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Correction of Acoustics in Historic Opera Theatres with the Use of Schroeder Diffuser

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The paper deals with the problem of acoustic correction in historic opera theatres with the auditorium layout in the form of a horseshoe with deep underbalcony cavities limited with a semicircular wall surface. Both geometry of the cavities and excessive sound absorption determine acoustic phenomena registered in this area of the hall. The problem has been observed in the Theatre of Opera and Ballet in Lviv, Ukraine, where acoustic tests were carried out, simulation calculations performed, and finally a diffusion panel worked out designed for the rear wall of the underbalcony space. Acoustic measurements carried out after installation of the diffusers revealed favourable changes in the sound strength factor G within the range of medium and high frequencies in the underbalcony and auditorium centre area. By replacing textile tapestry with diffusion panels, a significant reduction of sound absorption was achieved for the frequency range above 1 kHz and an increase of uniformity of acoustic parameters registered in the hall. The method presented in the paper can be applied in historic halls of the similar type as well as contemporary rooms where there is a need for correction of acoustic flaws related to sound focusing or the echo effect.

Keywords: opera house, Schroeder diffuser, Lviv, underbalcony, horseshoe plan, focusing, scattering.

1. Introduction

Period opera theatre houses on a horseshoe plan also contemporarily maintain their special position as outstandingly fine interiors. Such halls offer the sense of closeness of the sound source and good eye contact among the audience. Large number of boxes and sumptuous decor contribute to better sound diffusion on one hand, but increase acoustic absorption on the other resulting frequently in excessive reduction of the reverberation time. Another problem encountered in halls of that type consists in transferring the first reflection of the sound from walls, that in many cases are fully occupied by boxes. Other elements difficult for both an architect and an acoustician are underbalcony cavities situated by the hall's rear wall with concave geometry. Unfavourable dimensions of the cavity, acoustic absorption of the wall tapestry and chair upholstery as well as sound focusing effect of the rear wall result in deterioration of subjective reception of both music and speech.

A complex of unfavourable acoustic phenomena occurring in underbalcony areas of theatres with layout in the form of a horseshoe induced the present author to undertake studies on possible ways to overcome the difficulty. The issues reported in this paper are based on acoustic simulation and experimental studies carried out in connection with rehabilitation of the Lviv Theatre of Opera and Ballet started in 2008 (Kamisiński *et al.*, 2009) (Fig. 1). Installation of Schroeder diffusers on the rear semicircular underbalcony wall of the house in May 2012 constituted

Fig. 1. An overall view of the Opera House in Lviv.

a crowning of the planned acoustic correction of the interior.

The Salomea Kruszelnicka Lviv State Academic Theatre of Opera and Ballet designed by Zygmunt Gorgolewski has been erected in the year 1900. The Opera's auditorium has the volume of 5,500 m^3 and 998 seats (of which 404 in stalls and 576 in boxes), resulting in the space volume of 4.69 m^3 per person with the stage volume of 10,700 m^3 and orchestra pit volume of about 100 m^3. The research work on and analysis of the Opera House's acoustic parameters and materials carried out by the present author revealed that in the underbalcony space there was excessive sound attenuation in the range of higher frequencies. In order to improve audition conditions it has been decided that the quantity of sound-absorbing element would be reduced by a change of finish of the rear wall under the balcony.

Reduction of sound absorption introduced by the rear wall results in more acoustic energy being reflected and directed back to spectators. In theatres constructed on a horseshoe plan, the rear wall is concave in most cases with the focal point located in the region of the hall centre (Iannace, Ianniello, 2008). Therefore application of a reflective material would result in intensified focusing of sound reflected from the rear wall and consequently, arising of acoustic faults such as coloration in the auditory centre or an echo on the stage and in the front portion of the auditorium area (Gołaś, Suder–Dębska, 2008).

An example of the use of Schroeder diffuser in a concert interior of historic interest is the Carnegie Hall in New York (Fig. 2). On the rear flat wall, the diffuser was installed in order to reduce echo heard on the stage (Cox, D'Antonio, 2003).

Fig. 2. Schroeder diffusers (QRDs) applied to the rear wall of Carnegie Hall to prevent echoes.

