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Acoustic design approach for ensuring low frequency balance in musical instrument study rooms: A case study

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Abstract
In musical instrument study classes, it is important to establish a balance between frequency bands to ensure acoustic comfort. Porous absorbers generally used in the room, air absorption also shorten the reverberation time in the mid and high frequency bands, but the reverberation time in the lower frequency bands is usually longer compared to mid and high frequencies. In order to balance the lower frequency band, the reverberation time values should be reduced; Helmholtz resonator panels may be preferred to increase the absorption at low frequency bands. The room's eigenvalues and eigenfunctions were determined by the aid of a computer software (ANSYS 2023 R1 Modal Acoustic Module) that uses the finite element method. Helmholtz panels suitable for the mode frequencies have been designed and mounted in the high-pressure regions seen in the mode shapes. In order to determine the success dimension of the design, ISO 3382-1 parameters, ISO 18233 room response curves and FEM simulation results obtained as a result of measurements made at 26 measurement points before and after the arrangement were compared. It was found that the use of panels provided optimum reverberation time values in the 125 Hz and 250 Hz octave bands according to the BS EN ISO 23591 standard, and that there was a significant improvement in the 63 Hz octave band. Hence, the distribution of sound in the space was improved according to the results obtained for the 26 measurement points.

Keywords
Architectural acoustic, FEM, Helmholtz resonator, Low frequency, Room response.

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1. Introduction

Music study classes have a very important function as musical instrument study environments. Students who receive conservatory education work in these classes for many years. At the same time, instructors use these classes for many years. Individuals who are trained to specialize in a certain musical instrument from a young age need to establish a good relationship with the musical instrument. If the sound of the instrument that is practiced for long hours a day is disturbed by the acoustics of the room, problems such as rapid fatigue and the disturbing effects of noise after a certain point can be encountered. It is important that the acoustic character of the rooms to be used as musical study environments meet the criteria determined by international standards.

The BS EN ISO 23591:2021 "Acoustic quality criteria for music rehearsal rooms and spaces" standard, which shows the acoustic criteria for music study environments, divides study rooms into four groups according to size and number of people. The study environments, which are divided into four as personal, small, medium and large study classes, were examined in 3 different groups according to music sound levels as low sound, high sound and reinforced sound. As a result of these classifications, the optimum acoustic criteria deemed necessary were determined based on room dimensions, reverberation time and background noise level values. This standard shaped the study environments based on this parameter depending on the sound power levels of musical instruments (British Standards Institution, 2021).

The most frequently used parameter when evaluating the acoustics of music practice environments is the reverberation time (Sinal & Yilmazer, 2018; Tămaş-Gavrea et al., 2019). The desired result is that the reverberation time values are at the optimum values. (Katunský et al., 2016). The perceived reverberation time can vary depending on the sound source (Vechi et al., 2020). Therefore, when measuring reverberation time values, one of the phenomena examined is that the signal used consists of musical sounds (Kendrick et al., 2006, 2008). The sound emission patterns, sound fields and sound power levels of musical instruments can change the reverberation time values (Shabtai et al., 2017). The acoustic properties of music rooms are decisive in the emergence of the sound character of the instruments as it should be.

Determination of room modes in small rectangular rooms can be done with simple calculation methods (Bistafa & Morrissey, 2003; Jian et al., 2022). It is seen that computer software is used because more complex calculations are required in non-rectangular rooms (Bai, 1992; Kelle & Yılmaz Demirkale, 2022). This software using the finite element method are less accessible due to high license fees and hardware requirements (Mehra et al., 2012). FEM is preferred for room acoustic simulations due to its extraordinary potential in accurately modeling irregularly shaped rooms and various acoustic materials (Yoshida et al., 2021). ANSYS APDL software can determine room eigenvalues (natural frequencies) and eigenfunctions (mode shape), sound pressure levels in the lower frequency bands using the finite element method. (Lau et al., 2017).There are differences between the methods used in the geometric acoustic model and the methods used in the wave model. While the scattering coefficients of the surfaces are used in software using the geometric ray tracing method, the scattering surface is provided by 3D modeling of the geometric form in FEM software using the wave-based method (Aretz & Vorländer, 2014).

Since resonance effects such as standing waves that affect the reverberation time and sound timbre are particularly effective in the lower frequency band, it is necessary to intervene with special acoustic tools in this frequency band (Panteghini et al., 2008). These acoustic materials can be bass trap, diaphragmatic absorbers, polycylindrical absorbers, membrane absorbers, Helmholtz panel absorbers. (Everest, 2001). The design of these panels is changeable and important in terms of controlling the absorption effects required in the lower frequency band

(Yang et al., 2024). The positions of the acoustic materials designed for the lower frequency band can change both the modal reverberation times and the reverberation time values of the octave band (Meissner, 2008). Calculations should be made by considering the frequency domains of the acoustic materials to be used in order to regulate the room acoustics. Special acoustic absorbers and diffusers should be used in order to intervene in the lower frequency bands in a controlled manner (Kleiner & Tichy, 2014). Lower frequency band absorbers are absorbers that work based on resonance (Jun et al., 2021). The use of these panels in places such as sound recording studios and music study classes where sound quality is important ensures that the bass ratio is at optimum values (Panteghini et al., 2008). The positions of the resonator panels should be determined in a way that can reduce the effects of room resonances. On walls where room resonances show maximum pressure, more balanced room conditions will be created as a result of positioning panels calculated to affect resonance frequencies (Kanev, 2020). Porous absorbers that will affect medium and high frequencies and will be applied together with low frequency sound absorbing panels should be used in a quantity that will not disrupt the room balance and in positions that will eliminate acoustic defects.

