1, even if ENV solutions are provided with the documents including drawings and specifications in the design phase, the details including the precision, quality, and tolerance of construction suitable for the site condition must be determined in the construction phase after design review. As shown in routines (3), (4), and (5) in Figure 1, if design errors or omissions are confirmed after design review, construction details are determined after performing supplementary design. In other words, additional designs can be carried out according to the site situation at the construction phase. Solutions applied to the design and construction phases and integrated management of them are defined as CM solutions in this paper. The aim of this study is to propose CM solutions to mitigate the ENV of HRB.

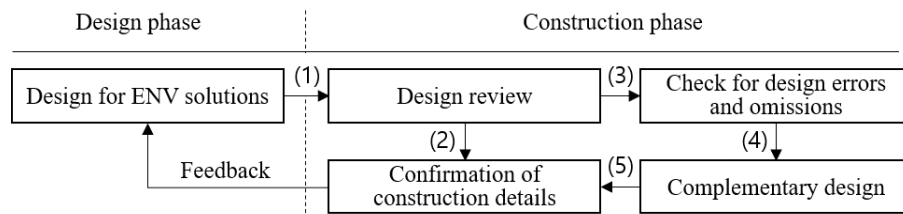


Figure 1. Design and construction integrated construction management (CM) solutions for elevator noise and vibration (ENV) problems.

Figure 2 shows the methods and procedures of this study. First, review the definition of HRB and elevator and ENV sources and transmissions by surveying the design guidelines. Second, analyze the ENV sources and the transmissions of HRBs through documents and examine the site, and then measure ENV as a designated HRB that CM solutions have not been applied to as a case study. Third, propose design and construction solutions that have been confirmed using multiple documents that have been presented and studies that have been previously conducted. Moreover, confirm the effectiveness of CM solutions proposed in this study after measuring ENV of a case HRB that these solutions are applied with. Fourth, discuss the consistent improvement of problems that occur in high-rise elevators as per the results of this study and then describe results in the conclusion.

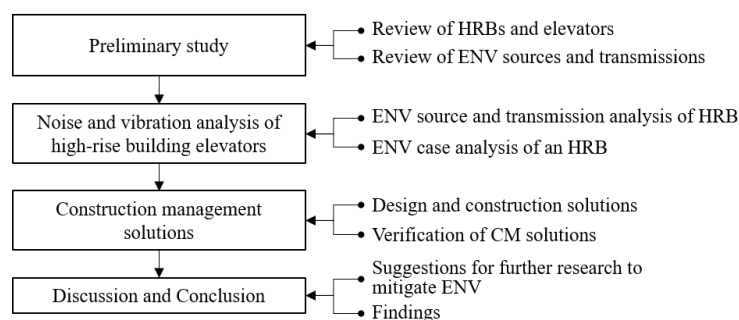


Figure 2. Research process and methodology. HRB = high-rise residential buildings.

2. ENV of HRBs

2.1. Review of HRBs and Elevators

Emporis Standards defines a high-rise building as a multi-story structure between 35 and 100 m or a building of unknown height from 12 to 39 floors [40]. Korea Land and Housing Corporation (KLHC), Korea, which develops public apartments, classifies low-rise buildings as those with 5–6 floors, mid-rise as those with 7–15 floors, high-rise as those with 16–20 floors, and super high-rise as those with 21–49 floors as per residential building guidelines [41]. For construction at a relatively large scale, residential building projects comprise many buildings with different numbers of floors. Depending on the number of floors and households per floor, the capacity and speed of elevators in each building varies [41]. As shown in Table 1, the capacity comprises many passengers, loading capacity, box size, size of exits that are available, and elevator speed regulated by KLHC guidelines comprising six levels with the range from 60 m/min as a minimum to 180 m/min as a maximum as per the number of floors in a building. For the reference, HRBs in Korea have mostly 12–40 floors, and there is recently a case of a building with >40 floors. This study is precisely processed on HRBs with >12 floors and elevators at a speed of >90 m/min.

Table 1. Elevator speed by operating floor [42].

No. of Floors	Elevator Speed	Remarks
Under 10th floor	60 m/min	
10 to 14th floor	90 m/min	
15 to 25th floor	105 m/min	Applied to elevators installed after June 2011
26 to 30th floor	120 m/min	
31 to 40th floor	150 m/min	
Over 40th floor	180 m/min	

The change of air pressure, noise, and vibration generated while HRB elevators are being operated cause passengers to be discomforted and has a negative effect on the residential environment of nearby residents [4,8,11–13]. As per the building code of many countries, the characteristic noise level, because of a life within an apartment building, should not exceed 30 dB(A) in any bedroom or living room of apartments [15,43–45]. However, for many HRBs, there are multiple cases that noise level exceeds 30 dB(A) in the apartments around elevators [15,19,21]. Many researchers state that any noise problem may be described in terms of a source, a transmission path, and a receiver; furthermore, noise control may take the form of altering any one or all elements. The noise source is the one in which the vibratory mechanical energy originates because of a physical phenomenon such as mechanical shock, impacts, friction, or turbulent airflow [14,46,47].

Both noise and vibration that occur in HRB elevators are said to be noise sources; moreover, the parts of elevating system and structure of building are transmission paths and residents are considered as receivers. Therefore, it is primary solutions in response with the location of the source that reduce mechanical shock, impacts, and friction sources occurring while elevator machinery is being operated, or alleviate the occurrence of turbulent air noise generated while an elevator car is on the move. The secondary solution is controlling transmission paths in which elevators are arranged in isolation in the housing units of HRB, or they are designed to have a buffer space between them. Although many studies have been focusing on primary solutions, the ENV problems of HRBs have not been sufficiently solved [14,15,24,25,27,36]. Therefore, in-depth studies on primary and secondary solutions are required and then applied. The reason is that it is difficult to reduce elevator noise under 30 dB(A) caused at a high speed of it, even if noise and vibration can be partly alleviated by primary solution in the case of HRB elevators. This is because the damage largely escalates if ENV problems occur because the number of HRB residents is less.

2.2. Review of ENV Sources

Fullerton [14] and Ingold [23] specifically described sources, transmission paths, and control of ENV. Torres and Haugen [27] reported a case study regarding noise and vibration because of machine room-less (MRL) elevators of apartment buildings and proposed an approach for alleviation [27]. Based on multiple studies, MRL elevators as gearless synchronous machines reduce electric energy by 50% compared to the geared traction elevators [27,48,49].

Moreover, many researchers published studies on ENV sources and transmissions [14,16,18–21,35]. The noise source is the one in which the vibratory mechanical energy originates because of a physical phenomenon such as mechanical shock, impacts, friction, tonal sound, or turbulent airflow [14,27,34,50–52]. Especially, interactions between the pulley and the cables that suspend the elevator cab show the potential for a tonal sound. These sounds vary in loudness and frequency with the system's speed, with the loudest airborne sounds being attributed to the fastest speed of operation [14,19]. The elevators of HRBs runs at a high speed from 90 to 180 m/min, which caused tonal sound at a considerable level.

