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Acoustic treatment of interiors with non-standard geometry – case study

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Abstract When designing acoustic treatment for interiors with non-standard geometry, we often have the opportunity to consider unfavourable phenomena that disturb the proper perception of sound. The determinants are usually the expected functions of the room, the expected acoustic parameters and the type of sound system [1]. The paper presents selected results of model and experimental acoustic tests of two interconnected rooms created by horizontal division of the hall, one of which retains its arched vault. Taking into account the need to adapt a larger interior to accommodate small musical forms, performances and meetings, an attempt was made to correct acoustic defects and even use the unfavourable concavity of the ceiling to support the first reflection of sound. The summary also indicates material proposals enabling the implementation of the proposed solutions.

Keywords: acoustic treatment, concert hall, acoustic parameters of the interior, concave ceiling, caustics.

1. Introduction

The historic building of the former riding school with its characteristic semicircular roof is currently an element of the Krakow Opera complex built in 2008 [2]. The building serves as the entrance hall to the Opera on the ground floor, while the mezzanine is dominated by the entertainment and conference function. The upper floor, which is the mezzanine, has a semicircular ceiling, which is the main cause of acoustic defects. Excessive reverberation and sound focusing are significant factors that hinder the proper propagation and perception of music and speech. Considering the planned modernization of the historic building, an attempt was made to analyse and formulate assumptions for acoustic adaptation that would meet the current needs of users. The impact of the non-standard geometry of the concave ceiling can be precisely described by the phenomenon of caustics, which in optics is a special form of imaging the concentrations of reflected light rays. In the range of audible frequencies, the presence of caustics in the room outside the focus is effectively masked by the broadband nature of the sound and the reverberant field of the interior [3]. Therefore, this method of analysis in interior acoustics is not used. In another article, Kamisiński proposed a method for correcting sound focusing by sub-balcony cavities using Schroeder diffusers [4]. This article presents a case study of acoustic adaptation of an interior for the needs of small musical forms, solo performances, acting rehearsals and the organization of banquets and conferences. The analysed room has a semicircular ceiling and is divided into two floors, with the upper floor being a mezzanine. Non-standard geometry is a source of many acoustic defects but at the same time provides opportunities for interesting solutions.

2. Analysis of acoustic parameters of the multipurpose hall

2.1. Description of the hall

The hall is designed with a rectangular floor plan as illustrated in Fig. 1a and its roof is supported by an arched construction with a radius of 14.4 m. A roof based on an arched structure with a concave surface often causes numerous issues in sound propagation. It can lead to phenomena such as sound focusing and flutter echo [1]. Additionally, in architectural acoustics, where concave surfaces (fragment of the sphere or a cylindrical surface) are present, it is essential to consider caustics, which are surfaces formed by rays tangential to it reflected from the concave surface. The audible presence of caustics is challenging to detect due to the broadband nature of sounds, as well as reverberation and diffraction of waves at the edges. According to an article by A. Kulowski [3], in acoustics, the practical (audible) significance of caustics is limited to the creation of areas with increased sound pressure levels, whose size depends primarily on the wavelength of the incident wave. In the following article, the application of various perforations on the ceiling also aims to mitigate the effect of sound focusing by the cylindrical surface of the vault [3].The building has a volume of 8440 m^2. The interior consists of a ground floor and a mezzanine, accessible by stairs and an elevator. The ground floor includes a spacious lobby with a ticket office and a sanitary section, while the upper floor containsa gastronomic segment. The mezzanine is enclosed on both sides by a 1.1-meter high wall, and both levels are connected by open spaces on the left and right sides (see Fig. 1b). The side walls each have 20 symmetrically arranged windows, with 10 on each side.

a) b)