Low-frequency sound waves have more energy and longer wavelengths than high-frequency sound waves. Therefore, it is quite difficult to absorb and attenuate low-frequency sound waves (Tıraş&İlgürel, 2025). Impractical thick applications arise in arrangements made with porous materials. To overcome this problem, resonator absorbers are used as low-frequency sound absorbers (Jun et al., 2021; Lai, 2024). Helmholtz resonator panels can be applied to points where room modes have high pressure, reducing the reverberation time in the low-frequency region (Tıraş&Akdağ, 2024; Inacio et al., 2005). The most common problem in the acoustic design of small rooms that are important in terms of sound design, such as sound recording studios and rehearsal rooms, is the inability to provide the necessary absorption at low frequencies (Tıraş&Akdağ, 2024; Gilford, 1952). In this study, the hypothesis was determined as "Helmholtz resonator panels applied to areas where room modes are pressurized in order to provide optimum reverberation time in music study classes provide improvement in reverberation time for low frequency sounds". In order to test this hypothesis, room acoustic measurements were made in the music study class located in ITU Music Advanced Research Center, optimum conditions were evaluated according to BS EN ISO 23591 standard, room modes and shapes were determined by performing modal acoustic analysis. The required Helmholtz resonator panels were calculated, application points were determined and assembly was carried out. After the arrangement, field measurements were made and the success dimension of the design was determined (Figure 1).

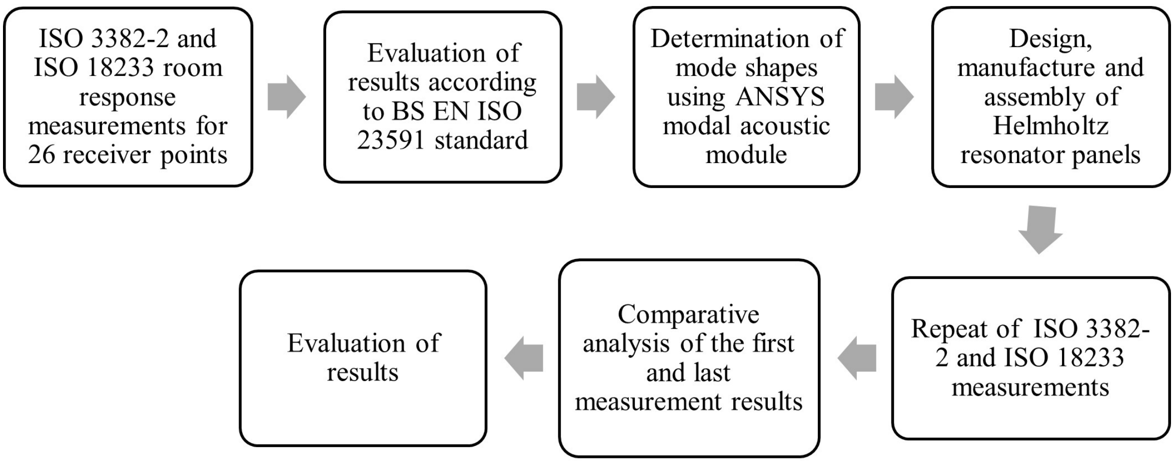

Figure 1. *Steps of the method followed.*

2. Method

In this study, the acoustic design criteria of a fan-shaped room with an area of 30.78 m^2 and a volume of 86.8 m^3 (Figure 2), used as a piano practice classroom at the ITU (Istanbul Technical University) Center for Advanced Music Studies, were determined. In the room where the study was conducted, 26 receivers and 1 source position were determined, ISO 3382-1 "Acoustics — Measurement of room acoustic parameters Part 1: Performance spaces" acoustic parameters were measured and room response measurements were made according to the ISO 18233-SS "Acoustics — Application of new measurement methods in building and room acoustics" standard. The reason for determining 1 corner as the source position is to determine the change of peak responses at each measurement point by reducing the variables. The measurement results taken at 26 points were compared with each other, the averages and standard deviations of T30, EDT, C80 values were found, and the distribution of the sound was examined. The optimum value range of the musical instrument study class was determined according to BS EN ISO 23591 standard and compared with the measurement results (British Standards Institution, 2021) . The Q quality factor and Tmodal values of the peak points from the room response curves were found and analyzed. The room eigenfunctions resulting from the placement of rigid and absorber elements were determined using the ANSYS 2023 R1 Modal Acoustic module. As a result of these analyses, the acoustic materials to be used in the room walls were determined and their manufacturing and assembly were carried out. The initial measurements were repeated and the success of the design was evaluated.