In many studies, although ENV sources were introduced, most of them were from the perspective of a mechanical system and little was covered in terms of CM solutions for HRB [14,15,26–36,48]. Thus, in this study, ENV sources and transmission paths of HRB are analyzed. Confirming clearly airborne and structure-borne transmission paths through a study is to obtain clues to CM solutions to alleviate the ENV of HRBs. Several researchers, including Fullerton [14], Ingold [23], and Torres and Haugen [27], have partially presented ENV solutions from a design and construction perspective. However, they did not proceed from the perspective of a CM solution that integrates the design and construction phases as introduced in Figure 1.

3. Noise and Vibration Analysis of HRBs

3.1. ENV Source and Transmission Analysis of HRBs

Figure 3 shows the paths on which noise and vibration generated in the traction elevators of HRBs are transmitted to a residence. ENV occurs only when the machinery primarily runs in a machine room and a hoist way. Noise caused from various sources comprises airborne noise transmitted in the form of soundwaves through air particles, as shown in Figure 3, as well as structure-borne noise transmitted through the slabs, walls, and ceilings of buildings [7,14,17,18,21,27]. These two types of noises are delivered to a space that requires quietness, such as bedrooms and living rooms of residences, and consistently hinders living comfort.

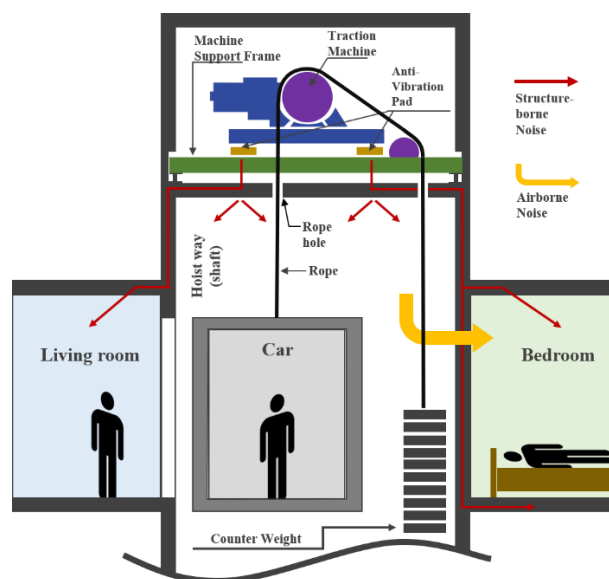


Figure 3. The transmission paths of traction ENV [17,18,21].

By considering various studies [14,16,18–21,27,34,35,50–53] and the research of previous years, the sources, causes, and types of traction elevators have been identified, which are organized in Table 2. For machine rooms, noise is generated by operating multiple machine parts along with the high-frequency rotation of motors, meshing frequency of the gear system, on-and-off brakes, and electrical contact switches to control the elevator. For the hoist way, the sources are noise caused in the process of operation of door parts and by the misalignment of the door and the noise caused when an elevator car goes up and down as per the rails and elevator car guide, and from activities such as the rotation of bearings and rollers, passing through rail joints, and interactions between pulleys and cables.

As shown in Table 1, elevators at a high speed of >90 m/min are used in HRBs. At this time, inrush, air friction, and puff noises generated by elevator cars work as sources [8,9,38,39]. Moreover, the operation of devices such as machine cooling fans, car ventilation fans, car arrival signals, and friction and impact of machine parts work as sources. As shown in Table 2, various forms of noises comprise mechanical shock, impacts, friction, tonal sound, or turbulent airflow in a physical sense.

Table 2. Noise sources, causes, and types of traction elevators.

	Sources		Causes		Types of Noises
Machine Room	Motor	-	High frequency rotation	-	Tonal sound
	Gear and brake	-	Meshing frequency of the gear system	-	Mechanical shock, Impact, Friction
		-	On-and-off the brakes	-	Impact
	Control panel	-	Electrical contact switches to control the elevator	-	Impact
Hoist Way	Door	-	Operation of door parts	-	Friction
		-	Misalignment		
	Rails and elevator car guide	-	Rotation of bearings	-	Tonal sound
		-	Rotation of rollers	-	Tonal sound, Friction
		-	Pass through rail joints	-	Mechanical shock, Impact
Car	-	Interactions between pulley and cables	-	Tonal sound, Friction	
	-	Inrush, air friction, and narrow-section pass of car	-	Turbulent airflow	

Table 3 shows the specific analysis of paths in which noises generated from various sources, as introduced in Figure 3, are transformed into structure-borne and airborne noises and transmitted to the residence. For structure-borne noise, vibratory noise generated by elevating machinery in the machine room is transmitted to residences via an anti-vibration pad, a machine support frame, a machine room slab, and a hoist way wall. Recently, it is common that an anti-vibration pad is designed double-layered between traction machine and support frame and is designed as a vibration transfer area and the size of the machine support frame are reduced, which leads to the considerable reduction of structure-borne noise transmitted from the machine room compared to the past. For structure-borne noise, vibratory noise generated by an elevator car as well as the ascent and descent of counter weight is transmitted to residences via an elevator car guide, rails, rail brackets, and hoist way.

Table 3. Transmission paths of ENV [14,21,39].

Description	Sources	Transmission Paths
Structure-borne noises	Machine room	Machinery → Anti-vibration pad → Machine support frame → Machine room slab → Hoist way wall → Residences
	Hoist way	Elevator car guide → Rails → Rail brackets → Hoist way wall → Residences
Airborne noises	Machine room	Rope hole → Hoist way wall → Residences Outside ventilation openings → Neighboring residence windows → Residences
	Hoist way	Hoist way → Hoist way wall → Residence

Airborne noise produced in a machine room is transferred via a rope hole because Figure 3 shows passing by a hoist wall to residences; moreover, airborne noise is transferred to residences past ventilation openings and neighboring residence windows of the machine. Airborne noise produced in the hoist way is transferred to residences through a hoist way wall. Moreover, there could be airborne noise produced in the hoist way, which can be easily controlled by a >200-mm-thick reinforced concrete (RC) wall and tightly closed concrete placement without any cracks.

3.2. ENV Case Analysis of an HRB

To present CM solutions, it is necessary to analyze ENV problems and the actual condition of the ENV of HRB. We performed measurements of 2 buildings, as Figure 4 shows, as designating one area of apartment complex 'W' located in Seoul known for ENV problems. As shown in Figure 4, the elevator is adjacent to the bedroom or living room and is a traction-type, having a machine room. Figure 4a shows a case that the elevator of Building 'A' is adjacent to a living room of a nearby residence, whereas Figure 4b is a case that the elevator of Building 'B' is adjacent to a bedroom of a nearby residence. As shown in Figure 4c, the vibration was measured with four sensors attached to the wall, and another four sensors were then installed on the upper part of a room floor to measure noise. The measurement time was 50 seconds, and the elevator speed was 60 m/min as the lowest speed of HRB classified in Table 1. Table 4 shows the measurement system used to measure noise and vibrations produced by the elevator with a capacity of 550 kg, i.e., 8 persons.

