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Sound Reflection from Overhead Stage Canopies Depending on Ceiling Modification

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Reflecting structures placed over the stage in auditoria and concert halls should provide sound reflection in a way that enhances sound emission from the stage without causing acoustic defects in the interior. Model studies conducted by the authors were used to determine the relative level of sound reflection by reflecting structures as a function of frequency for a number of geometric configurations and materials. Analysis of the results allowed drawing conclusions about the effect of modifications of the ceiling over the reflecting panels on the quality of the sound reflected from them. It was shown that modification of the ceiling over the reflecting panels by employing highly sound absorbing materials significantly improved the characteristics of the reflected sound. Also, certain configurations of elements located in the space under the ceiling should be avoided, as the experiments indicated the occurrence of adverse acoustic effects.

Keywords: sound reflection, room acoustic, reflecting structures

1. Introduction

Acoustic interiors of concert halls and auditoria should possess listening conditions that conform to their basic function. A uniform sound level in the audience and good hearing conditions for musicians on the stage are required. In order to ensure a uniform distribution of the first sound reflection reflecting surfaces are designed to be placed on the side walls, ceiling, and above the stage. Also, the interior can be properly shaped, so that no additional reflecting elements are placed in the hall (Kamisiński, 2010; Pilch, 2011). In contrast to profiled ceilings and walls overhead stage canopies (Fig. 1) in the interior design do not reduce the volume of the room and can be designed as a dedicated acoustic system.

The main role of the overhead stage canopies is to transmit the first reflection of the sound wave. Consequently, this ensures good hearing conditions for musicians (Kulowski, 2010) on the stage, sound clarity in the audience, and a uniform sound level. It is worth noting, however, that poorly designed structures can direct the sound particularly and cause phenomena adversely affecting its quality.

Another important function of the reflecting screens suspended above the stage is to correct acoustic defects such as single and multiple echoes and the sound focusing caused by large facing planes, concave surfaces, or too high ceilings.

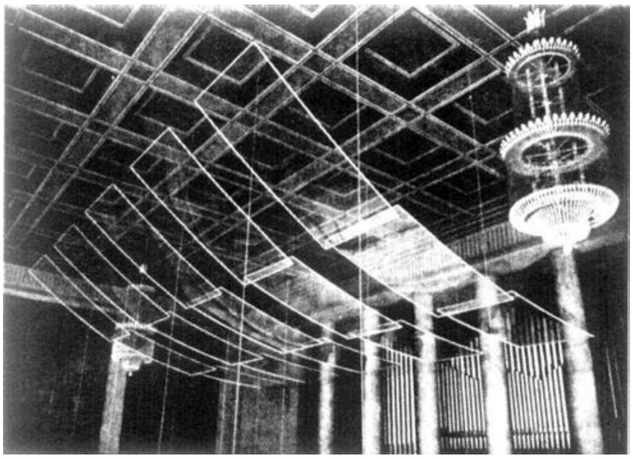

Fig. 1. First application of the overhead stage canopy – Herculessaal, Munich (Kulowski, 2007).

Properly designed canopies placed over the concert hall stage should provide the sound reflection in the frequency range of at least 500 Hz to 4 kHz. It is also recommended that in this range the frequency response spectrum should be flat (±3 dB) and the sound level differences between neighbouring measurement points should be small. The frequency response of such reflecting structures can be considered to be high-pass filters and described by the relationship between the relative sound reflection level and the frequency (Fig. 2) (Skålevik, 2006; 2007).

$$f_g = 64 \cdot \varepsilon, \tag{1}$$

where f_g is the cut-off frequency and ε is the panel edge density.

$$L_x = 20 \log \mu, \tag{2}$$

where L_x is the relative level of the sound reflection and μ is the panel relative density.

