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Project of Acoustic Adaptation of the Church with a Long Reverberation Time

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Abstract Long reverberation times are a problem in modern churches. General methods of solving the problem are given in the literature. The basic approach is to increase the acoustic absorption of the church, and this can be achieved by placing sound-absorbing materials on the walls. Due to the price, materials with a high absorption coefficient are not used. They are replaced with sound-absorbing plasters. For the known coefficient of sound absorption by plaster, the problem is to calculate the surface of the plaster coverage and its distribution on the surface. This problem was solved for the Academic Church in Rzeszow, the Roman Catholic Parish of St. Jadwiga Queen. The reverberation time before adaptation is equal to 6.78 s, while the predicted time after adaptation is 1.98 s.

Keywords: interior acoustics, reverberation time, sound-absorbing materials, plaster.

1. Introduction

The acoustics of contemporary churches is the subject of many articles [1-4]. The problem is difficult because both the perception of speech and music are equally important; in the Catholic church the organ music accompanies liturgy [5]. But for organ music, the recommended acoustic parameters are entirely different from those for speech [6-7].

The churches acoustic properties can be measured by many different parameters [6, 8] or by means of the global parameter [9-15]. The most important and, at the same time, the first noticeable parameter of the poor acoustics of the church is too long reverberation time [5, 16-19].

The churches acoustics depends on their geometry, sound absorption or diffusivity of the acoustic energy [20]. Acoustic adaptation consists in changing these parameters. Due to the accepted architecture of the church, acoustic adaptation ought to be minimally invasive. Adaptation cannot visually deteriorate the space or generate too high costs. One of the best possible solutions is to cover the selected surfaces of the ceiling and walls with acoustic plaster. Acoustic plaster is not a new sound-absorbing material; it was patented in 1920 under the name Akoustolith. Modern acoustic plasters do not have a very high sound absorption coefficient, but they are cheaper compared to other materials or sound-absorbing structures.

The aim of this article is to reduce the reverberation time of a chosen church by selecting the size of the acoustic plaster surface and arranging it appropriately over the church surface. The study is divided into three stages: First, the reverberation time of the present church was measured. Secondly, the surface of the acoustic plaster was calculated and the method of its distribution in the church was indicated. Finally, approximate analytical calculations were used to estimate the achieved reverberation time.

2. Geometric and physic parameters of the church

Long reverberation time is mainly caused by cuboidal geometry (walls are parallel in pairs) and very low absorption coefficient of the hard plaster on sides walls and ceiling and of hard granite on the floor. In addition, there is a negligible amount of architectural details, which translates into low sound absorption and diffusion. There are only four rows of benches on the floor, unfortunately hard, which disperse the sound a bit. The main geometry of the church is given in Tab. 1, and its general appearance is shown in Figs. 1-5.

Table 1. Geometric parameters of the church, important for acoustics.

	Surface [m²]			Volume [m³]
Church areas	floor + ceiling	side walls:left + right	walls: front or rear	
Presbytery	219.4	219.4	213.2	1600.8
Main nave	477.4	492.2	-	3632.1
Aisle	57.2	49.4	51.2	189.9
Church yard	240.4	61	54.0	444.6
Choir	439.6	374.6	192.1	2879.3
	sum: 1434	sum: 1196.6	sum: 510.5	
sum	~ 3141			~ 8747

Figure 1. Academic Church in Rzeszow, the Roman Catholic Parish of St. Jadwiga Queen.

Figure 2. Main altar, Presbytery.

Figure 3. Rear wall, church yard and choir.

Figure 4. Left wall of the nave.

Figure 5. Right wall of the nave with a small nave.

3. Acoustic measurements

The acoustic measurements were carried out in accordance with the PN-EN ISO 3382-2:2010 and PN-B-02151-4:2015-06. An omnidirectional spherical sound source (B&K 4292) was placed in three points, see Fig. 6, measurement microphone (B&K 4189) was equally distributed at 34-35 points on the nave floor in order to evaluate the spatial average acoustic properties of the church and measurements were made with a B&K 2270 Sound Lever Meter (Analyzer). The sound signal was generated in the form of periodic pink noise. Reverberation time was arithmetically averaged for each microphone position and each source position. During the research in the presbytery, the main nave, under the choir and in the choir, there were standard equipment such as chairs and benches; there were no believers.

a) b) c)

Figure 6. Position: a) Z1, b) Z2, c) Z3.