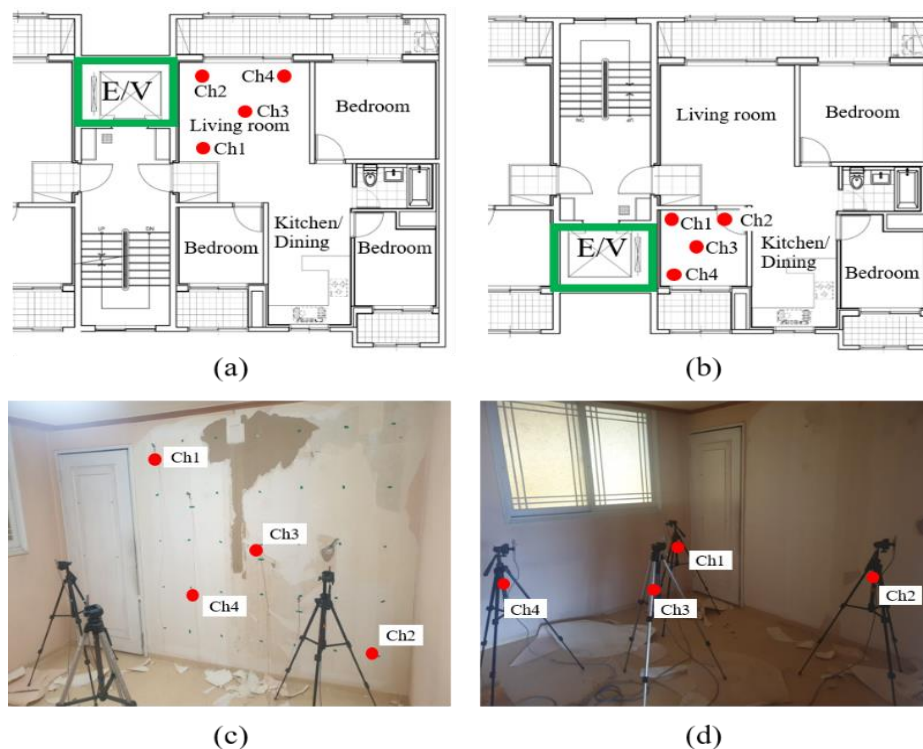


Figure 4. ENV measurement of HRB 'W': (a) The living room in Building 'A'; (b) the bedroom in Building 'B'; (c) the vibration measurement sensors on the living room or bedroom wall; (d) the noise measurement sensors in the living room or bedroom space.

Table 4. Measurement system.

	Description	Model	Manufacturer	Details
Noise	Analyzer	Apollo	SINUS	Bandwidth: DC~80 kHz/Dynamic range: 120 dB
	Microphone	CLASS 0 (LEMO)	G.R.A.S	Bandwidth: 3.15~20 kHz/Dynamic range: 135 dB
Vibration	Analyzer	SA-01	RION	Bandwidth: 0.5~20 kHz/Dynamic range: 140 dB
	Accelerometer	Single Axis Accelerometer (SW)	B.S.W.A	Bandwidth: 0.5~14 kHz/Maximum Acceleration: 0.0002 g rms

Figure 5 shows a graph in which noise and the result of vibratory measurements are simultaneously written; it is a case in which a living room is adjacent to the elevator-like Figure 4a. Figure 5b shows a case in which the bedroom is adjacent to the elevator-like Figure 4b. To date, elevator noise has shown a sound pressure level of 35 dBA on an average when reviewing the result of the noise measurement of the elevator in an apartment building in Korea. Although this noise level is quieter than the sound level criteria in a library, many residents face discomfort because the noise in low-frequency bands has a considerable influence on them. Note that the energy distribution of the general environment noise ranges from 125 Hz to 4 kHz; however, as shown in Figure 5, elevator noise is distributed up to 63 Hz or even up to 32 Hz. In other words, the noise accompanying vibrations is sensed with considerable discomfort even if it is low. The common tendency identified in both graphs is the increase in value of contrast measurement data of the background noise (BGN), and the background vibration (BGV) appears to be high within the range of low-frequency bands of <500 Hz. This corresponds to a figure reported in the guidelines of many previous published studies [16,54,55].