Figure 3 shows a view of the underbalcony space in the Lviv Opera House hall before installation of diffusion panels. In this case, it has been decided that the diffuser would be installed on a semicircular wall which would allow to test the function of the structure in different geometrical situations.

Fig. 3. A view of semicircular underbalcony space in Lviv Opera House before installation of diffusion panels.

2. Numerical simulations

In order to evaluate the effect of the diffusing structure planned to be installed on the hall's rear wall, computer simulations were carried out for distributions of acoustic parameters in this area. The numerical model was implemented in CATT-Acoustic program with the use of geometrical data characterising the hall and results obtained from laboratory tests of decor materials (upholstery, tapestries, lambrequins) (Kamisiński *et al.*, 2010b). Validation of the model was based on the measured acoustic parameters of the interior before installation of the diffusion panels. The numerical simulations were carried out for situations without the diffuser and for the conditions taking into account the sound absorption and diffusion parameters of the diffuser's prototype measured by means of the laboratory method.

Results of both simulations are presented in Figs. 4a and 4b. To illustrate the effect of the planned adaptation, the parameter known as the sound strength G was selected, defined by means of formula (Kulowski, 2011):

$$G = 10 \log \frac{\int_0^\infty p^2(t)\,\mathrm{d}t}{\int_0^\infty p_{10}^2(t)\,\mathrm{d}t} \qquad (1)$$

where $p(t)$ is the impulse response (acoustic pressure as a function of time) and p_{10} – the impulse response in free field at distance of 10 m from a sound source with the same acoustic power as the source used in the measurements.

Parameters G_{mid} and $G_{4\,\mathrm{kHz}}$ used further in this paper refer to the octave frequency bands for which the calculations were carried out, 0.5–1 kHz and 4 kHz, respectively.

The performed analyses of distribution of the sound strength G revealed that in the area close to the

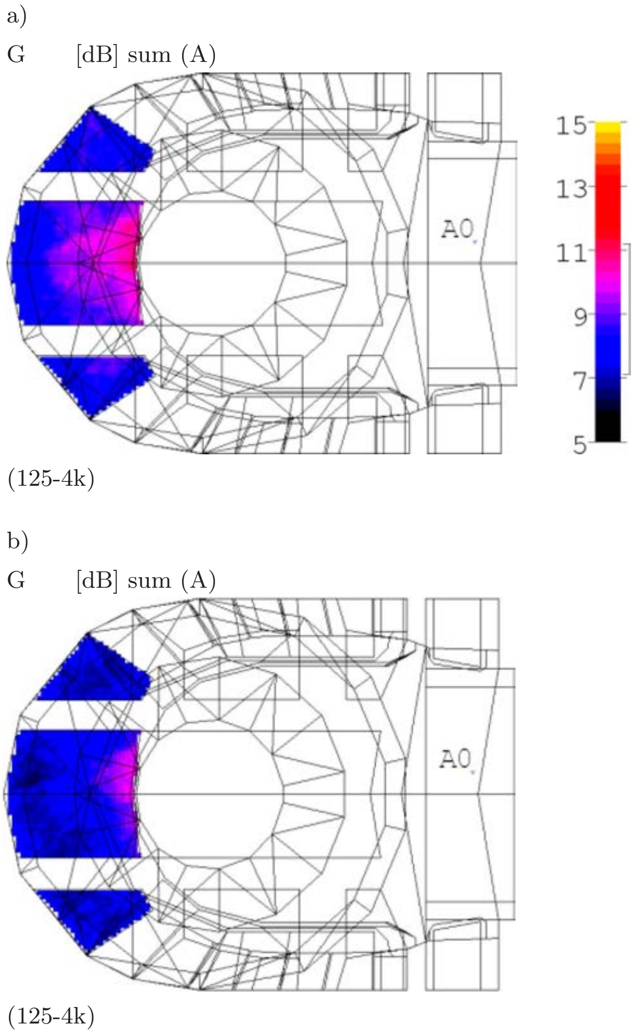


Fig. 4. The forecasted distribution of G values under the balcony in the hall's stalls: a) wall with tapestry; b) wall with the diffuser.

