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The Study of the Proscenium Area in an Opera House

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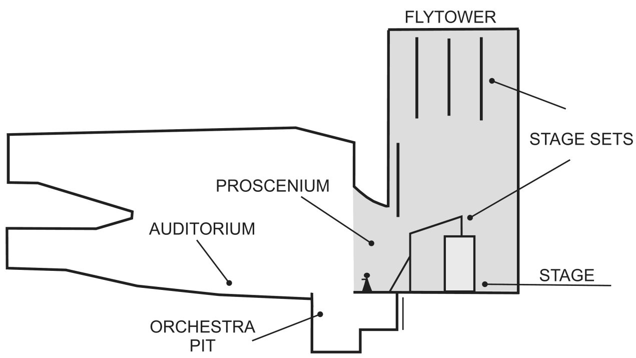
The paper describes issues of the proscenium area shown on the example of two opera houses. The subject of the analysis was the design of the Chamber Opera House in Kalisz and the already existing building of the Opera House in Krakow. It covers the influence of the proscenium walls and forestage ceiling on the acoustic conditions in the auditorium. Another subject of the investigation was the influence of the primary proscenium, designed in the very first opera houses in Baroque. The analyses were carried out by means of two computer softwares: Ray Model and Catt Acoustic, and such parameters as sound strength (G), reverberation time (RT), early decay time (EDT), C_{80} (clarity) index and center time (T_S) were calculated. The parameters were further analyzed in the auditorium for three positions of the sound source on the stage.

Keywords: proscenium; acoustic screen; opera house.

1. Introduction

The stage takes up most space in the theatre and is the centre of theatrical life. In a concert hall, the stage and the auditorium are in the same acoustic space along with the audience. The opera hall is much more problematic because the stage area (the so-called proscenium stage) is separated from the audience, and, in addition, the orchestra is situated in the pit below the stage (Fig. 1). We should take note of the fact that the flytower area is a dominant element in the body of the building. Therefore, if the flytower area is large, it seriously affects acoustics between the stage and the auditorium. The main acoustic issue is to design the stage area so that singers are audible beyond the orchestra. One of the vital acoustic solutions which can ensure the singer's audibility is to shape the expanse of the proscenium. It is the proscenium opening and the forestage walls along with the ceiling that have a great impact on acoustics in the auditorium. Figure 2 shows schematically shown elements that occur in the stage area in the opera house. Two aspects are shown – one in which there are no forestage walls in the stage area and the other in which forestage walls occur. In addition, two types of proscenium openings are depicted – the contemporary one and the Baroque one.

a)



b)

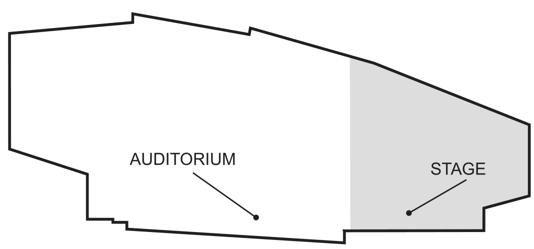


Fig. 1. Longitudinal section through: a) typical opera house and b) typical concert hall.

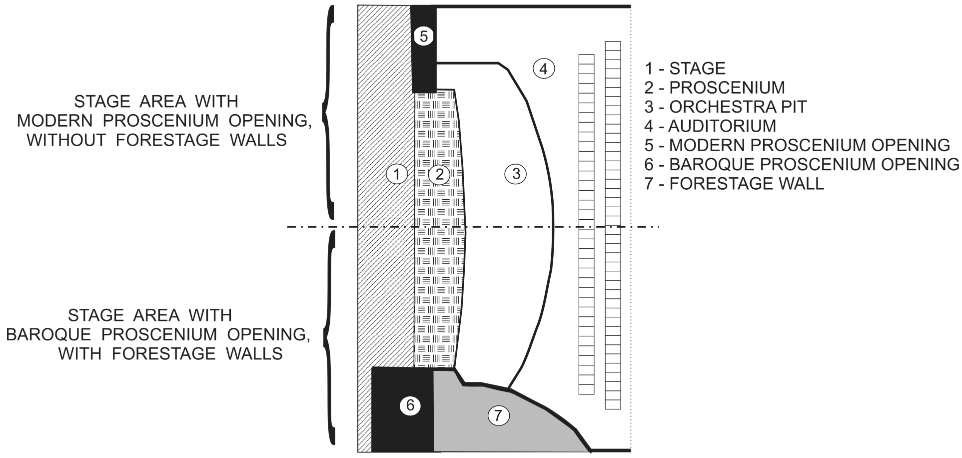


Fig. 2. Stage area in opera house.

Fig. 3. Comparison of the Baroque proscenium with the modern proscenium (sketch by A. Sygulska).

In the Baroque opera house the proscenium opening looked entirely different from how it looks nowadays. The opening walls were very wide. They acted as acoustic baffles. The artist sang standing between them and the sound was reflected and directed towards the audience. The function of the proscenium opening was to amplify the artist's voice. In 1676 Motta wrote in his book *Treatise on the structure of theatres and scenes* about an enormous acoustic importance of a deep proscenium opening. The author comments that performers who sing within the stage opening area are heard as clearly as the orchestra. He also adds that it is the most acoustically crucial place (Edwards, Kahn, n.d.). Figure 3 shows the difference in the shape of the proscenium area in the Baroque opera house and in the modern opera house.

The architectural changes within the space can be easily observed. The proscenium in the form widely known in Baroque ceased to exist, which had to involve changes in the acoustics of the auditorium.

Intuition that can be observed in the design of the area is noticeable long before the Baroque opera house came into existence. As early as in the ancient theatre we can see that the skene was shaped to reinforce the voice of actors. The skene building had a hard-surfaced overhang to provide sound reflection toward the audience (Fig. 4.).

ANCIENT THEATER

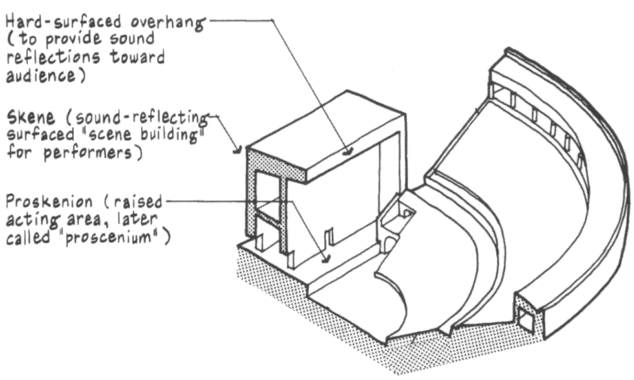


Fig. 4. Ancient theatre with acoustic solution of later proscenium (Egan, 2007).