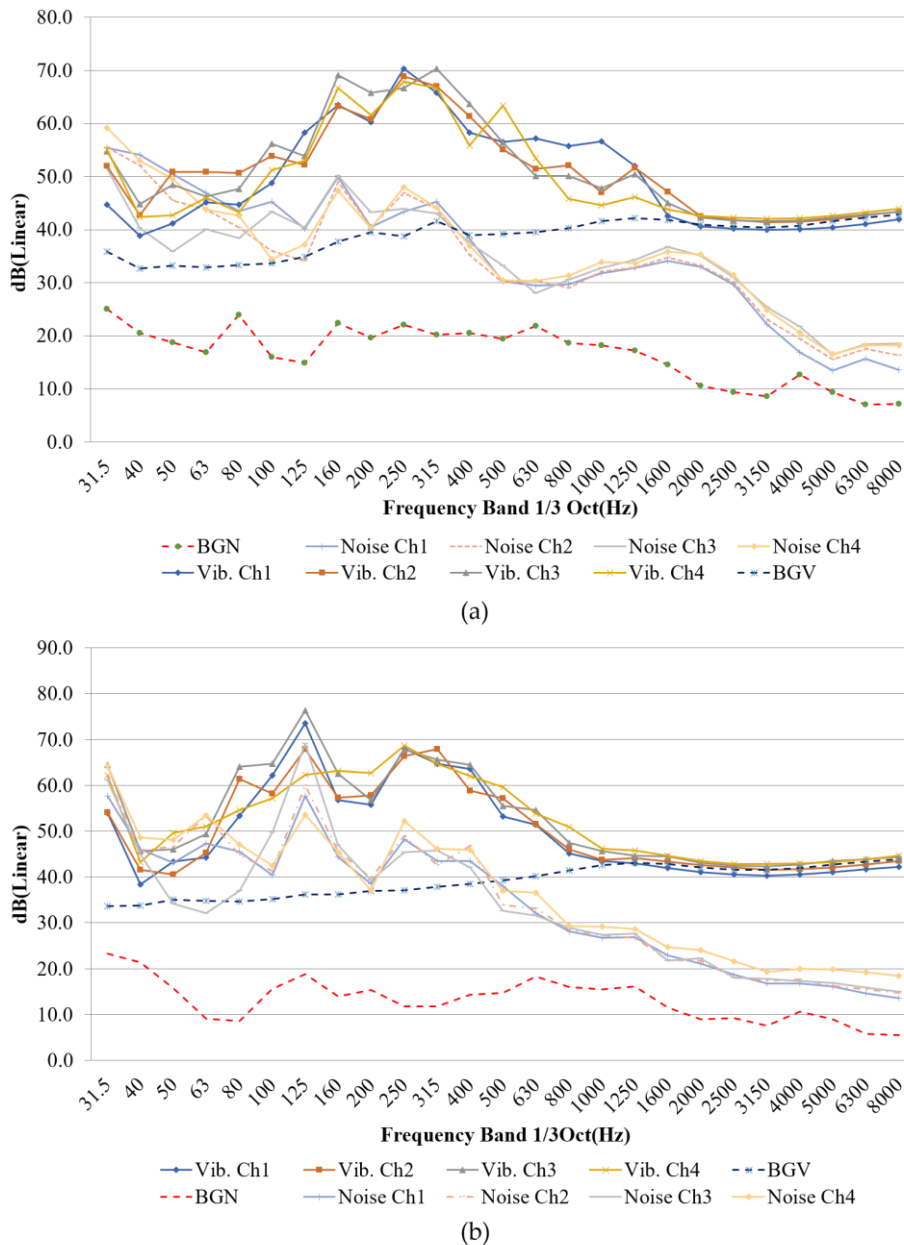


Figure 5. ENV measurement results of HRB ‘W’: (a) the ENV measurement results of living room; (b) the ENV measurement results of bedroom.

The measurement results in Figure 5 confirmed that the noise in the low-frequency band among noises transferred in the form of structure-borne noise and produced by the operation of the elevator affected the living comfort of residents. For measurements in the living room, the effect appeared to be the most in the range of 250 Hz. Moreover, for measurements in the bedroom, the effect appeared to be considerable in the range of 125 Hz. Regarding noise and vibration, the same tendency was confirmed in both the living room and bedroom. Based on these results, solutions should be presented in low-frequency bands in which noise and vibration produced during the operation has considerable influence on residences so as to reduce the elevator noise.

4. CM Solutions

4.1. Design Solutions

4.1.1. Separation of Residences and Elevators

In the ground of residents, to relieve ENV damages of HRBs, solutions applied in the design phase comprise two approaches. First, to separate space that is sensitive to noise such as bedrooms and living rooms from hoist ways or elevator shafts. Second, to arrange a buffer space between the rooms that are adjacent to hoist ways to increase the thickness of machine room slabs and hoist way walls, and to supplement partly building components similar to the detailed changes of hoist ways.

The most efficient approach to relieve the effects of noise and vibration of HRB elevators that run at a high speed is to separate elevators from residences and arrange them. By comparing the results of noise measurement from the case when an elevator is attached to a living room or bedroom, like Figure 4, with the results of noise measurement from the case when an elevator is separated from residence, the effect can be confirmed. In particular, it is confirmed that noise became as low as 10–20 dB in the band of >125 Hz where the elevator is separated from residences. However, in a limited building area, residence design with high density should be high and if considering design-constraint conditions, such as daylight, view, and space function, there is a case that space that is sensitive to noise like living rooms and bedrooms cannot be separated and arranged. In this case, the second design solutions should be identified.

4.1.2. Buffer Space Design

As shown in Figure 6a, because the elevator hoist way is adjacent to bedrooms, noise and vibration are directly transferred if the elevator is operated. The case of toilet has a reduced impact of ENV; the case of a bedroom has a bad influence on rest and sleeping time. For HRBs in Korea, because a hoist way is designed with a 200-mm-thick bearing walls, airborne noise is blocked. However, the shield effect of structure-borne noise is not high. Thus, to relieve the transmission of structure-borne noise, residents feel it can be reduced if a wardrobe is placed similar to Figure 6b. To check the effect of it, one case of noise measurement in an apartment bedroom where there was a wardrobe sharing the wall with the elevator shaft was measured in comparison with another case without the wardrobe in the same condition. In Figure 6b, similar to the case of the installed wardrobe, the installation of wardrobe reduced noise level by ~7.6 dB, although Figure 6b is in the same plane compared to the general rectangular shape bedroom of Figure 6a. Such noise reduction was basically made possible by the effect of sound absorption or sound insulation using sound-absorbing materials such as blanket and clothing, both of which are filled at both sides of the wardrobe and inside of it. Moreover, the installation of the wardrobe made it possible to control the phenomenon of noise in a low-frequency band, known as room mode, which breaks the rectangular shape of a bedroom.

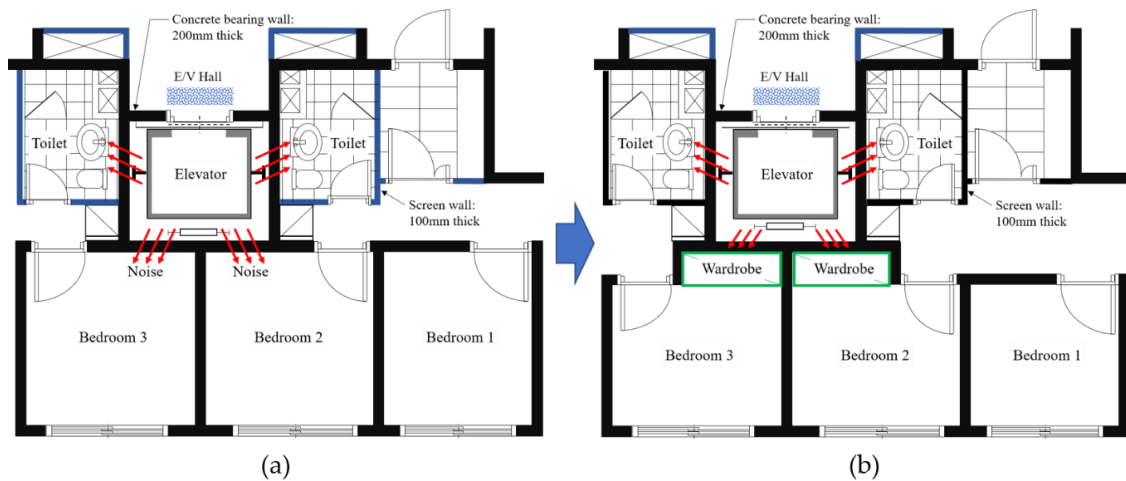


Figure 6. Noise reduction design using a wardrobe: (a) A floor plan without a wardrobe; (b) a floor plan with a wardrobe [17,21].

4.1.3. Change of Hoist Way Details

The elevator that runs at 120 m/min should be installed in HRBs with >26 floors (Table 1), and for HRBs with >40 floors, the elevator should run at a high speed of 180 m/min. For elevators that run at a high speed, turbulent airflow is produced, which leads to air friction noise, puff noise, inrush noise, and draft noise [38,39,56]. Design solutions regarding airborne noises are attributed to such a turbulent airflow.

