

MEASUREMENTS OF PARAMETERS OF SOUND REFLECTING SCREENS

SUMMARY

Sound reflecting panels are commonly used in concert and conference halls in order to transmit reflected sound to the audience and improve hearing conditions among musicians. The main problem is to design these elements properly. In this paper, the frequency limits of a useful sound transmission range and the efficiency of reflecting structures are theoretically estimated and experimentally verified.

Keywords: sound reflecting panels, concert hall, sound reflection efficiency, acoustic upgrade

POMIARY PARAMETRÓW AKUSTYCZNYCH STRUKTUR REFLEKSYJNYCH

Panele refleksyjne są powszechnie stosowane w salach koncertowych i audytoryjnych. Głównym ich zadaniem jest przekazywanie odbitego dźwięku w kierunku publiczności oraz poprawa słyszalności pomiędzy muzykami na scenie. Odpowiednie zaprojektowanie takich struktur jest jednak bardzo skomplikowane i czasochłonne.

W artykule porównano otrzymane doświadczalnie wartości wybranych parametrów akustycznych struktur refleksyjnych z wartościami wyznaczonymi z teoretycznych wzorów.

Słowa kluczowe: panele refleksyjne, sala koncertowa, współczynnik odbicia dźwięku

1. INTRODUCTION

Overhead stage canopies are commonly used in concert and conference halls (Fig. 1 and 2). These reflect sound towards the audience and improve hearing conditions among musicians. Moreover, they can be used to eliminate some architectural faults, like parallel and concave surfaces or too high ceilings.

Properly designed canopies should have a wide and flat frequency response. This is possible to obtain by selecting

the adequate shape, size and arrangement of reflecting panels. However, literature dealing with the mathematical basis for overhead canopy design is rather limited. Also, it is worth noting that due to the occurrence of wave phenomena, computer modeling based on geometrical acoustics does not always give satisfactory results. Therefore it is important to develop simple analytic formulae useful for architects and acoustical consultants.

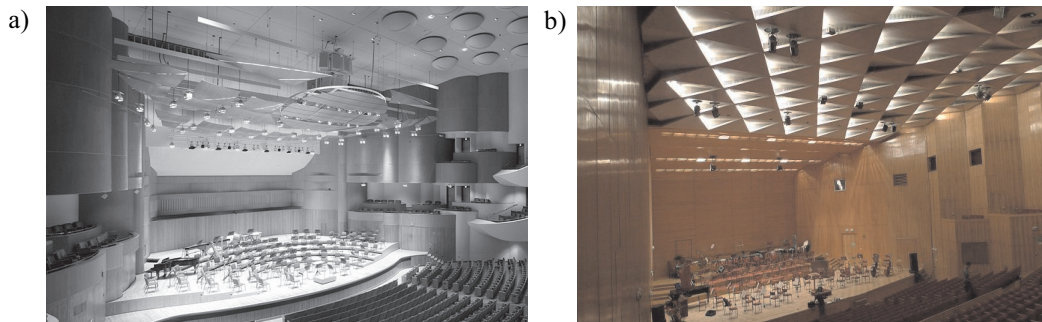


Fig. 1. The canopy over the stage in Joseph Meyerhoff Symphony Hall, Baltimore (Long 2006) (a); Philharmonic Concert Hall in Rzeszów (Kamisiński 2010) (b)