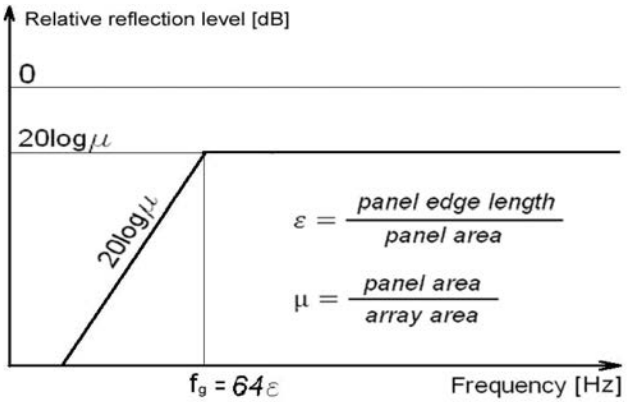

Fig. 2. Relative level of sound reflection by the reflecting structure shown as a high-pass filter.

In designing overhead stage canopies one should also take into account the effect of the ceiling itself. Frequency characteristics of the relative level of the sound reflection will depend strongly on the acoustic modification of the ceiling and its distance from the reflecting panels.

2. Method

The measurement setup located in an anechoic chamber consisted of a full range loudspeaker, five G.R.A.S. 40AE microphones, and movable mounting frames with mounting grids (Fig. 3). Positioned on the grids are 60 cm × 70 cm reflecting structures forming an array of elements made of HDF panels with dimensions of 3 cm × 60 cm.

On the basis of impulse responses obtained from measurements on reflecting structures arranged in various model configurations individual frequency responses were determined. The following algorithm was adopted: the frequency response determined for the empty measurement system was subtracted from the response obtained from the array of reflecting elements and from the response obtained from a reference panel (full panel). This eliminated the direct sound and reduced the effect of unwanted reflections from structural elements of the measurement system. Then a Fourier transform was applied to the resulting differences of each impulse response. Finally, the relative level of reflections from the reflecting panel array was determined as a function of the incident acoustic wave frequency on the basis of the following formula (Polaczek, Rubacha, 2010):

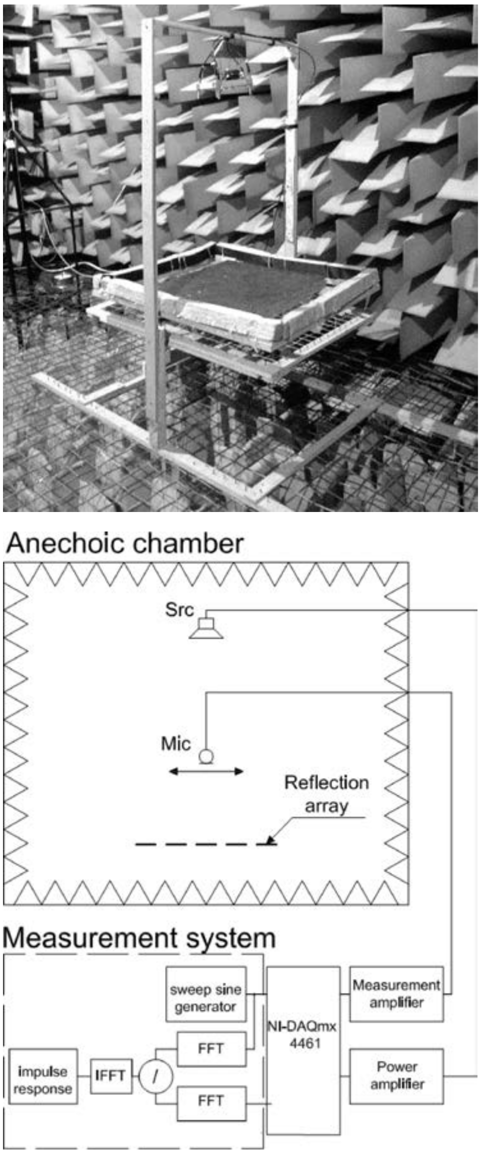

Fig. 3. Measurement setup in the anechoic chamber and a block diagram of the measurement chain (Kamisiński *et al.*, 2010).

$$L_x = 20 \log \left[\frac{FFT(IR_{\mathrm{array}} - IR_{\mathrm{empty}})}{FFT(IR_{\mathrm{ref}} - IR_{\mathrm{empty}})} \right], \tag{3}$$

where FFT is the Fast Fourier transform; IR_{array} is the impulse response of reflection from the reflecting panels; IR_{ref} is the impulse response of reflection from the reference panel (100% relative density, $\mu = 1$); IR_{empty} is the impulse response of reflection from the measurement setup without tested structures.