(1) Air Friction Noise

As an elevator runs at a high speed in a hoist way (Figure 7a), air is compressed in a car-heading direction and elevator piston effect that increases air pressure [4,8,9,37–39,57,58]. Compressed air travels through the cramped gap between car and hoist way to the upper part of the car, which creates noise known as an air friction noise. The air friction noise gets louder as the area of the gap gets smaller compared to the area of the car with a faster speed of the elevator. This occurs as either a single elevator or double elevators run at a high speed in a hoist way. When two elevators run at the same time and in the same direction, the noise gets even louder. There is not an issue in the case that the elevator runs at 120 m/min in the hoist way for a single elevator, and the elevator runs at 180 m/min in the hoist way for double elevators. Note that the area of the hoist way should be designed to be bigger than normal by 40% at a higher speed such as Figure 7b [38,39].

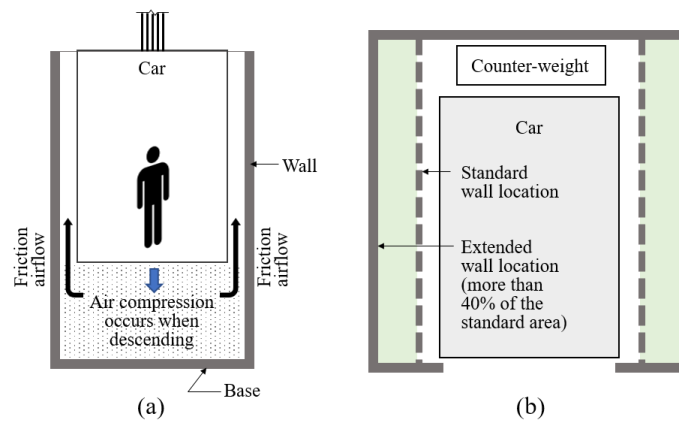


Figure 7. Air friction noise and design solution: (a) Air friction noise; (b) a design solution for air friction noise.

(2) Narrow-Section Passing Noise

Narrow-section passing noise, called puff noise [38], is a noise that is produced when an elevator goes through protruding steel installed as Figure 8a because of the structural mechanism or the installation of a guide rail. The elevator goes through an RC beam, which creates wind pressure that contributes to the noise. For HRBs, such protruding parts are reported per floor; therefore, the noise repeatedly occurs. To prevent this, architectural designing should be processed without the protruding parts inside the hoist way. However, in cases where it is unavoidable to have protruding parts, it is appropriate to install an air sliding panel upon and underneath the protruding parts to relieve the wind pressure that occurs in that area (Figure 8b). The appropriate angle of the air sliding panel is $4\text{--}8^\circ$ [38,39]. This solution is required in the hoist way for a single elevator that runs at a speed of >150 m/min; in other words, with >31 floors in HRBs. The same solution is to be considered in the case that the car speed is >180 m/min in a hoist way for double elevators.

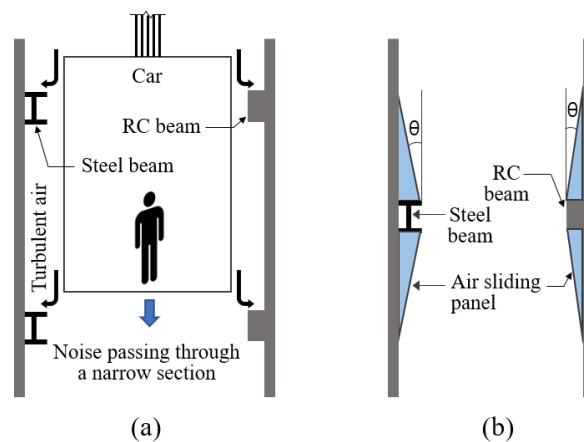


Figure 8. Narrow-section passing noise and design solution: (a) Noise generation; (b) the design solution.

(3) Inrush Noise

It is common to arrange more than two elevators in HRB where there are >20 floors and four householders on each floor. When only one elevator of multiple elevators enters in the single hoist way (Figure 9a), noise is produced by compressed air flow, which is called inrush noise [38]. It is common that the car vibration occurs along with noise when the inrush noise by the high speed is considerable. This is preventable because the cause of inrush noise is rapid air compression when an elevator rushes in. The best approach is not to have the single hoist way; however, in the case where it is unavoidable to have one because of structural constraints, two solutions can be considered. First, similar to Figure 9b, ventilation openings can be placed either on one side or both sides of the single hoist way wall. The size of the opening varies depending on the size and speed of the car; however, there is no trouble if it is designed within 1.5 m^2 . If it is difficult to place the ventilation opening, the wall is expanded such that the floor area of the hoist way is increased by $>40\%$ (Figure 9c) [38,39].

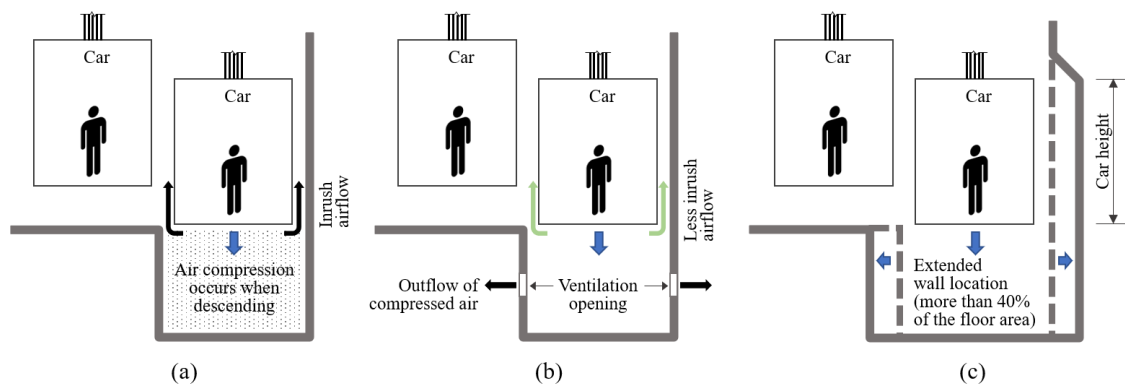


Figure 9. Inrush noise and design solution: (a) Inrush noise; (b) a ventilation opening arrangement; (c) expansion of the hoist way floor area.

(4) Draft Noise

Generally, in a high-lift elevator, a pressure difference is generated between the landing and hoist way. Therefore, air flows into and out of the hoist way from the gap around the landing door; at that time, a blowing sound called draft noise is generated [39,56]. In particular, this noise gets worse when the air produced by a heater in winter flows in the hoist way and the elevator ascends. The solution to this is to design an entrance door that is double-layered or a revolving door such that cold air outside does not enter within HRB. Moreover, it should be designed with air-shielding details between and around elevator opening frame of the landing floor such as a landing door, jamb, and sill [56].