hall centre a decrease of value of the indicator occurred after installation of the diffuser in the underbalcony cavity, but distribution of the parameter has clearly gained in evenness as a result of occurrence of diffused reflections. Based on the observation one can conclude that introduction of sound diffusing element onto the rear wall will cause reduction of the sound focusing phenomena in this area and have a positive effect on audition qualities. Much better results should be expected when observing the simulated parameters for frequencies above 1 kHz, as in this very range the sound absorption is being reduced, and diffusion increased (Fig. 4). When interpreting the plots, one should also bear in mind the limitations of the ray method used by CATT-Acoustic program.

Figure 5 shows the forecasted distribution of C_{80} parameter under the balcony on the hall's stalls for: (a) the back wall with textile tapestry; (b) the same wall with Schroeder diffuser. The parameter, known as the clarity and expressed in dB, is defined as (Miśkiewicz *et al.*, 2012):

$$C_{80} = 10 \log \frac{\int\limits_0^T p^2(t)\,\mathrm{d}t}{\int\limits_T^\infty p^2(t)\,\mathrm{d}t}, \qquad (2)$$

where T (80 ms) is the time elapsed after arrival of the direct sound.

Analysis of simulation shows (Fig. 5) that the use of the diffuser will result in an increase of the sound clarity C_{80} in last rows of the stalls.

Figure 6 shows the comparison of sound absorption coefficient values for textile tapestry and the diffusion panel.

According to the adopted assumptions, a solution that will allow to avoid the effect consists in application

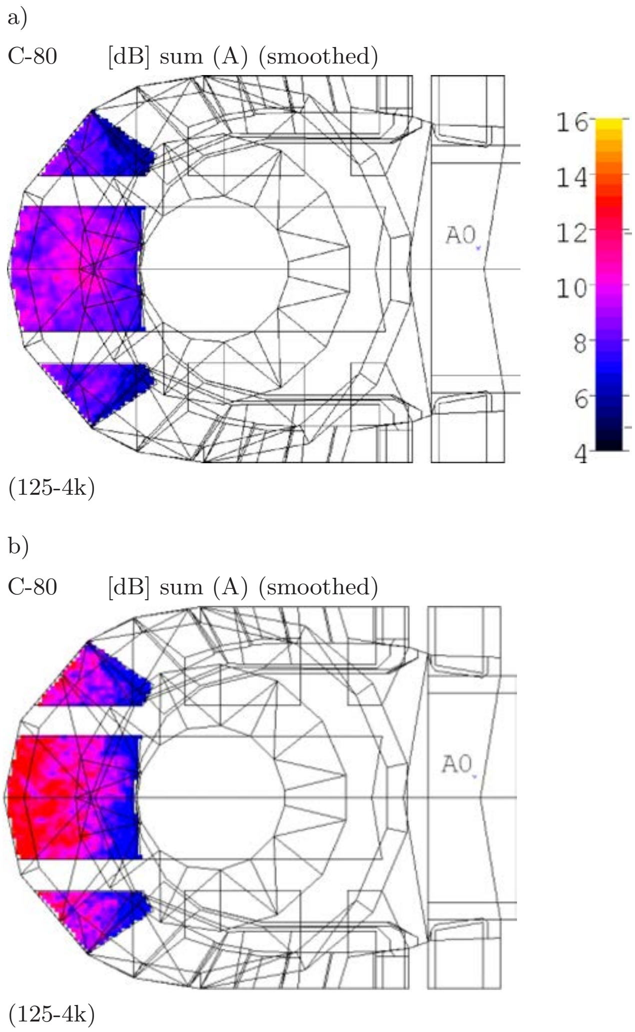


Fig. 5. Forecasted distribution of C_{80} values under the balcony in the hall's stalls: a) wall with tapestry; b) wall with the diffuser.