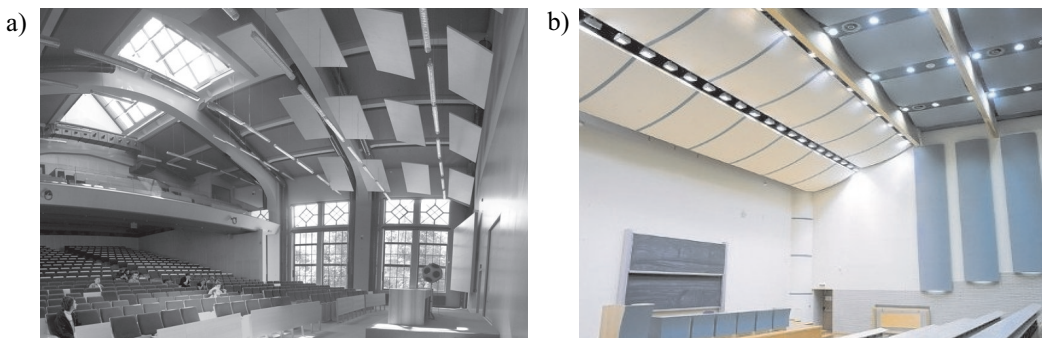


Fig. 2. Reflection panels in conference hall, AGH, Cracow (a); conference hall, University of Gdańsk (b)

* Department of Mechanics and Vibroacoustics, AGH University of Science and Technology, Krakow, Poland; kamisins@agh.edu.pl

In this paper, the frequency limits of a useful sound transmission range and the efficiency of reflection structure are estimated. Afterwards, these parameters are experimentally verified by scale model measurements of reflecting structures in an anechoic chamber.

2. THEORY

Reflecting structures forming a canopy can be seen as a high-frequency pass filter with two independent low frequency limits. These limits result from the attenuation of wavelengths that are large compared to the size of an array's element and attenuation caused by diffraction (Long 2006; Pierce 1981). The high frequency limit is dependent on the canopy structure, i.e. whether the sound "sees" the canopy as a continuous object or as a set of panels with spaces between them.

The frequency response of reflection array can be predicted accurately by the Boundary Element Method or from the Kirchhoff-Fresnel approximation. However, there are some algorithms which provide adequate accuracy with less computational effort. A simplified formula for the low frequency limit f_g deduced from scattering theory (Skålevik 2006) was proposed by Skålevik (Polaczek and Rubacha 2010; Polaczek *et al.* 2010):

$$f_g = 64\varepsilon \quad (1)$$

where ε (panel edge density):

$$\varepsilon = \frac{\text{panel edge length}}{\text{panel area}} \quad (2)$$

The pass band level was described by Rindel (Pierce 1981).

If the projection of the reflected ray on the array plane is parallel to one of the edges of the array, attenuation due to diffraction may be given as:

$$\Delta L_{diff} = 10 \log K = 10 \log(K_1 \times K_2) \quad (3)$$

where K_1 and K_2 refers to coefficients of sound reflection by the array in the X and Y directions, respectively. The coefficient in the direction shown in Figure 3 is equal to

$$K_1 = \frac{1}{2} \left\{ \sum_{i=1}^l [C(v_{1,i}) - C(v_{2,i})]^2 + \sum_{i=1}^l [S(v_{1,i}) - S(v_{2,i})]^2 \right\} \quad (4)$$

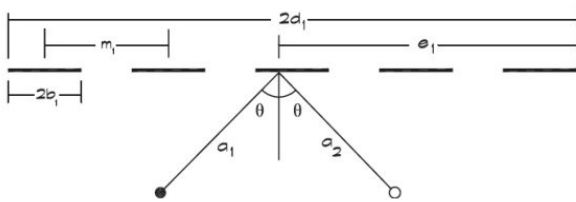


Fig. 3. Section through a reflector array with five rows of reflectors

To calculate K_1 from formula (4), Fresnel integrals are used:

$$C(v) = \int_0^v \cos\left(\frac{\pi}{2} z^2\right) dz \quad (5)$$

$$S(v) = \int_0^v \sin\left(\frac{\pi}{2} z^2\right) dz$$

where:

$$v_{1,i} = \frac{2}{\sqrt{\lambda a^*}} (e_1 - (i-1)m_1) \cos \theta \quad (6)$$

$$v_{2,i} = \frac{2}{\sqrt{\lambda a^*}} (e_1 - 2b_1 - (i-1)m_1) \cos \theta \quad (7)$$

and the characteristic distance a^* :

$$a^* = \frac{2a_1 a_2}{a_1 + a_2} \quad (8)$$

Fresnel integrals have no analytical solution, therefore Rindel (Pierce 1981) made a rough approximation:

$$K = \mu^2 \quad (9)$$

where μ (relative density):

$$\mu = \frac{\text{panel area}}{\text{array area}} \quad (10)$$

According to the Rindel approach, approximate solution of eq. (3) for reflecting array with reference to attenuation for whole array is shown in Figure 4 and called reflection structure efficiency.