2.1. Evaluation of existing acoustic conditions by measurement

Measurements were carried out in accordance with the ISO 3382-2 "Acoustics — Measurement of room acoustic parameters Part 2: Reverberation time in ordinary rooms" standard to determine the current acoustic conditions of the music instrument study class. 1 source and 26 receiver points were selected (Figure 2), the source position was 150 cm above the floor, and the receiver points were positioned 120 cm above the floor. In the measurements, Bruel-Kjaer 12-sided speaker, Behringer ECM 8000 measurement microphone, microphone tripod, Audio Real Time Analysis (ARTA 1.9.4.1) software, microphone calibrator was used. ISO 3382-1 acoustic parameters T30, EDT and C80 were measured at 26 receiver points in accordance with ISO 18233-SS standard. Sweep signal, which usually gives more accurate results for room response measurements was also used in this study. (Lim et al., 2016; Prato et al., 2016).

Based on the formulas and graphs in the BS EN ISO 23591 standard, the optimum ranges of the optimum reverberation time according to the frequencies were determined and the measurement results were evaluated. As can be seen in Figure 6, which presents the average of the measurement results determined at the receiver points, the T30 values are above the limit values in the 63 Hz, 125 Hz and 250 Hz center octave frequency bands. The EDT values are above the limit values in the 63 Hz and 125 Hz octave bands. Since carpets and curtains are in the class of porous absorbers, they show a very high absorption coefficient at 500 Hz and above compared to the lower frequency region (AFMG Ease 4.4, 2024). The fact that the floor is carpeted and that thin curtains are used in the glass section ensures that the T30 and EDT parameters remain within the limit values at 500 Hz octave band and above.

The change of T30 value according to the receiver points is the greatest in the 63 Hz octave band. The T30 values measured at 26 receiver points having a standard deviation value of 0.39 were the lowest at receiver 20 with 1.35, and the highest at receiver 21 with 2.84. The standard deviation was 0.09 in the 125 Hz octave band. The highest value for 125 Hz was found as 1.28 at receiver 12, and the lowest value as 0.99 at receivers 7 and 21. In the 250 Hz octave band, the standard deviation was 0.07,

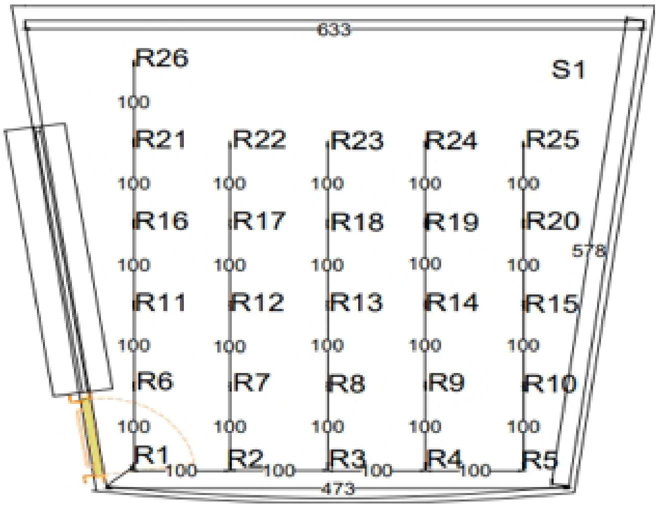

Figure 2. *Measurement layout.*

the lowest value as 0.75 at receivers 13 and 15, and the highest value as 1.03 at receiver 3. The standard deviation values decreased at 500 Hz and above and varied between 0.03 and 0.01. Evaluation of these results show that, in the pre-editing situation, a diffuse sound field of 500 Hz and above was formed in the room.

2.2. Evaluation in terms of room mode distributions

When making acoustic arrangements in small rooms, the determination of room modes becomes important. The effects of room modes are felt more in the lower frequency bands. In the lower frequency bands where the diffuse sound field is not formed, some frequencies can create more effective sensations than others due to the effect of standing waves (Beaton & Xiang, 2017). Since these frequencies are heard more than others, problems called coloration can occur (Bonello, 1981; Louden, 1971). While room modes can be determined with simple calculation tools in rectangular rooms, FEM solutions are needed in more complex geometries. The resonance peaks of some low-frequency room modes below the Schroder frequency are defined as frequency range where room modes are effective.

ANSYS Modal acoustic module was used to determine the modes of the fan-shaped room where the study was conducted. Before the treatment, the wall absorption properties were defined in the program and the eigenvalues and eigenfunctions were determined. At the same time, the room response was determined for 26 separate measurement points according to the ISO18233 SS standard and the peak frequencies were analyzed. As a result of these analyses, the frequencies that peaked at the highest measurement points and the total peak numbers in the 1/3 octave bands were revealed. The simulation results and the measurement results were compared.

The axial room mode shapes and frequencies obtained with the ANSYS Modal Acoustic module using the finite element method are shown in Figure 8. It was determined that room modes created high pressure points at wall-ceiling junctions and corners. It was observed that tangential and oblique modes also created high pressure in these areas.

The room mode frequencies below the Schroder frequency and the difference values between them are shown in Table 1. The 3 largest differences were determined to be between 30.8 Hz-44.3 Hz, 44.3 Hz-59.1 Hz, and 75.9-85.3 Hz. It is anticipated that there will be dips in the room response curve in these frequency ranges. The resulting dips will occur as a result of large gaps between the room resonance frequencies (Kleiner & Tichy, 2014; Kuttruf, 2001).

3. Improvement studies

Improvement studies were carried out in the musical instrument study class to bring the room acoustic parameters within the standard value range. First of all, the required acoustic materials were determined by calculation and then they have been positioned by considering the reverberation time and room modes.