The function of the forestage walls is similar to that of the wide proscenium opening. Most of the early sound reflections come from forestage walls and from auditorium side walls (Hidaka, Beranek, 2000). In some opera houses there are screens on the forestage. In Carol Morsani Hall in Tampa Bay, USA (architect: D. Fred Lebensold, Arcop), on the ceiling of the proscenium there is a large acoustic canopy with theatrical and concert lighting (Fig. 5). In Dreyfoos Hall in West Palm Beach, the proscenium area features an acoustic screen, the form of which resembles the Baroque proscenium.

Fig. 5. Carol Morsani Hall, Tampa Bay Performing Arts Center, Tampa Bay, Florida, USA (reprinted with permission of Artec Consultants Inc., New York, USA).

Fig. 6. Dreyfoos Hall, Kravis Center for Performing Arts, West Palm Beach, Florida, USA, (reprinted with permission of Artec Consultants Inc., New York, USA).

Similar solutions were applied in Hammerson Hall in Toronto in Canada (architect Zeidler Partnership), or in Thrivent Financial Hall in Wisconsin in USA (architect Zeidler Partnership).

The issue of the proscenium was investigated by these authors (Edwards, Kahn, n.d.). They showed the results of a computer simulation for stages with the Baroque and the contemporary proscenium opening. The issue of the influence of the proscenium was also addressed in the paper by (Hidaka, Beranek, 2000). The example of Komische Oper in Berlin shows changes of the area to which lateral reflections come in relation to the position of the singer on the stage. The article (Maffei *et al.*, 2000) describes the issue of forestage walls in Teatro San Carlo in Naples. The paper (Beranek *et al.*, 2000) presents issues related to the design of the New National Theatre, Opera House in Tokyo. Particular attention was drawn to forestage walls, which were found in the most important surfaces reflecting sound. Paper (Halmrast *et al.*, 2003) describes an acoustic situation in the Norwegian National Opera. It was shown that too big screen (reflector), which enclosed a considerable part of the auditorium, did not yield as satisfactory results as its smaller equivalent, which was located exclusively within the proscenium area.

The issue of Baroque opera houses has been discussed by various authors; what deserves attention is the research of preserved Baroque opera houses with a view to measuring their acoustic properties against those of renovated opera houses. In the following papers, the authors present research and simulations of selected opera houses, in which the original Baroque style has been entirely preserved. The paper (Dolejši *et al.*, 2011) presents research and simulations of Baroque Theatre in Litomyšl, while the paper (Dolejši *et al.*, 2013) presents research and simulations carried out in the ODEON programme for four Baroque opera houses. Yet another paper (Rychtáriková *et al.*, 2014) presents acoustic properties of two objects – Baroque Theatre in the State Castle in Česky Krumlov and Baroque Theatre in the Swedish Royal Palace in Drottningholm.

2. Numerical research of acoustics

The analyses of the influence of the proscenium area on acoustics of the auditorium were carried out for the design of the Chamber Opera House in Kalisz and the existing object of the Opera House in Kraków.

In both cases, the following factors were examined: sound strength G along and across the auditorium, reverberation time RT, early decay time EDT, clarity index C_{80} and center time T_S.

2.1. The project of the Chamber Opera in Kalisz

The influence of the proscenium area for the design of the Chamber Opera in Kalisz (Sygulska, 2011) was examined as first. Figure 7 shows visualizations of the project of the Chamber Opera in Kalisz. The computer simulations were conducted using RAY MODEL software (Kulowski, 1985; 1991) based on the modi-

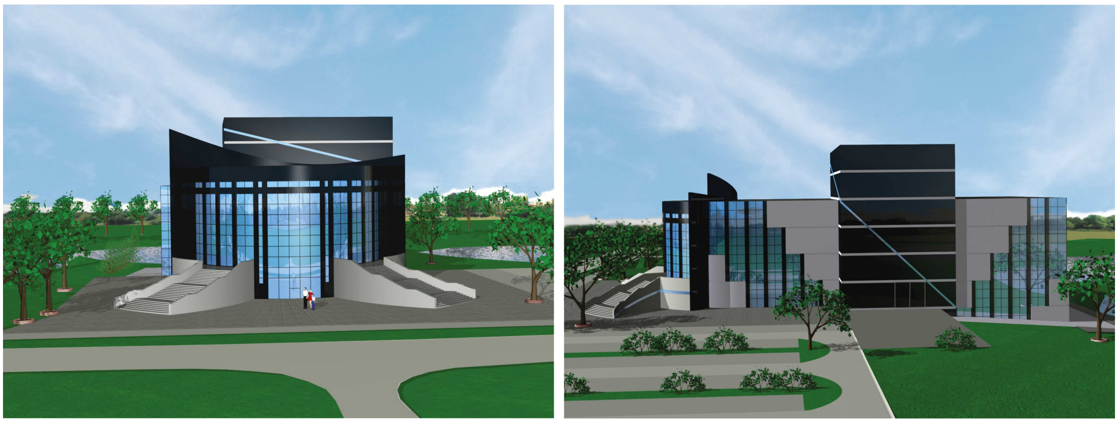


Fig. 7. Visualization of the Chamber Opera in Kalisz.

fied ray method of analyzing acoustic field. Computer simulations are often employed to design acoustic treatment, e.g. (Kamisiński, 2012; Kamisiński *et al.*, 2016), or to evaluate acoustic properties of a given interior, e.g. Dolejši *et al.* (2011), Rychtáriková *et al.* (2014).

Additionally, with a view to measuring sound strength G, theoretical values of sound G were calculated on the basis of the revised theory suggested by (Barron, Lee, 1988).

The volume of the U-shaped auditorium is equal to 2,300 m^3; its dimensions are: total length of 19.0 m, width of 14.0 m, height of approximately 11.0 m. The cubature of the stage along with the backstage and the stagehouse is equal to 10,700 m^3; the area has the following dimensions: 27.5 m in length, 17.4 m in width, 22.4 m in height. On the parterre there are 292 seats. In the auditorium there is one balcony, and there are 89 seats. The dimensions of the proscenium opening are: 8.6 m in width and 7.0 m in height. For the auditorium, the assumption was that the side walls were covered with wooden panels, while the ceiling was covered with acoustic plaster; the stage was wooden, and the walls of the stage and the orchestra pit were covered with plaster.