4.1.4. Other Design Solutions

Note that design solutions should be considered, in addition to design solutions that are suggested, so as to alleviate the ENV that residents of HRBs feel.

- As shown in Figure 3, a machine support frame should be suspended from a machine room floor slab.
- The thickness of the machine room floor is designed to be possibly >350 mm, including a 200-mm-thick RC slab and 150-mm-sized light-weight concrete.
- The thickness of the wall in the machine room is designed to be >150 mm, whereas the sound absorption layer is placed within the wall.
- The thickness of the hoist way wall is designed to be >200 mm.
- If the hoist way space is sufficiently big, separated beams are supplemented. Moreover, the installation of rail brackets reduces noise a lot while an elevator is running.
- The counter-weight of the elevator is planned to be installed on the staircase or external wall rather than adjacent residences.

4.2. Construction Solutions

Construction solutions are the ones to be applied to at the construction phase and are about the selection of elevating machinery, the location, and the method of installation, in addition to design solutions that present solutions to ENV problems at a planning phase. Similar to Table 5, the problems are classified into structure-borne and airborne noises, and again classified into the machine room and hoist way (shaft), and then construction solutions are analyzed and presented. They are subdivided into either controlling elevator vibration or noise sources and controlling transmission paths.

Table 5. Construction solutions to mitigate ENV.

Description	Sources	Solutions
Structure-Borne Noises	Machine room	Measures for vibration sources <ul style="list-style-type: none"> - Use of high-quality motors - Precise balance of brakes, gears, and elevator car Measures for anti-vibration <ul style="list-style-type: none"> - Isolation of the traction machine from the support frame - Isolation of the switchgear cabinet from the machine room slab
	Hoist way	Measures for vibration sources <ul style="list-style-type: none"> - Improvement of guide rail machining accuracy: Machining error within ± 2 mm/5 m - Improvement of guide rail installation accuracy: Seam surface difference between rails within ± 0.05 mm Measures for anti-vibration <ul style="list-style-type: none"> - Fastening rail brackets at the edge of slab - Isolation of guide rails from hoist way wall
Airborne Noises	Machine room	Measures for noise sources <ul style="list-style-type: none"> - Use of high-quality motors - Precise machining and fabrication of brakes, gears, and coupling parts - Use of low-noise cooling fan or self-cooling system Measures for anti-noise <ul style="list-style-type: none"> - Installation of sound insulation cover over the rope hole - Isolation of airborne noise inside machine room
	Hoist way	<ul style="list-style-type: none"> - Precise installation of elevator doors for silent operation - Volume adjustment of door enunciator

Table 5 shows the construction solutions to mitigate ENV that are obtained through the studies for years after contemplating various research documents [14,18–21,27,38,39,50–52]. Structure-borne noise generated in the machine room primarily occurs via the vibration of the elevating machinery. To alleviate this, elevating motor with power filters with high quality basically are used and brakes, gears, and elevator car should be installed to maintain the precise balance of elevator machinery. Moreover, vibration isolation pads that have high damping performance such as neoprene or rubber should be inserted at fixing points such that the vibration is generated in the traction machine and switchgear cabinet [14,18–21,50–52]. When anti-vibration pads are installed in the traction machine, the first natural vibration frequency of the whole elevator should be maintained at a less than audible frequency band. For the traction machine to work precisely aligned with the height between elevator car and hall landing, elevator machinery and anti-vibration pads should be installed, thus maintaining balance to minimize isolation deflection. For this purpose, close cooperation with an elevator manufacturer and installer is required at the installation phase.

To alleviate structure-borne noise generated in the hoist way or elevator shaft, the machining errors of guide rails are to be maintained within ± 2 mm/5 m, and seam surface difference between guide rails of the guide rails should be installed within ± 0.05 mm, which alleviates vibration because of the movement of rollers. Vibration-borne noise produced in the hoist way occurs between the guide rollers of the car and rails. To prevent this, brackets should be installed next to the floor slab to fixate the rail (Figure 10). The floor slab edges are inherently stiffer than the shaft walls and will limit the transmission of rail and roller guide interactions from generating the structure-borne noise in adjacent spaces [14,17,21]. Furthermore, anti-vibration pads should be installed between brackets and floor slab edges. For reference, depending on the location of the rail brackets, it is confirmed that the noise difference by ~ 4 dB on an average occurs because of the measurement of noise while an elevator is running [21].

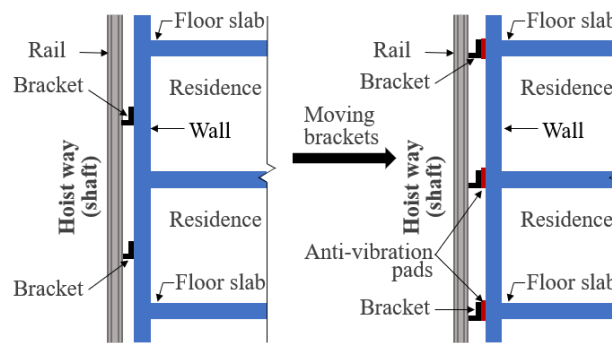


Figure 10. Fastening rail brackets at the edge of a slab.

Measures in correspondence with the construction phase should be considered because airborne noises generated in the machine room primarily occur by the tonal sound of the elevating machinery. It is essential to select motors of good quality to encounter noise sources and precise machining; moreover, the fabrication of brakes, gears, and coupling parts should be performed.

A low-noise cooling fan or self-cooling system in the machine room should be used. As shown in Figure 3, sound insulation cover should be installed around the rope hole as transmission paths of airborne noises in the machine room. Moreover, soundproofing materials should be used to encounter isolation of airborne noise on the interior wall and the ceiling in the machine room. After glass wool as thick as 50 mm is placed on the wall and ceiling in the machine room, it is confirmed that the level of noise generated in the elevating machinery is reduced by 6.2 dB on average. In particular, it is confirmed that the noise level in the range of 1 kHz frequency is reduced by 9.4 dB at the maximum.

Airborne noises generated in the hoist way are primarily related to the elevator door. The primary noise sources of the door are its misalignments or improper installation and alarm sound for arrival on each floor. To solve such problems, the precise installation of doors is required, and the volume of the door enunciator is to be adjusted to <60 dB(A).

4.3. Verification of CM Solutions

In this study, the suggested CM solutions are applied and how much ENV is alleviated should be confirmed. For this purpose, after selecting the HRB project with a 25-story building as a case, the most effective elevators of CM solutions and design solutions, such as separation of residences and elevators as well as the hoist way wall as thick as 200 mm, were applied. One noticeable aspect is that it is designed using MRL elevators [49] that are generally used for buildings of <20 floors. Moreover, after selecting an OTIS elevating machine of good quality at the construction phase, the construction solutions suggested in Table 5 were mostly applied. The case project was completed in 2020, whereas the elevator noise of two buildings was measured in the same method of Figure 4d. The vibration measurement with the sensors attached on the wall was not done without the agreement of the residents (Figure 4c).

