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Research paper

ACOUSTIC TREATMENT OF SPACE BY IMPLEMENTING PARAMETRIC PANELS

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Abstract

The development of software tools has enabled more detailed analysis of the acoustic properties of a space. Therefore, this research explores the possibility of improving the acoustic and aesthetic qualities of a space through the implementation of parametric wall panels. The research was conducted in two phases. As part of the first phase, the sound absorption coefficient was measured. The absorption coefficient of the intended material was tested by the experimental method using a Kundt's tube. For research purposes, the absorption coefficient of Styrodur XPS d=10mm, Styrofoam d=10mm, MDF d=10mm and MDF d=6mm sheet materials was measured. The second phase of the research includes the design of parametric wall panels, and then the analysis of the impact of their implementation on the reverberation time. Panel design was done using the software tool Rhinoceros and the Grasshopper plugin. The application of parametric design made it possible to easily generate different geometric forms. The influence of the implementation of parametric panels was examined by using the Odeon tool, using the software modeling method. Through the software modeling method, the impact of the depth of folds and the distance between the elements of the parametric wall panel (diffuser) on the acoustic properties of the concert hall was analyzed. The results of the research contribute to a new approach to the design of wall panels, the implementation of which would contribute to the aesthetic value of the space, as well as to the knowledge of how their implementation affects the acoustic characteristics.

Key words: *Parametric Design, Room Acoustic, Sound Absorption Coefficient, Reverberation Time, Wall Panels*

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1. INTRODUCTION

Acoustic quality is a crucial architectural attribute in venues designed for live performances such as theaters and concert halls. A large number of performance halls built in the past do not meet appropriate acoustic quality standards. In the present day, advancements in software tools have given engineers and designers the ability to analyze spaces with greater accuracy, opening new possibilities for enhancing acoustic performance. Acoustic quality is a key architectural feature, especially in venues designed for live performances like theaters and concert halls. However, challenges often emerge when trying to upgrade existing performance halls. Many of these halls weren't acoustically optimized in the past, largely due to the lack of proper tools. Today, to effectively improve a hall's acoustic performance, designers must be skilled in using advanced tools to evaluate current acoustic conditions. A central aspect of acoustic analysis is reverberation time—the amount of time it takes for sound to decay by 60 decibels after the sound source has stopped. Ideal reverberation times vary depending on the type of performance, typically falling between 0.6 and 2.2 seconds [1-3]. Many existing buildings face issues due to insufficient acoustic treatment during their original design. Although different types of performances require specific acoustic conditions, these halls were often not designed with a particular function in mind [4]. To ensure that such halls can support various types of performances while maintaining high acoustic quality, it is essential to optimize the reverberation time through targeted acoustic interventions. The primary factors that influence reverberation time are the volume of the space, the sound absorption coefficients and geometry of the interior surfaces. For this reason, the aim of this research is to propose the design of a parametric acoustic panel, whose geometry, material composition, and implementation at specific points within the interior would contribute to eliminating the phenomenon of sound focusing in the auditorium space.

In the initial stage of this research, experimental measurements were conducted to determine the sound absorption coefficients of selected panel materials: Styrodur XPS (thickness 10 mm), Styrofoam (10 mm), MDF (10 mm), and MDF (6 mm). The objective of these measurements was to evaluate the acoustic performance of each material and to identify comparable absorption characteristics, with the aim of selecting suitable candidates for the construction of acoustic panels. The measurements were carried out using a Kundt's tube (impedance tube) in accordance with standard testing procedures for small sample acoustic analysis.

This study presents a design proposal for parametric wall panels, divided into segments with varying fold depths. The dynamic geometry of the structure contributes to diffuse sound scattering and the formation of a more uniform sound field. The design process was carried out using Rhinoceros software in combination with the Grasshopper plugin. Using the Odeon Acoustic software tool, an analysis of the propagation of sound waves through space was performed. The ray tracing method identified the parts of the interior surfaces that reflect the highest percentage of sound energy and create focusing points of sound in the space. By placing acoustic panels at points that reflect the greatest amount of sound, a diffuse sound field is created and the possibility of creating focused sound spots in the hall is reduced.