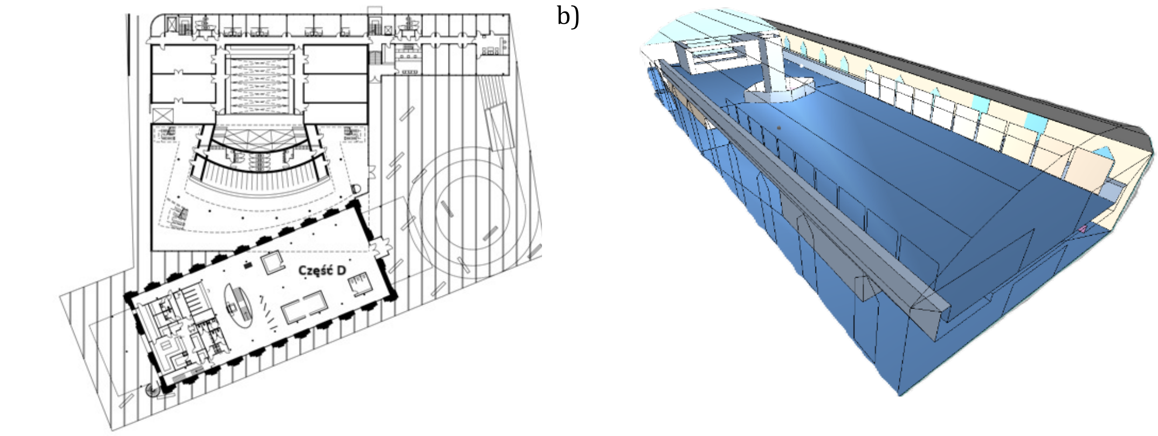

Figure 1. a) The Krakow Opera complex with Section D highlighted [5]
b) Numerical model of Section D in CATT-Acoustic software.

The facility predominantly features surfaces with poor sound absorption, such as concrete, glass, and gypsum board. A detailed list of materials and the surfaces they cover can be found in Table 1.

Table 1. List of surfaces and materials considered in the building modelling.

Surface	Material	Area [m^2]
floor (groundfloor)	concrete + tiles	735
floor (mezzanine)	concrete + PVC flooring	690
archedceiling	gypsumboard	1071
ceiling on the ground floor	gypsumboard	536
windows, entrancedoors	double-paneglass	293
railings / elevator shaft, ticket office	glass	110
walls	gypsumboard	702
café / wall around the mezzanine	glass	671

2.2. Analysis of acoustic parameters of the hall in its current state

The acoustic parameters in the current state were analyzed and evaluated based on measurements carried out following the recommendations of ISO 3382-2 [6]. These parameters were calculated from the recorded impulse responses within the interior. A swept sine served as the excitation signal, and measurements were taken in octave bands with center frequencies ranging from 125 to 4000 Hz. The measurements were conducted using an omnidirectional source and 1/2'' omnidirectional condenser microphones.

The measurements were conducted in three configurations. In the first, both the sound source and the receivers were located on the mezzanine; in the second, the source and receivers were placed on the ground floor; and in the third configuration, the sound source was set on the ground floor while the receivers were left on the mezzanine. The results of the reverberation time calculations for the examined variants are presented in the graph (Fig.2a).

An important factor impacting the usability of the interior is the sound transmission from the ground floor, where the ticket hall is located, to the mezzanine, which is used for the aforementioned functions. Therefore, the difference in sound pressure levels, D, between the ground floor and the mezzanine was adopted for analysis as a measure of the transmitted sound (Fig. 2b).

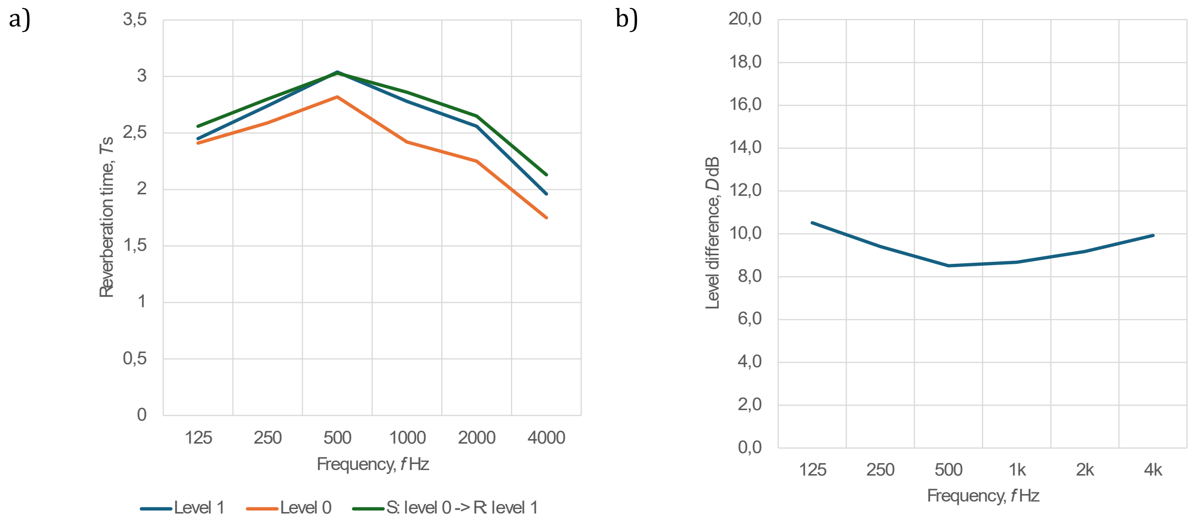

Figure 2. a)Measured reverberation time in the hall,
b) Difference in acoustic pressure levels between the ground floor and the mezzanine.

