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Study of the Effect of the Orchestra Pit on the Acoustics of the Kraków Opera Hall

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The orchestra pit acoustics are mostly assessed by musicians and directors of musical performances using the sense of hearing, i.e. in a subjective manner. This paper proposes a method for an objective assessment using such parameters as Support (ST) and Sound Strength (G), which are obtained by measurements. ST defines the quality of how orchestral musicians hear one another in the orchestra pit, whereas G determines the impression of loudness at selected points of the auditorium. To determine the value of these parameters, acoustic measurements were performed in the orchestra pit and the auditorium of the Kraków Opera Hall. A numerical model was also developed, which was employed for multivariant computer simulations using the CATT-acoustic software. The purpose of the paper is to present a methodology for objective assessment of the orchestra pit acoustics.

Keywords: orchestra pit, opera hall, acoustic model, acoustic upgrade.

1. Introduction

The orchestra pit is an architectural element of the opera houses and music theatres intended for the orchestra. Its main role is to locate the orchestra in a way that allows the action happening on the stage to take precedence over both visually and acoustically. A positive aspect of such a separation of the orchestra from the hall is the reduction of the sound level from the orchestra, which allows singers' voices to be emphasized. A negative aspect is the musicians' discomfort since they have a limited space at their disposal and a reduced ability to hear actors on the stage and to hear one another in the orchestra pit.

Questionnaire surveys conducted in 46 opera halls identified the main problems in this respect in the following way [6]:

- insufficient space – 68%,
- too high a sound level – 69%,
- difficulties in the arrangement of seats for orchestral musicians – 48%,
- unsatisfactory sound quality – 36%.

These results show that most disadvantages of the orchestra pit are related to the acoustics and can therefore be tackled hopefully at the stage of designing and constructing.

The orchestra pit of the Kraków Opera Hall was built in accordance with current requirements for the 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 allows the adaptation of the size of the pit to 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. Over the orchestra pit there are located surfaces reflecting sound toward the auditorium. A view of the orchestra pit of the Kraków Opera Hall is shown in Fig. 1a and b, whereas its cross-section is shown in Fig. 2 [7]. Currently, work is going on to adjust and complete the interior and the outfitting of the opera hall.

a) b)

Fig. 1. View of the orchestra pit in the Kraków Opera Hall.

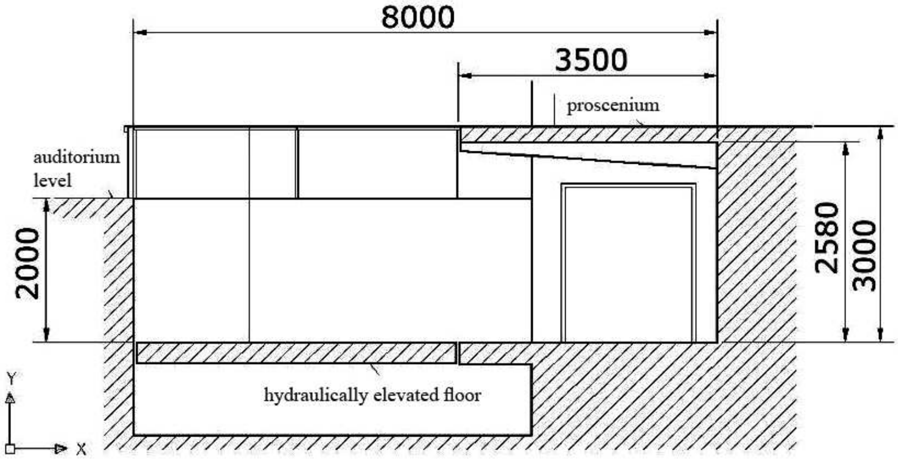

Fig. 2. Cross-section of the orchestra pit in the Kraków Opera Hall.

2. The acoustic parameters ST and G

To formulate an objective assessment of the orchestra pit acoustics, two parameters were identified, which can be found by measurements or calculation: the Support (ST) and the Sound Strength (G). The former makes it possible to assess the acoustic conditions in the orchestra pit in terms of the musicians' needs, whereas the latter allows the assessment of the acoustic conditions in the auditorium.