In order for the reverberation time values of the room designed as an music instrument study class to reach the optimum value range, Helmholtz resonator panels with replaceable front plates were designed. These resonator panels were created using the formula that determines the frequency band in which the panels will be effective (Equation 1). In this formula, p represents the hole percentage, d represents the depth, and t represents the effective hole depth. Since sound absorbing foams are placed behind the front perforated face of the resonator panels created according to the formula, the effective frequency band is expanded (Kleiner & Tichy, 2014). For this reason, the resonance frequencies were determined in a way that would be closest to the problematic frequency band. A 1 mm change in the hole diameter can change the resonance frequency by around 20 Hz. However, the effective bandwidth is increased by using sound absorbing porous materials behind the perforated front section of the panels.

Figure 3 shows the parts of the panels and the process of joining them. Figure 3a shows the structure of the wooden box. Wooden slats were placed in the middle of the edges to ensure that the foam to be placed later would be close to the perforated front surface. Metals were placed on the parts of these slats close to the edges to ensure that the magnets that would hold the front cover would work. Foams measuring 60 cm-60 cm-4 cm were placed on the slats inside the box (a) and the required front panel would be placed on the slats (b). The front panels would be fixed with the help of magnets (c). The resonators whose dimensions are given in Table 2 were used in positions where room modes were active.

The walls where the room modes occur were determined and resonator panels were placed on the surfaces where the pressure points of these modes were maximum. While determining the panel positions, ANSYS Modal Acoustic program was used and room mode shapes were taken into consideration. Figure 8 includes images showing the pressure points of axial room modes. It was determined that room modes created maximum pressure points at corners and wall-ceiling junctions, and it was observed that the pressures of axial, tangential and oblique modes were common at corners. Considering that Helmholtz resonator panels, which were designed to be effective in the lower frequency band, gained broadband efficiency thanks to the porous sound absorbing foam used behind them, these panels were placed in corner positions to both reduce the coloration caused by room modes and to reduce the reverberation time values, which are excessive in the lower frequency bands. As seen in Figure 4, the resonator panels coded as 1, 2, 3 were placed at the ceiling-wall junctions. Panels numbered 1, 2, 3 and 4 were placed in other corners where the pressure points of room modes were dense. These resonator panels are tuned to frequencies of 69.4 Hz, 86.75 Hz, 120.1 Hz and 140.12 Hz, and sound absorbing foam is placed behind the holes. It is envisaged that the panel will be effective in a wider band as a result of the use of sound absorbing material inside. At the same time, it is frequency aimed to provide faster sound absorption by reducing the Q value of the resonator panel and as a result, to prevent sounds that will be distributed to the environment by the resonator panel for a longer time than the reverberation time (Biswas & Agrawal, 2013).

The axial modes at frequencies of 59.1 Hz, 60.4 Hz and 61.6 Hz are very

Table 1. *Room mode frequencies and mode ranges.*

Mode Frequency (Hz)	(x,y ,z) mode	Difference (Hz)
29.9	1,0,0	
30.8	0,1,0	0.9
44.3	1,1,0	13.5
59.1	2,0,0	14.8
60.4	0,2,0	1.3
61.6	0,0,1	1.2
67.8	2,1,0	6.2
68.5	1,0,1	0.7
68.9	0,1,1	0.4
72.3	1,2,0	3.4
75.9	1,1,1	3.6
85.3	2,0,1	9.6
86.2	2,2,0	0.9
86.3	2,0,1	0.1
88.2	0,3,0	1.9
90.8	3,0,0	2.6
91.6	2,1,1	0.8
95	1,2,1	3.4
95.1	3,1,0	0.1
102.6	1,3,0	7.5
106	2,2,1	3.4
107.6	0,3,1	1.6
109.1	3,2,0	1.5

$$f_0 = 200.\sqrt{\frac{p}{(d).(t)}}$$

Equation 1.

close to each other, and the presence of two axial modes around 90 Hz may create a coloration problem in the room. When we look at the shapes of these room modes (Figure 8), it is seen that they create high pressure in the corners and upper corners opposite the piano. For this reason, Type 1 and Type 2 resonator panels were placed in these sections. It was expected that these panels would both reduce the coloration that is the modal effect and ensure that the reverberation time values in these frequency bands would approach the optimum value range. After the production of the panels, the panels were assembled in accordance with the layout plan seen in Figure 4.

4. Comparison of results before and after improvement

After the panels were applied, the T30, EDT, C80 and room response measurements were repeated to evaluate the success of the design. In addition, the frequencies and shapes of the new room modes that will occur as a result of the design were revealed using the ANSYS Modal acoustic module. Post-editing room photos are shown in Figure 5.

