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Analysis of the Acoustic Parameters of the Maria Zankovetska Theatre in the Lviv Before and After Modernisation of the Audience

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Abstract. The building of the Maria Zankovetska Theatre in Lviv was founded in 1837-1842. In the years 1941-1944, as a result of damage to the building structure, the building was partially reconstructed. In place of four balconies with boxes, two balconies with amphitheatre arrangements of the audience were built. Currently, the audience has 799 seats, including 531 on the ground floor and 268 on two balconies. Renovation work carried out in 2017 included the replacement of worn-out armchairs and the renovation of the floor. Previous chairs were covered with thick upholstery made of seagrass and velour. Newly mounted seats also have thick layers of upholstery made of PU foam covered with velour. The aim of the research was to analyse the acoustic parameters of the theatre's historic interior before and after changing the armchairs. The article presents the results of acoustic parameters measurement of the hall without spectators before and after modernisation. The measured parameters were used to calibrate the numerical model of the hall. Next, the acoustic analysis was carried out. The reverberation time T20 and the speech transmission index STI were calculated and used to assess the hall acoustics with spectators. A comparison of the results showed that after installing new seats in the theatre the reverberation time values for medium and high frequencies decreased, while for low frequencies they increased. In turn, after replacing the seats, the STI values increased. The obtained results showed that the most important impact on the acoustic parameters of the theatre is provided by upholstered armchairs with high sound absorption, which is related to their construction, thickness of the upholstery as well as their quantity and arrangement in the room.

1. Introduction

The theatre was constructed between 1837 and 1842 based on projects by Ludwig Pichla and Johanna Zalzman. The architectural layout of the theatre was designed without compromises making it the biggest theatre facility in Europe, housing artists and cultural institutions. From the beginning of its existence the theatre was a centre of cultural life in eastern Galicia. In its initial shape there were about 1460 seats in the audience distributed over the ground floor, side boxes and four balconies. In 1941-1944 due to construction damage caused by pile foundation the object was partially rebuilt. The original balconies and side boxes were replaced by two amphitheatrical balconies.



The numerical analysis of historic concert and opera halls was made by Kamisiński. The research included comparison of halls acoustic parameters in various hall configurations [16] and analysis of Schroeder diffuser application for acoustic defects correction in recesses under balconies [15]. Beranek [1] research on sound absorption by the audience in big halls indicates linear relation between the equivalent sound absorption area and the audience surface. However, the sound absorption of the audience is determined by many features such as the seat design, arrangement density, audience profile and sector layout. According to Nishihara [2] and Kulowski [3] the audience is a main factor determining the equivalent sound absorption area of a concert hall with contribution up to 80%. It defines the reverberant conditions of the interior. Bradley [17] and Rubacha [9] showed that absorption of audience depends on size of chair blocks. Therefore, it is crucial to estimate the sound absorption coefficient of the audience with the greatest degree of accuracy.

The aim of this research is to examine the impact of audience parameters and stage on the acoustic parameters of the theatrical hall. The analysis was made for three different seat upholstering options - light, medium and thick. The analysis of total sound absorption was made for the hall. The observed parameters included reverberation time T20, clarity index C80 and Speech Transmission Index STI.

2. Research on acoustic parameters of the theatre

2.1. Description of the object and its modernization

The audience of the Maria Zankovetska Theatre has 799 seats, 531 on the ground floor and 268 distributed over two balconies (figures 1 and 2). The main hall volume (about 5400m³) is connected with 8000m³ scenic box. Detailed theatre hall parameters are listed in table 1.