2. SOUND ABSORPTION COEFFICIENT MEASUREMENT

This study investigated the acoustic performance of various building materials using the impedance tube method in accordance with [5]. The tested samples included MDF of different thicknesses, styrofoam, and extruded polystyrene (XPS). The measurement process, including calibration with correction factors, ensured accuracy and reliability of the data. These findings provide valuable insight for architects and engineers seeking to optimize sound absorption in built environments. Overall, the results support strategic use of both material selection and configuration to achieve desired acoustic outcomes.

2.1. Test Method and Test Samples

Laboratory measurements of sound absorption coefficients were conducted using an impedance tube, following the test method outlined in [5].

Table 1. The tested samples data

Identification	Description	Thickness [mm]
Sample 1	Medium density fiberboard (MDF)	6
Sample 2	Medium density fiberboard (MDF)	10
Sample 3	Styrofoam	10
Sample 4	Extruded polystyrene (XPS)	10
Calibration sample	Open-cell polyurethane foam	25

The test samples were mounted in a large sample holder (UA-1119), an aluminum tube with a movable piston, ensuring the sample's front surface was perpendicular to the tube axis. Measurements were conducted within the frequency range of 50 Hz to 6400 Hz.

A random sound source generated plane waves, and sound pressures were recorded at two microphone positions near the sample. The complex acoustic transfer function was calculated to derive acoustic properties [5-9].

The two-microphone method decomposes the broadband signal into incident (p_i) and reflected (p_r) components using pressures measured at two positions (Fig. 1.).

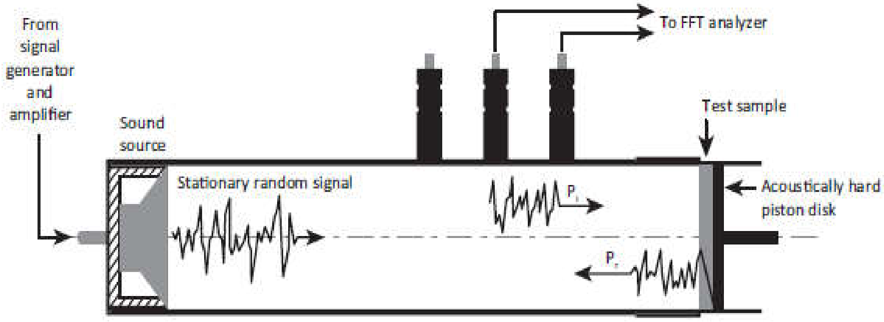

Figure. 1. Cut-away diagram of the impedance measurement tube [2]

The complex reflection coefficient (R) is computed as [5]:

$$\underline{R} = \left(\frac{\underline{H}_1 - \underline{H}_i}{\underline{H}_r - \underline{H}_1} \right) e^{2jk(l+s)} \quad (1)$$

where $\underline{H}_1$ is the frequency response function, $\underline{H}_i$ and $\underline{H}_r$ are incident and reflected components, *k* is the wave number, *l* is the distance from the first microphone to the sample (in mm), and *s* is the microphone spacing (in mm) [1].

The normalized impedance ratio (*z*/*ρc*) and sound absorption coefficient (α) can be calculated from the following equations [5]:

$$\frac{z}{\rho c} = \frac{1+\underline{R}}{1-\underline{R}} \quad (2)$$

$$\alpha = 1 - \left| \underline{R}^2 \right| \quad (3)$$

The frequency response function is obtained from the cross-spectrum of the two microphone signals. Any mismatch in phase or amplitude between the microphone channels can distort computed response. To correct for this, calibration involves calculating the frequency response function first with the microphone in one arrangement and then after swapping their positions. The geometric mean of these two measurements is used as a correction factor that can be applied to all subsequent tests, effectively removing errors caused by microphone channel mismatches.

Calibration corrected for microphone mismatches by calculating the frequency response functions in standard (H_{C1}) and interchanged (H_{C2}) positions, yielding a calibration factor ($\underline{H}_C$) applied to all measurements.

2.2. Analysis and Discussion of Test Results

Sound absorption coefficients were measured in one-third octave bands from 50 Hz to 6400 Hz, with results analyzed for different materials.

