ACOUSTIC RENOVATION OF A CIRCULAR-SHAPED SMALL MUSIC HALL

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1 INTRODUCTION

The acoustic environment of a music performance venue significantly impacts both the performers and the audience[1]. Concert halls designed for classical performances, where electric amplification is not used due to the nature of the genre, require appropriate architectural acoustics to complement the music[2]. Typically, concert halls designed for classical music follow traditional shoebox-shaped or fan-shaped layouts, with excellent sightlines[3]. However, more recently, concert halls with a vineyard-style layout have also been designed[4,5]. Nevertheless, some venues have a circular floor plan, which inherently includes acoustic deficiencies such as sound focus issues.

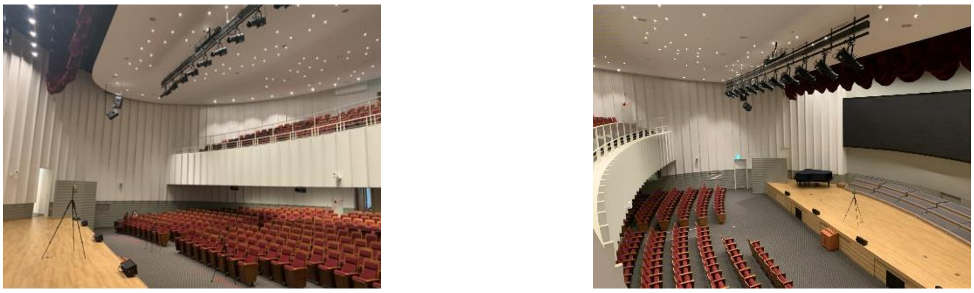
In general, concave and curved interior spaces result in a non-uniform sound field distribution due to focused reflections[6]. Furthermore, early reflections from the lateral walls may propagate only to the rear walls due to the rotunda effect, resulting in a poor sense of space in the center[7]. However, there are examples of venues where various design elements have been applied to overcome the acoustic disadvantages of circular spaces[8,9,10]. In his design of the ORBIS hall at the Kobe Fashion Museum, Ando[8] used convex and asymmetrical ceiling reflectors and a diffuse reverberation chamber under the floor to create a sense of space and reverberation. Ottley[9] designed a circular conference room and used ceiling reflectors to reinforce early reflections to create a space for intelligible speech. Meanwhile, Kanev and Livshits[10] examined the design elements of three concert halls with circular floor plans to consider ways to improve acoustics.

This study focused on a specific small music hall designed in a circular layout and aimed to derive design elements for acoustic improvement and propose specific design solutions using computer simulations. The proposed improvements incorporated design elements aimed at mitigating the acoustic focusing phenomenon caused by the circular floor plan and enhancing the weakened lateral reflected sound in the central area to improve the spatial impression. Then, measurements of the indoor sound characteristics were conducted after the renovating construction works according to the proposed design solutions, to validate their effectiveness using simulations.

