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ACOUSTICAL CORRECTION OF UNDER BALCONY CAVITIES IN THEATHER HALLS ON A HORSESHOE-SHAPED PLAN

Tadeusz Kamisiński and Jerzy Wiciak
Department of Mechanics and Vibroacoustics, AGH University of Science and Technology,
al. Mickiewicza 30, 30-095 Kraków, Poland. kamisins@agh.edu.pl

In theatres where audience halls are built on a horseshoe-shaped plan, the ceiling of the area under the balcony at the back of the hall is relatively low. Most people seated there experience poor reception. Efforts have been made to formulate general guidelines addressing this problem. Acoustical measurements on several halls have been performed together with computer simulations of the field. In the computer model, the acoustical data of finishing materials and acoustical structures obtained from laboratory tests have been used. In particular, QRD sound diffusing structures have been examined. Those structures were designed specifically for the halls. In all cases the simulations showed improvement in the acoustical parameters.

1 Introduction

Theatre halls based on a horseshoe-shaped plan were mainly built at the turn of the 19th and 20th centuries, but even nowadays they rank high as particularly fine interiors. Such rooms ensure a sense of proximity to the sound source and good eye contact between people in the auditorium. A large number of boxes and rich interior décor contribute to the sound dispersion but also increase sound absorption which often leads to excessive reduction in the reverberation time. This is particularly the case of theatre halls with auditorium capacities below 1000 seats. In such rooms there is also no direct access to side walls which transmit the first sound reflection very effectively. A difficult task in designing, for both the architect and the acoustician, is the part of the auditorium located in the space under the balcony at the back wall of the hall. This space is relatively deep considering its disproportionately low height, which leads to deterioration of the subjective reception of music and speech. It also happens sometimes that the back wall generates an echo towards the stage. The unfavourable acoustic phenomena occurring in the space under the balcony in horseshow-shaped halls was the reason why numerous studies were undertaken with the goal of reducing these problems.

Acoustic studies were carried out in several theatre halls of this design and with those characteristics of the space under the balcony. The Lviv Opera was selected for detailed analysis: this is where, expert studies, acoustic measurements and numerical simulation of the acoustic field were performed occasioned by the flooring replacement in 2008. The Salomea Kruszelnicka Academic Opera and Ballet Theatre in Lviv was built in 1900 according to a design by Zygmunt Gorgolewski. The auditorium has a capacity of 4374 m^3 and has 998 seats (Figure 1).

Some expert studies were carried out on a numerical model of the theatre hall using CATT-Acoustic software. The input data for calculations came from architectural records and acoustic measurements which had been performed. Numerical simulation was also performed for acoustic data obtained from laboratory measurements on materials planned to be used for finishing and for the construction of acoustic systems.

Figure 2 shows the part of the auditorium located in the space under the balcony at the back wall of the Lviv Opera House. Based on the analysis of the study results [2, 3, 4], it was proposed to cover the back wall above the seats with a sound-scattering structure based in quadratic residue sequence [1]. The structure was designed and manufactured as die stamped panels made from PVC mixed with sawdust. The method of selection of the diffuser system and laboratory studies of such diffuser are described below.

Figure 1. The Lviv Opera house concert hall

Figure 2. Back wall of ground floor

2 Selection and laboratory studies of diffusers

Acoustic systems are currently classified chiefly in terms of their acoustic absorption and insulation properties. Knowledge of the sound scattering coefficient can significantly improve the functional properties of materials and show the best ways of applying them. This is particularly important in the acoustic design of interiors. In order to select and test the acoustic parameters of a sound diffuser to be installed on the back wall of the Opera hall, simple calculations and laboratory acoustic measurements were performed. In designing the diffuser's geometry, an important consideration was not only the limited space behind the last row of seats in the auditorium, but also a more versatile application range of the diffuser system. The sound scattering coefficient *s* was measured in accordance with standard ISO 17497 - 1:2004, Acoustics - Sound-scattering properties of surfaces – Part 1: Measurement of the random-incidence scattering coefficient in a reverberation room.

The sample diffuser was designed on the basis of quadratic-residue sequence with the length of the period N=7 (Figures 5). The terms of the sequence s_n are calculated from formula (1)

$$s_n = n^2 \bmod N \tag{1}$$

where:

n – are non-negative integers (0,1, …, n-1),

N – is the length of the period.