Subjective studies showed that two elements of the orchestra pit acoustics are essential for the musicians: the ability to hear themselves and to hear others. The relationship between these elements can be assessed by a group of objective ST indicators [7]. These represent the ratio of the energy of early reflections to the energy of direct sound. Consequently, the ST parameter shows how early reflections support the direct sound and help musicians in hearing themselves. Three varieties of the ST parameter are currently identified: $\mathrm{ST}_{\mathrm{early}}$, $\mathrm{ST}_{\mathrm{late}}$, $\mathrm{ST}_{\mathrm{total}}$. The measurements are made at a distance of 1 m from the source. Figure 3 show the means of calculating these varieties of the ST parameter.

$$\mathrm{ST}_{\mathrm{early}} = 10 \cdot \log\left(\frac{E2}{E1}\right),$$

$$\mathrm{ST}_{\mathrm{late}} = 10 \cdot \log\left(\frac{E3}{E1}\right),$$

$$\mathrm{ST}_{\mathrm{total}} = 10 \cdot \log\left(\frac{E2+E3}{E1}\right).$$

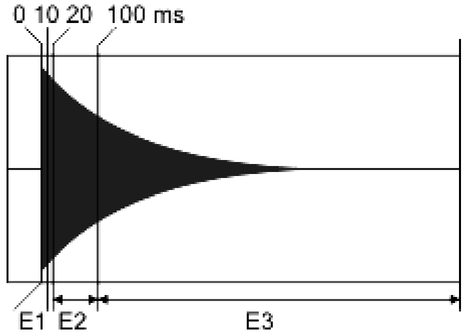

Fig. 3. Impulse response on the stage with indicated ST integration time intervals [2].

Figure 4 [5] shows measured values of the ST_{early} parameter as a function of frequency for nine concert halls with renowned acoustics. Basing on these results it was assumed that the correct ST_{early} values for 500 and 1000 Hz should range between −11 and −16 dB.

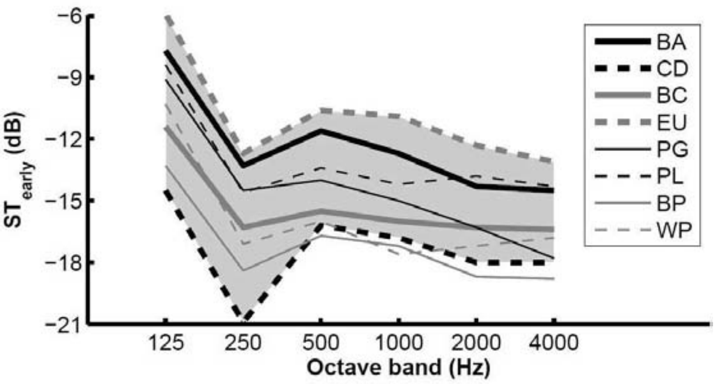

Fig. 4. Octave band values for ST_{early}. Shaded areas define the preferred ranges for the majority of halls [5].

The sound strength parameter (G) is determined from the impulse response measured in a room in accordance with the EN ISO 3382 standard. The (G) parameter is measured using a standard omnidirectional sound source and is defined as a logarithm of the ratio of the sound pressure exposure at the listening point to the acoustic pressure exposure of the impulse response for the same sound source measured in the free field at a distance of 10 m.

$$G = 10 \cdot \log \frac{\int\limits_0^\infty p^2(t)\,\mathrm{d}t}{\int\limits_0^\infty p_{10}^2(t)\,\mathrm{d}t} \quad \text{[dB]}.$$

Values of this parameter are given for octave bands from 125 Hz to 4000 Hz. According to Beranek, the impression of loudness is best described by the mean value G_{mid} for the 500 and 1000 Hz bands and should range from 4 to 5.5 dB, with 5 dB being the preferred value.