Based on the analysis, it is clear that the average reverberation time at 500 and 1000 Hz is over 2.9 seconds on the mezzanine (variant 1) and for the interaction between the ground floor and the mezzanine (variant 3). For the ground floor, the reverberation time is slightly over 2.6 seconds. These values are quite high considering the intended functions of this interior [6]. Additional results of other interior parameters for the mezzanine and ground floor are provided in the Tab. 2.

Table 2. Comparison of acoustic parameters of the hall in the current state

Parameter	Level	Value
STI	ground floor	0.46
	mezzanine	0.55
C_{80} [dB]	ground floor	-1.6
	mezzanine	2.2
$G_{500-1000}$ [dB]	ground floor	12.9
	mezzanine	12.2

The Speech Transmission Index (STI) indicates that speech intelligibility is poor on the mezzanine, but sufficient on the ground floor. On the other hand, the C80 parameter on the mezzanine meets the level appropriate for symphonic music performance due to high reverberation within the interior [8].

2.3. Concept of acoustic adaptation of the hall

The acoustic adaptation project is based on analysing the current state of the space. Since the space is meant to accommodate a wide range of events, the main goal is to reduce the reverberation time, which currently exceeds 3 seconds at 500 Hz. According to literature recommendations, the ideal reverberation time for the functions analysed should fall between 1.2 to 1.7 seconds [6], so a recommended reverberation time of 1.3 seconds has been adopted. Another goal is to equalize the frequency response of the reverberation time, allowing for an increase in low-frequency values and a decrease in high-frequency values. The guidelines also aim to improve the acoustic parameters on both floors, with a specific emphasis on enhancing the acoustic performance of the mezzanine. For the intended use of the mezzanine as a conference/lecture hall, the target Speech Transmission Index (STI) value has been set above 0.6, which indicates good speech intelligibility. The criteria include a Sound Strength Level (G) ranging from 1 to 10 dB [9]. After the adaptation, the interior should also eliminate acoustic defects such as flutter echo and minimize sound transmission between the ground floor and the mezzanine to enable simultaneous use of both levels without interference, particularly from the ground floor to the mezzanine.

3. Analysis of the results

After conducting thorough analyses and consulting with architects, an acoustic adaptation has been proposed. This adaptation involves using mobile partitions lined with sound-absorbing material to create separate areas within the mezzanine space (see Fig.3). This way, we can have a section for dining separated from the area primarily used for concerts and rehearsals. The partitions are movable, which allows us to adjust the acoustic parameters such as reverberation time and early sound reflections. When spread-out, exhibition screens provide an additional sound-absorbing area covering 270m^2.

The stage on the mezzanine changes its position depending on its use. When the room functions as a conference hall, the stage platform is positioned along the axis of the room near the front wall. For concert hall and rehearsal room functions, the stage is placed along the side wall (Fig 4). For events where the stage is positioned along the hall's axis near the front wall, we considered using reflective panels above the stage to reduce the delay time of the first reflection and direct reflections towards the audience. We have introduced four panels suspended at a 30-degree angle, positioned one meter from the front wall and hung approximately 4.2 meters above the mezzanine floor. Each panel measures 2.4 meters in width and 1.2 meters in length.

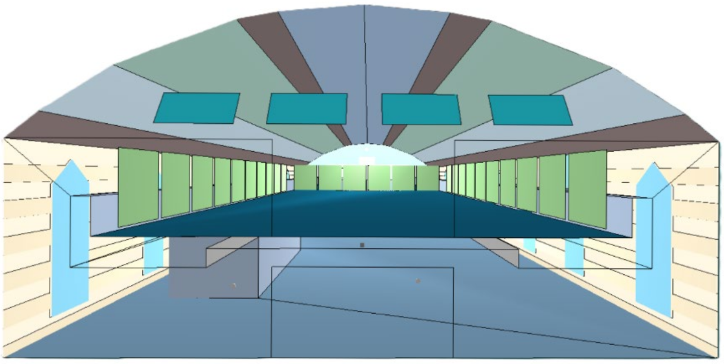

Figure 3. View of the arrangement of individual elements of the acoustic adaptation of the hall.