The numerical model of the auditorium and the stage included 126 nodes and 99 surface elements. Each surface was assigned sound absorption coefficient α for each of the six octave bands accordingly (125–4000 Hz).

The analysis of the acoustic field in the auditorium was conducted for the sound source placed 1.6 m above the stage level. The sound pressure level for each of six octave bands (125–4000 Hz) was 80 dB. The influence of the change of the distance between the sound source and the proscenium opening on acoustic field parameters was also examined.

Figure 8 shows the projection of the stage and the auditorium. In the auditorium there are 9 measuring points to analyze echograms (3×3 eyelets 4.8×4.8 m), marked in the picture with squares. Sound pressure

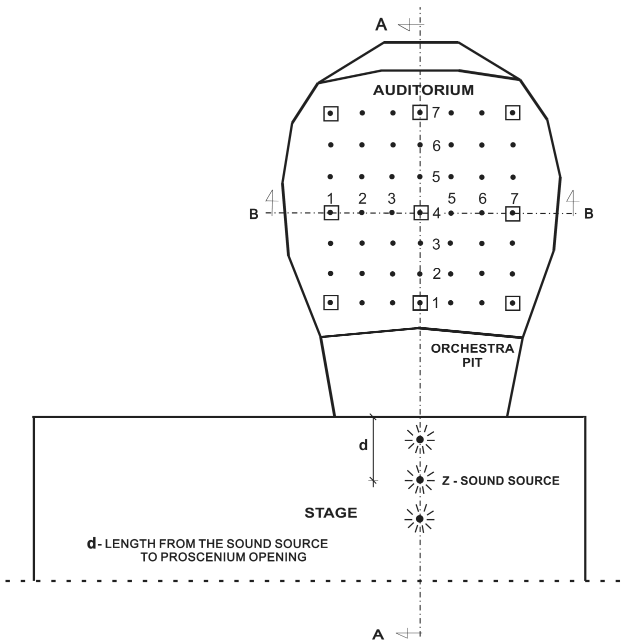


Fig. 8. The view of the auditorium with marked measurement points in the Chamber Opera in Kalisz.

level for the established state was analyzed in 49 measuring points (7×7 eyelets 1.6×1.6 m) shown in the picture with points. The corners of the observation plane of sound pressure level coincide with corner points of the analysis of echograms. The assumed measuring points are marked with digits displayed in the graphs

2.1.1. The analysis of the proscenium area

To examine the influence of the proscenium, this area underwent some modification. The lowering of the ceiling was applied, which acts as a baffle in front of the stage. Also, the Baroque proscenium opening was designed. The existing forestage wall was widened from 0.4 m to 2.4 m.

The full modification ('a' modification) consists in the application of the Baroque proscenium opening (wider walls of the proscenium opening) and the application of a lowered ceiling of the forestage.

The partial modification ('b' modification) consists solely in the application of a lowered proscenium ceiling.

Figure 9 shows the aforementioned modifications. The sound strength G along and across the auditorium for 3 positions of the sound source (d = 2, 4, 6 m) is depicted in the following figures: Fig. 10: proscenium without modification; Fig. 11: 'a' modification; and Fig. 12: 'b' modification.

The comparison of the sound strength G along and across the auditorium for 'a' modification and 'b' modification (d = 4 m) is shown in Fig. 13.

The comparison of the sound strength G along and across the auditorium for 'a' modification and for the proscenium with no modification (d = 4 m) is shown in Fig. 14.

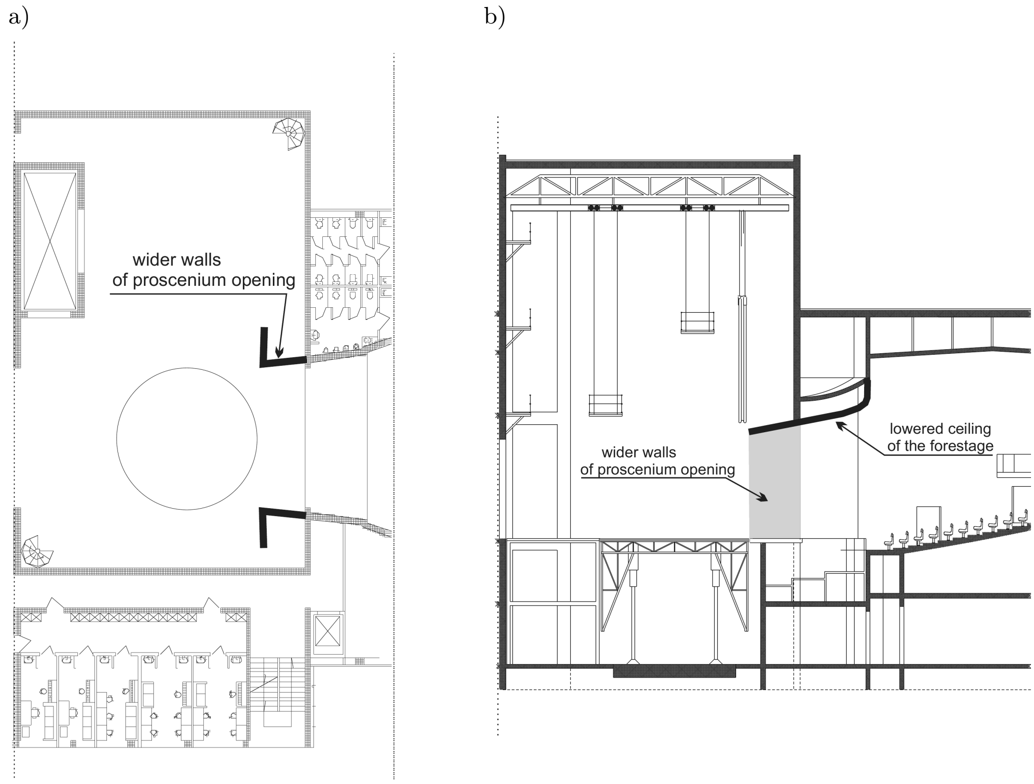


Fig. 9. Aforementioned modification in the Chamber Opera in Kalisz:
a) view of the stage, b) longitudinal section of the stage.