3. Acoustic measurements

The measurements were performed in the auditorium hall of the Kraków Opera Hall in the absence of audienceat the dropped curtain. Impulse responses were recorded for 17 measurement points located in the auditorium and two sound source positions in the orchestra pit. Assuming the hall being symmetrical, the measurement points were located only in one half of the auditorium. The echograms recorded were used to determine the distribution of the (G) parameter in the auditorium and the ST parameter in the orchestra pit. The measurement of ST was performed in conformity with the procedure specified by A.C. Gade [6]. The measurements and subsequent data analysis were performed with the DIRAC software.

Impulse responses needed to determine the (G) parameter were recorded at 10 points in the auditorium for two sound source locations in the orchestra pit (Fig. 5). The values of the G_{mid} parameter are shown in Fig. 6. The values of

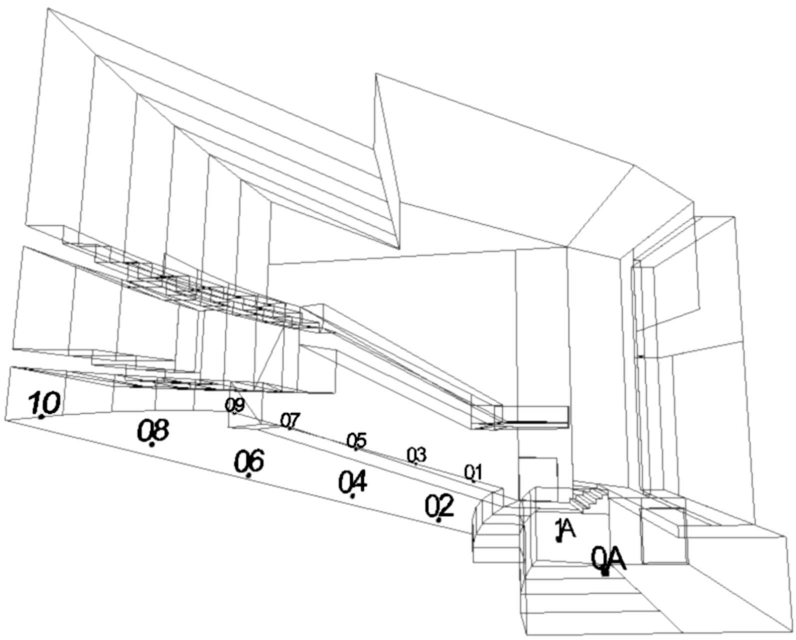

Fig. 5. Distribution of observation points on the ground floor of the auditorium in the Kraków Opera Hall.