Table 2. Mean reverberation time $T_m = T_1$ [s].

Source position	Octave bands [Hz]					
	125	250	500	1000	2000	4000
Z1	7.62	7.52	7.92	7.48	6.08	4.02
Z2	7.64	7.55	7.91	7.47	6.04	3.99
Z3	7.69	7.54	7.93	7.49	6.06	4.08
T_m in octave bands	7.65	7.54	7.92	7.48	6.06	4.03
T_m	6.78					

4. Acoustic calculations before adaptation

The recommended reverberation time T for churches, depending on their cubature, is depicted in Fig. 7 [21]. Dark grey colour is recommended for churches with organ music concert but light grey colour for churches where speech is dominant. Optimal acoustic conditions in a church are defined as a balance between requirements for speech and for music.

The red line in Fig. 7 indicates the recommended reverberation time for the considered church. By accepting a compromise between speech and organ music, the optimal reverberation time is at the border of the areas, i.e. $T_0 \approx 1.8$ s, so it is within the limits of $T \in (1.6;\, 2.3)$ s. Hence it follows that in all octave bands the reverberation time is exceeded many times.

For the measured reverberation time before adaptation, the mean sound absorption coefficient $\alpha_{m,S}$ of the total surface of the church was calculated according to the Sabine's formula:

$$T_m = \frac{0.161V}{S\,\alpha_{m,S}} \tag{1}$$

where V = 8747 m^3 is internal church volume, S = 3141 m^2 is total church surface, T_m = 6.78 s; hence $\alpha_{m,S}$ = 0.066.

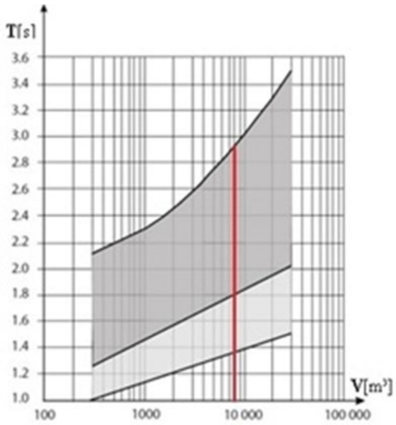

Figure 7. Range of optimum reverberation time for churches [21].

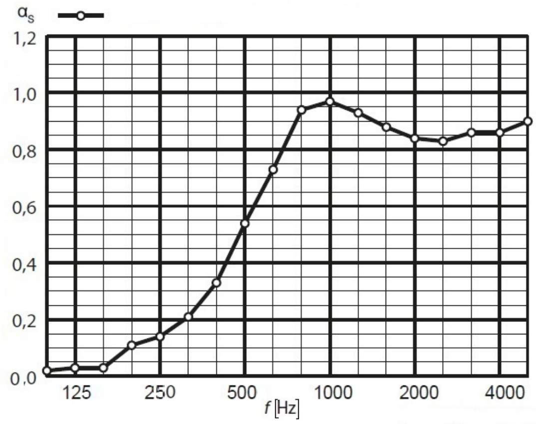

Figure 8. Sound absorption coefficient of the acoustic plaster α_S (ISO 354).

5. Acoustic adaptation

Sound absorption coefficient of acoustic plaster (Sabine's, $\alpha = \alpha_S$) is given in Fig. 8. According to the PN-EN ISO 11654 standard, one value is taken into account, i.e. $\alpha = \alpha_w = 0.45$.