The well depth d_n of the diffuser is calculated from (2)

$$d_n = \frac{s_n \lambda_0}{2N} \tag{2}$$

where:

λ_0 – is the wavelength corresponding to the lower frequency f_0 of the band in which sound scattering occurs

The depth of the diffuser depends on the frequency f_0 whereas the upper band limit f_g depends on the well depths, which are calculated from formula (3):

$$w = \frac{\lambda_{\min}}{2} \tag{3}$$

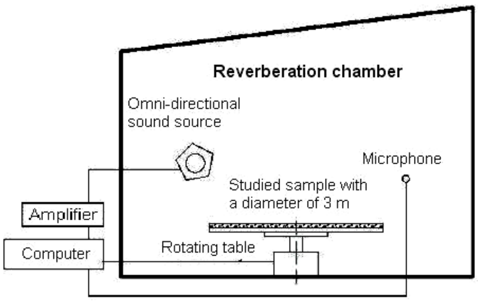
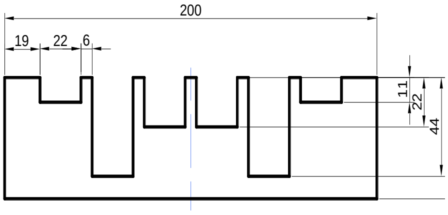
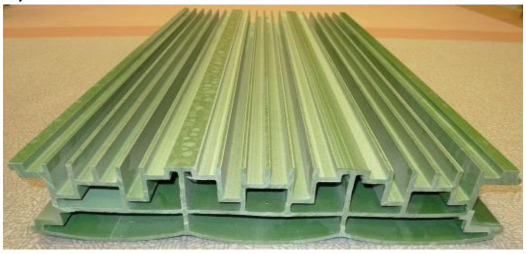


Figure3. Block diagram of the measurement system for sound scattering coefficient, **S**

Figure 4. Sample of diffuser in reverberation chamber



a)



b)

Figure 5. Cross-section of the diffuser

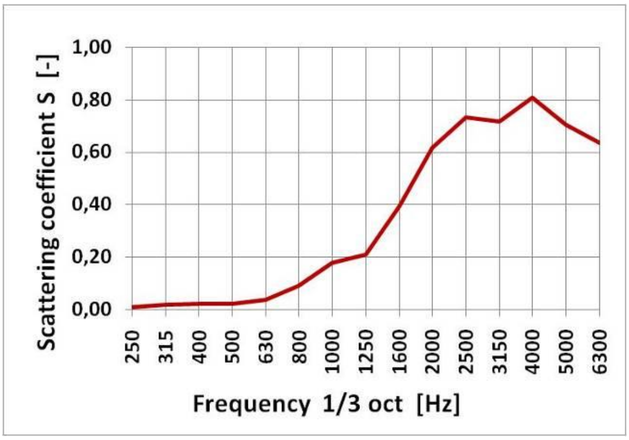
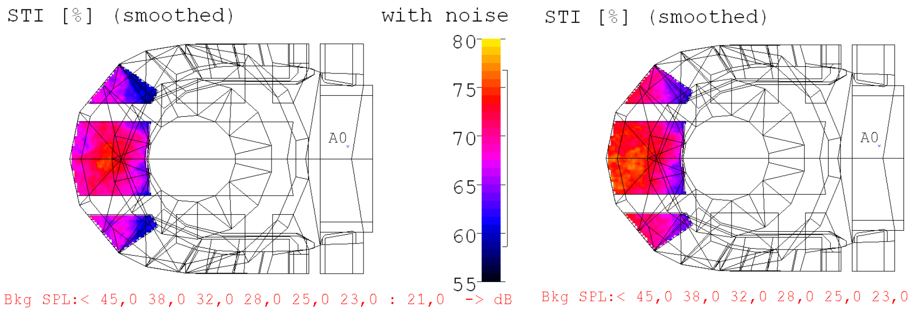


Figure 6. Sound dispersion coefficient of the diffuser

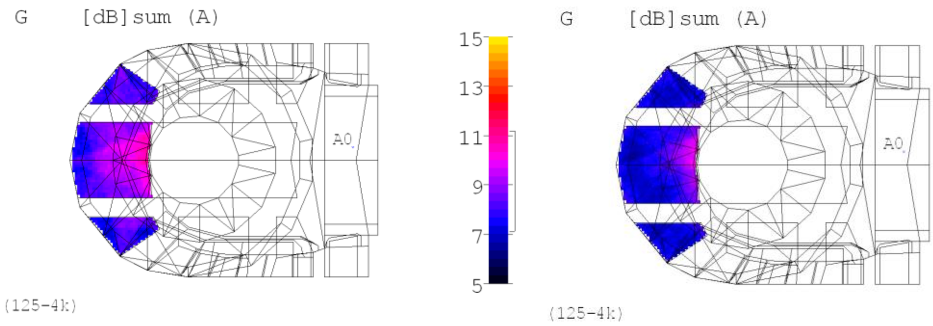
3 Numerical simulation

The purpose of the simulation was to obtain a distribution of acoustical parameters in the part of the auditorium located under the balcony. The results of the simulation, showing the expected consequences of the application of diffusers at on the back wall of the ground floor of the hall are shown in Figures 7-11.