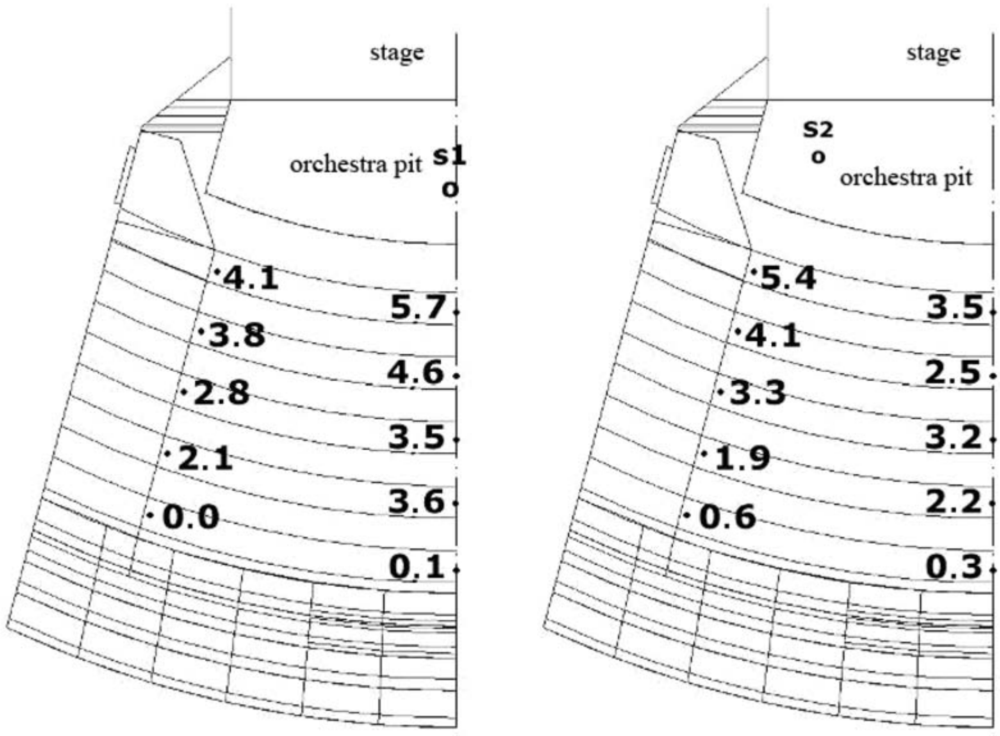

Fig. 6. G_{mid} distribution in the auditorium for two positions of the sound source in the orchestra pit.

the ST_{early} and ST_{late} parameters were calculated from the impulse responses recorded in the orchestra pit at a distance of 1 m from the sound source. Tables 1 and 2 show the mean values of the ST_{early}, ST_{late} and G_{mid} parameters for middle frequencies of the 500 Hz and 1 kHz bands.

Table 1. Values of stage parameters ST (*Support*) [dB].

	ST_{early}	ST_{late}
sound source position 1	12.7	19.8
sound source position 2	11.2	19.5

Table 2. Mean values of sound strength G_{mid} [dB].

f [Hz]		500	1000	G_{mid}
Ground floor	sound source position 1	4.5	1.6	3.0
	sound source position 2	3.5	1.8	2.7
Balcony	sound source position 1	3.0	0.7	1.9
	sound source position 2	3.3	0.5	1.9

4. Computer simulation

In order to determine the effect of the acoustic adaptation to the orchestra pit on the (G) parameter, a numerical model of the Kraków Opera Hall was employed (based on the CATT-acoustic ver. 8 h software). The simulation was performed for various extreme positions of the sound-reflecting surfaces suspended over the orchestra pit and for the much higher acoustic absorption of the orchestra pit (Figs. 7–10). Table 3 shows the values of the G_{mid} parameter on the ground floor of the auditorium for various options of the interior adaptation.

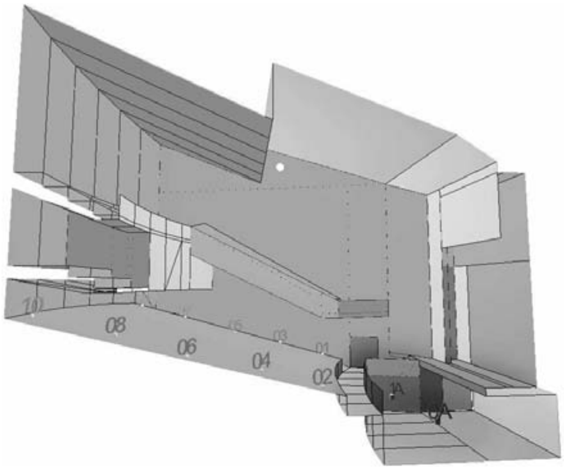

Fig. 7. Sound-absorbing material on all available surfaces of the orchestra pit.

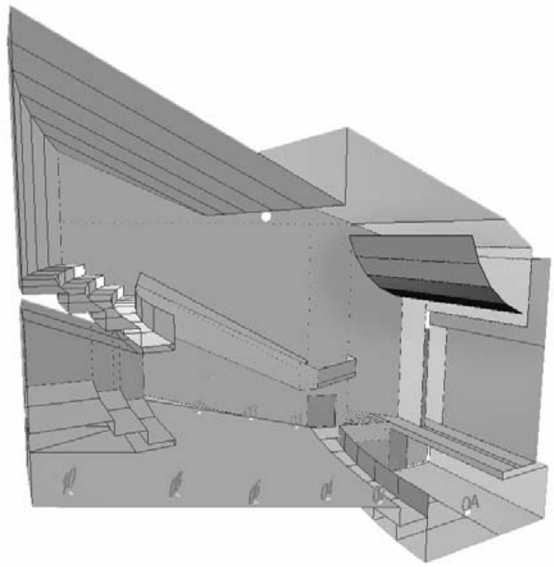

Fig. 8. Additional sound-reflecting surface placed on the stage.