3. Experiments and results

The choice of an appropriate shape, size, and arrangement of reflecting panels can influence the scope and course of the frequency response for the sound reflected from them. In order to illustrate the interaction between the reflecting structure and the ceiling in a real room model studies were performed in the measurement system which were to compare the frequency response of a selected array of panels placed in the free field over a reflecting plate imitating the ceiling and without this plate (Figs. 4, 5).

Fig. 4. Studied reflecting structure ($\mu = 0.6$, $\varepsilon = 70$) positioned over the reflecting plate simulating the ceiling and without this plate.

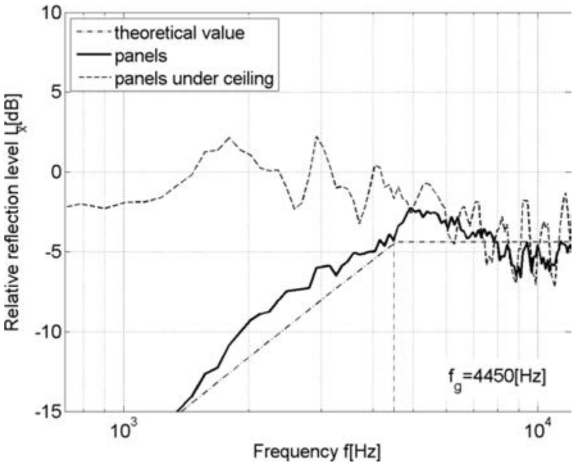

Fig. 5. Comparison of the relative level of reflections from the studied reflecting structure placed in the free field over a reflecting plate imitating the ceiling and without this plate.

As a result of the interference of acoustic waves the frequency response in the pass band was disturbed. A phenomenon known as comb filtering occurs, which negatively affects the quality of the reflected sound. A similar phenomenon will occur for low frequencies that are neglected when analysing reflecting structures placed in the free field.

The next stage of the study was to determine the effect of acoustic modifications of the ceiling on the characteristics of the reflected sound and to attempt to reduce the observed adverse acoustic phenomena. In one experiment the reflecting panel imitating the ceiling was covered with a layer of carpet, and in the other it was covered with 3 cm thick mineral wool. The corresponding frequency characteristics are shown in Fig. 6.

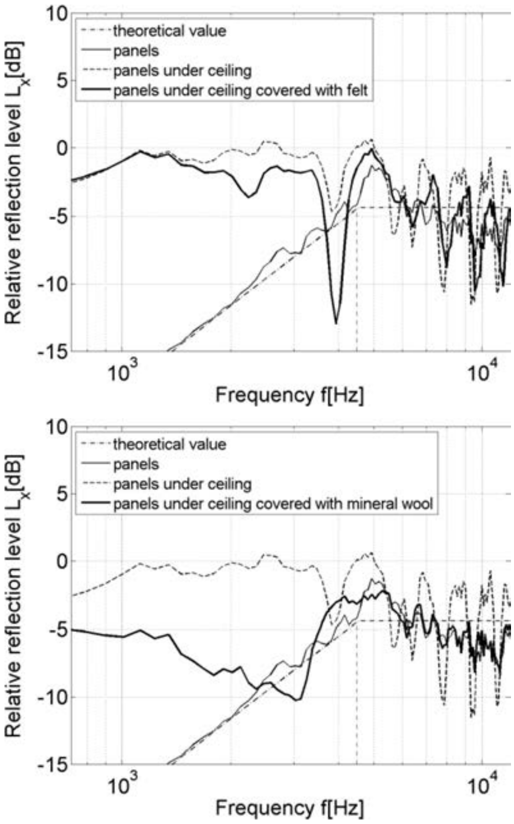

Fig. 6. Comparison of the relative level of reflections from the reflecting structures studied ($\mu = 0.6$, $\varepsilon = 70$), placed in the free field over the reflecting plate imitating the ceiling and over the plate covered with felt (top) and with mineral wool (bottom).