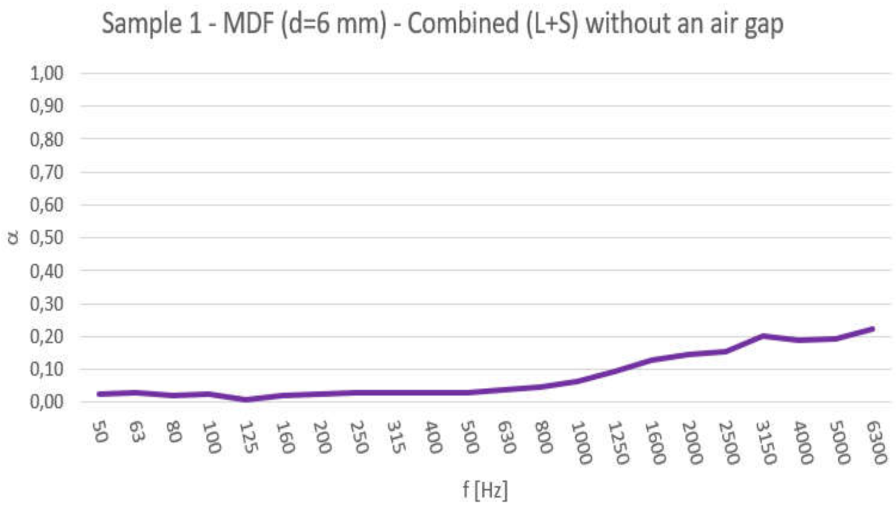

Figure. 2. Sound absorption coefficient of 6 mm MDF samples

Figure 2 shows the results of measurement of the normal sound absorption coefficient according to [5]. MDF, 6 mm, exhibited low absorption, especially at low and mid frequencies, with slight improvement above 1600 Hz.

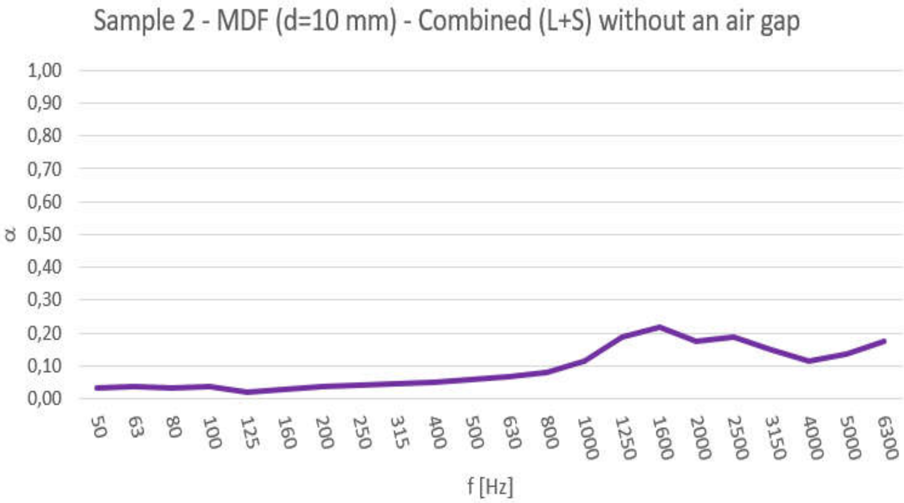

Figure. 3. Sound absorption coefficient of 10 mm MDF samples

Figure 3 illustrates the sound absorption coefficient of MDF (10 mm thick) across a frequency range of 50 Hz to 6400 Hz. Similar to 6 mm MDF, the 10 mm MDF demonstrated limited absorption, with marginal improvement at higher frequencies. However, it exhibited slightly better high-frequency absorption compared to the thinner sample.

According to reference [10], 18 mm MDF has greater stiffness, which increases acoustic impedance and reduces low-frequency absorption. Nonetheless, it performs better in the mid-frequency range (1–2 kHz), particularly when surface properties are optimized.

The comparison between 6 mm and 10 mm MDF samples shows that increasing material thickness leads to improved sound absorption at higher frequencies. This indicates that material thickness has a significant influence on absorption behavior, particularly in the mid-to-high frequency range.