As shown in Figure 11a, the staircase was placed between the elevator and the bedroom of residence. Two elevators were placed as per design guidelines because there were four householders on each floor in Building 'A' [41,42]. Figure 11b shows that the elevator is separated from residence using the elevator hall. For this measurement, it was conditional that the elevator runs departing from the second floor as the lowest floor and stopped on the 25th floor. The measurement was made in bedrooms on the 25th floor as the highest floor. Moreover, the measurement time was 90 seconds, and the elevator speed was 105 m/mm, which is the speed of the 25-story HRB classified in Table 1. The same measuring system as in Table 5 was used for measuring noise generated by the elevator with a capacity of 15 persons and 1150 kg.

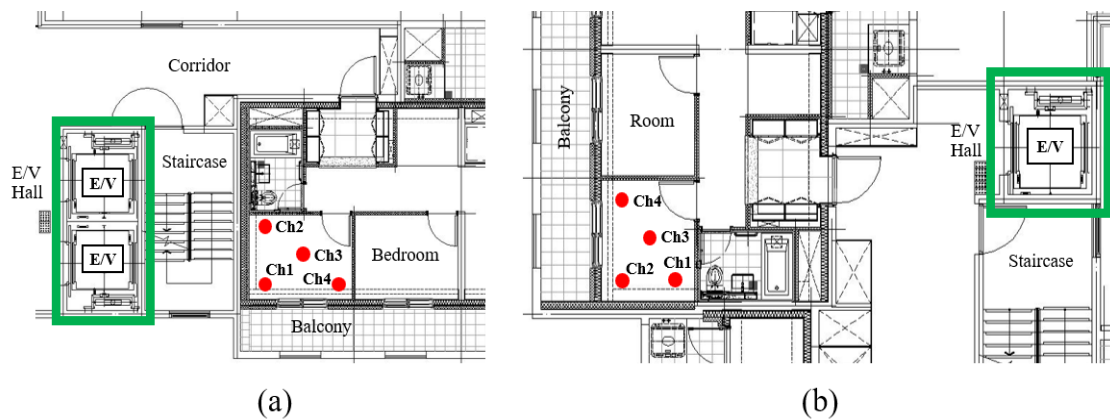


Figure 11. Elevator noise measurement of HRB 'D': (a) The 25th floor plan of Building 'A'; (b) the 25th floor plan of Building 'B'.

Figure 12 shows the result of noise measurement for the case that elevators and residences were isolated, as seen in Figure 11a,b. Similar to Figure 5, the effect of noise measurements compared to BGN in the range of <500 Hz appears to be extensive. Note that regardless of different conditions, it shows that it was a low-frequency band that had an influence on elevator noise. In particular, the effect of the two cases seemed to be extensive at 63 Hz; moreover, the common aspect is that the effect of low-frequency bands at the central measuring point appeared to be less. The reason is that the low-pitched superposition phenomenon by the room mode was most remarkably noticeable at the corners of rectangular bedrooms. Figure 13 shows the distribution of the sound pressure level by the overlapping and offsetting of sound energy per frequency band in the rectangular room. The low sound energy at 63 and 125 Hz certainly demonstrated the phenomenon of remarkable overlap at the corners of the room [59].

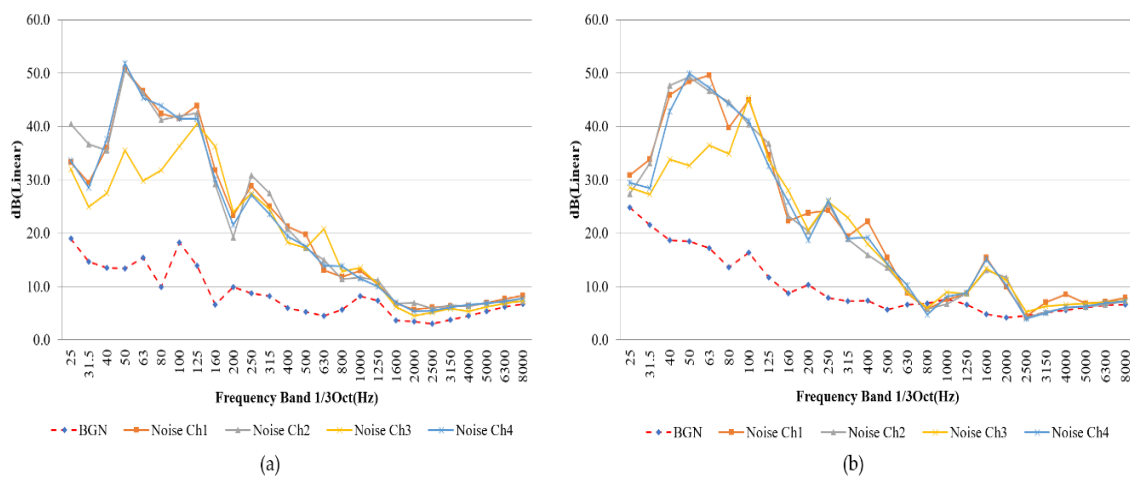


Figure 12. Elevator noise measurement results of HRB 'D': (a) The measurement results of 'Building A'; (b) the measurement results of 'Building B'.