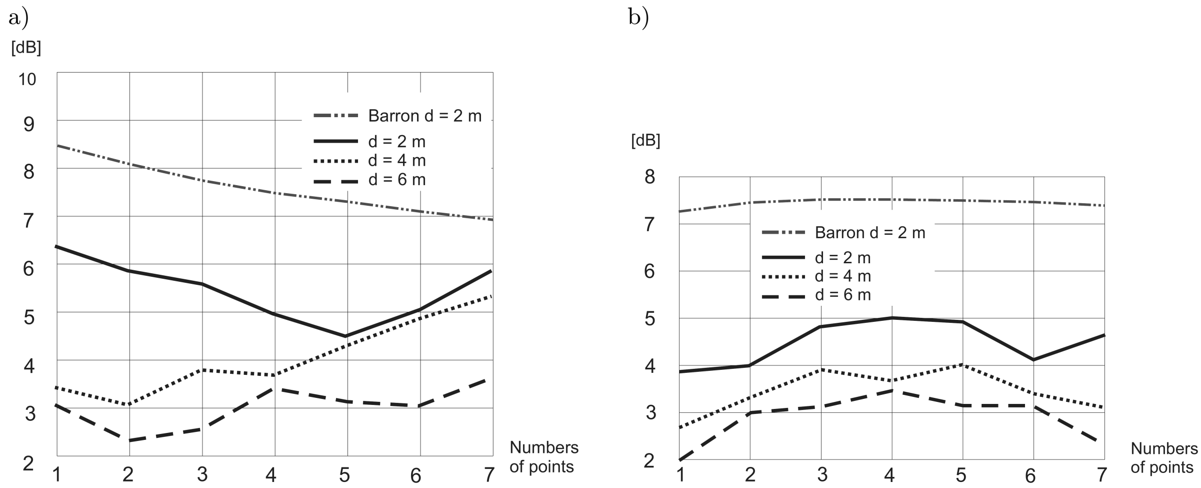


Fig. 10. Sound strength G along and across the auditorium, the proscenium without modification:
a) longitudinal section, b) cross section.

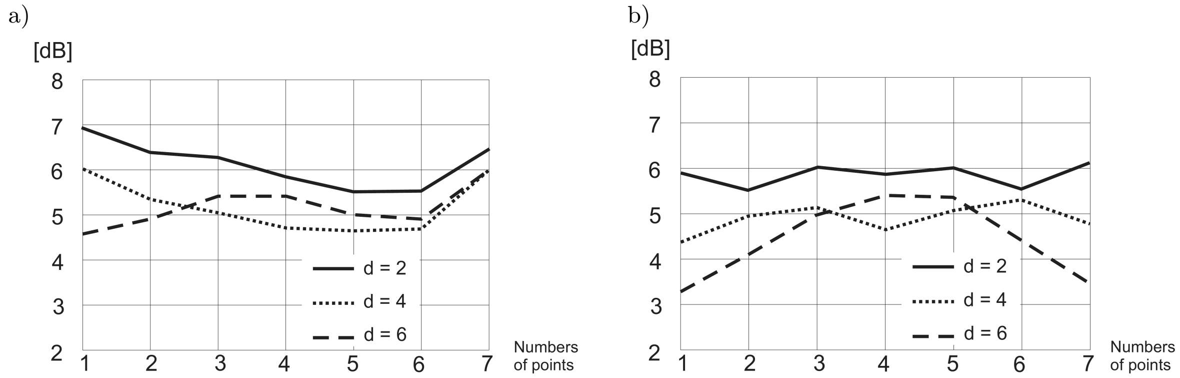


Fig. 11. Sound strength G along and across the auditorium, full modification – 'a' modification: a) longitudinal section, b) cross section.

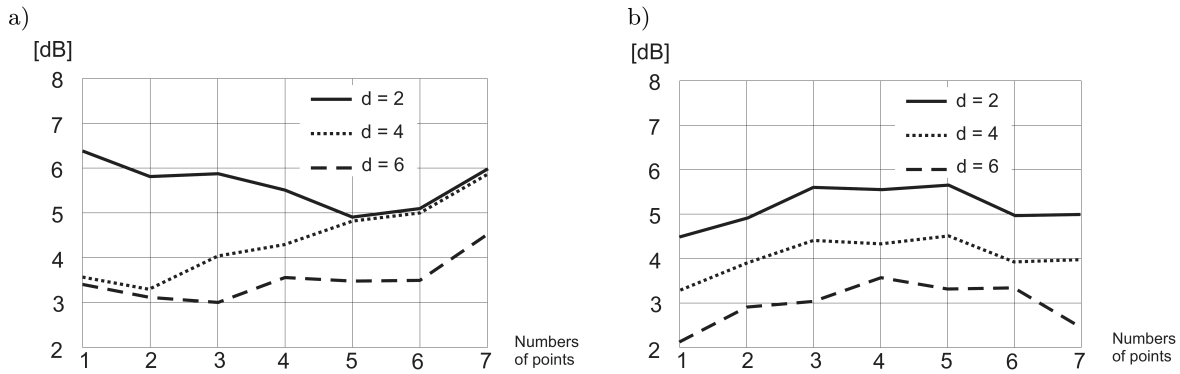


Fig. 12. Sound strength G along and across the auditorium, partial modification – 'b' modification: a) longitudinal section, b) cross section.

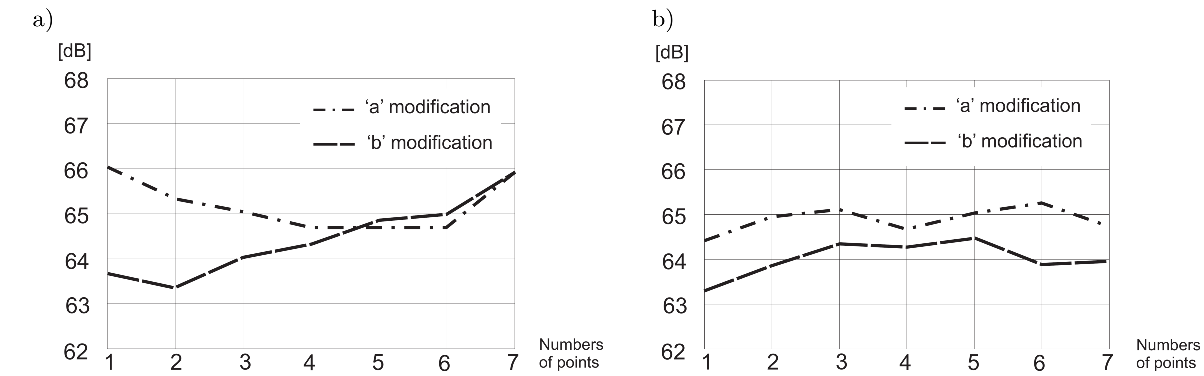


Fig. 13. Sound strength G along and across the auditorium – comparison for 'a' modification and 'b' modification, $d = 4$ m: a) longitudinal section, b) cross section.