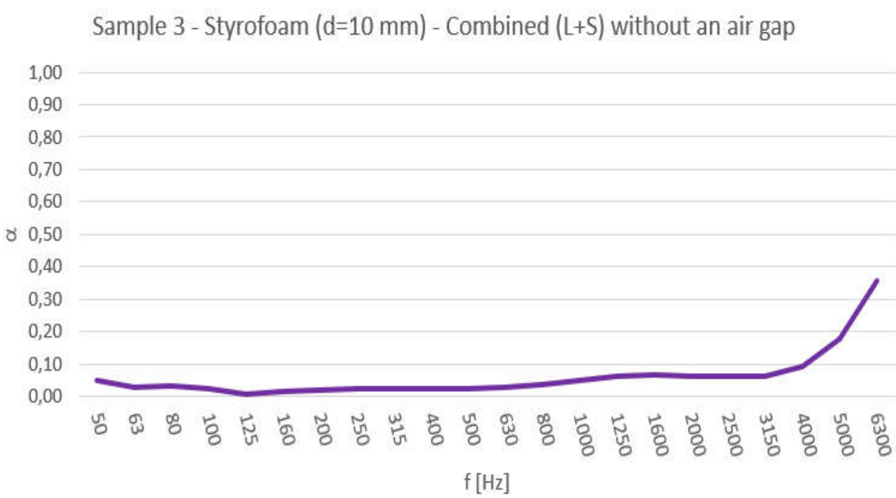

Figure. 4. Sound absorption coefficient of 10 mm styrofoam samples

Styrofoam had stable but low absorption coefficient (0.2–0.3), with a slight increase above 1500 Hz. Although both the MDF and styrofoam samples share the same thickness (10 mm), their absorption characteristics differ notably due to variations in composition. Styrofoam's higher porosity and lower density contribute to its relatively higher sound absorption in the upper frequencies, underscoring the importance of material structure.

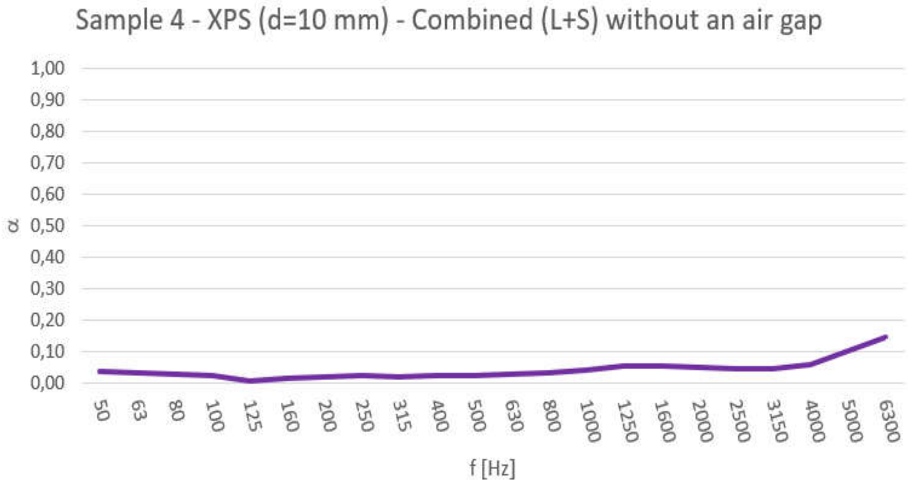

Figure. 5. Sound absorption coefficient of 10 mm extruded polystyrene samples

This figure shows that the 10 mm thick extruded polystyrene (XPS) sample has a very low sound absorption (< 0.1) across all frequencies, with a slight dip at 100–200 Hz and minor improvement above 1500 Hz. This indicates that XPS performed poorly compared to styrofoam, indicating limited suitability as a standalone absorber.

3. ACOUSTIC TREATMENT OF THE HALL

For research purposes, a performance hall of the National Library in Ćićevac was analyzed. The hall, which is primarily rectangular in shape, has dimensions of 25.15 x 9.0 m, with a ceiling height that varies due to its curved form. It is designed to accommodate 202 people - 142 on the ground level and 60 in the balcony area. The total volume of the space is 1618.4 m^3. The interior surface materials, which significantly affect the room's reverberation time, are distributed as follows: the ceiling and the upper portions of the walls (above approximately 220 cm) is coated with a layer of plaster; the lower sections of the walls are finished with wooden paneling; the auditorium floor is covered with linoleum. The stage area features brick walls coated with plaster and partially draped in fabric; the stage floor is finished with wooden parquet, and the stage ceiling is coated with a layer of plaster applied directly onto the structural surface [2, 4, 11].