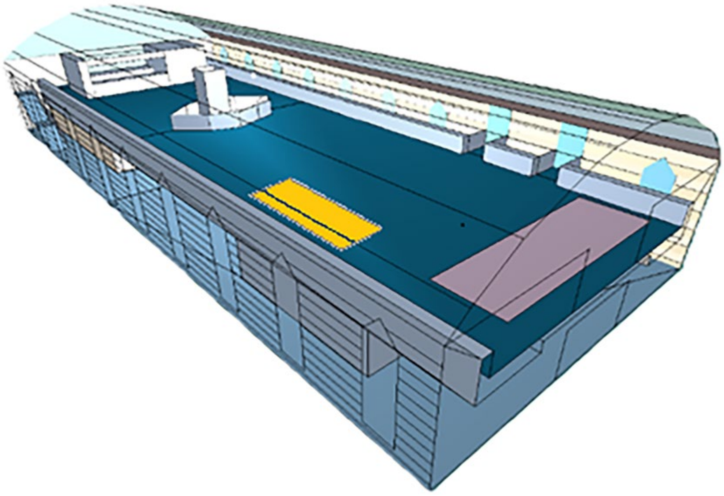

Figure 4. Visualization of the location of the stage platform on the mezzanine, which serves as: conference room (pink), concert room (yellow).

In order to improve the acoustics of the hall, we have proposed to use perforated panels with varied sound absorption characteristics on the ceiling. Panels with the highest perforation ratio and sound absorption coefficients for mid and high frequencies were installed at the highest point of the ceiling to reduce sound reflections and eliminate multiple echoes in that area. Additionally, panels with a lower perforation ratio were placed near the side walls to ensure the transmission of initial reflections from the stage to the audience. The side walls also have perforated panels to reduce reverberation time and limit sound transmission from the ground floor to the mezzanine. We used CATT-Acoustic software for acoustic parameter calculations and compared the calculated reverberation time values against the recommended values, which are presented in the graph below (Figs 5a,b).

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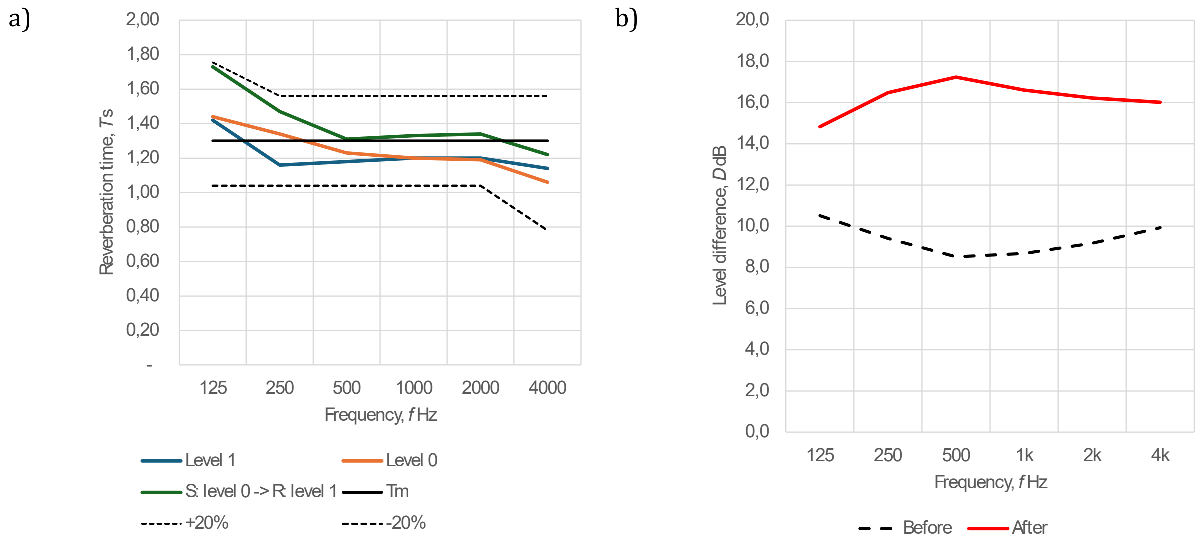


Figure 5. a) Calculated reverberation time values for the presented acoustic adaptation variant, b) Difference in acoustic pressure levels between the ground floor and the mezzanine after acoustic adaptation.

The reverberation time values for the ground floor and mezzanine, as well as their interaction, fall within the accepted tolerance range. Therefore, the use of sound-absorbing perforated panels on the ceiling and mobile panels on the mezzanine has significantly reduced the reverberation time in the hall (see Fig. 5a). Additionally, the installation of sound-absorbing panels on the side walls has effectively reduced the noise transmission from the ground floor to the mezzanine. The difference in acoustic pressure levels due to these adaptations reaches approximately 17 dB across the mid-frequency range (see Fig. 5b). The values of the remaining acoustic parameters after the hall adaptation are presented in the Tab. 3.