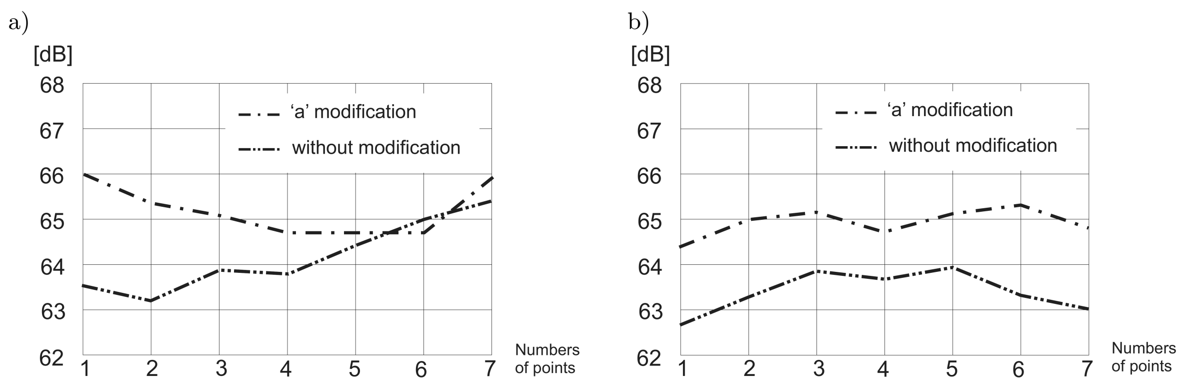


Fig. 14. Sound strength G along and across the auditorium – comparison for 'a' modification and the proscenium without modification, $d = 4$: a) longitudinal section, b) cross section.

2.2. Opera House in Kraków

A series of investigations was carried out in the hall of the Opera House in Kraków. The building of the Opera House became available to the public a few years ago. The hall has two rows of balconies and side balconies (Fig. 15).

The rooms of the stage (stage, stagehouse, backstage, orchestra pit) in the Opera House in Kraków are perpendicular in shape and have the following dimensions: total length of 13.5 m, maximum width of 27.6 m, height of approximately 11.0 m, and volume of 5,800 m^3. The auditorium is fan-shaped and there are two balconies. On the parterre there are 490 seats, on the first balcony there are 43 seats, and on the second balcony there are 152 seats, and on the side balcony there are 48 seats.

All the walls are finished with acoustic structures made of MDF board with various perforation patterns and various absorptive properties. Over the auditorium there is a ceiling made of two acoustic screens positioned at an angle. Also, over the proscenium there is a controlled reflective plane.

“The orchestra pit of the Krakow Opera House was built in accordance with the current requirements for opera hall architecture and stage technology. The 120 m^2 area of the orchestra pit can house an 80 member orchestra. The floor of the open part consists of two segments which can be elevated, which enables adaptation of the size of the pit for the number of members in the orchestra. The front and rear walls are covered with material that reflects sound to a high degree, whereas the ceiling over the stage is covered with sound-absorbing material” (Kamisiński *et al.*, 2009).

2.2.1. The analysis of the proscenium area

In order to examine the influence of the structure type of the stage, acoustic measurements investigations were carried out as first. The measurements were taken in compliance with the PN-EN ISO 3382-1 standard. The results were employed to carry out predictive validity of the acoustic model. Thus, reverberation time T_{20} was adopted. It was assumed that the mean value of reverberation time for all measuring points for individual bands could vary no more than by JND (just noticeable difference); for reverberation time, JND stands at 5% (pursuant to the PN-EN ISO 3382-1) standard.

The results rendered it possible to create a computer model in the CATT-Acoustic environment, and to carry out predictive validity. To predict acoustic parameters, the software uses the mirror image source method and the cone-trace method. The model of the interior was built according to the principles of design of such interiors, i.e. necessary simplified geometry was applied. Side walls in the model were modified, i.e. lengthened by about 2 m toward the back of the stage, and acoustic reflective screens (reaching the orchestra pit) were added. The shape of the screens was to ensure that the first reflection reaches the whole auditorium. Similarly to the simulation of the Chamber Opera in Kalisz, it was assumed that full modification ('a' modification) consists in application of the Baroque proscenium opening (wider walls of the proscenium opening) and application of an acoustic screen in the forestage, while the partial modification ('b' modification) consists solely in the application of an acoustic screen in the forestage. The assumed modifications are shown in Fig. 16. Due to the symmetry of the interior, reception points in the auditorium were located only on one side (Fig. 17).

Sound strength G for particular modifications is shown in Fig. 18, Fig. 19 and Fig 20. Comparison of sound level distribution for particular modifications is shown in Fig. 21 (comparison of full 'a' modification and partial 'b' modification) and in Fig. 22 (comparison of full 'a' modification with the proscenium without modification).

Fig. 15. Pictures of the Opera House in Kraków.

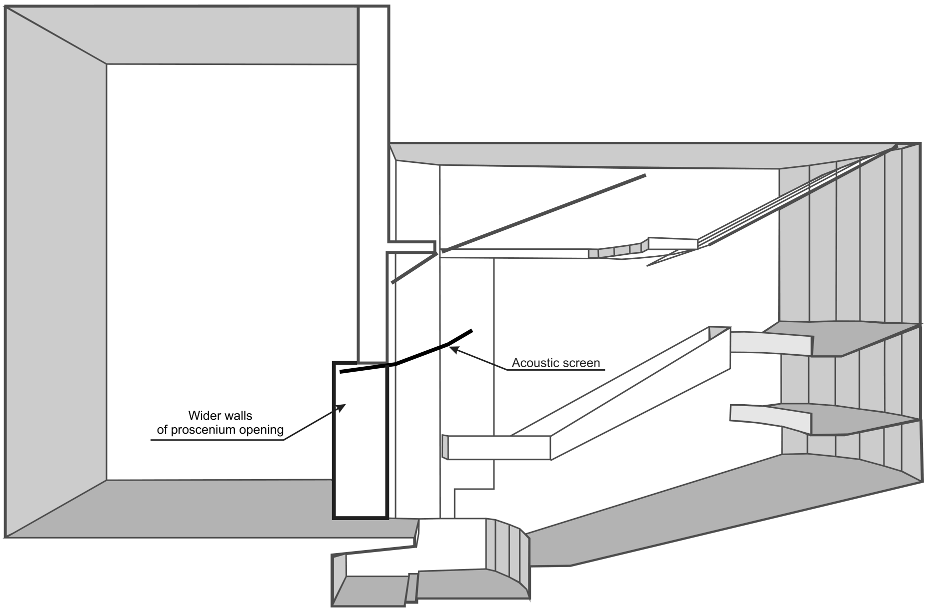


Fig. 16. Longitudinal section with perspective – the Opera House in Kraków.