3.1. Analysis of the Current Situation

Room acoustics were simulated using the Odeon Acoustic software tool through a modeling approach. The using of "ray-tracing" and "hybrid" method enabled highly accurate predictions of the acoustic behavior of the space. These methods lead to the creation of secondary sound sources at points of sound wave reflection. The underlying algorithms calculate the proportions of diffusely reflected, directly reflected, and absorbed sound upon interaction with interior surfaces. Additionally, incorporating geometric parameters enhanced the accuracy of the acoustic simulation [12, 13].

The simulation using the Odeon tool aims to analyze the existing state of the performance hall space, with a special focus on the graphical representation of the amount of sound wave exposure to surfaces in the interior. The importance of graphic analysis is reflected in the fact that based on the graphics we can determine which points in the interior reflect the greatest amount of sound. The results of software modeling will provide insight into which points of the interior surface require acoustic treatment. The geometry of the space affects the reflection of sound waves, and inadequate treatment of the space can lead to focusing of sound and the creation of a standing wave in the hall [4, 12].

The exposure of the interior surface to sound levels, based on the current state of the performance hall, is shown in the graph (Figure 6). The graph shows the distribution of sound pressure levels (SPL) [13]. In the graphs we can see increased exposure to sound waves in the balcony area on the side walls and the back wall. Greater exposure of interior surface areas also means a greater amount of reflected sound from those points. The distribution of sound reflection from surfaces depends on the geometry and materials in the interior. Uneven distribution of sound reflection is a common occurrence in halls with balconies and such halls require special approach of design. A higher amount of reflected sound, in this case in the balcony area, can lead to the sound being focused on certain points of the auditorium. Focusing the sound can create an uncomfortable feeling for the audience in that area. In addition, direct reflection of sound waves from the back wall can lead to the appearance of a standing wave in space, which also has negative consequences on the quality of performance [14, 15].

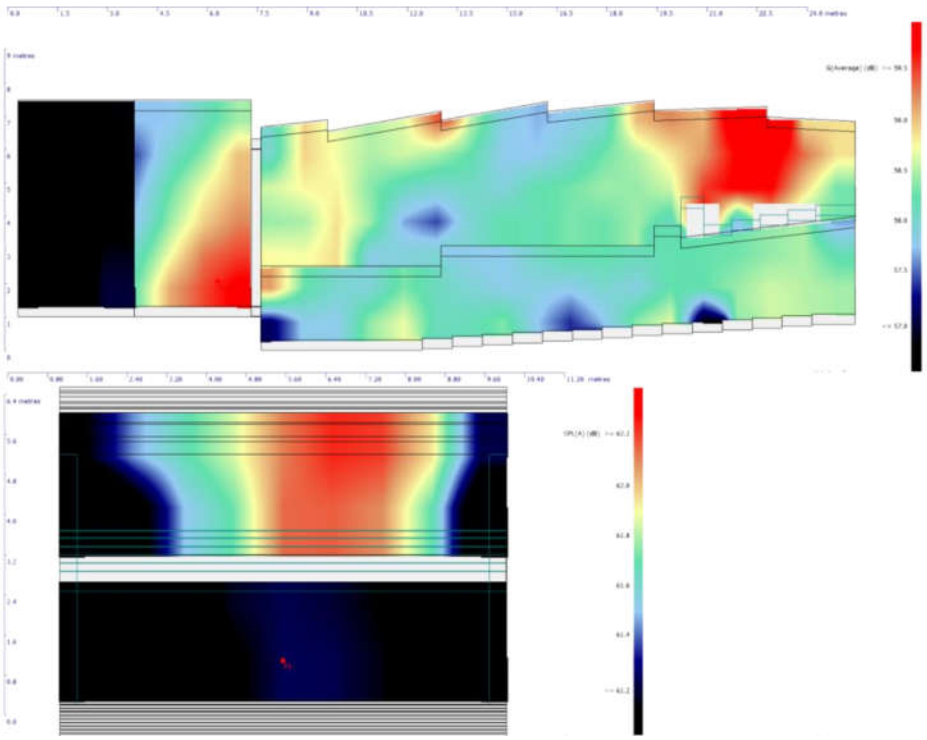

Figure. 6. Graphical representation of side and back wall exposure by sound pressure level

The software tool performed measurements in octaves for frequencies from 125 to 4000 Hz [13]. The graph shows the results for a frequency of 1000 Hz, at which the largest oscillations in the sound intensity level occur. In order to improve the acoustics of the space, it is necessary to carry out acoustic treatment of the hall by implementing diffuser panels on parts of the surface that are exposed to a greater amount of sound.