Table 1. Parameters of the Maria Zankovetska Theatre in Lviv

No.	Parameter	Value
1	Total volume V [m ³]	13400
2	The volume of the audience V _w [m ³]	5400
3	The volume of the stage V _{sc} [m ³]	8000
4	Orchestra pit volume V _{or} [m ³]	80
5	Stage surface S _{sc}	410
6	The surface of the orchestra pit S _{or}	40
7	Number of seats joined together N	799
8	Number of seats on the ground floor N _p	531
9	Number of seats in boxes N _l	268
10	Volume of the audience per person m ³ /person	5,63

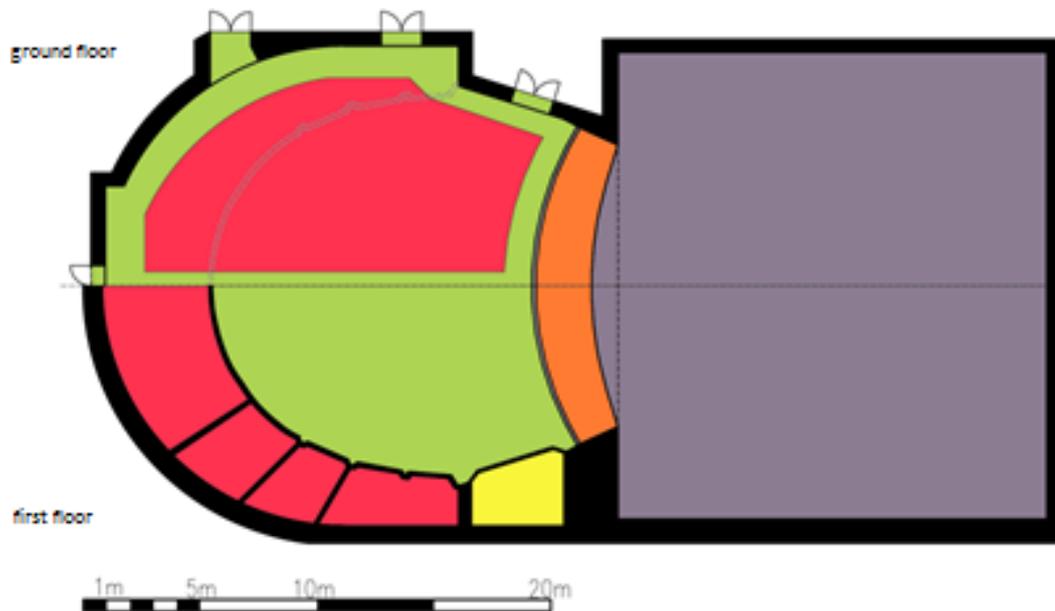


Figure 1. Plan of ground and first floors of the Maria Zankovetska Theatre in Lviv