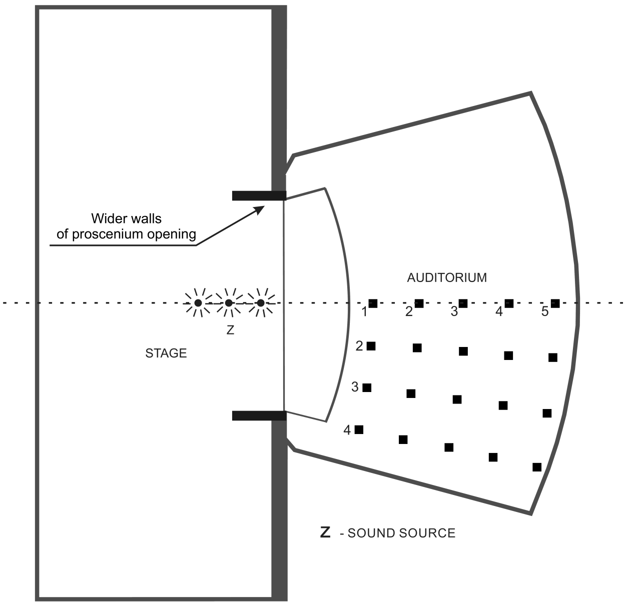


Fig. 17. View of the Opera House in Kraków.

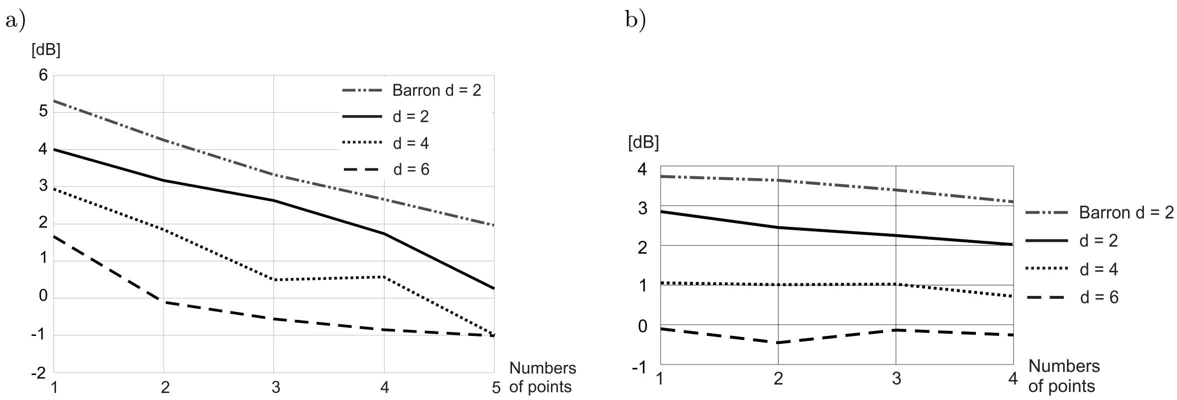


Fig. 18. Sound strength G along and across the auditorium, the proscenium without modification: a) longitudinal section, b) cross section.

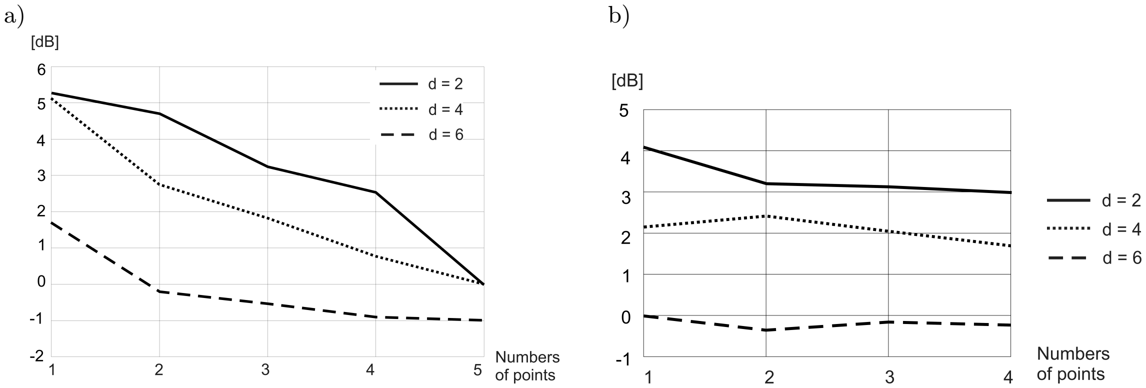


Fig. 19. Sound strength G along and across the auditorium, full modification – 'a' modification: a) longitudinal section, b) cross section.

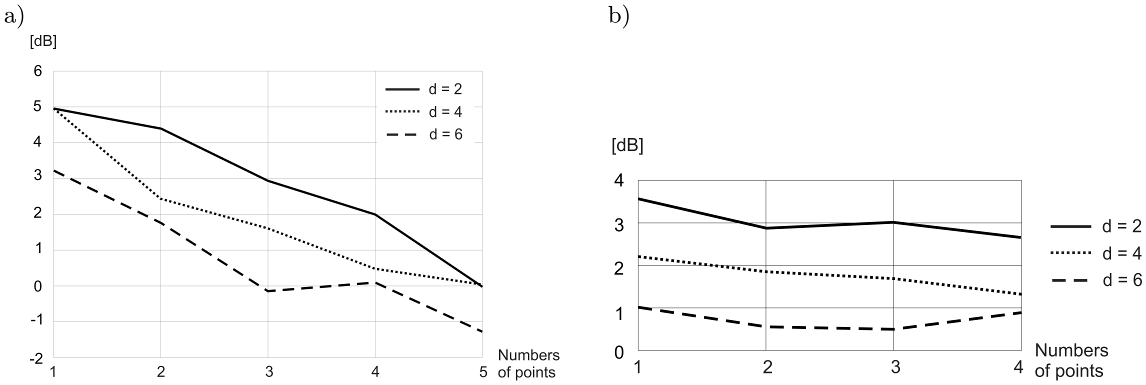


Fig. 20. Sound strength G along and across the auditorium, partial modification – 'b' modification: a) longitudinal section, b) cross section.