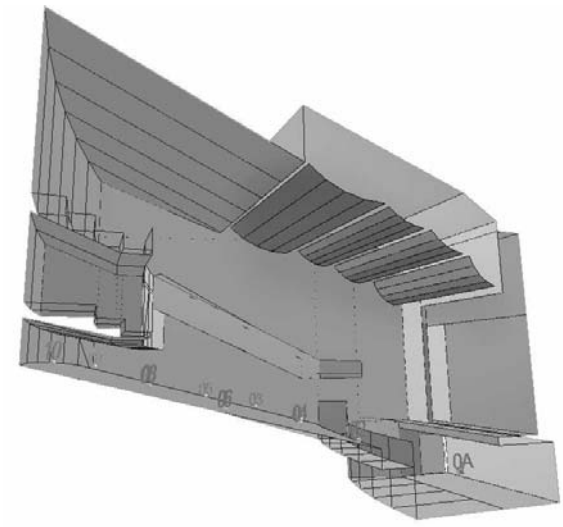

Fig. 9. Sound-reflecting surfaces placed above the stage and part of the auditorium.

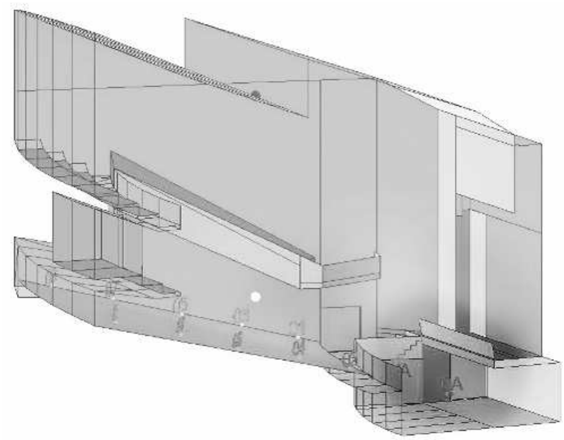

Fig. 10. Sound-reflecting surface placed at the orchestra pit.

Table 3. Average values of the (G) obtained by computer simulation for various variants of the orchestra parameter pit adaptation.

G_{mid} [dB]		
Orchestra pit lined with sound-absorbing materials	sound source position 1	1.7
	sound source position 2	1.7
Sound-reflecting surface over the stage	sound source position 1	2.7
	sound source position 2	2.3
Sound-reflecting surfaces over the stage	sound source position 1	2.9
	sound source position 2	2.7
Sound-reflecting surface at the orchestra pit	sound source position 1	3.9
	sound source position 2	4.0

5. Summary and conclusions

The values of the ST_{early} parameter obtained by measurements show that the conditions prevailing in the orchestra pit favour good hearing among the musicians themselves. On the other hand, the discrepancy between the parameters ST_{early} and ST_{late} ($\gg 3$ dB) shows that they do not have complete information concerning the concert hall's acoustics. There is some hope for improving the acoustics by placing sound-reflecting surfaces near the orchestra pit, increasing the reverberation of the hall and increasing the level of sound diffusion in the orchestra pit.

The measured values of the G_{mid} parameter at points located in the ground floor are 3 dB and 2.7 dB. These values are lower than that recommended [1] for concert halls ($G_{mid} = 5$ dB), but these recommendations are pertaining to sound sources located on the stage.

The computer simulation performed for various locations of the sound-reflecting surfaces (Figs. 7–10) shows that the surfaces located directly at the edge of the orchestra pit have the greatest effect on the increasing value of the (G) parameter. Such solutions are not always practically feasible, it is however worth pointing out to the stage designer what effects can be produced by various locations of the stage elements.