4.1. T30 comparison

In the measurements made before the acoustic treatment, T30 values were above the optimum limit value ranges determined according to BS EN ISO 23591 standard in the 63 Hz, 125 Hz and 250 Hz octave bands. They were within the limit value range at 500 Hz and above. It was determined that the Resonator panels used for the acoustic treatment provided improvement in the lower frequency bands where they were effective. While they were within the optimum limit value range in the 125 Hz and 250 Hz octave bands, they were below the 63 Hz octave band (Table 3). It was found that the reverberation time, which was 2.28 seconds, was reduced to 1.33 seconds. Although a significant improvement was achieved, it remained above the limit value. Due to the working mechanisms of the panels, it did not affect frequencies of 500 Hz and above as expected before the regulation, and these frequency bands, which were within the limit value range before the acoustic treatment, maintained their status.

a b c

Figure 3. *The process of assembling the parts.*

Table 2. *Dimensions of Helmholtz Resonator panels.*

Helmholtz Resonator Design	Type 1 (16 holes with 10 mm diameter)	Type 2 (25 holes with 10 mm diameter)	Type 3 (36 holes with 12 mm diameter)	Type 4 (49 holes with 12 mm diameter)
Hole depth (cm)	1.2	1.2	1.2	1.2
Effective hole depth (cm)	2	2	2.15	2.15
Hole diameter (cm)	1	1	1.2	1.2
Percentage of holes	0.44	0.69	1.44	1.96
Depth (cm)	10	10	10	10
Resonance frequency (Hz)	69.40	86.75	120.10	140.12

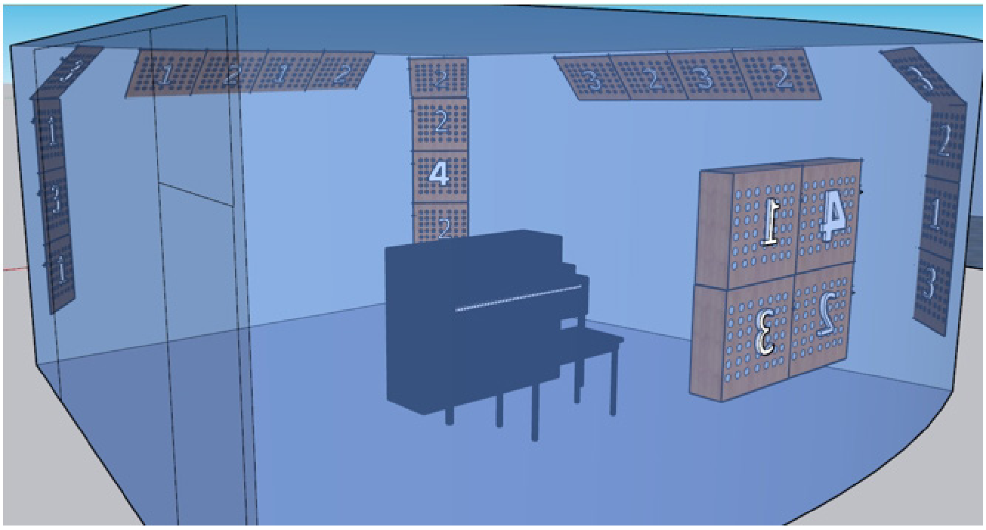

Figure 4. Room acoustics design of the musical instrument study class.

Figure 5. Room photos after treatment.

Standard deviation values were found to determine how much T30 values differ from each other according to 26 measurement points. The standard deviation, which was 0.39 before the adjustment in the 63 Hz center octave frequency band, decreased to 0.24. It was observed that the panels used for the lower frequency band provided benefits in terms of equal distribution of sound in the 63 Hz frequency band. The standard deviation values of 0.09 at 125 Hz, 0.06 at 250 Hz, 0.03 at 500 Hz; 0.02 in the 1000 Hz, 2000 Hz, 4000 Hz frequency regions did not change before and after the adjustment.

4.2. EDT comparison

Before the acoustic treatment, EDT values were above the limit values at the center octave frequencies of 63 Hz and 125 Hz. After the acoustic treatment, 125 Hz entered the limit value range, while 63 Hz remained slightly above the limit value. At 63 Hz It decreased from 1.73 seconds to 1.15 seconds, and from 1.02 seconds to 0.54 seconds at 125 Hz. The limit value range was maintained in the 250 Hz and 500 Hz octave band. Although there was no change at 1000 Hz, 2000 Hz and 4000 Hz, it remained slightly below the limit value before and after the acoustic treatment (Figure 6).

When we compare the EDT values according to 26 measurement points, there is a significant decrease in the 63 Hz octave band and a decrease in the 125 Hz octave band. While the standard deviation value in the 63 Hz octave band was 0.5 before the acoustic treatment, it decreased to 0.18 after acoustic treatment. It also decreased from 0.19 to 0.16 for 125 Hz octave band. There was no significant change in the other frequency octave bands. Evaluation of these results show that, the distribution of the EDT value, where the effect of early reflections is seen, has improved at the 26 measurement points.

4.3. C80 comparison

C80 values increased between 63 Hz and 500 Hz compared to the before acoustic treatment state. The increase in the C80 values in these frequency bands indicates that the energy rate in the first 80 ms has increased. It was determined that the highest increase was in the 125 Hz octave band. There was no change in the 1000 Hz, 2000 Hz and 4000 Hz octave bands. The clarity parameter varies according to the volume for music study classes, but it has been found to be around 15 dB in volumes below 100 m^3 (Cabrera, 2007).

The changes in the standard deviation values, where changes are observed according to 26 measurement points which was determined that the standard deviation value decreased from 2.02 to 1.48 in the 63 Hz octave band, while it increased from 1.32 to 2.95 in the 125 Hz octave band (Table 3).