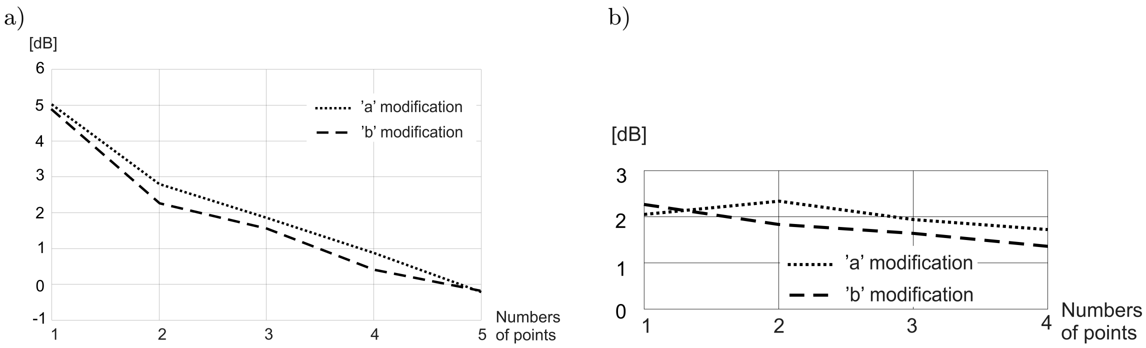


Fig. 21. Sound strength$G$ along and across the auditorium – comparison for 'a' modification and 'b' modification, $d = 4$ m: a) longitudinal section, b) cross section.

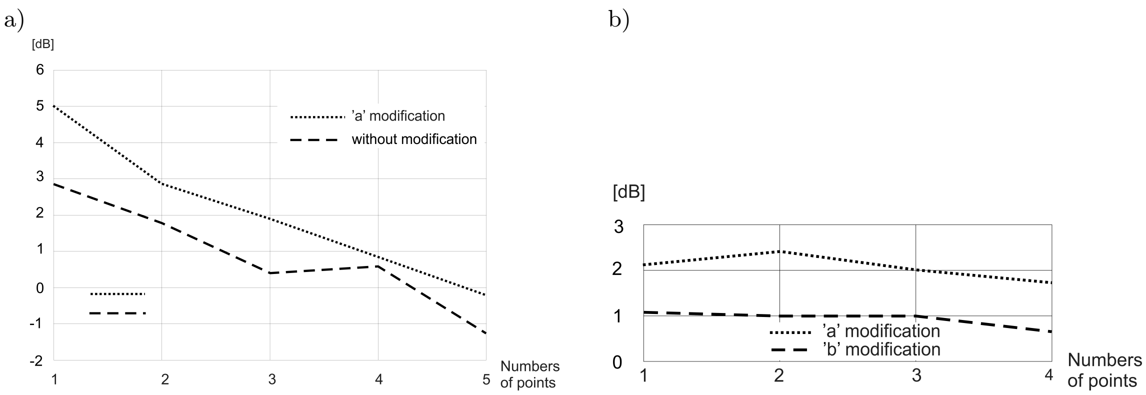


Fig. 22. Sound strength G along and across the auditorium – comparison for 'a' modification and the proscenium without modification, $d = 4$: a) longitudinal section, b) cross section.

3. Summary and conclusions

The analysis of the results shows that the introduced reflecting elements evenly amplify sound level in the auditorium. Both in the Chamber Opera in Kalisz and in the Krakow Opera House, application of 'a' modification caused an average sound level to rise by approximately 1 dB.

For the Chamber Opera in Kalisz for 'a' modification, the distribution of sound strength G became steadier and not entirely dependent on the position of the sound source on the stage. The computer analyses also show that the introduction of the Baroque proscenium opening plays a vital role. What follows is a substantial improvement of the sound strength at the front and in the middle of the auditorium. As far as the default setting with no modifications is concerned, the sound volume in the first rows is lower when the sound source moves back into the stage. The introduction of full 'a' modification considerably improved the distribution of sound strength G In the front part of the auditorium, the sound strength rose by approximately 2.5 dB for $d = 4$ m (Fig. 14). It can be also seen that the introduction of the lowered proscenium ceiling itself ('b' modification) did not yield satisfactory results (Fig. 13). It was not until the introduction of the Baroque proscenium opening along with the application of a lowered ceiling in the front of the stage that a considerable change in the sound level distribution in the auditorium could be obtained. The introduction of the baffle (the lowered ceiling) only in the forestage, which is a common practice in contemporary opera houses, does not bring about a considerable improvement.

In the Opera House in Kraków, for 'a' modification, the highest increase of sound strength in relation to the stage without modification was registered when the sound source was located as deep on the stage as possible ($d = 6$ m).

For the Opera House in Kraków there is very little difference between the 'a' and 'b' modifications, while in the Chamber Opera in Kalisz there is a considerable difference between the full 'a' modification and the partial 'b' modification, especially for the first front rows, where the application of the full modification results in the increase in sound strength G by 2.5 dB. In both interiors there is a considerable increase in sound strength G when the full 'a' modification is applied in comparison to the case without modification. As the volumes of the two auditoriums (the Chamber Opera in Kalisz $V = 2,300$ m^3, the Opera House in Kraków $V = 5,800$ m^3) are very different, the influence of the modification is greater in the Chamber Opera in Kalisz.

Diagrams 10 and 18 present both sound strength G derived through computer simulation and values of this parameter calculated on the basis of the revised theory suggested by Barron and Lee. It should be noted that the Barron model was prepared for concert halls where there are no absorptive materials within the stage area, which considerably influences early reflections; thus, the values obtained in the simulations are lower in the case of the Chamber Opera in Kalisz and slightly lower in the case of the Opera House in Kraków. Still, in the latter no anomalies occur, while in the case of the Chamber Opera is possible to notice an increase in the value of sound strength G in the back rows, which is caused by considerable reverberance of the flytower.

Table 1 and Table 2 include collective listing of 5 averaged acoustic parameters: sound strength G reverberation time RT (range 500–1000 Hz), early decay time EDT (range 500–1000 Hz), clarity index C_{80} and center time T_S for $d = 4$ m.

Figure 23 concludes the results of reverberation time RT and early decay time EDT calculations for the sound source at the distance of 4 m for the Chamber Opera in Kalisz. The calculations show that reverberation time RT is too big for an opera house. It is caused by including an empty flytower in the calculations, as well as the use of plaster (having sound reflective properties) as a finishing material for the flytower. On top of that, the auditorium area would require a special selection of finishing materials. Poor sound absorption of the flytower also influences the fact that RT is considerably bigger than EDT. Figure 24 shows frequency characteristic of reverberation time RT and

Table 1. Chamber Opera in Kalisz.