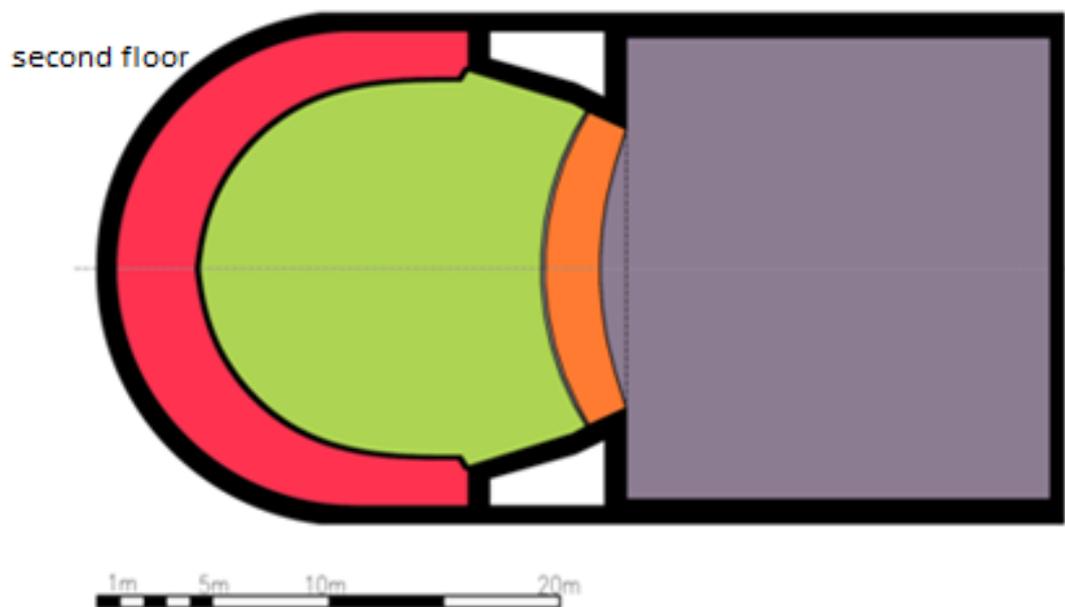


Figure 2. Plan of second floor of the Maria Zankovetska Theatre in Lviv

In 2017 the theatre underwent a modernization including replacement of flooring in the audience area and seats. Seats mounted before the renovation were heavily upholstered on seat bottom and back. After the rebuilt in '40s, the audience was the only sound absorbing element in the hall. As a consequence, the reverberation time was too long for theatrical venue. It was decided to use seats of similar construction to prevent further increase in reverberation time. The audience before and after the modernization is presented on figure 3.

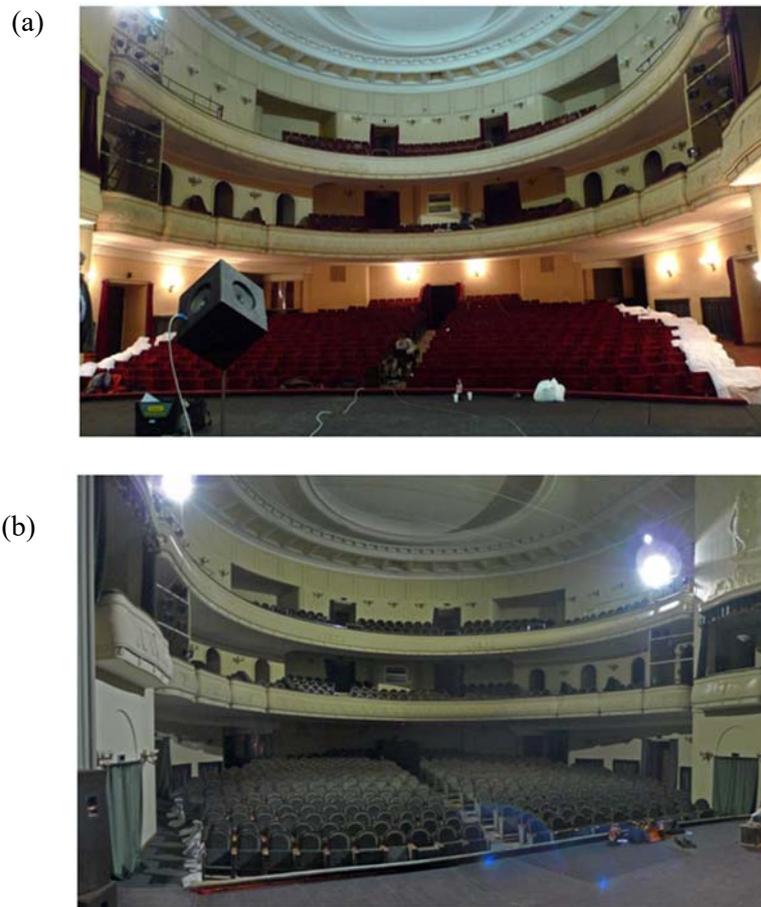


Figure 3. View of the hall before (a) and after (b) the renovation

2.2. Method of measurement

The theatre acoustic parameters were measured according to general literature recommendations [4], international standards [5] and authors' experience. To evaluate the acoustic conditions in the examined interior we selected the reverberation parameters (T20), clarity (C80) and speech transmission index (STI). The measurements were taken with open curtain and typical scenography on the stage.