The ST parameters define the needs of the musicians in the orchestra pit, however there is no parameter defining the needs of listeners in the auditorium. It is impossible to asses the orchestra pit separately from the auditorium. In order to assess the orchestra pit, one would need a different indicator, which would combine the loudness in the auditorium for the sound source located on the stage with the G_{mid} parameter for the sound source located in the orchestra pit. Basing on the analysis of the calculation procedure of the (G) parameter, it can be supposed that the difference between the value of the G_{mid} parameter for the sound source located on the stage and the corresponding value for the source located in the orchestra pit is a good indicator for the assessment of proper acoustic "co-operation" between the orchestra pit and the entire concert hall.

The few measurements published so far do not support this concept because there is a disparity in the results achieved for a variety of opera houses. For instance, the measurements of the (G) parameter performed by Beranek in the Garnier Opera House in Paris and in the Staatsoper in Vienna showed that the difference between the two G_{mid} values, i.e. between the sound source on the stage and in the orchestra pit in the two opera houses were 0.6 dB and -1.2 dB, respectively. The comparison of these results should in fact contradict the proper functioning of the orchestra pit, but in actual case the acoustics of both these opera houses enjoy a good reputation.

In order to use this difference between the (G) parameters to assess the orchestra pit, one should determine the interval of values which would represent the acoustic performance considered subjectively to be a good one. Thus, it will be necessary to perform many acoustic studies in numerous opera halls and collect subjective opinions from competent people. Considering the varying geometries of concert halls, the procedure described in this paper will have to be probably modified.

References

[1] Beranek L.L., *Concert and Opera Halls, How They Sound*, Woodbury, NY: Published for the Acoustical Society of America through the American Institute of Physics, 512–513, 526–530 (1996).

[2] Bruel&Kjaer, Technical Documentation, DIRAC Room Acoustics Software Type 7841, User Manual v. 4.0; Bruel&Kjaer, Sound & Vibration Measurement A/S, Nerum, June 2007.

[3] Dammerud J.J., Barron M., *Early subjective and objective studies of concert hall stage conditions for orchestral performance*, 19th International Congress on Acoustics Madrid, 2–7 September 2007, akuTEK, [online August 2009], http://www.akutek.info/Papers/JD_MB_stage_conditions_2007.

[4] Dammerud J.J., Barron M., *Stage acoustics in concert halls – early investigations*, Proceedings of the Institute of Acoustics, **28**, Pt.2., Bath 2006.

[5] Dammerud J.J., Barron M., *Concert hall stage acoustics from the perspective of the performers and physical reality*, Proceedings of the IA, University of Bath, England, **30**, Pt.3, 2008.

[6] Gade A.C., *Acoustics for choir and orchestra* Publications issued by the Royal Swedish Academy of Music, 52, 23–43 (1986).

[7] Gade A.C., Kapenekas J., Andersson B.T., Gustafsson J.I., *Acoustical problems in orchestra pits: causes and possible solutions*, [in:] Proceedings of 17th International Congress on Acoustics, Rome, Italy, 2–7 September, 2001, apper 5A.11.01, 2 pp.

[8] Halmrast T., Buen A., Ihlen G., *The influence of a large reflector over the orchestra pit in an opera house*, ULTRAGARSAS 2003: Baltic-Nordic Acoustical Meeting (B-NAM 2002) Proceedings: Volume II, **48**, 3, 62 (2003).

[9] Kamisiński T., *Acoustic simulation and experimental studies of theatres and concert halls*, XVI Conference on Acoustic and Biomedical Engineering, Zakopane 2009.

[10] Kamisiński T., Czaja K., *Modernisation of the technical acoustics laboratory*, Archives of Acoustics, **31**, 3, 396 (2006).

[11] Kosała K., *Global index of the acoustic quality of sacral buildings at incomplete information*, Archives of Acoustics, **33**, 2, 165–183 (2008).

[12] Kulowski A., *Akustyka sal*, Wydawnictwo Politechniki Gdańskiej, Gdańsk 2007.

[13] Kulowski A., Kinasz R., Kamisiński T., *Acoustical recommendations to interior design of Concert Hall at the Academy of Music in Gdańsk*, Archives of Acoustics, **31**, 3, 398 (2006).