4.4. Comparison of room response

According to the room response measurements made at 26 measurement points, 223 peaks were formed acoustic conditions before treatment while 220 peaks were detected after acoustic treatment. 13 peaks were formed in the 80 Hz 1/3 octave frequency band before the editing, while 1 peak was formed after the editing. In the 100 Hz 1/3 octave frequency band, there were 4 peaks before the acoustic treatment while this increased to 12 after the acoustic treatment. It can be said that there is a shift from 80 Hz to 100 Hz. A similar situation is seen between 160 Hz and 200 Hz. While there were 22 peaks at 160 Hz before the acoustic treatment, this decreased to 9. At 200 Hz , while there were 11 peaks before the acoustic treatment, this increased to 22. Evaluation of these results show that, the acoustic treatment created an effect on the 63 Hz and 125 Hz center octave frequency bands.

The peaks in the 80 Hz 1/3 octave band before the editing decreased after the editing and shifted to the 100 Hz one-third octave band. Evaluation of these results show that, there is a similar transition between 160 Hz and 200 Hz one-third octave bands.

Table 3. *C80, EDT and T30 values before and after editing.*

	Frequency (Hz)	63	125	250	500	1000	2000	4000
BS EN ISO 23591	Lower limit	0.37	0.40	0.42	0.44	0.44	0.40	0.35
	Upper limit	0.92	0.79	0.72	0.69	0.69	0.69	0.69
T30	Before treatment	2.28	1.14	0.87	0.61	0.48	0.44	0.43
	Std deviation	0.39	0.09	0.07	0.03	0.01	0.02	0.02
	After treatment	1.33	0.73	0.72	0.58	0.45	0.43	0.41
	Std. deviation	0.24	0.09	0.06	0.03	0.01	0.02	0.02
EDT	Before treatment	1.73	1.02	0.71	0.59	0.41	0.38	0.34
	Std deviation	0.5	0.19	0.12	0.06	0.05	0.05	0.03
	After treatment	1.15	0.54	0.66	0.54	0.41	0.37	0.34
	Std deviation	0.18	0.16	0.12	0.08	0.05	0.06	0.04
C80	Before treatment	2.37	5.43	6.49	8.32	11.98	12.98	13.97
	Std deviation	2.02	1.32	1.55	1.75	1.35	1.13	1.00
	After treatment	3.42	8.43	7.71	9.74	11.95	12.81	14.09
	Std deviation	1.48	2.95	1.95	1.52	1.19	0.94	1.03

As a result of the room response measurements made at 26 measurement points before the acoustic treatment, the repetition frequency of the frequencies forming the peak was analyzed. The frequencies that are effective in the room were determined. The frequency with the most frequent peak formation was found to be 86.6 Hz. It formed a peak at measurement points numbered 5, 12, 16, 22 and 24. At the same time, 83.9 Hz formed a peak at number 3, 84.8 Hz at numbers 10 and 15, 85.7 Hz at numbers 23,25 and 26, and 87.5 Hz at measurement points numbered 8 and 18. After the acoustic treatment, only 90.4 Hz formed a peak at measurement point numbered 18 between 75.5 Hz and 97.3 Hz. The frequency that formed the highest peak after the acoustic treatment, 97.3 Hz, peaked at a total of 8 measurement points. This situation was evaluated as a result of the shift of the room modes from the 80 Hz 1/3 octave band to the 100 Hz 1/3 octave band. The graph in Figure 6 shows how many measurement points the peaks formed at.

4.5. Comparison of room modes

Before the treatment, the room modes were simulated and the eigenvalues and eigenfunctions were determined. According to these mode shapes and other acoustic measurement results, Helmholtz resonator panel placements were made. In order to determine the change that will occur in the room modes as a result of the design, the panels to be placed in the room were drawn in the ANSYS modal acoustic module and the absorption coefficients were defined. This coefficient was used assuming that the panels would have an absorption of 0.9 in the 63 Hz and 125 Hz frequency bands (Tıraş&Akdağ, 2024).

The room modes formed in the frequency range below the Schroder frequency after the adjustment are shown in Figure 7. There have been changes in both mode shapes and mode frequencies compared to the room modes before the acoustic treatment. The first axial mode, 29.9 Hz, shifted to 30.4 Hz after the acoustic treatment and the high-pressure points came to the corner. The panels placed on the inclined wall shifted the high-pressure region, which appears red, towards the corner. In the 010 mode, the red and blue pressure regions seen in two adjacent corners shifted to opposite corners, and the green zero pressure line inclined and went towards the corner. The frequency of this mode shifted from 30.8 Hz to 31.6 Hz. When we examine the other mode shapes, we see that there are such frequency and pressure region shift.