2.3. Model studies - CATT, description of the model and input parameters

To estimate the acoustic parameters of the theatre with full audience we created a numerical model in CATT-Acoustic software (figure 4). The application simulates the sound propagation using advanced geometrical model based on ray tracing and image sources method [6, 7]. The model was created using geometric data gathered using photogrammetric method and sound absorption and scattering coefficients of the interior surfaces. The absorption coefficients of particular surfaces are comparable between similar objects therefore a set of coefficients measured in laboratories of Department of Mechanics and Vibroacoustics for Lviv Opera [8] and for wood materials [14] and curtains [10] was adapted. Absorption coefficients of the stage were determined based on measurements taken in the theatre. Scattering coefficients of surfaces used in the model were measured in the laboratory [11, 12, 13]. The numerical model was calibrated to match the measured reverberation times.

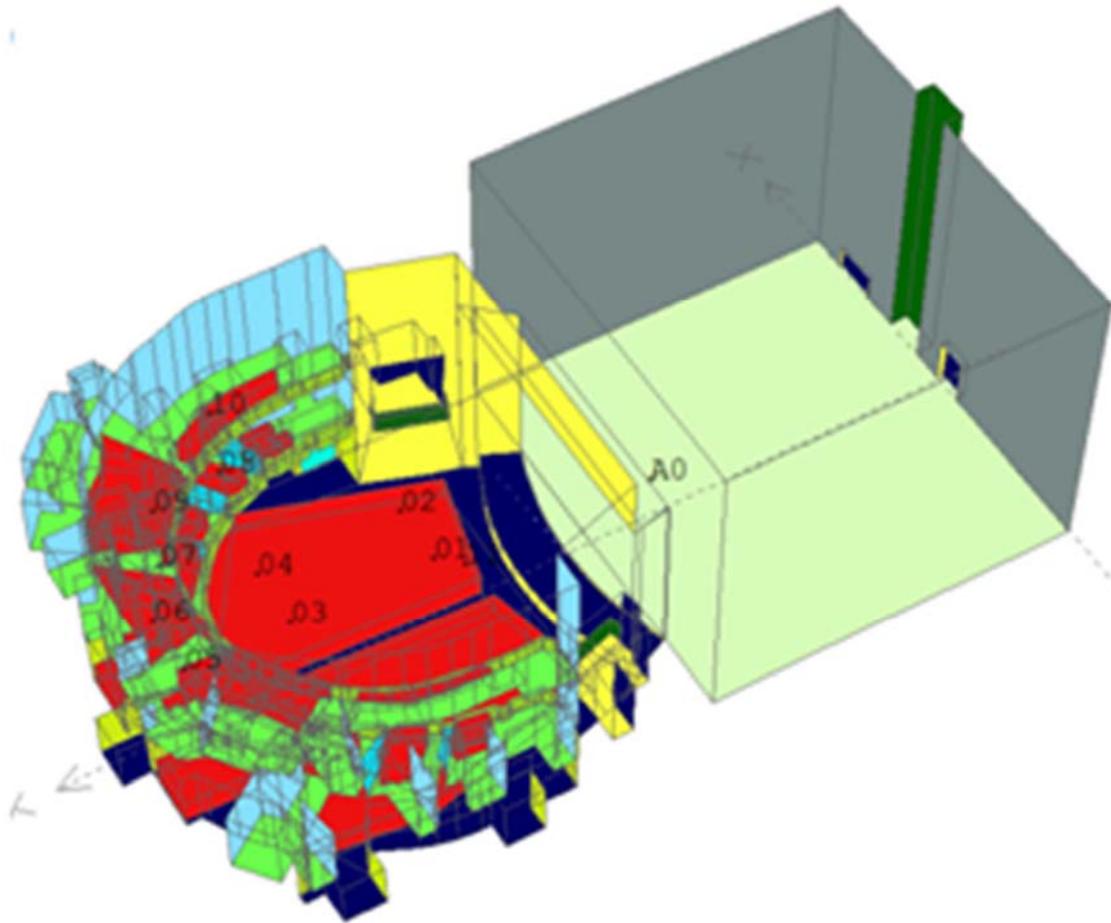


Figure 4. View of the Zankovetska Theatre inside, CATT-Acoustic model, actual state

The impact of seat upholstery on the acoustic parameters of the theatre was examined for three groups of seats - lightly, medium and heavily upholstered. The division into such groups was proposed by Beranek based on his research on concert halls acoustics. Details of the upholstery layers are presented in table 2.