3.2. Parametric Sound Diffusion Panel Design

In architectural acoustics, interior elements are commonly classified as absorbers, reflectors, or diffusers, based on their acoustic properties, which are influenced by both the material type and surface geometry [1, 14]. The formation of surface folds affects acoustic performance by introducing diffuse sound reflections. A smaller spacing and greater depth of these folds increase the potential for surfaces to diffusely scatter sound, particularly at lower frequencies [14, 16].

A diffusion coefficient of $s = 1$ is used in calculations when the spacing between folds is $r = \lambda/2$ and the depth of the folds is $d = \lambda/2$, where λ represents the wavelength[5]. This equation suggests that, depending on the geometry, higher-frequency sound waves may be diffusely scattered, whereas lower-frequency sounds tend to be directly reflected. Furthermore, surface geometry can also enhance sound absorption due to multiple reflections occurring within surface cavities. This effect becomes more pronounced when the spacing between folds is sufficiently small and the fold depth is greater. With each additional reflection, the intensity of the sound energy returning to the listener decreases, owing to the absorption by the material upon which the sound wave reflects [14 - 16].

In order to improve the acoustics of the test performance hall, it is necessary to implement acoustic panels. At points where there is an increased amount of reflected sound, it is necessary to install wall acoustic panels for sound diffusion [14]. Due the points of exposure to higher sound pressure levels in the interior do not cover the same area, this research envisages the implementation of two types of panels, of the same design, one panel measuring 4.0 x 2.0 m and two panels measuring 2.0 x 2.0 m. The maximum depth of the fold on the panel is 15 cm (Figure 7).

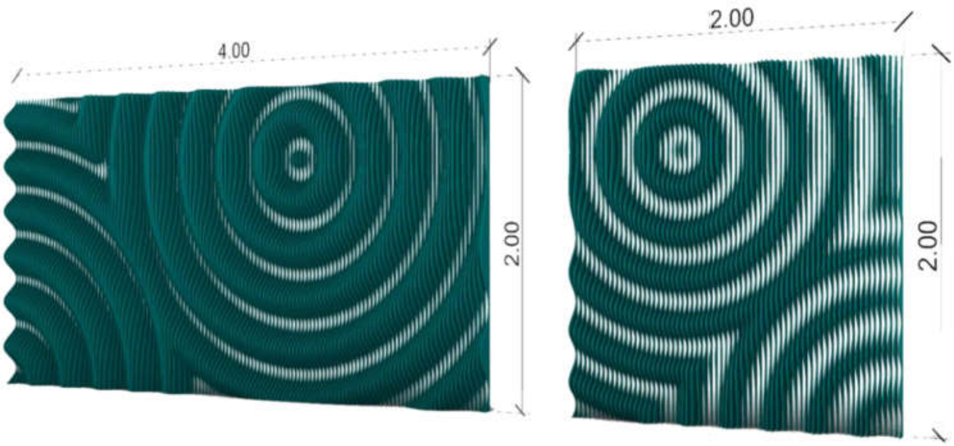

Figure. 7. Design of sound diffusion wall panels

[5] Wavelength - λ[m]

The acoustic panel design was carried out using Rhinoceros software tool with the Grasshopper plug-in. The panel materialization was planned using sheet-based materials. Accordingly, the sound absorption coefficient was measured for several samples made of wood-based and polystyrene-based sheet materials (described in chapter 2.2.). The acoustic panel design proposal was inspired by the waves created by the agitation of the water surface by throwing pebbles. The geometry of waves was randomly generated using the Grasshopper plug-in. The dimensions of the waves on the acoustic panel were generated so that the height and width of the folds were approximately 15 cm. By combining architecture, acoustics, and art, a unique interior element has been created - one that enhances both the aesthetics and acoustics of the space through the use of accessible materials shaped by intelligent design [16, 17]. Throughout the design process, parameters such as panel dimensions, wave height, and width were systematically controlled, whereas the final geometry was derived through stochastic generation. The proposed acoustic panel design has two advantages. First, its wavy geometry enhances sound diffusion in different directions. Second, cavities between panel elements contribute to sound absorption through repeated internal reflections, thereby reducing the amount of sound reflected from treated surfaces [14, 15].