In analysing the responses in the pass band, only partial smoothing of the response can be noted after modifying the ceiling with a carpet, whereas the use of mineral wool as sound absorbing material considerably improved the response, resulting in uniformity comparable to the model of a reflecting structure placed in the free field without the reflecting plate. Introduction of a sound-absorbing material over the reflecting structure reduces the comb filter effect but also reduces the structure's reflecting capacity in the low frequency range. In this range, however, a sufficient amount of acoustic energy reaches the audience with reflections from other surfaces. A decrease in the relative level of sound reflection in the low-frequency range in the case of the ceiling covered with wool will not thus have a significant effect on the quality of the sound audible to the audience. However, in the case of the carpet lining (a material with a lower sound absorption), a sudden, very significant reduction in the relative level of reflection around the cut-off frequency occurs, which consequently disqualifies this means of ceiling modification.

In another experiment, influence of the distance of reflecting structures from the ceiling on the frequency response and the occurrence of the comb filter effect was determined. The results show two extreme cases, the distances of 4 cm and 17 cm (Fig. 7). One can clearly see that with the increase in distance between the reflecting panels and the "ceiling" panel, the comb filter effect decreases and the frequency response is smoothed out, though it is not sufficiently uniform. Thus, in the cases described here, the ceiling was modified with 3 cm thick mineral wool. The corresponding responses are shown in Fig. 8. In both cases the modification produced positive results, although for a distance of 17 cm the disturbances around the cut-off frequency should be reduced.

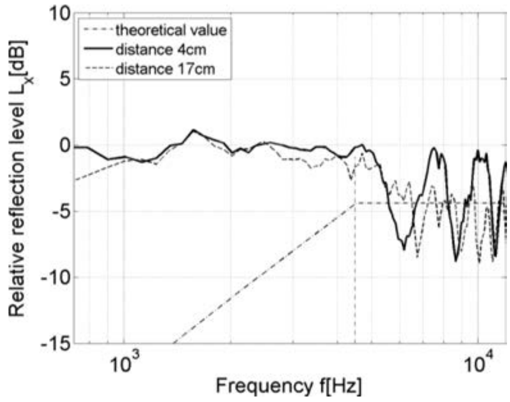

Fig. 7. Comparison of the relative level of reflections from the studied reflecting structures ($\mu = 0.6$, $\varepsilon = 70$) placed over a reflecting panel at distances of 4 cm and 17 cm.

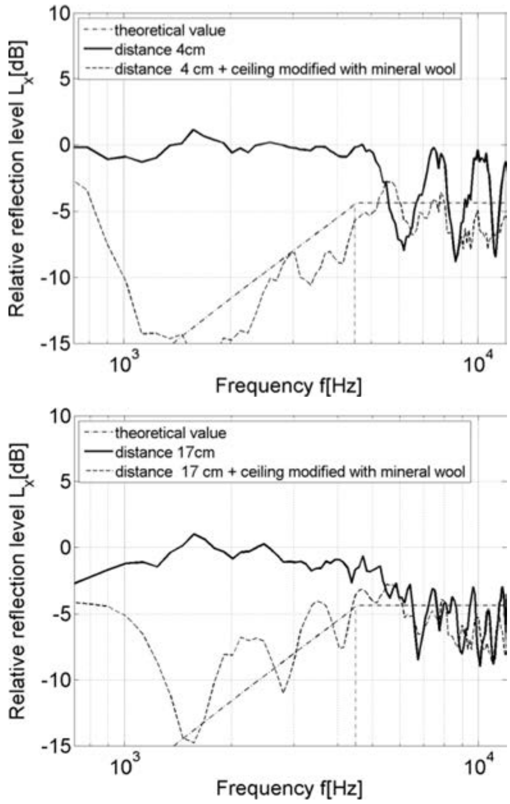

Fig. 8. Characteristics of the relative level of sound reflection from the studied reflecting structure ($\mu = 0.6$, $\varepsilon = 70$) placed over a reflecting panel imitating the ceiling and over a panel covered with wool at distances of 4 cm and 17 cm.