Table 2. Seat groups based on upholstery thickness [1]

No.	Type of seat	Front side of seat Back	Rear side of seat Back	Top of seat bottom	Arm rest
1	Heavily upholstered, group 1	75 mm	Sometimes	10 mm	20 mm
2	Medium upholstered, group 2	25 mm	0	50 mm	Solid
3	Lightly upholstered, group 3	15 mm	0	25 mm	Solid

Sound absorption coefficients of the seats with and without the audience for each type of upholstery are presented on figures 5. Presented values were used as input parameters to computational model of the theatre. The simulations carried for different seat options were used to examine the impact of the seat construction on the acoustic parameters of the examined interior.

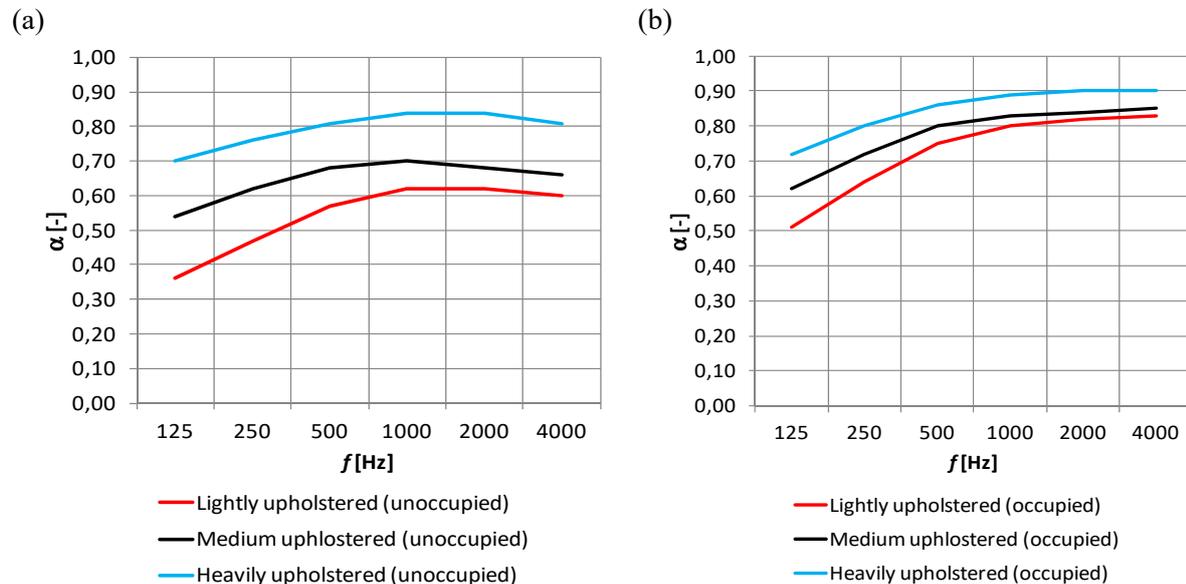


Figure 5. Sound absorption coefficients of the seats with (a) and without the audience (b) [1]

3. Results and discussions

In the first stage of the research we calculated the acoustic parameters of Maria Zankovetska theatre with audience before and after the renovation. According to literature recommendations, the average reverberation time in a theatre without a sound system should be 1.4 s in frequency range 500 and 1000 Hz. Moreover, the reverberation time characteristic in frequency domain should be linear and fit within +/-20% from recommended value. For frequencies over 2 kHz the reverberation time can decrease 10% per octave.