5. Discussion

In order to define the acoustic character of the room where the study was conducted, 26 measurement points

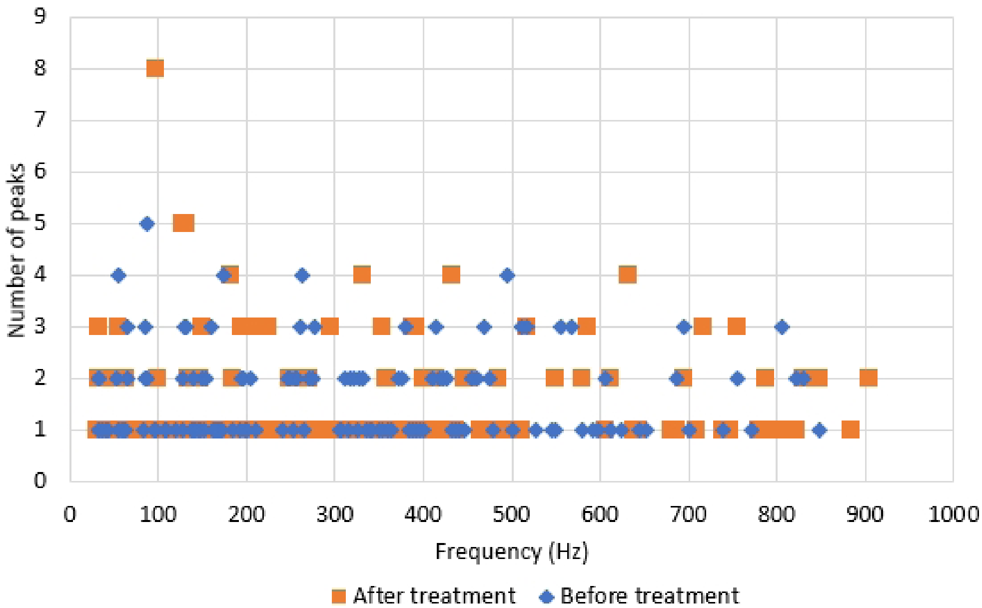

Figure 6. *Number of repetitions of peaks at measurement points according to frequencies before and after treatment.*

were determined, the distribution of sound in the room and the optimum values of acoustic parameters were examined. As a result of the ISO 3382-1 measurements, T30, EDT and clarity (C80) values were measured before the treatment. T30 and EDT values were determined to be within the limit values of 500 Hz and above according to the BS EN ISO 23591 standard. They were measured to be above the limit values at frequencies of 250 Hz, 125 Hz and 63 Hz. It was seen that there was a need for an improvement for these frequency bands. In order to evaluate the effectiveness of the panels to be used in the acoustic design after their production and assembly, ANSYS Modal acoustic simulation and room response measurements were made in accordance with ISO 18233 standard. By looking at the eigenfunctions and eigenvalues obtained from the modal simulation, the hole diameters and numbers of Helmholtz resonator panels, the depth of the box forming the panel and the thickness of the front panel were decided and 4 different panel front faces were manufactured. Since the perforated front part of the designed panel was connected to the panel with a magnet, the front perforated covers of the panels were produced as interchangeable. ANSYS simulation data was used to mount these panels, which were specially designed to reduce the reverberation time in the 63 Hz, 125 Hz and 250 Hz octave bands, in the correct positions. Since Helmholtz panels work with the resonance effect, they were used in regions where high pressure occurs. After the assembly of the design was completed, ISO 3382-1 acoustic parameters and ISO 18233 room response measurements were repeated. In order to determine the