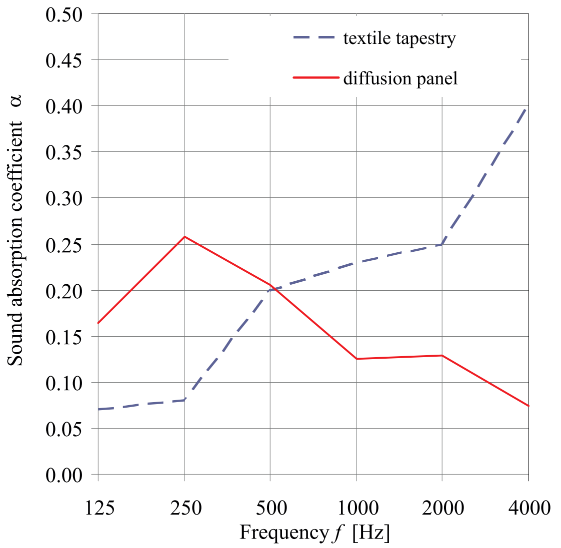


Fig. 6. Comparison of sound absorption coefficient values for textile tapestry and the diffusion panel.

of sound diffusing structures (Figs. 7 and 8) thanks to which the sound wave incident onto the wall will be diffused uniformly in all directions (Kamisiński *et al.*, 2010a).

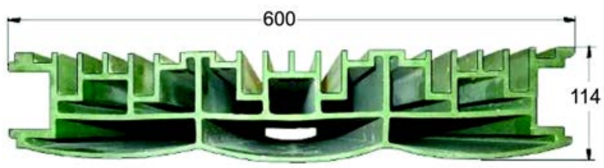


Fig. 7. Cross-section of the diffusion panel.

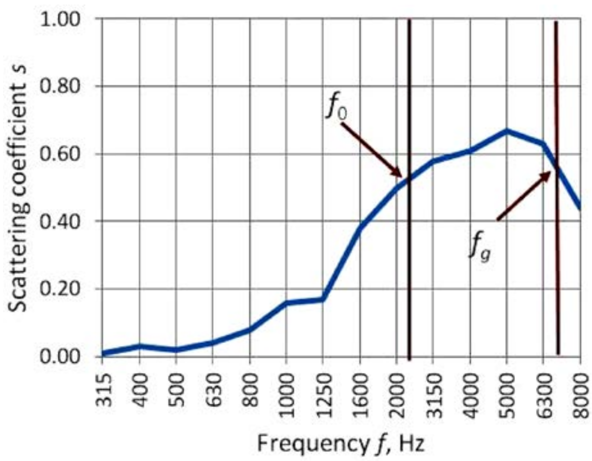


Fig. 8. The sound scattering coefficient s of the diffusion panel determined according to ISO 17497-1 (2004).

In Fig. 8, the lower f_0 and the upper f_g limit frequencies for sound diffusing effect of the examined structure are marked. It is assumed that the structure has the capacity to redirect the sound starting from frequency equalling 0.5 f_0 (Cox, D'Antonio, 2004). The design frequency f_0 is determined by the maximum depth of the diffuser. In the Opera House there was a very limited space designed for the diffuser, therefore it was very difficult to lower f_0. What is more, as indicated by (Pilch, Kamisiński, 2011), the higher deep-to-width ratio of one well of diffuser, the bigger sound absorption of the entire structure in low and mid frequency range. Consequently it was impossible to increase the range of effective diffusion of panels without interference with the reverberation time of the hall.

3. The follow-up tests in the Opera House

Repeated examination of the Opera House hall's acoustic parameters carried out, according to the predetermined methodology, before and after installation of the structure on the rear wall, was used for verification of the implemented system. To increase precision of the analysis of acoustic phenomena occurring in locations where main changes were forecasted, the grid of measurement points has been condensed in the area under the balcony in the centre of the Opera's stalls (Fig. 9).

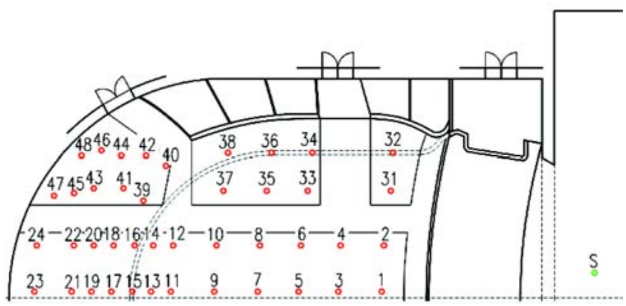


Fig. 9. Distribution of measurement points in the hall's stalls.