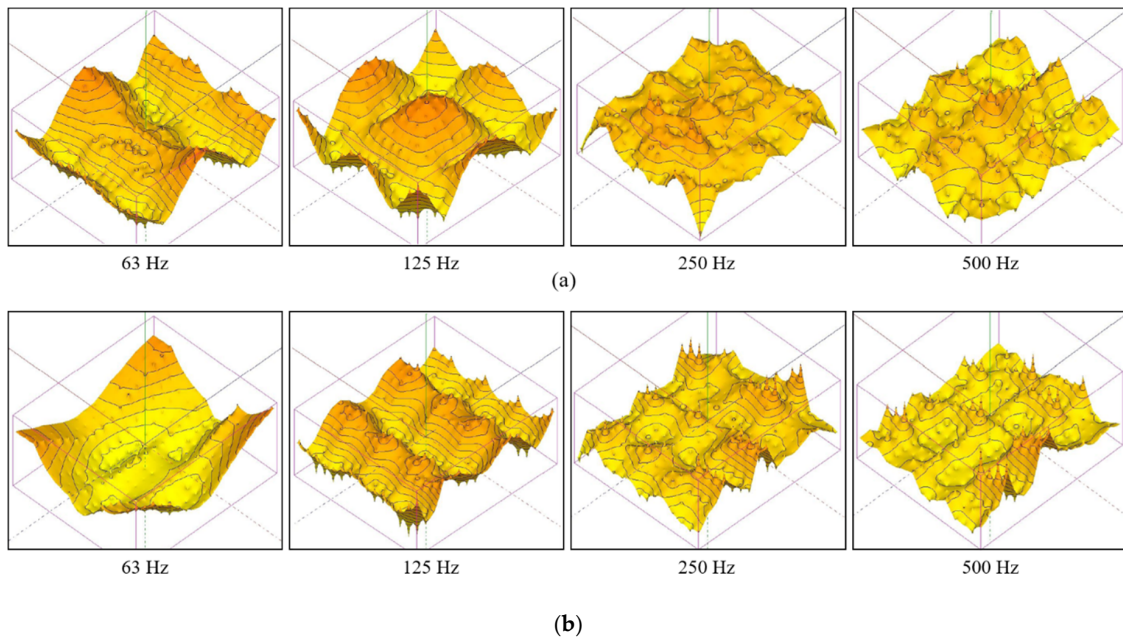


Figure 13. Different patterns of spatial distribution of sound pressure level in a room according to the frequency bands [59]: (a) The noise measurement results at the center; (b) the noise measurement results at the corners.

Figure 14 shows the analysis of the level of noise reduction and noise characteristics as per the frequency band after the average conversion of the measurement results of Figures 5 and 12. The measurement results of Figure 12 show that, in this study, CM solutions that were applied as suggested demonstrate the remarkable reduction of noise in the frequency band of >100 Hz. Figure 12 shows that there was no considerable difference at frequencies of <125 Hz; however, it was confirmed that noise of HRB ‘D’, in which elevators and residences are isolated in the frequency of >125 Hz, was measured at a noise level lower than that of HRB ‘W’. As shown in Figure 13, for HRB ‘W’, while the average value of the noise level compared to BGN makes a difference within 26 dB(A), the case of HRB ‘D’ maintains the level of 5 dB(A). This is explained to be the alleviating noise that residents feel with CM solutions suggested in this study. However, regardless of the isolation of elevators and residences in the low-frequency band of <125 Hz, the noise level compared to BGN seems to be high. The structure-borne noise generated by the operation of the elevator is analyzed to be high in the low-frequency band.

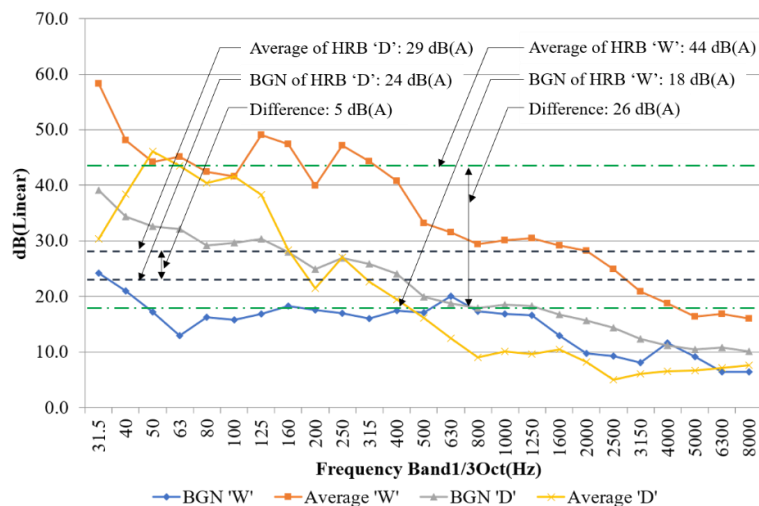


Figure 14. Noise analysis by frequency band according to the location of elevators and residences.

5. Discussion

To solve ENV problems of a building, multiple studies regarding mechanical solutions have been conducted; in certain studies, solutions were presented from the perspective of design and construction, which are only for residential buildings of less than ten floors. Thus, to alleviate the ENV of HRBs that run at >90 m/min, solutions that consider the characteristics of high-speed elevators and HRB floor plans on the basis of knowledge obtained from the results of their study are necessary. We analyzed the characteristics of noises and vibrations produced in machine rooms and hoist ways through ENV-related studies of HRBs for the past few years and sources vs. transmission paths of airborne and structure-borne noises, and then presented solutions that control the stage of design and construction. A case study was processed to confirm the given solutions. CM solutions applied to the case of HRB 'D', including isolation arrangement of elevators and residences, 200-mm-thick RC wall design of hoist way and most other solutions are presented in Table 4; they were then applied to the construction phase. We were then able to confirm considerable improvement compared to HRB 'W' case because of the measurement on noise of HRB 'D'. Vibration measurement was impossible because the residents opposed to sensors being installed on the wall; however, it is assumed that there may have been improvement of vibration corresponding to that of noise considering the HRB 'W' case.

Studies on identifying the effectiveness of alleviating noise should continue with thorough experimentation in each item to clarify the utility of the CM solutions given in this study. The extra application of researches of CM solutions should be processed by the subject area of HRBs presented in Table 1.

6. Conclusions

There have been many studies regarding ENV worldwide, which is proof that the more sensitive humans have been to noise, the more comfortable life environment they have demanded. In particular, for HRBs built in many downtown areas where there are external noise sources, residents demand more static environments, while noise is more likely to occur because of the use of high-speed elevators. To solve such a dilemma, we contemplated multiple documents and presented CM solutions to alleviate ENV of HRBs in this thesis by means of the study of years. An HRB project with ENV problems and an HRB project that uses solutions given in this study were processed as a case study, and its effectiveness was verified, with the results as following.

First, BGN and BGV appear to be relatively high in the range of low frequency of <500 Hz if an elevator hoist way is adjacent to the living room or bedroom. It was confirmed that the noise produced at low-frequency bands of 250 Hz for a living room and those of 125 Hz for a bedroom had a considerable impact on the living comfort of residents.

Second, in the case of HRBs to which CM solutions are applied, the effect of the measured noise compared to BGN is within the range of <500 Hz. This shows that what affects elevator noise were low-frequency bands of <500 Hz. CM solutions application effects appeared to be the most in the range of 63 Hz; moreover, a common aspect is the effects of low-frequency band turning out to be little at the central measurement point Ch3. The reason is because it is analyzed that the distribution of sound pressure level by overlapping and offsetting of sound energy per frequency band in the rectangular room was remarkably noticeable.

Third, compared to the measurement results of the two case projects, the elevator noise of HRBs that CM solutions were applied to in the frequency band of >100 Hz are confirmed to remarkably reduce noise. Especially, it is confirmed that the CM solutions-applied noise of HRB 'D' was measured to be relatively low, in the frequency band of >125 Hz. While the average value of noise level compared to BGN in the case of HRB 'W' with ENV problems makes a difference of 26 dB(A), the case of HRB 'D' that the CM solutions were applied to maintain the level of 5 dB(A). Thus, it is comprehended that, in this study, the CM solutions suggested largely alleviated noise.

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