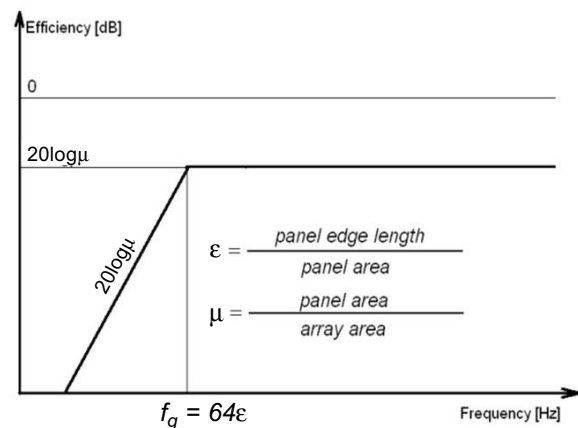


Fig. 4. Frequency response of reflecting array dependent on panel density μ and panel edge density ε

3. MEASUREMENT SETUP

For experimental verification of the theory presented in point 2, some models of sound reflecting structures were measured. Measurement setup and its flow-charts are shown in Figure 5 and 6.

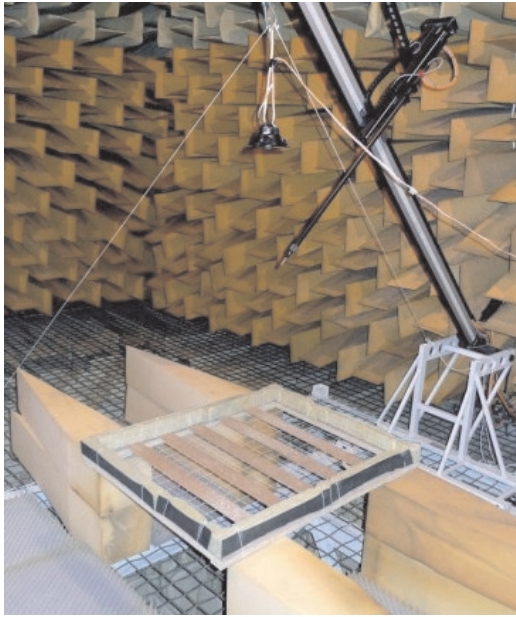


Fig. 5. Model of sound reflecting structure in anechoic chamber

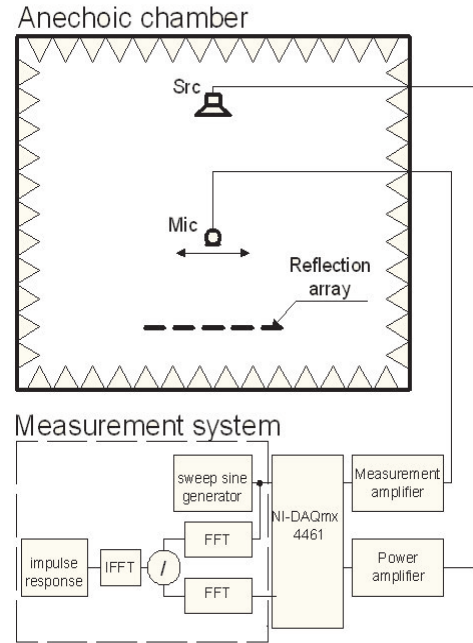


Fig. 6. The flow-chart of the measurement system

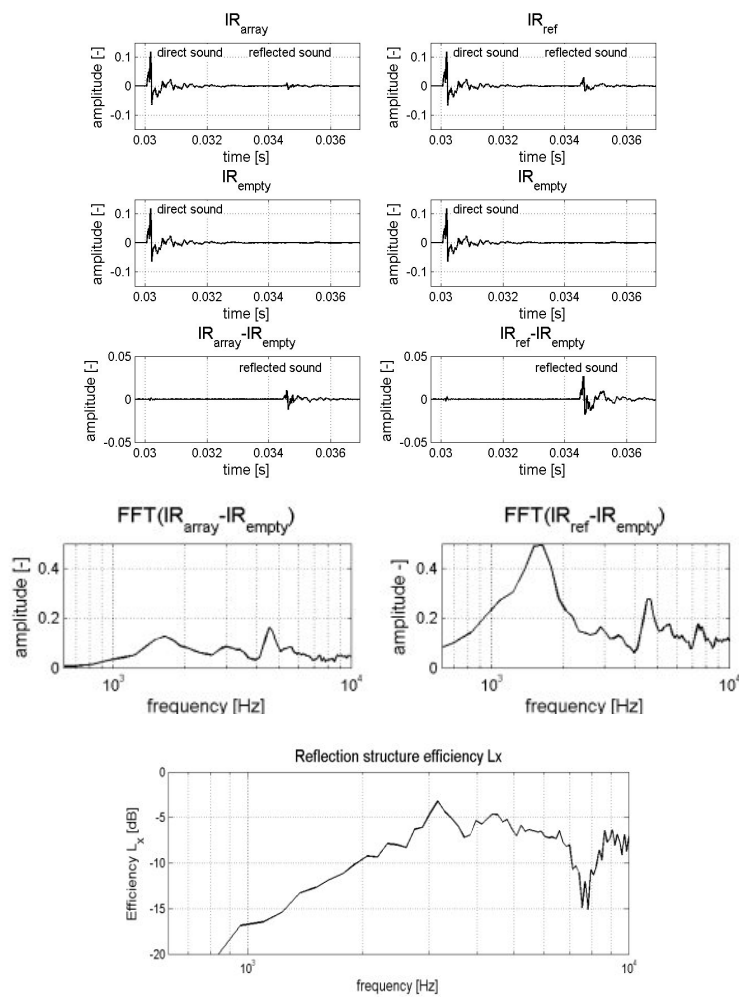


Fig. 7. The procedure used to calculate reflection structure efficiency L_x , where: IR_{array} – impulse response of reflection array; IR_{ref} – impulse response of reference array (100% density, $\mu = 1$); IR_{empty} – impulse response of measurement setup without tested structures

Measurements were made for normal incidence of sound. Impulse responses were obtained by means of the MLS technique. The further calculations were made using the following procedure (Fig. 7):

$$L_x = 20 \log \left[\frac{\text{FFT}(\text{IR}_{\text{array}} - \text{IR}_{\text{empty}})}{\text{FFT}(\text{IR}_{\text{ref}} - \text{IR}_{\text{empty}})} \right] \quad (11)$$