Figure 10 shows a view of semicircular back wall of the underbalcony space in the Lviv Opera House after installation of diffusion panels in the course of verification measurements.

Fig. 10. A view of the semicircular back wall behind the underbalcony space in the Lviv Opera House after installation of diffusion panels.

A comprehensive review of the measured acoustic parameters of the hall revealed that the parameters showing the highest sensitivity to introduction of the structure were the sound strength factors G_{mid} and $G_{4\,\mathrm{kHz}}$. The following Figs. 11 and 12 show distribution of the parameters on the auditorium's stalls surface.

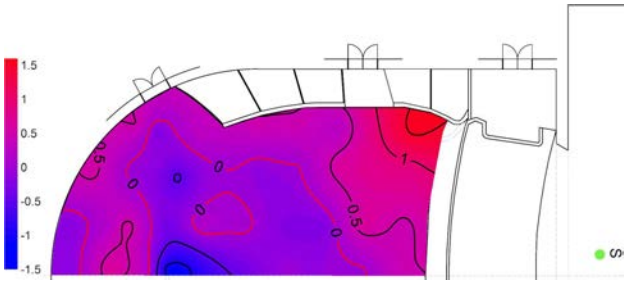


Fig. 11. Distribution of the sound strength G_{mid} increase after installation of the diffuser.

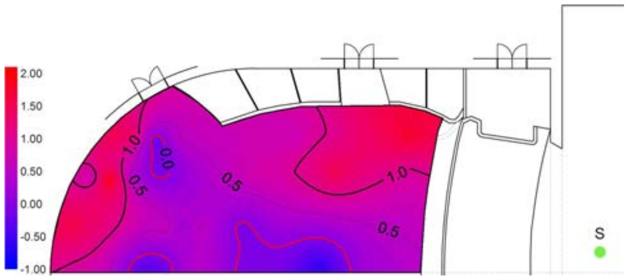


Fig. 12. Distribution of the sound strength factor $G_{4\,\mathrm{kHz}}$ increase after installation of the diffuser.

After application of the diffuser on the rear wall, one can observe a slight increase of value of the sound strength factor G_{mid} in the underbalcony area, while in the central part of the hall, values of the parameter have been reduced.

Values of the $G_{4\,\mathrm{kHz}}$ parameter, as shown in the figure above, are subject to distinct decrease in the central part of the hall, and locally increased as a result of providing the semicircular wall with the diffuser.

Analysis of the sound clarity index C_{80} for the 4 kHz has revealed (Fig. 13) that as a result of installation of the diffuser, values of the parameter significantly decreased on the hall's axis.

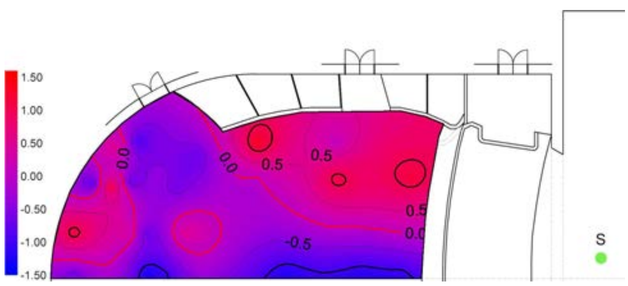
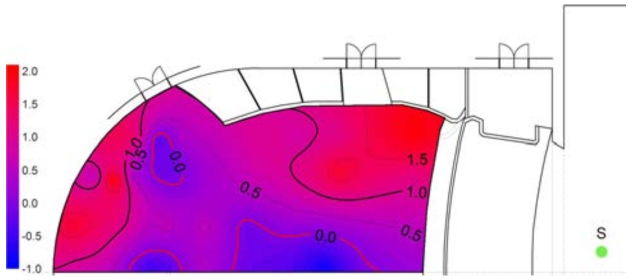


Fig. 13. Distribution of the sound clarity index $C_{80\ 4\,\mathrm{kHz}}$ increase after installation of the diffuser.

