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ScienceDirect

Energy Procedia 78 (2015) 1623 – 1628

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Analysis and acoustic correction of a contemporary Italian church

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Abstract

Nowadays, architects and designers build new churches primarily considering the architectural shape to emphasize the iconographic message without sufficiently investigating the acoustic climate. In many cases, designers propose elliptical or irregular geometries for the shapes of these buildings and, in addition, the furniture of indoor surfaces have unsuitable absorption and diffusivity coefficients. Thereby, it can be observed the arise of serious acoustical problems such as standing waves, flutter echo, sound focusing and intensive late reflections (greater than 100 ms) which seriously decrease speech intelligibility and diminish the effectiveness of the early sound energy. This paper presents the results of an acoustic survey on the Catholic Church "Invaluable Blood of Jesus", situated in Ragusa (Italy), which is characterized by many problems mentioned above. During last years, some refurbishment interventions have attempted to reduce the acoustic discomfort, but an uncorrected approach has completely compromised the speech intelligibility, especially during liturgical functions. Recently, the authors have been involved to propose suitable interventions for improving the acoustic quality of this environment. Preliminarily, a measurement survey was conducted to evaluate the main acoustic indices (RT_{60}, STI, EDT, C_{80}, D_{50}) and portray the current acoustic climate. After that, it was developed an acoustic computer simulation on a 3D model of the church, in order to calibrate the model comparing measured and simulated data. This procedure allowed testing the reliability and accuracy of the model.

Finally, We propose two different interventions of acoustic correction. Globally it is possible to obtain an improvement of RT_{60} from 7.3 to 2.5 s at 1 kHz and STI increases from 33% to 40%, at 1000 Hz.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Modern Churches; Acoustics; Acoustic Indexes; Acoustic Correction

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.240

1. Introduction

Churches have a unique architectural style and are of great social importance in city life. They are built with a very specific objective, namely, to serve as places of worship. Acoustically, churches have a complex mission.
Indeed, they must meet the requirements of both speech and music, which often seem incompatible. The interest in church acoustics has increased in recent years and many studies have been carried out in different Countries, such as: Italy [1] and [2], Portugal [3] Germany [4], Spain [5]. This paper presents the results of an experimental investigation on the acoustic performance of the Catholic Church called "Preziosissimo Sangue di Gesù" located in Ragusa. With the aim to characterize the distribution of the sound energy and the room acoustic quality, the authors have proceeded through the following steps:

- measurements of the acoustic indexes (RT_{60}, *STI*, *EDT*, C_{80}, D_{50}) based on experimental.
- modelling the geometrical and acoustic features of the church using the computer code Catt-Acoustic.
- validation and calibration of the computer model
- proposal of suitable interventions for the acoustic corrections
- evaluation of the quality of the acoustic climate after the corrections

2. Material and Methods

In order to get good acoustic quality, it is important to satisfy the requirements of the acoustic parameters that define the quality of the sound field and the listener sensations [6,7,8,9]. These parameters, according to ISO 3382 [10], include the Sabine's Reverberation Time (RT), the Definition Index (D), the Clarity (C80), the Early Decay Time (EDT) and the STI Index. The Reverberation Time is defined as the time it takes for a signal to drop by 60 dB from its initial stationary level. In accord with ISO 3382, the measurements can be made between -5 and -35 dB or between -5 e -25 dB. The reverberation time is obtained by mathematical extrapolation, assuming a purely linear decay; RT is called T_{30} and T_{20}, if deduced from the first or the second approach [11]. The Early Decay Time (EDT) is the reverberation time measured over the first 10 dB of the decay. Unlike late reverberation, early reverberation just comprises few primary reflections that are integrated with the direct sound, thus reinforcing it. This early reverberation can affect the clarity of sound, as well as the perception of liveliness: indeed, the greater the energy in the early reverberation, the better the clarity. On the contrary, high late reverberant energy can increase liveliness or fullness, but decreases the clarity. Furthermore, clarity (C_{80}) is defined through the difference between the sound energy in the first 80 msec, and the late reverberation energy arriving after the first 80 msec. In some cases, a single C80 value is used, which averages clarity at 500, 1000 and 2000 Hz. Definition (D) or early-to-late energy ratio characterizes the speech intelligibility [11]:

$$C_{80} = 10log \int_0^{80ms} p^2(t)dt / \int_{80ms}^{\infty} p^2(t)dt \quad (1)$$

$$D = \int_0^{50ms} p^2(t)dt / \int_0^{\infty} p^2(t)dt \quad (2)$$

The speech transmission index (STI) is widely used for assessing room acoustics [12]. The scientific principle, on which the STI is based, is that information in speech is represented acoustically in the form of modulations: a loss of these modulations translates into a loss of intelligibility. The STI measures the ability of a transmission channel – the room in this case – to carry across the characteristics of a speech signal without loss of modulation. In practice, the field measurement of this parameter is based on a well-established procedure. The result is an index ranging from 0 to 1: the closer the STI value approaches zero, the more information is lost. There are standardized ratings linking certain ranges of the STI to subjectively experienced intelligibility, [13].

3. The case study

This research is focalized on the Catholic Church "Preziosissimo Sangue di Gesù" located in Ragusa (Italy), which was built in 1980, featured by an unusual asymmetric radial shape, as shown in Figure 1. Probably, the designer would depict the figure of the heart.

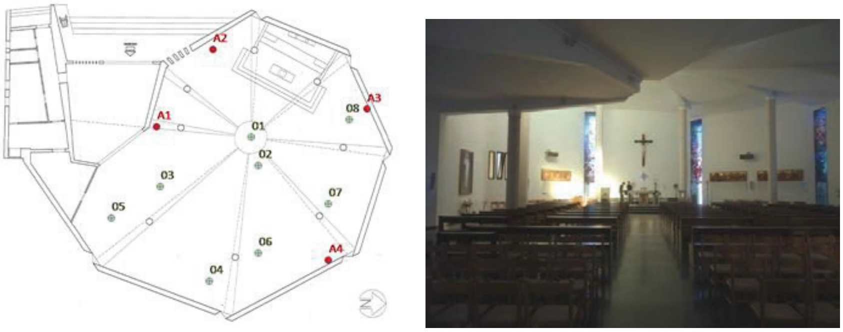


Fig. 1. (a) Floor Plan of the Church (b) View of the altar from audience area

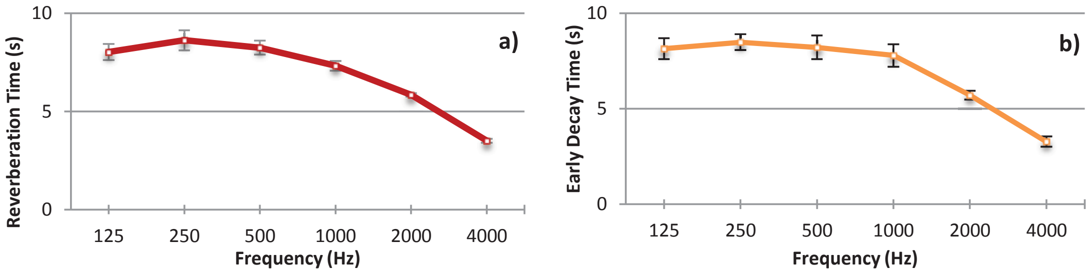
The maximum dimensions are 23.10 m in length and 18.40 in width, while minimum and maximum height of the ceiling are respectively 6.05 m and 10.30 m. The volume is about 3580 m^3. The floor surface is subdivided into eight parts, according to ceiling sectors subdivision: each sector has a proper slope, both in radial and tangential direction. All the sectors of the ceiling rejoin toward a skylight located at the height of 10.80 m, about on the center of the church. The floor finish is marble, while walls and ceiling are entirely covered by extremely smooth plaster. Also, furniture includes only wooden pews in audience area, which cover about the 50% of whole plan area. The wide volume and smooth surfaces lead to a lack in the acoustic quality, as evidenced by high values of reverberation times and poor speech intelligibility.