The simulation results indicated that the reverberation time after seat replacement hasn't change significantly. A decrease of reverberation time is observed in medium and high frequency range. Average reverberation time before the renovation was $T_m = 1.38$ s, after the renovation the value dropped to $T_m = 1.29$ s. In the low frequency range the reverberation time increased for 125 Hz octave band it changed from 1.94 s to 2.20 s. The obtained reverberation times in the room both before and after the seats replacement deviate from the recommended linear characteristics what is typical for horseshoe-shaped halls. In such case the finishing materials have significant impact on the reverberation time characteristics. Most of the surfaces in the theatre are hard walls with low absorption coefficients in whole frequency range. The only significant sound absorbing area is the audience which has high absorption values in medium and high frequency range, what leads to uneven reverberation time characteristics (figure 6).

Apart from reverberation time we examined parameters corresponding to speech intelligibility STI and music clarity C80. Based on the numerical model we calculated the parameters for a hall with full audience. According to [3] the STI for theatre without sound system should be higher than 0.6 at the ground floor and on middle balconies. The recommended average C80 in 500, 1000 Hz frequency range for music theatre is -2 to +3 dB.

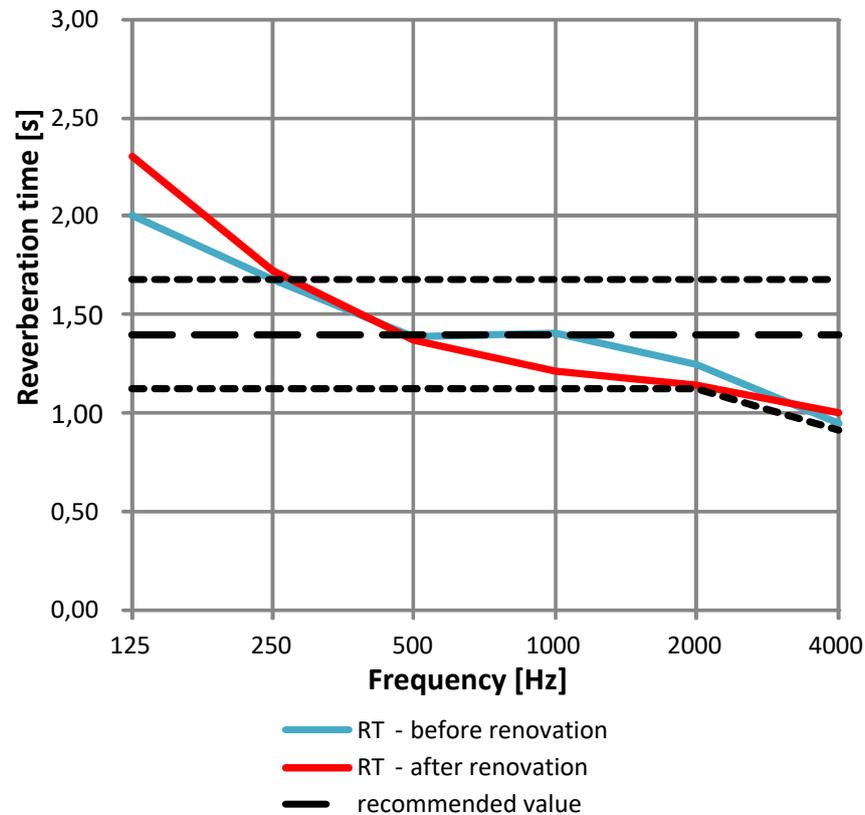


Figure 6. Evaluation of the reverberation time value in the audience room (estimated calculations)

Table 3. Intelligibility parameters STI and C80 before and after the renovation

Point no	Before seats replacement		After seats replacement	
	<i>STI</i>	<i>C80</i>	<i>STI</i>	<i>C80</i>
1	0.66	5.2	0.67	5.3
2	0.66	4.7	0.66	4.9
3	0.63	4.3	0.62	4.8
4	0.62	3.5	0.60	3.9
5	0.71	6.5	0.70	7.1
6	0.68	6.1	0.65	6.2
7	0.62	4.2	0.62	4.5
8	0.63	4.1	0.62	3.8
9	0.64	2.6	0.61	3.2

The change of speech intelligibility parameter STI before and after the renovation is not significant (table 3). The highest difference in examined parameters is 0.03 for STI and 0.6 for C80. The new seats have similar sound absorbing properties what is caused by thick upholstery used in both cases.