The influence of closeness of the reflecting panels arrangement regarding the relative level of sound reflection was also included in the experimental studies. Using identical elements, four different arrays were arranged with panel packing densities covering a surface area of 25, 50, 70 and 90%. Then the structures were placed over the reflecting panel (Fig. 9) and measurements were conducted. The experiment was also repeated for the arrays positioned in the free field. The results are shown in Fig. 10.

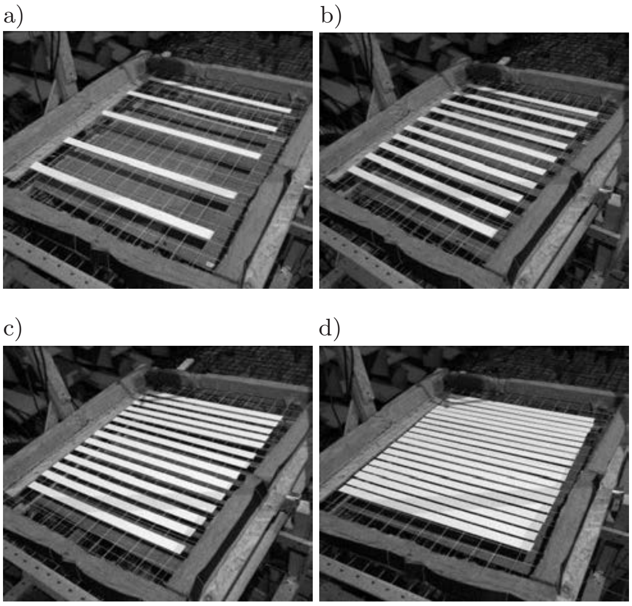

Fig. 9. Studied reflecting structures with a different packing density of the panels. From the: a) 25% ($\mu = 0.25$, $\varepsilon = 70$), b) 50% ($\mu = 0.5$, $\varepsilon = 70$), c) 70% ($\mu = 0.7$, $\varepsilon = 70$), d) 90% ($\mu = 0.9$, $\varepsilon = 70$).

In both graphs there is smoothing of the frequency characteristics of the reflected sound with the increase in density of the reflecting panels.

The last issue analysed here involved somewhat more complex reflecting structures. A model of a double array of reflecting panels was made and placed in the free field. With such a construction it was possible to present two situations: the first one, in which the frequency response of the sound reflected from multilayer reflecting structures was determined, and another one, in which the back layer can be viewed as a ceiling covered alternately with reflecting and absorbing materials. This provides further insight into possible options for the acoustic modification of the ceiling. The results are shown in two graphs (Fig. 11).

While comparing the frequency responses for a single and double reflecting structure, significant disturbances in the response of the latter case were observed: the comb filter effect occurred in the entire band, negatively affecting the quality of the reflected sound. Even the alternate arrangement of the panels in both layers was not able to eliminate this adverse phenomenon at low frequencies, whereas in the higher frequency range the shape of the response was only slightly affected.

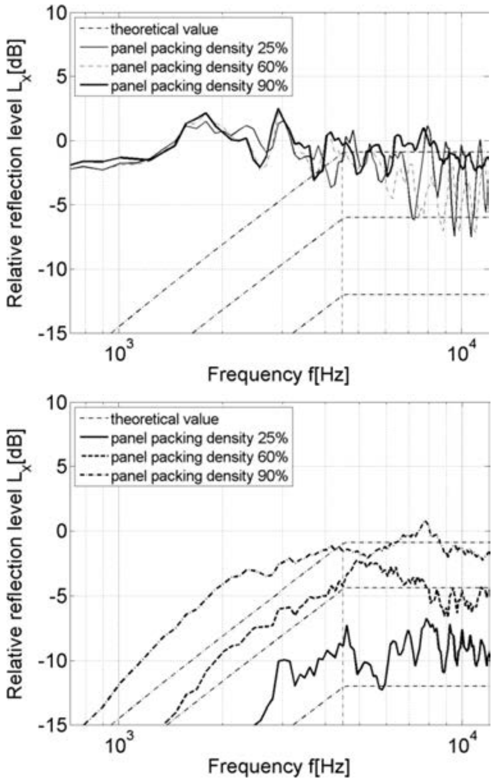

Fig. 10. Comparison of the relative level of reflection from the studied reflecting structures with a different packing density and arrangement of the panels. Top: structures located over the reflecting plate. Bottom: structures located in the free field.