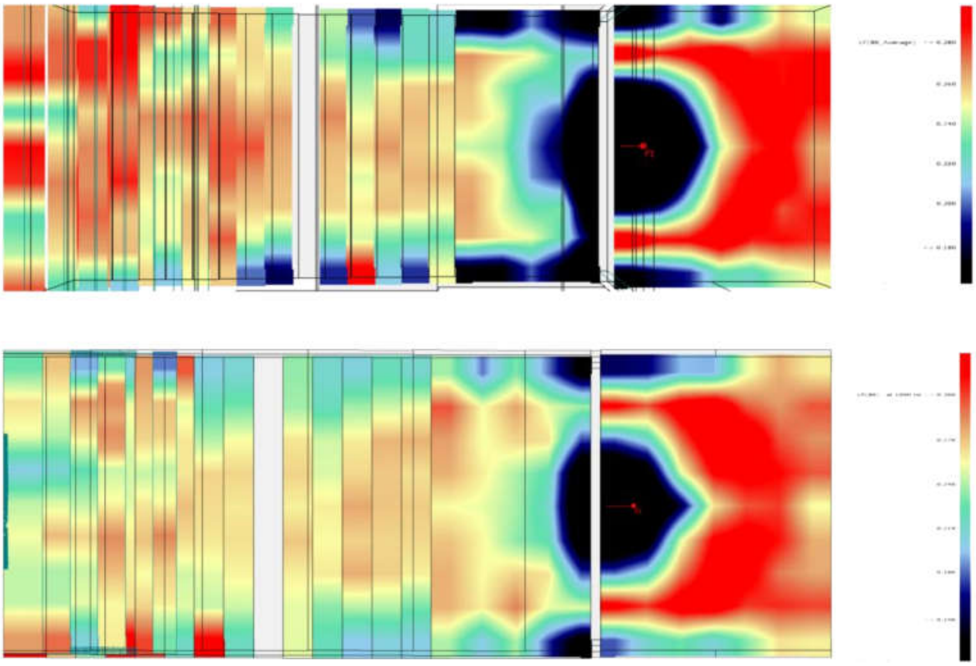

Figure. 8. Graphical representation of lateral sound reflections in the auditorium and balcony area - existing state (above), state after acoustic panels implementation (below)

Following the integration of the acoustic panel model in Odeon simulation of the performance hall, an analysis was conducted to assess their acoustic impact. Extruded polystyrene (XPS) boards were selected for panel materialization for its uniform sound absorption performance at all octave bands, their stability lightweight, and ease of shaping. Additionally, its function as a geometric diffuser within the panel context mitigates its material limitations. The selection was justified by minimal variation in the sound absorption coefficients of the tested materials. Using the Odeon Acoustic software, the impact of the implementation of the proposed acoustic panels on the amount of sound reflected from the walls (lateral fraction – LF) was examined [13]. The graph (Figure 8) shows the amount of sound reflected from the walls. In the graphical representation of the existing condition (Figure 8, above), certain points within the audience area on the balcony can be identified where focused sound reflections occur, caused by reflections from the walls. With the implementation of the acoustic panels described in this chapter, the second graphical representation (Figure 8, below) shows a noticeable reduction in the amount of sound reflected from the walls toward the balcony area, compared to the existing condition. A comparative analysis of the results shown in the graph leads to the conclusion that the implementation of acoustic panels on targeted areas on the wall contributes to the elimination of sound focal points in the hall.

4. CONCLUSION

The aim of this study was to investigate the potential for eliminating sound focusing points in performance halls through a precise analysis of areas reflecting increased amounts of sound, followed by targeted acoustic treatment using diffusion panels installed at those critical points. By measuring the sound absorption coefficients of different materials and simulating sound behavior within a specific hall, critical points of sound reflection and focalization were identified in the performance hall of the National Library in Ćićevac. Based on the obtained data, a design proposal for acoustic panels with a dynamic, wave-like geometry was developed to promote sound diffusion and reduce the possibility of creating points with focused sound. Post-implementation software simulations showed a significant improvement in the distribution of sound energy within the space, particularly in areas with higher exposure to reflected sound, such as the balcony. By using lightweight materials like extruded polystyrene (XPS), additional economic value was achieved without significantly compromising acoustic performance. Based on the results obtained through software simulation using the Odeon tool, it can be concluded that the implementation of sound diffusion panels at critical wall points would eliminate the occurrence of points with focused sound in the audience area, which would lead to the improvement of performance quality in the hall.

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