We analysed the impact on the acoustic parameters of the Maria Zankovetska theatre room with armchairs of various thicknesses of upholstered layers. The calculations were carried out for the hall with audience for three types of upholstery (figure 7).

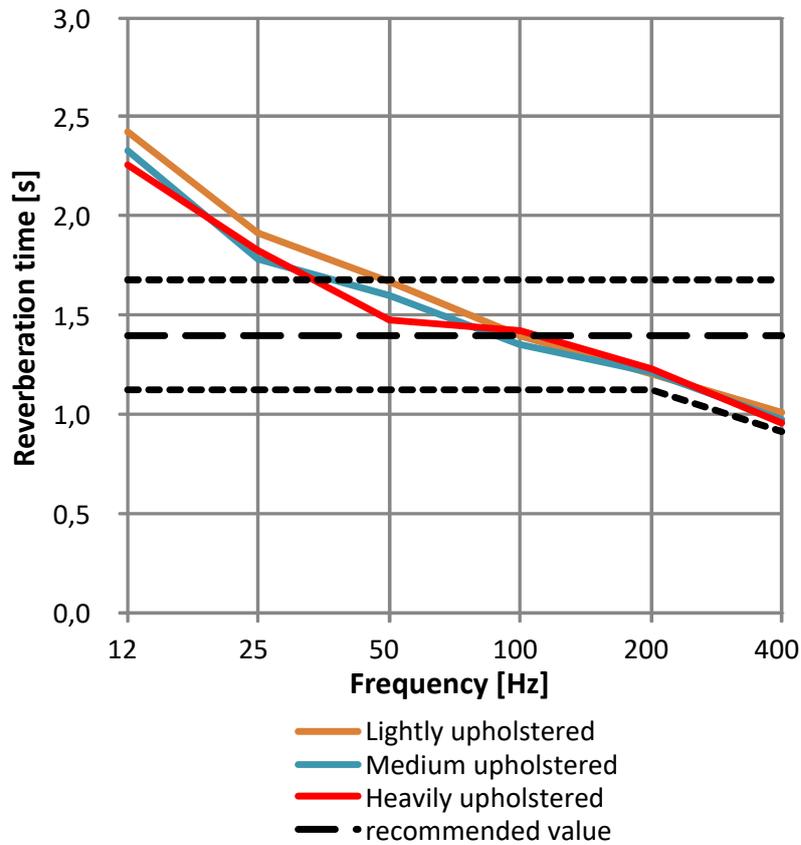


Figure 7. Calculated reverberation time for hall with audience

Based on the results, it can be noticed that the change in the thickness of the upholstered layers on the seats has no significant effect on the reverberation time in the theatre hall. Changes were only observed for the low and medium frequency range.

Table 4. STI and C80 for hall with the audience for different seats upholstering options

Point no	L	STI			C80 (500Hz -1kHz)		
		M	H	L	M	H	
1	0.64	0.65	0.66	4.6	4.8	5.2	
2	0.65	0.62	0.66	4.5	4.1	4.7	
3	0.62	0.61	0.63	4.0	3.9	4.3	
4	0.61	0.69	0.62	3.0	3.5	3.5	
5	0.69	0.66	0.71	6.0	6.2	6.5	
6	0.66	0.64	0.68	5.5	5.7	6.1	
7	0.62	0.62	0.62	3.5	4.5	4.2	
8	0.62	0.62	0.63	2.9	3.7	4.1	
9	0.61	0.61	0.64	2.3	2.5	2.6	

Table 4 presents the comparison of the values of STI and C80 parameters for different types of seat upholstery in the hall. Based on the results, it can be noticed that the change in the thickness of the upholstery also has no significant effect on the values of STI and C80. For lightly upholstered armchairs, the obtained STI results change by 0.08 while the biggest difference for C80 is 3.7 dB.