No.	Type of arrangement	Sound strength G [dB]	RT [s]	EDT [s]	C_{80} [dB]	T_S [ms]
1.	Proscenium without modification	4.1	2.76	1.77	4.6	131
2.	'a' modification	5.2	2.40	1.27	7.0	108
3.	'b' modification	4.5	2.73	1.67	5.5	125

Table 2. Opera House in Kraków.

No.	Type of arrangement	Sound strength G [dB]	RT [s]	EDT [s]	C_{80} [dB]	T_S [ms]
1.	Proscenium without modification	2.4	1.00	0.84	5.5	50
2.	'a' modification	2.3	0.96	0.82	5.8	48
3.	'b' modification	0.6	0.97	0.96	5.5	53

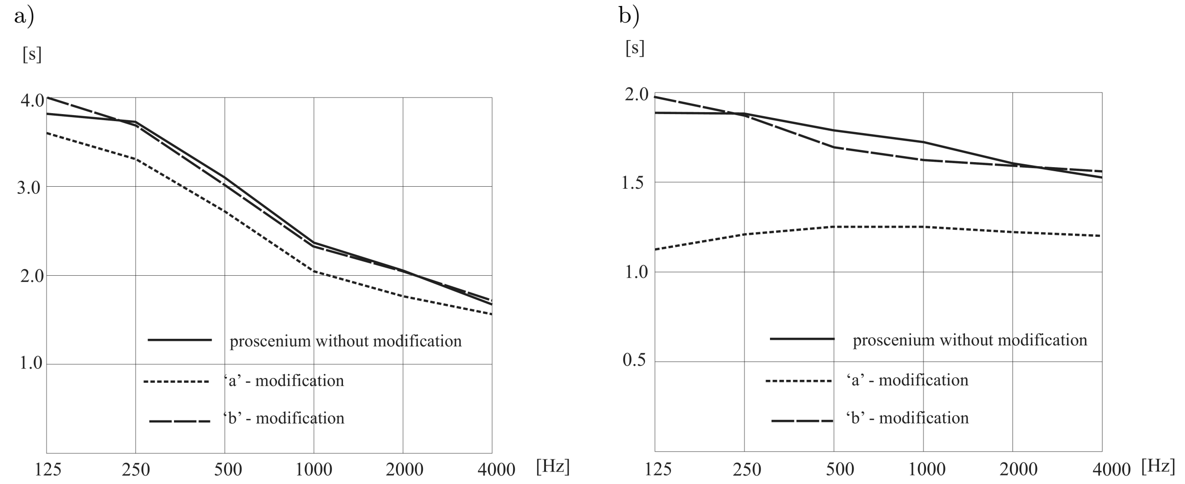


Fig. 23. Chamber Opera in Kalisz, frequency characteristic of reverberation time RT and early decay time EDT for $d = 4$ m: a) reverberation rime, b) early decay time.

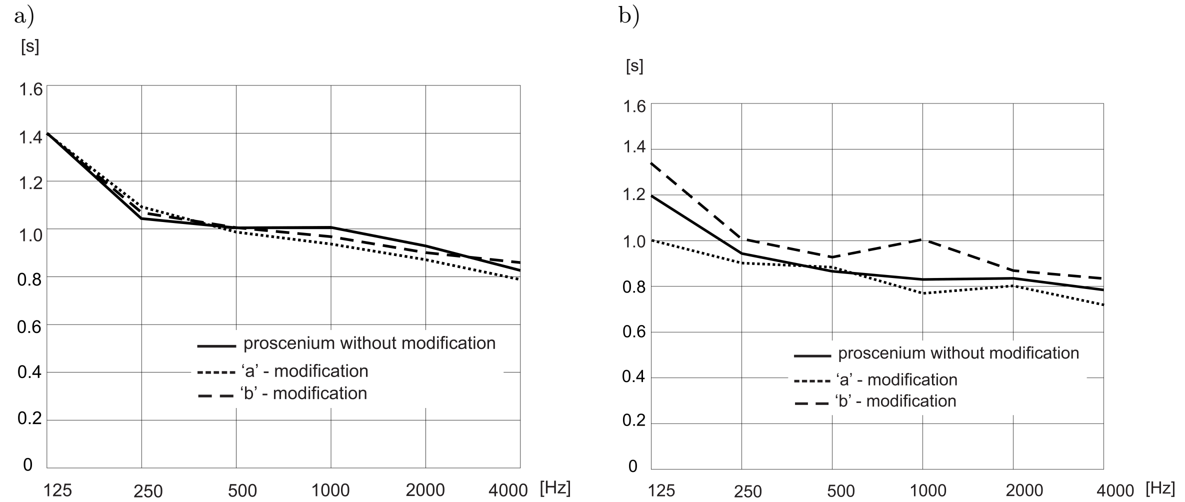


Fig. 24. Opera House in Kraków, frequency characteristic of reverberation time RT and early decay time EDT for $d = 4$ m: a) reverberation time, b) early decay time.

early decay time EDT for $d = 4$ m for the Opera House in Kraków. As with the Chamber Opera in Kalisz, it can be observed that the application of full 'a' modification lowers early decay time EDT In both cases, lowering the value of EDT is favourable for soloists because the level of speech intelligibility rises. In the case of the Opera House in Kraków, the surfaces of the fly-tower were given sound absorption values on the basis of validity of the model for the measurements taken in the actual building; therefore, the obtained reverberation time values RT were satisfactory for opera performances.

Clarity C_{80} is employed to evaluate clarity of music; it defines ability to differentiate between details of a piece of music received by audience. In a logarithmic scale, it is the relation of sound energy reaching a given measuring point in the first 80 ms to the sound energy reaching it after 80 ms. The parameter compliant with recommendations (Marshall, 1995) for opera music should be limited to 3–7 dB. It can be noticed that in both opera halls, the parameter has the recommended values in all configurations; however, in the case of the Chamber Opera in Kalisz, the range of the parameter values is wider depending on the assumed solutions. The highest value of C_{80} is reached for the full 'a' modification.

Another parameter used to evaluate clarity of music is center time T_S, which is defined as the time of the center of gravity of the squared impulse response. The recommended values for this parameter for operas, operettas and musicals oscillate between 70 and 90 ms (Fasold *et al.*, 1984). In the considered cases, T_S does not reach the recommended values as in the Opera House in Kraków, the values are lower, while in the Chamber Opera in Kalisz, they are higher.

Despite substantial volumetric differences between the analyzed buildings, it can be easily observed that application of the Baroque proscenium opening as well as application of a lowered proscenium ceiling ensured a visible improvement of acoustic conditions in the auditorium.

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