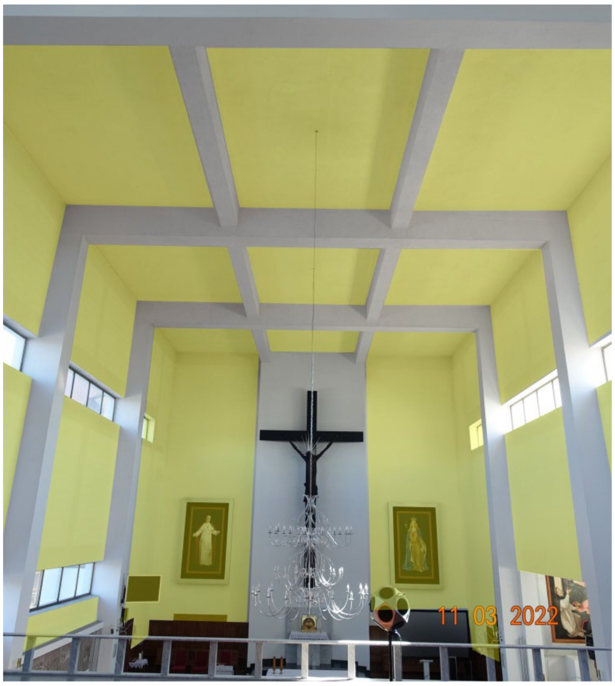

Figure 9. Presbytery, parts of the ceiling and side walls.

Figure 10. Choir, parts of the ceiling and side walls.

Figure 11. Left side wall of the nave.

Figure 12. Right side wall of the nave.

Note, that the rear wall and the coffers above the organs are not covered with plaster. This is to provide a better sound to the organ music in the nave. Before arranging the acoustic plaster, the approximate area of it is calculated in order to achieve the reverberation time $T_o \approx 1.8$ s. According to Sabine's formula, $S_w \approx 1739$ m². Whereas, for $T \in (1.6 - 2.3)$ s, the area range $S_w \in (2086, 1361)$ m². Arrangement of sound-absorbing plaster (yellow colour) is presented graphically in Figs. 9-12.

6. Acoustic calculations after adaptation

These calculations concern to the reverberation time and they were made again according to the Sabine's formula, where

$$\alpha_m = \frac{\sum_i \alpha_i S_i}{\sum_i S_i} \tag{2}$$

and α_m is mean value of the absorption coefficient, α_i is absorption coefficient of the surface S_i .

The first calculations take into account only the acoustic plaster. So, for acoustic plaster $\alpha_1 = 0.45$, $S_1 = 1268$ m² and for the rest of the surface $\alpha_2 = 0.066$, $S_2 = S - S_1 = 1873$ m². For this data $\alpha_m = 0.221$ and, based on the formula Sabine's $T_m = T_2 = 2.03$ s.

The second calculation takes into account acoustic plaster and padded benches. So, now there are the following acoustic parameters: the acoustic plaster: $\alpha_1 = 0.45$, $S_1 = 1268$ m², padded benches: $\alpha_3 = 0.215$ $S_3 = 122$ m² and the rest of the surface: $\alpha_2 = 0.066$, $S_2 = S - S_1 - S_3 = 1751$ m². For such data $\alpha_m = 0.227$ and based on the formula Sabine's $T_m = T_2 = 1.98$ s.

7. Discussion and conclusions

In the contemporary church in Rzeszów, Poland, the acoustic adaptation was proposed. Subjective reverberation impressions were confirmed by reverberation time measurements, $T_1 = 6.78$ s; limit of it was significantly exceeded. There are organs in the church, hence the acoustic adaptation took into account not only speech, but also organ music.

The primary purpose of the adaptation was to shorten excessive reverberation time. Acoustic adaptation was based on the use of acoustic plaster with $\alpha_w = 0.45$. Such a solution does not disturb the architecture to a large extent and is relatively cheap.

The optimal reverberation time was found to be $T_o \approx 1.8$ s. In order to obtain T_o, the optimal surface covered with plaster should be $S_o = S_w \approx 1739$ m². The proposed plaster surface $S = 1268$ m², thus it is less than optimal S_o. This results in a slightly worse reverberation time, i.e. $T_m = T_2 = 2.03$ s. Reverberation time can be brought closer to optimal by padding the benches in the central part of the nave. Then it achieves $T_m = T_2 = 1.98$ s.

The general conclusion is as follows: both adaptation methods reduce the reverberation time to the recommended range, namely $T \in (1.6 - 2.3)$ s. Nevertheless, after adaptation, other parameters of speech, i.e. RT (or the T_{30}), EDT, C_{50} , D_{50}, RASTI (or STI) and music quality, i.e. t_S, C_{80}, should be tested [22].

Additional information

The authors declare: no competing financial interests and that all material taken from other sources (including their own published works) is clearly cited and that appropriate permits are obtained.

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