4. THEORETICAL AND MEASURED FREQUENCY RESPONSES

Measurements were performed for different shapes of reflection panels. The panels were made of fiberboard and intensely reflected sound in a wide frequency band. The panels were arranged in an array of size 70×70 cm. For normalization of the results, all frequency responses were related to the measurement on the reference object (one large panel), which removes the influence of the measurement equipment, especially the speaker and the microphone, and undesirable reflections.



Fig. 8. Array of rectangular panels. $\mu = 0.5$, $\varepsilon = 31.43$

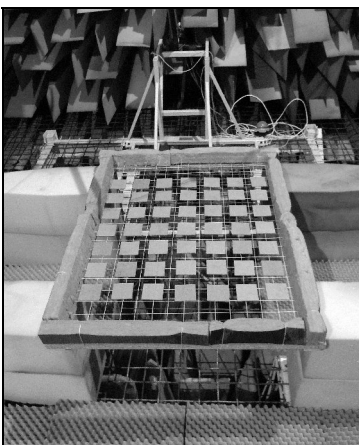


Fig. 9. Array of square panels. $\mu = 0.49$, $\varepsilon = 57.17$

Figure 10 shows the frequency response of an array consisting of rectangular elements (Fig. 8). The efficiency values at two exemplary measurement points, the average measured value and the calculated one from the theoretical formulae are given. Averaging of the results is necessary due to sound scattering by the array. For this reason, signals at twenty different measuring points were registered. In all cases an incidence angle was normal.