Table 3. Comparison of acoustic parameters of the hall after acoustic adaptation.

Parameter	Level	Value
STI	ground floor	0.63
	mezzanine	0.61
C_{80} [dB]	ground floor	5.03
	mezzanine	3.63
$G_{500-1000}$ [dB]	ground floor	7.77
	mezzanine	4.82

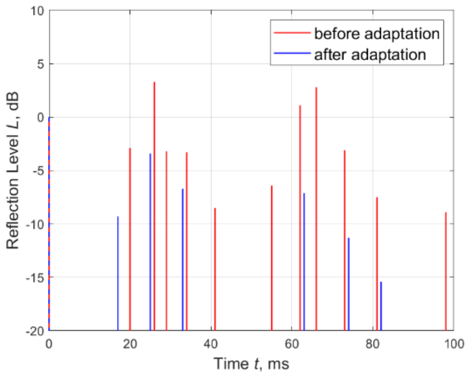
The presented acoustic adaptation approach has significantly improved the Speech Transmission Index (STI) in the hall. The obtained STI values on both the ground floor and the mezzanine are above 0.60, corresponding to good speech intelligibility. Additionally, the clarity index C80 achieved approximately 5 dB on the mezzanine, suitable forelectronicmusic clarity. Furthermore, the average sound strength G has been reduced and also falls within the target range of values.

In order to assess the effectiveness of the proposed solutions in reducing acoustic defects such as sound concentration and flutter echo, an analysis of early sound reflections was carried out for both stage locations on the mezzanine.

The analysis showed that the stage position has a significant effect on the amplitude of reflections at the listening position located in the middle of the audience. For the stage position along the front wall in the hall before adaptation, reflections with an amplitude greater than the direct sound can be observed (Fig. 6a) arriving at times of about 25 ms and 65 ms. This is influenced by the sound focusing by the concave ceiling, in particular the position of the sound source and the listening position on the hall axis. As a result, this causes an audible flutter echo. For comparison, the position of the stage along the side wall ensures that the sound source is not located on the hall axis, which significantly limits the sound focusing by the ceiling and reduces the amplitude of early reflections at the listening position (Fig. 6b).

The use of the described acoustic adaptation of the ceiling allows for a significant reduction of early reflections from the ceiling. For the stage layout along the front wall, a reduction of the level of the first reflection (25 ms) by 5 dB and of subsequent reflections (65 ms) by almost 10 dB was achieved. In turn, for the system along the side wall, the reduction of the level of the first reflection is about 2 dB and about 5 dB for subsequent reflections. The simulation results confirm that placing sound-absorbing material with the highest absorption coefficient at the highest point of the ceiling will allow for a significant reduction of acoustic defects in the hall.

a)



b)

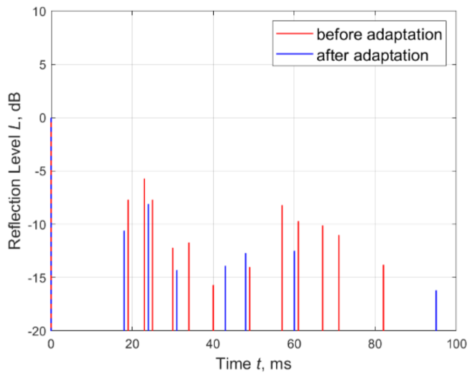


Figure 6. Analysis of the early reflections for a) stage positioned along the front wall and b) along the side wall.

4. Conclusions

The article introduces the concept of adapting the acoustics of a hall with non-standard geometry. The interior includes a concave ceiling supported by an arch and a mezzanine used for conferences, orchestra rehearsals, and small musical group performances. After researching the space, several acoustic issues were identified, such as excessive reverberation, sound focusing, multiple echoes, and sound transmission between floors, rendering the interior unsuitable for its intended functions.

The findings from the analysis were used to establish requirements for the acoustic adaptation project. These requirements included specifying recommended reverberation times for different functions, required Speech Transmission Index (STI) values for conferences, and Clarity (C80) values for rehearsal and performance spaces. Recommendations for reducing sound transmission between floors were also crucial.

Using computational simulations and a numerical model of the interior, an acoustic adaptation of the hall was proposed. The adaptation aimed to create a dedicated space on the mezzanine that met the established project criteria. As a result, the proposed solution significantly reduced reverberation time, improved speech intelligibility, and addressed acoustic issues such as multiple echoes and sound transmission between floors.

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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