2 THE HALL BEFORE THE ACOUSTICAL RENOVATION

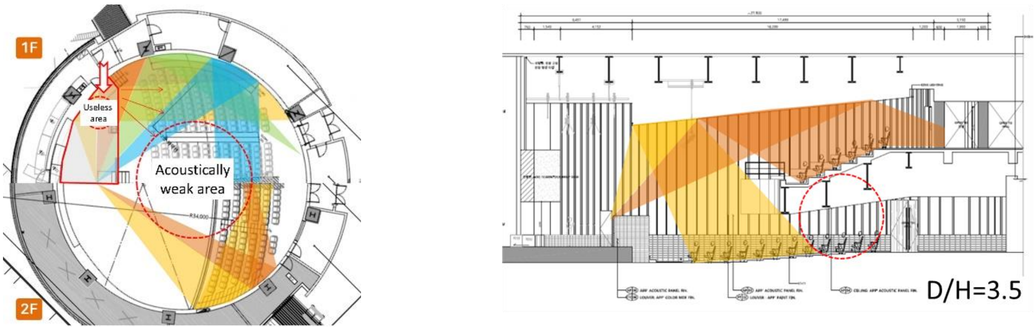
2.1 The target hall

The target hall has a circular shape with an approximately 500 seats. The target hall has 364 seats on the first floor and 169 seats on the second floor. Figure 1 shows the interior of the target space before renovation. It is anticipated that the circular configuration may lead to a deficiency in the distribution of lateral reflected sound as shown in Figure 2(a), resulting in a lack of sound reaching the central portion of the seating area due to the phenomenon of sound focus on the center of the circular stage. In addition, as shown in the cross-section in Figure 2(b), the soffit space under the balcony was designed too deep (D/H=3.5) so that ceiling reflections barely reached it, and the viewing angle of the rear row was also impeded.



(a) Interior view from the stage (b) Interior view from the balcony

Figure 1. Interior views of the target hall



(a) Floor plan (b) Sectional plan

Figure 2. Floor and sectional plans of the target hall with lateral reflection paths before the renovation

2.2 Measurement method

To analyze the current acoustic properties, measurements were conducted on-site according to ISO 3382-1[3]. For on-site measurements, a total of 56 measurement points were selected, with an omni-directional sound source placed at a height of 1.5 m on the center stage platform and measurements taken at intervals of 1 m at various positions within the seating area as shown in Figure 3.

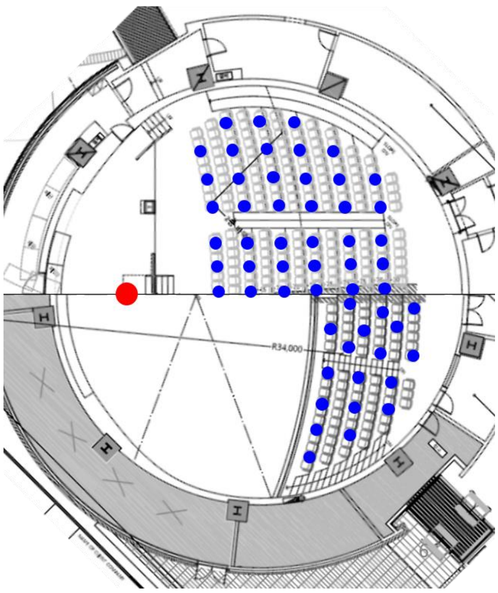
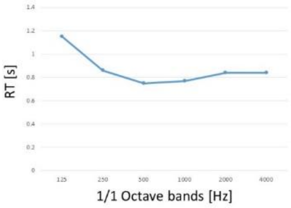


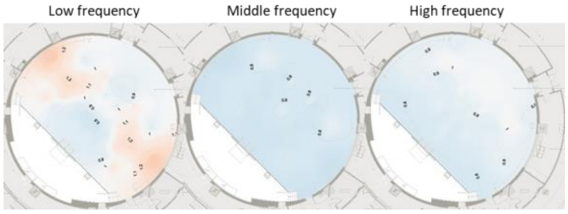
Figure 3. Measurement positions of the sound source and the receivers before the renovation

2.3 Measurement results

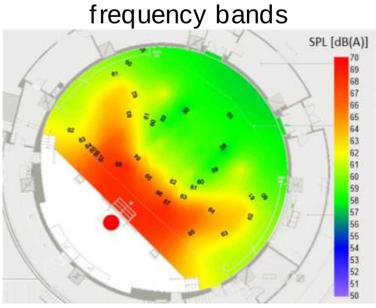
The results showed that in Figure 4(a), the reverberation time in the mid-frequency range was 0.76 s, which is considered very low for classical performances. It was evaluated as having an unbalanced tone due to being unusually low compared to the low-frequency and high-frequency ranges as shown in Figure 4(b). Additionally, Figures 4(c) and 4(d) showed the spatial distribution of A-weighted sound pressure level and lateral energy fraction, respectively. Despite its proximity to the sound source, the sound pressure level at the center of the first floor was unexpectedly low. The lateral energy fraction was below 0.2 except for the points close to the sidewalls, indicating a lack of spatial impression.