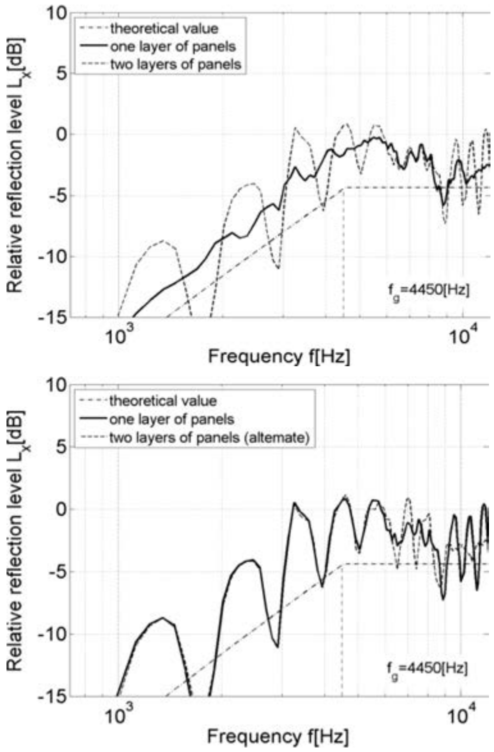

Fig. 11. Comparison of the relative level of sound reflections from the reflecting structures ($\mu = 0.6$, $\varepsilon = 70$) arranged in one and in two layers (top) and in two parallel and alternate layers (bottom).

The last graph (Fig. 12) presents the frequency response for three different double reflecting structures. The first layer was identical in all cases. Only the back array changed. It consisted of an increasing number of elements, therefore, the proportion of the sound reflected from this array increased. It can be seen from the results that this increase in the size of the rear array of elements results in decreasing of the comb filter effect below the cut-off frequency. In the pass band, however, the differences are insignificant.

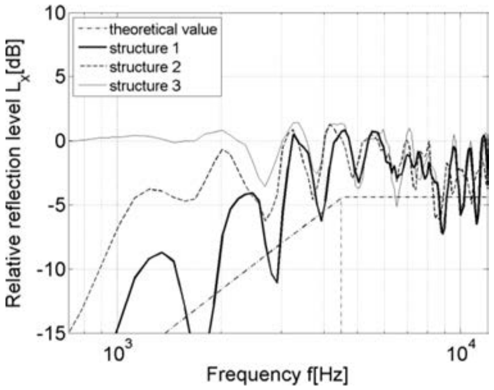

Fig. 12. Comparison of the relative level of reflections from the double-layer reflecting structures: structure 1: double array of panels, the upper layer with $\mu = 0.6$, $\varepsilon = 70$; Structure 2: double array of panels, the upper layer with $\mu = 0.6$, $\varepsilon = 70$, lower layer: $\mu = 0.7$, $\varepsilon = 23$; structure 3: double array panels, the upper layer: $\mu = 0.6$, $\varepsilon = 70$, bottom layer-a reflecting panel.

4. Summary

Based on the experimental results presented in this paper, one can conclude that adaptation of the ceiling above the reflecting panels with a strongly sound-absorbing material significantly improves the characteristics of reflection. Also, positioning of the elements in the space under the ceiling should be carefully controlled because, as it was found experimentally, an adverse acoustic phenomenon known as the comb filter effect can occur. The conducted model studies can be scaled up to the dimensions of the actual structures because the scope and level of the pass band depends directly on the geometric dimensions of the array of reflecting elements, whereas scaling of the effects of the phenomena associated with the sound absorption should be experimentally verified in real spaces.

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