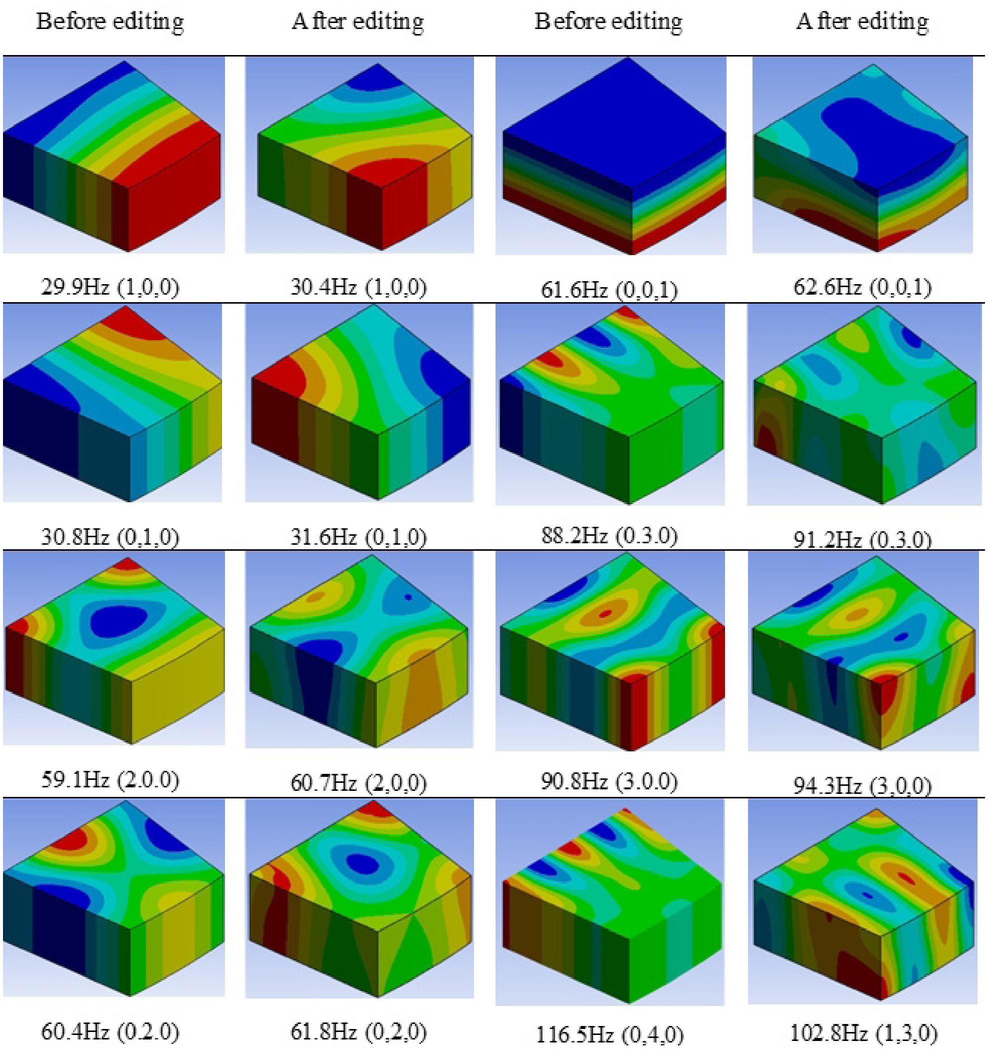

Figure 7. *Room mode shapes and frequencies before and after editing.*

new modal status of the room, ANSYS simulations were repeated by placing the resonator panels used in the room.

The most frequently used parameter in the acoustic evaluation of music practice rooms is the reverberation time (Katunský et al., 2016; Sinal & Yilmazer, 2018; Tǎmaş-Gavrea et al., 2019) When we look at the reverberation time T30 values, it is seen that the limit value range given for loud music according to the BS EN ISO 23591 standard is entered after the improvement at the center octave frequencies of 125 Hz and 250 Hz. It was determined that it decreased from 2.28 seconds to 1.33 seconds for the 63 Hz octave band and at the same time, the standard deviation value showing the differentiation of the T30 values at 26 measurement points in this frequency band decreased from 0.39 to 0.24. EDT values also gave similar results and the standard deviation value of 63 Hz decreased from 0.5 to 0.19. As a result of the adjustment, significant improvements were made in the lower frequency band and no change occurred in the middle and upper frequency bands. It has been found in previous studies that by using absorber elements that will be effective in the lower frequency region in rehearsal rooms, improvements in reflection time and clarity parameters occur and as a result, communication between musicians increases (Shearer et al., 2021; Zha et al., 2002).Before the treatment, an acoustic design that would affect the 63 Hz, 125 Hz and 250 Hz octave bands was targeted as the basis of the improvement and since the middle and upper frequencies were located in a position close to the lower limit value, it was desired that the absorption in these frequency bands be close to zero. This goal has been largely achieved.

As a result of the effectiveness of room modes, the peaks occurring in the room response can both decrease the Q values and shift towards the upper frequency region by being divided by the absorber elements used in the lower frequency regions (Kleiner & Tichy, 2014; Lai, 2024).In the room response measurements made to observe the effects created by room modes, it was observed that there were changes between the before-after treatment conditions. It was observed that the peaks at 80 Hz and 160 Hz shifted to the upper 1/3 octave and Q values decreased. Similar findings were encountered in the simulation studies, and it was observed that the room modes changed both in frequency and shape. It is important to prepare and position the absorber elements properly that would affect the lower frequency band. These absorbers, which work based on resonance, will not show any effect if they are not positioned correctly (Inacio et al., 2005). The design was carried out by evaluating the reverberation time, room response and modal simulation results together. It was seen that the results were close to the desired measurement. The reverberation time values were slightly higher at 63 Hz, but there was an improvement of about 1 second.

6. Conclusion

When the success of the acoustic design is evaluated, it is seen that the reverberation time values come within the targeted limit value range in the 125 Hz and 250 Hz octave bands, and although they cannot enter the limit value range in the 63 Hz octave band, a significant improvement is achieved. This study gains importance in terms of revealing the method of creating balance between frequency bands by creating absorption in the lower frequency band without affecting the middle and high frequencies. The fact that the room to be used as a musical instrument study class, as in many classes, shows high absorption in the middle and high frequencies due to the use of curtains and carpets, but does not create an effect in the lower frequency bands, and the failure to provide balance between frequencies and the emergence of acoustic defects such as distortion are the findings obtained at the beginning of this study. In accordance with these findings, the acoustic materials that will provide absorption only in the lower frequency band were manufactured and assembled. The mode shapes and the standing waves that will occur in the lower frequency band will create have gained importance in this manufacturing and assembly process. It was ensured that the front panels of the manufactured resonator panels only affect high pressure points and that the front panels can be changed in order to make fine adjustments. The front faces of the 24 panels used were prepared with 4 different perforations to create effects in different sub-frequency bands. It was observed that the distribution of sound within the space was improved as a result of the use of panels. As a result of the acoustic arrangement, it was found that the standard deviation values of the reverberation time values measured at 26 measurement points decreased and the spatial distribution of the sound was balanced.

The data obtained as a result of this study show that acceptable frequency balance can be achieved in the rooms with the method used. It is seen that replaceable Helmholtz panels can be used to provide effective balance. Future studies may investigate the use of interchangeable Helmholtz panels for musical instrument-specific room design. Perception of changes in room response may be investigated through survey studies in which subjective perceptions can be observed. The effect of room geometry on modal change may be investigated by comparing modal changes and room response changes as a result of improvement studies of rooms with multiple different geometries. Simulation effectiveness may be investigated by measuring sound intensity at several points within the room where white noise is given through modal simulation.

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