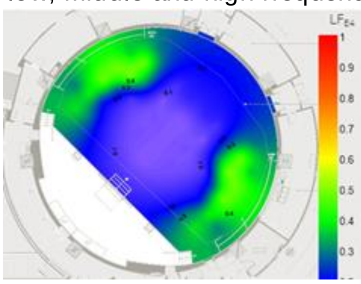
(a) Reverberation time (*RT*) as a function of frequency bands



(b) Spatial distribution of reverberation time (*RT*) for low, middle and high frequency bands



(c) Spatial distribution of A-weighted sound pressure level (*SPL*) on the first floor



(d) Spatial distribution of lateral energy fraction (LF_{E4}) on the first floor

Figure 4. The measured acoustical parameters before the renovation

2.4 Design items for acoustic improvements

From the review results of the drawings and measurements, it was observed that there were issues with poor visibility and sound pressure level beneath the balcony. The sound field distribution was uneven due to the rounded side walls, and there was mid-frequency band reverberation distortion caused by multi-perforated sound absorbers. Considering the current situation, it is deemed necessary to incorporate a side balcony to enhance the acoustics. This addition aims to establish both acoustic and visual intimacy, while achieving an appropriate level of reverberation for indoor music performances.

3 THE HALL AFTER THE ACOUSTICAL RENOVATION

3.1 Renovation progress

Figure 5 shows the floor plan of the evaluated space, depicting the existing design and the proposed improvements. To enhance intimacy, visibility, and spatial impression, side balcony seating on the first floor and side balconies on the second floor have been added. Additionally, the interior of the walls has been modified to reinforce reflection, and the second-floor balcony has been reduced in size. Figures 6 and 7 present the simulation results conducted to predict the acoustic effects of the proposed improvements in terms of *RT* and *LF*, respectively. Figure 8 shows the pictures of the renovated design and construction progress.

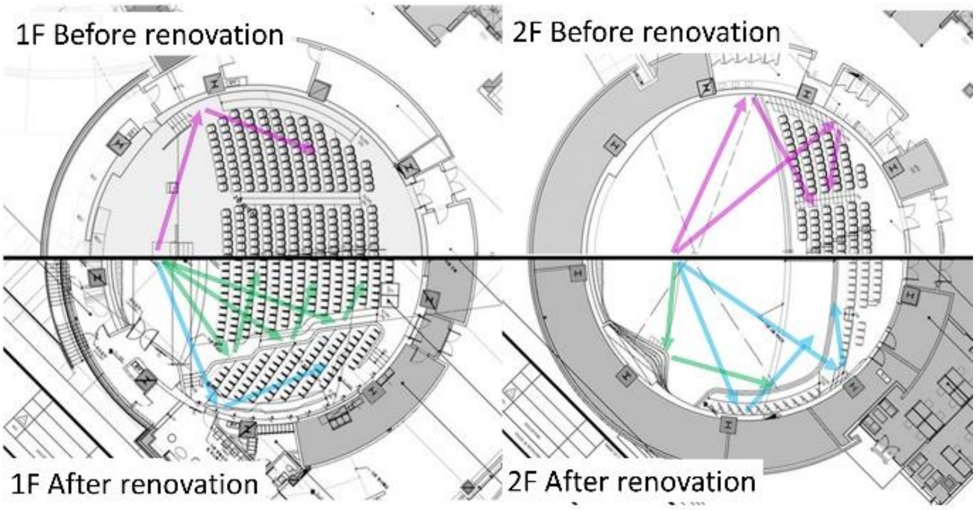


Figure 5. Floor plan of the evaluated space, depicting the existing design and the proposed improvements