$G_{80\ 4\,\mathrm{kHz}}$ (the early sound strength) and $G_{\mathrm{L}\ 4\,\mathrm{kHz}}$ (the late sound strength) for 4 kHz were also investigated. On the basis of measurement before and after installation of the diffuser (Fig. 14), it can be said that the sound strength is changed mainly in the early part, as $G_{80\ 4\,\mathrm{kHz}}$ is very similar to $G_{4\,\mathrm{kHz}}$. $G_{\mathrm{L}\ 4\,\mathrm{kHz}}$ distribution is very regular and reveals an about 0.7 dB increase for the whole stalls surface.

a)



b)

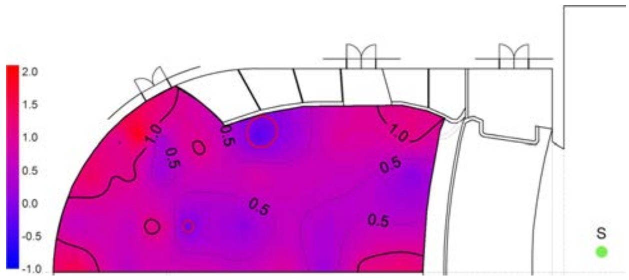


Fig. 14. Distribution of differences of sound strength factors: a) $G_{80\ 4\,\mathrm{kHz}}$ and b) $G_{\mathrm{L}\ 4\,\mathrm{kHz}}$.

4. Summary

The analysis of acoustic parameters of the Lviv Opera House hall measured before and after installation of the diffuser has shown that the best parameters allowing for observation of the discussed structure's effect were the sound strength values G_{mid} and $G_{4\,\mathrm{kHz}}$. To this end, interpolated distributions of measured values of the parameters over the stalls area were worked out. Parameters G_{mid} and $G_{4\,\mathrm{kHz}}$ are presented in the form of difference of values observed before and after installation of the diffuser (Figs. 11 and 12).

According to the generally observed regularity, value of the sound strength factor G_{mid} decreases with increasing distance to the sound source. On the other hand, in the central part of the hall, some increase of the parameter values can be observed caused by sound focusing effect of the back wall's concave surface. After installation of the diffusing structure, the effect has been reduced, as confirmed by the measured values of the sound strength factor and the distribution of increase in G_{mid} (Fig. 11). The observed change occurs for frequencies 500 and 1 kHz, i.e. below the frequency for which the designed diffusion panel effectively diffuses the sound. Analysing absorption characteristics of the textile tapestry and the diffusing structure (Fig. 6) it can be found that below the frequency of 1 kHz, the diffuser is characterised with the sound absorption coefficient higher than this of the tapestry. As a result, after installation of the diffuser, a portion of energy is absorbed and does not come back to the auditorium. Above 1 kHz, sound diffusion starts to manifest itself with low absorption, giving the acoustic energy back to the hall in a way ensuring its uniform distribution. The phenomenon has been confirmed by means of analogous observation of the parameter $G_{4\,\mathrm{kHz}}$ that more clearly depicts the effect of the diffuser on the hall's acoustic field.

The performed research work revealed that significant changes in acoustic parameters occur for early reflections of waves incoming within the time interval of 80 ms, as can be seen from distribution of parameters G_{80} and C_{80} (Fig. 13). Its effect in later instants of time is not noticeable, as can be found based on analysis of the factor G_{L} (Fig. 14b).

Considering the function that the applied diffuser has accomplished in the hall's space one can claim on the grounds of the obtained results of the study that the range of its effect encompasses the seats under the balcony situated in front of the diffuser and the seats in the centre of the stalls. These are the regions of old opera houses constructed typically on a horseshoe plan where significant unevenness in distribution of acoustic parameters is observed as a result of concave shape of the rear wall. The use of the Schroeder diffuser allows to eliminate at least some of the related flaws.

It is worth mentioning that despite some earlier fears, the technocratic design of the Schroeder diffuser, after careful selection of the colour scheme, has ultimately won the acceptance of both the artistic milieu and the heritage conservation supervising authorities.

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