An analysis of the absorption of individual surfaces was also carried out. On its basis, it is possible to determine areas of the hall which have a significant impact on the acoustic parameters. Five areas have been listed out (figure 8):

- The walls of the stage together with the stage equipment, the floor on the stage, including the absorption by the set design.
- Walls in the audience with boxes, balconies and doors.
- Ceiling above the audience.
- The audience in the hall composed of armchairs.

$$A_i = \alpha_i S_i, \quad (1)$$

where α_i is a sound absorption coefficient of a given area, S_i is a surface area.

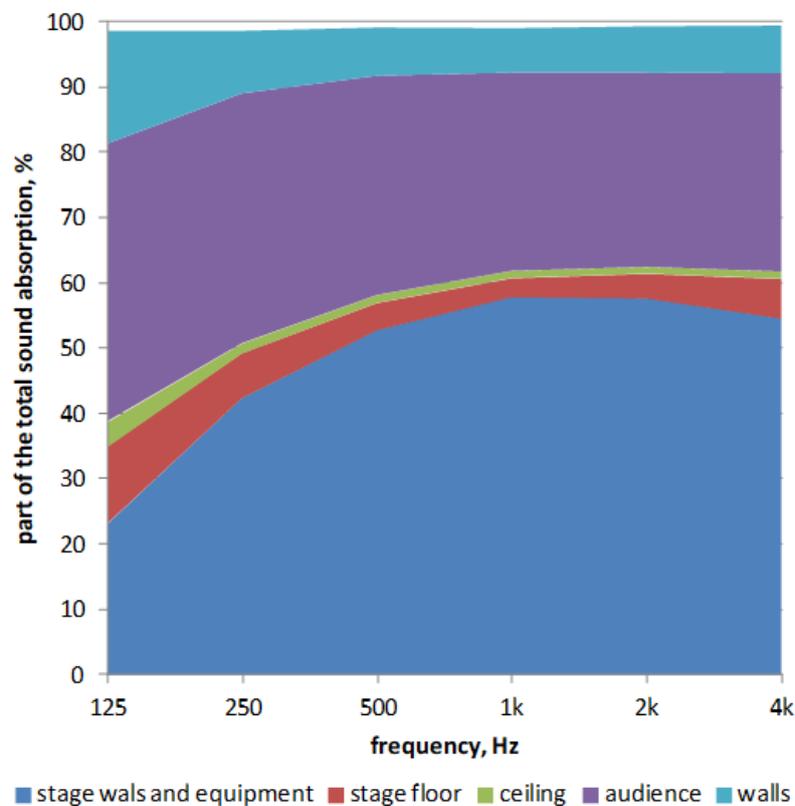


Figure 8. Analysis of the share of acoustic absorption of individual surfaces in the hall

The conducted analysis showed that a stage with equipment has the largest share in the total absorption capacity of the theatre hall in the medium and high frequency range. Total absorption share of the stage is approximately 60% for this frequency range. This is due to the very large volume of the stage tower in which the stage equipment was mounted, the scenery elements were suspended from the ceiling and the stage elements were placed on the floor. In turn, the hall with upholstered seats has a very significant impact on sound absorption in the low frequency range, where its share reaches 40%. The audience share is around 30% for medium and high frequencies.

4. Conclusions

The research shows that the most important elements shaping the acoustic parameters of the theatre hall interior are the stage along with the stage tower and the audience with upholstered chairs. Studies have also shown that changing the design of seats in the hall with audience has little effect on the acoustic performance of the hall. It is caused by small changes in the absorbency of seats with spectators sitting on them, where the main sound absorbing element is a person sitting.

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