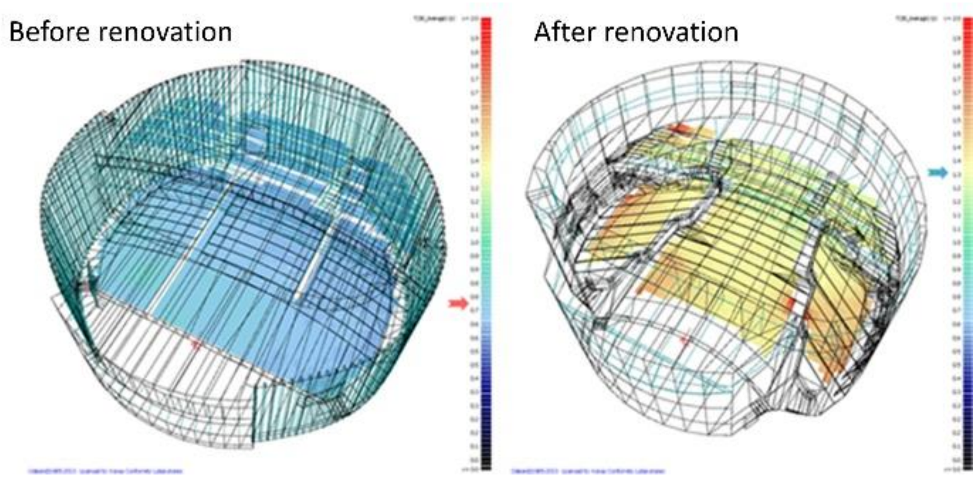


Figure 6. The simulated reverberation time values before and after the acoustical renovation

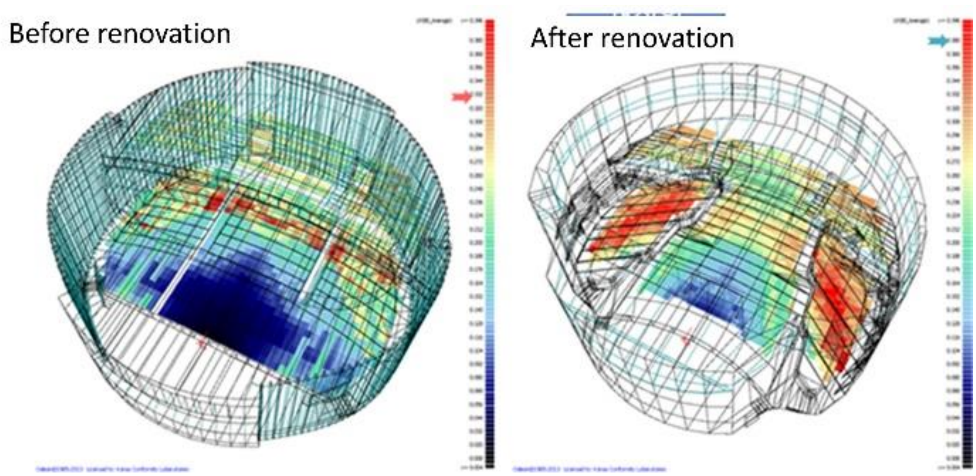
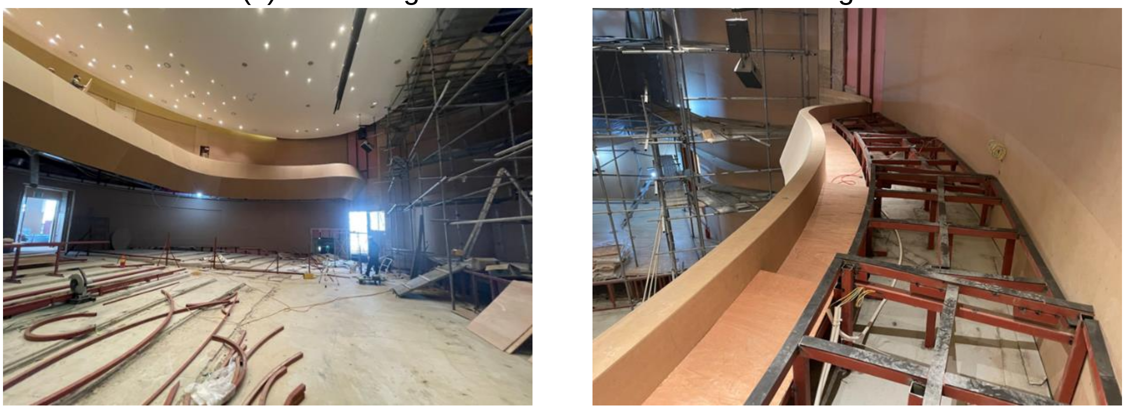