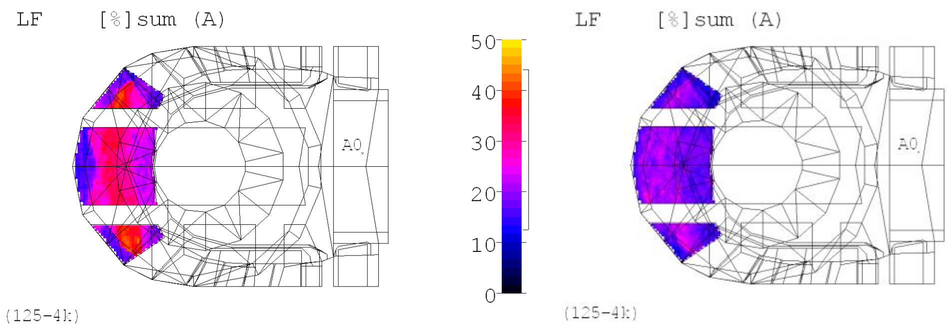
a) b)

Figure 7. Distribution of value STI under a balcony on a ground floor of a hall: a) present state b) with diffusers (prognosis). The preferred value of STI is >60%.



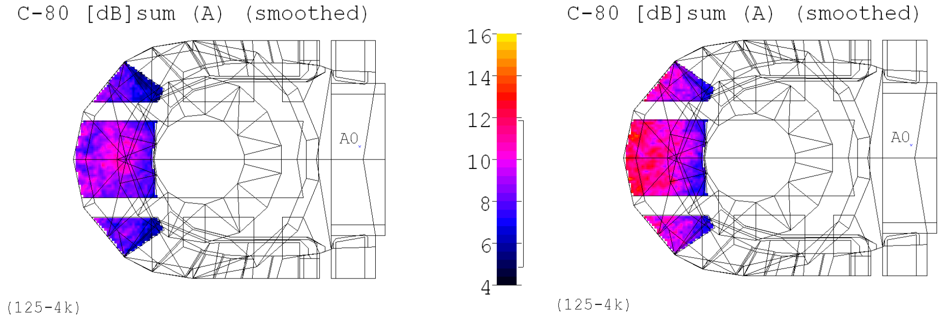
a) b)

Figure 8. Distribution of value G under a balcony on a ground floor of a hall: a) present state b) with diffusers (prognosis). The preferred value of G is from 4 to 5.5 dB.



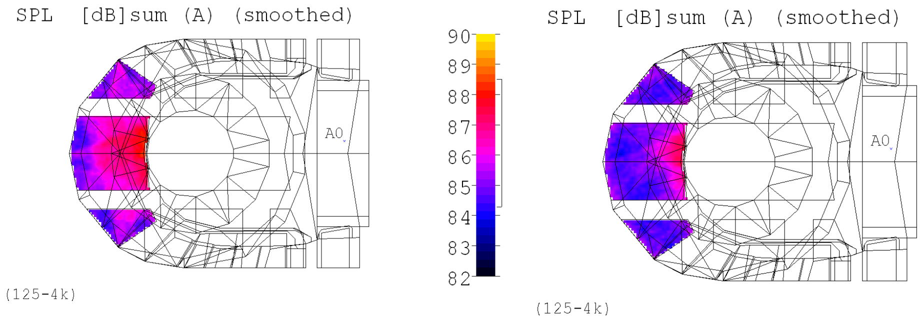
a) b)

Figure 9. Distribution of value LF under a balcony on a ground floor of a hall: a) present state b) with diffusers (prognosis). The preferred value of LF is from 15 to 25.



a) b)

Figure 10. Distribution of C80 under a balcony on a ground floor of a hall: a) present state b) with diffusers (prognosis). The preferred value of C80 is from 3 to 9.



a) b)

Figure 11. Distribution of SPL(A) under a balcony on a ground floor of a hall: a) present state b) with diffusers (prognosis)

4 Summary

The paper describes an attempt to solve a problem often encountered in theatre halls: the inferior acoustics of the space under the balcony. Adaptation of the back wall was proposed involving the use of sound scattering structures built on the basis of a square root sequence. The scattering structure was built with wider applications in mind. The acoustic model built under CATT-acoustic v8.0i software was developed on the basis of our own studies of sound scattering by the diffuser structure along with studies of sound absorption by materials used for the interior equipment and acoustic studies of the Opera hall interior.

All the simulated acoustic parameters showed a better distribution within the space under the balcony after diffusers had been installed on the back wall. The speech transmission index STI (Figure 7) increased from about 68% to about 73% on the average (the preferred STI values are greater than 60%). The sound strength parameter G (Figure 8) decreased from about 9.5 to about 7 (the preferred value of G is from 4 to 5.5 dB. The early reflection parameter LF (Figure 9) decreased from about 30 to about 20 (the preferred value of LF is from 15 to 25). The sound clarity parameter C80 (Figure 10) increased from about 9 to about 10.5 dB (the preferred value of C80 is from 3 to 9 dB). The average level of acoustic pressure (Figure 11) decreased by about 2 dB in favour of a more uniform sound distribution was provided for the discussed area.

Analysis of the numerical simulation of calculated acoustic parameters shows a favourable trend of improvement in the acoustic parameters after taking into consideration the diffusers. Only the C80 parameter showed an unfavourable trend, but one should note here that the main requirement of such an interior is to ensure good speech transmission. Also, theatre halls based on the horseshoe plan have shorter reverberation times. The historic status of the building requires the adaptation of the appearance of the diffusers to meet the conservator's requirements.

References

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