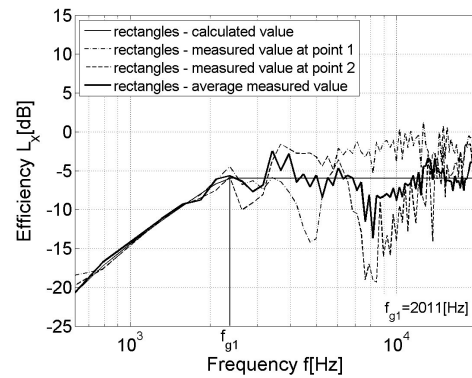


Fig. 10. Theoretical and measured frequency response of an array of rectangles from Figure 8; f_{g1} – low frequency limit for an array of rectangles

Figure 10 shows that the calculated and measured efficiency parameters for the array of rectangles are almost the same. Slightly larger, though still a small difference, is found for arrays of squares and circles (Fig. 14 and 15). Good confirmation of the theory is also seen in Figure 11 – two different low frequency limits obtained from measurement can be predicted theoretically with quite good accuracy. Thus, experimental verification of formulae (1), (2) and (9), (10) is confirmed.

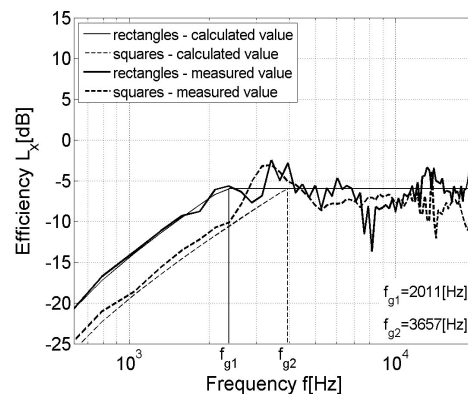


Fig. 11. Frequency responses of rectangular and square reflection elements from Figures 8 and 9; f_{g1} , f_{g2} – low frequency limits for arrays of rectangles and squares, respectively

However, such a good conformity with the theory does not occur for triangular panels (Fig. 12 and 13). Both the initial slope of the graph and the low frequency limit differ from these predicted theoretically. This may result from differences in the symmetry of the triangles' layout in X and Y direction. In such cases, scattering in X and Y directions differ more than is assumed in the Skålevik approach.

Some different formulae for low frequency limit can be found in the literature. Skålevik deducted formula (1) from the scattering theory. Afterwards, he measured some structures and found the trend of $f_g = 68\varepsilon$. Therefore more investigations are needed to study the influence of the element's shape on the low frequency limit.

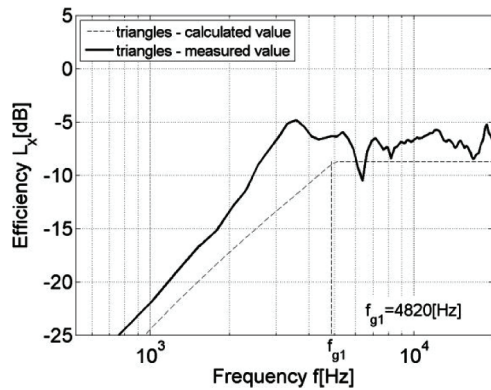


Fig. 12. Theoretical and measured frequency response of an array of triangles as shown in Figure 13; f_{g1} – low frequency limit for an array of triangles