Figure 7. The simulated lateral energy fraction values before and after the acoustical renovation

(a) Initial renovation design using Sketch-up

(b) Rendering view of the final renovation design



(c) Interior view of the target hall under the construction work

(d) Interior view of the target hall after the renovative construction work

Figure 8. Pictures of the renovation design and construction

3.2 Measurement methods

To assess the acoustic performance after the renovation, the same method as before the renovation was according to ISO 3382-1. Figure 9 shows the positions of the sound sources and receivers used in the acoustical measurements after the renovation. Basic acoustic parameters, including reverberation time (*RT*), were measured using omni-directional microphones, while the lateral fraction (*LF*) was measured using bi-directional microphones placed in the same locations. Additionally, an artificial head and torso system (dummy head) was used to measure interaural cross-correlation coefficient (*IACC*) for evaluation of spatial impressions.

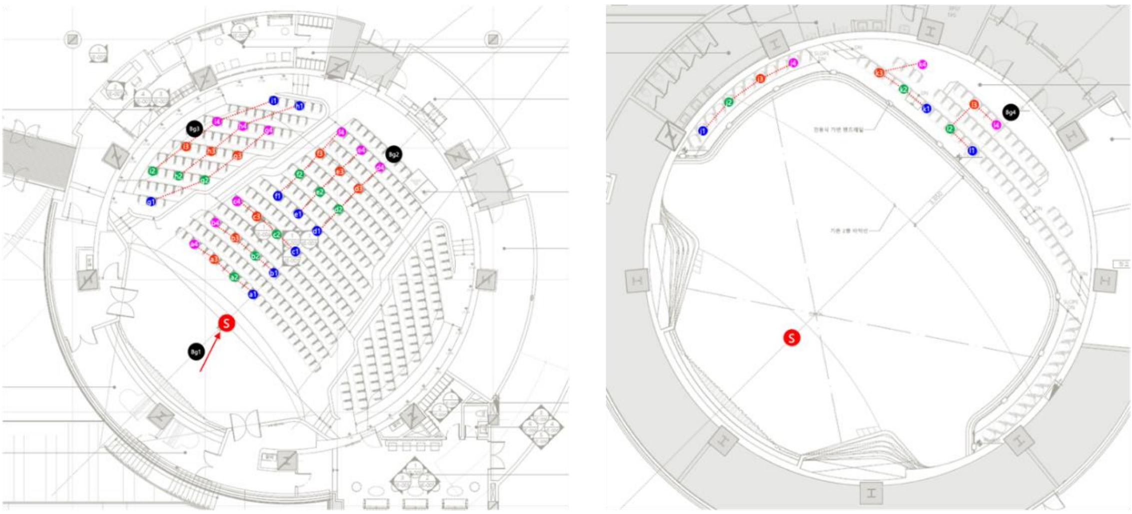
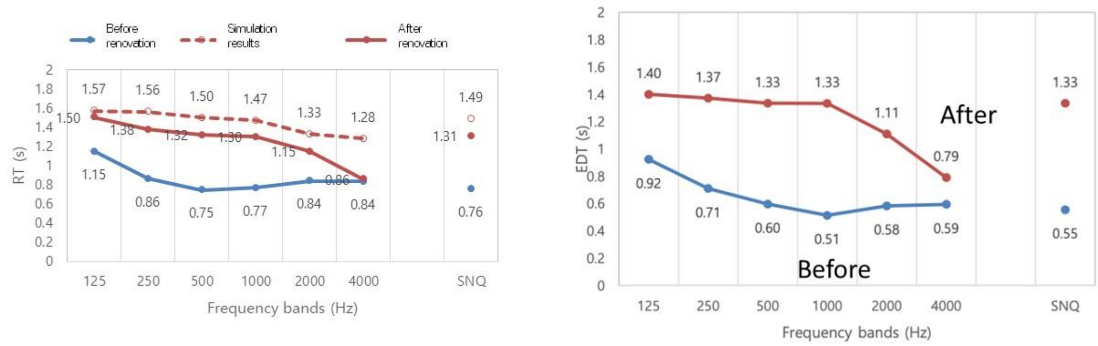


Figure 9. Measurement positions of the sound source and the receivers after the renovation

3.3 Measurement results

Figure 10(a) shows the measured results before the renovation, the simulation predictions, and the measured results after the renovation for the reverberation time across different frequency bands. The average reverberation time in the mid-frequency range before the renovation was 0.76 s, which was suitable for speech-oriented purposes. However, after the renovation, the average reverberation time in the mid-frequency range increased by 0.55 s, reaching 1.31 s. The simulation predictions for the reverberation time had a design target of 1.49 s in the mid-frequency range, which was not fully achieved. This discrepancy is presumed to be due to underestimating the sound absorption characteristics of the reused existing audience seats. However, it should be noted that the measured reverberation time corresponded to the typical range of 1.2 to 1.6 s for a classical recital hall, so it can be considered acceptable within that range.

Figure 10(b) shows the measured early decay time as a function of frequency bands before and after the acoustical renovation. *EDT* at 500 Hz and 1,000 Hz was dramatically improved from 0.60 s and 0.51 s to both 1.33 s, respectively. Since the results indicate that the early decay time (*EDT*) is higher than the reverberation time (*RT*) after the renovation, it is anticipated that the perceived early reverberation will be favorable.

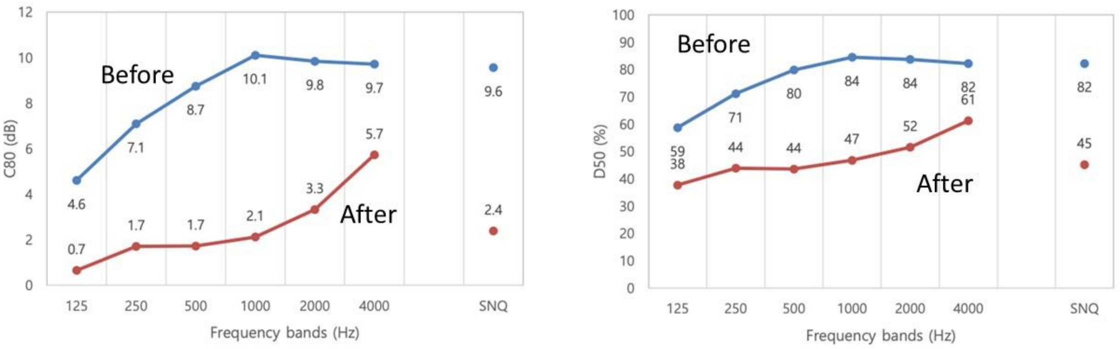


(a) Reverberation time (*RT*) as a function of frequency bands

(b) Early decay time (*EDT*) as a function of frequency bands

Figure 10. The measured reverberation time and early decay time values as a function of frequency bands before and after the acoustical renovation