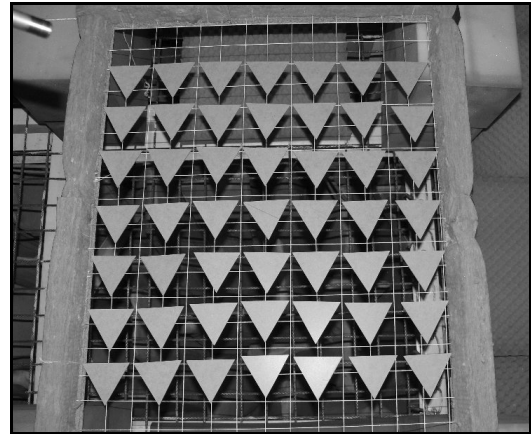


Fig. 13. Array of triangular panels. $\mu = 0.37$, $\epsilon = 75.31$

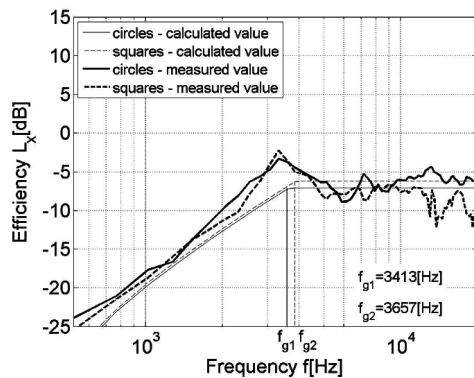


Fig. 14. Frequency responses of circle and square reflection elements as shown in Figure 15; f_{g1}, f_{g2} – low frequency limits for arrays of circles and squares, respectively

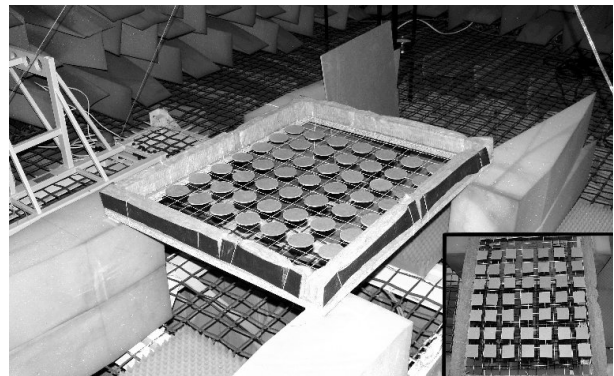


Fig. 15. Array of circles ($\mu = 0.44$, $\epsilon = 53.33$) and squares ($\mu = 0.49$, $\epsilon = 57.17$)

5. CONCLUSIONS

In the paper, the parameters useful in the design of overhead canopies have been experimentally confirmed. This can be helpful for architects and acoustical consultants dealing with large halls where such canopies are installed.

In the reported stage of research only four kinds of panels were tested, with normal incidence of sound. Due to the measurement setup used, panels are supposed to be suspended horizontally, parallel to the hall's floor. Using the methodology developed in this paper, the next stages of research are planned, in which the following conditions of a real hall will be considered:

- oblique incidence of sound (sound source on the stage, receiving point on the audience),
- panels of different shapes, e.g. rhomboidal, elliptical etc.
- non-flat plates, e.g. convex, inclined etc.,
- different kinds of material, e.g. rigid, transparent, semi flexible (glass, Perspex).

References

- Kamisiński T. 2010, *Acoustic Simulation and Experimental Studies of Theatres and Concert Halls*. Acta Physica Polonica A, vol. 118.
- Knudsen V.O., Leonard R.W., Delsasso L.P. 1964, *Diffraction of sound by an array of rectangular reflective panels*. JASA, 36(12).
- Long M. 2006, *Architectural Acoustics*. Elsevier Academic Press.
- Pierce A.D. 1981, *An Introduction to Its Physical Principles*. McGraw-Hill.
- Polaczek A, Rubacha J. 2010, *The shape and the size of reflector panels forming a canopy*. 13th International Symposium of Students and Young Mechanical Engineers "Advances in Chemical and Mechanical Engineering", Gdańsk.
- Polaczek A., Rubacha J., Kamisiński T. 2010, *The research of acoustic parameters of reflection structures*. XVII Conference on Acoustic and Biomedical Engineering, Kraków–Zakopane.
- Rindel J.H. 1991, *Design of New Ceiling Reflectors for Improved Ensemble in a Concert Hall*. Applied Acoustics, 34.
- Skålevik M. 2006, *Low frequency Limits of Reflector arrays*. Institute of Acoustics IOA conference on Auditorium Acoustics, Copenhagen.
- Skålevik M. 2007, *Low frequency limits of reflector arrays*. ICA 07 proceedings, Madrid.