Figure 11(a) shows the frequency characteristics of music clarity before and after the renovation. The $C_{80,3B}$, the average value of C_{80} in the frequency bands from 500 Hz to 2,000 Hz, decreased from 9.6 dB before renovation to 2.4 dB after renovation. This reduction occurred naturally in response to the increase in reverberation. However, $C_{80,3B}$ value after the renovation exceeds the recommended range of -2 dB to 2 dB for typical design guidelines. Figure 11(b) shows the frequency characteristics of definition (D_{50}) before and after the renovation. The average value of $D_{50,m}$ within the frequency range from 500 Hz to 1,000 Hz decreased from 82% before the renovation to 45% after the renovation. Typically, a $D_{50,m}$ value of over 50% is recommended for performance venues. However, the results after the renovation showed a slightly lower value than the recommended threshold due to the influence of the increased reverberation.



(a) Clarity (C_{80}) as a function of frequency bands

(b) Definition (D_{50}) as a function of frequency bands

Figure 11. The measured music clarity (C_{80}) and definition (D_{50}) values as a function of frequency bands before and after the acoustical renovation

In Figure 12, it can be observed that the average value of the lateral energy fraction (*LF*) after the renovation is 0.4, which is twice the value compared to before the renovation. This indicates a significant improvement in spatial perception, with a richer sense of spaciousness in the venue. In addition, the 1-$IACC_{E3}$, also known as the binaural quality index (*BQI*), was measured to be 0.63. This value indicates a good acoustic performance and shows a similar distribution pattern to other halls that are considered to have excellent sound quality.

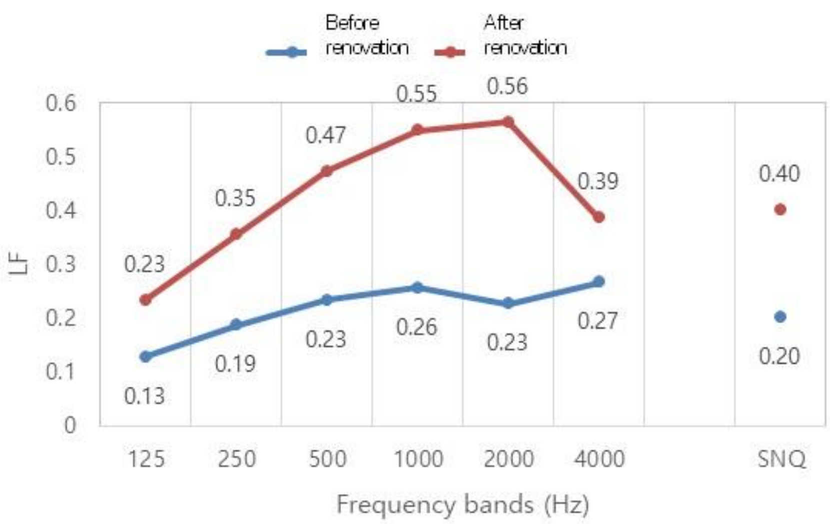


Figure 12. The measured lateral energy fraction values as a function of frequency bands after the acoustical renovation

4 CONCLUDING REMARKS

This study conducted on-site measurements to assess the acoustic performance of a remodeled circular-shaped small performance venue and compared and analyzed the acoustic performance before and after the improvements. The results showed that indicators of reverberation time and early decay time, which represent the sense of spaciousness, were improved, making the venue suitable for classical performances. Moreover, indicators related to clarity, such as musical clarity and speech intelligibility, were also improved within the recommended range for performance venues. Indicators related to spatial impression, such as lateral energy fraction and interaural cross-correlation coefficient, were also enhanced, resulting in a more immersive spatial experience. The major issues identified before the improvements, including a lack of spatial impression and low reverberation time, were significantly addressed through the renovation based on the proposed design solutions.

5 ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2022R1F1A1072690).

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