3.1. Acoustic Measurements

In order to evaluate the acoustic indices defined by ISO 3382 and identifying the causes of the lacks in acoustic quality, a measurement survey was conducted. The position of the sound sources (A_i in red color) and the receivers (0_j in green color) are depicted in figure 1. Microphones were placed at the height of 1.20 m (ears height in sitting position), aiming to the altar.

Measurements were carried out using a 01dB-Stell Symphonie precision audio-acquisition unit, powered by *dBBati32* software. An omnidirectional loudspeaker was used as sound source. The procedures employed are those established in the ISO 3382-1 and IEC 60268-16 standards, and all measurements were accomplished in the unoccupied room. The signal used to excite the rooms was an MLS (Maximum Length Sequence) signal with following parameters: 18th order, response length 10.2 s, and averages number 4. We have used the room responses to determine the acoustic parameters, at each octave band from 125 Hz to 4000 Hz, for all the receivers.

Figure 2 shows trends for average indices values and respective standard deviation calculated over the eight receivers. It is possible to see that receivers are not affected so much by spatial distribution: this is probably due to diffusion of late reflections. This is confirmed by low standard deviation values.



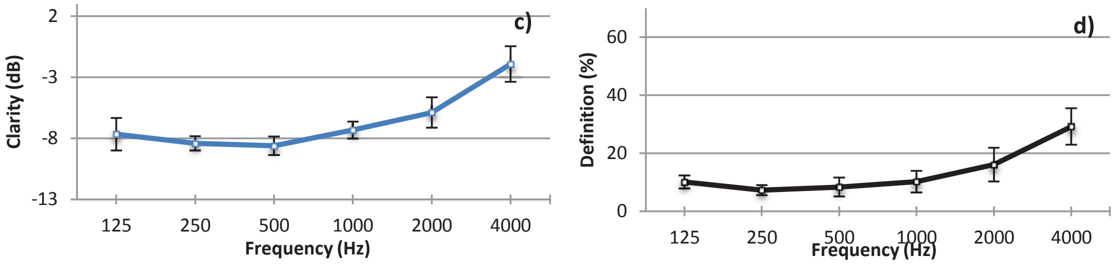


Fig. 2. Average indices values with standard deviation (grey bars).
(a) Reverberation Time T_{30}; (b) Early Decay Time *EDT*; (c) Clarity C_{80}; (d) Definition D_{50}.

Moreover, there are no significant differences between RT_{60} and *EDT* values in the overall frequency spectrum, which confirm the linearity of decays. Measurements of C_{80} and D_{50} feature very low values in comparison to optimum for speech halls. However, also the possibility of music performance should be taken in account within these typologies of building. Overall, acoustic treatment should certainly make the church be attractive for both possible purposes. Finally, *STI* values are quite constant in whole hall, even if they are not sufficient to guarantee a good quality for speech: the average is 33%, which means "POOR" speech intelligibility, according to ISO 3382.

3.2. Computer modeling

Measurements of the acoustic indexes were used for verification, validation and calibration of a 3D computer model in CATT-Acoustic. Sound sources and receivers were implemented in the same way of measurement process. Simulations in CATT-Acoustic were conducted through Randomized Tail Corrected Cone-Tracing algorithm, setting a number of rays of 28740 and a ray truncation time of 9000 ms. First, the virtual model was validated through an iterative procedure, based on the adjustment of absorption coefficients for cladding materials, in order to obtain values of simulated RT_{60} comparable with measured ones [14]. At the end of the process, simulated and measured values differ by no more than 5% for each frequency.

4. Acoustic corrections

In a place like a church, the aesthetic point of view plays a fundamental role about any kind of intervention that involves walls or ceiling, especially if a large amount of area needs to be treated. Thus, the upper part of the walls was chosen since allows to attenuate late reflections spread in the wide volume of the hall without strongly affecting the aesthetic of the church (see Figure 3a). This area has an extension of about 230 m^2, which corresponds to 46% of the whole surface of the walls. Two different acoustic treatments for such area of intervention were investigated.

- Wood Wool panels, operating as porous absorbers (Figure 3b);
- Micro-Perforated panels, operating as Helmholtz Resonator (Figure 3c).

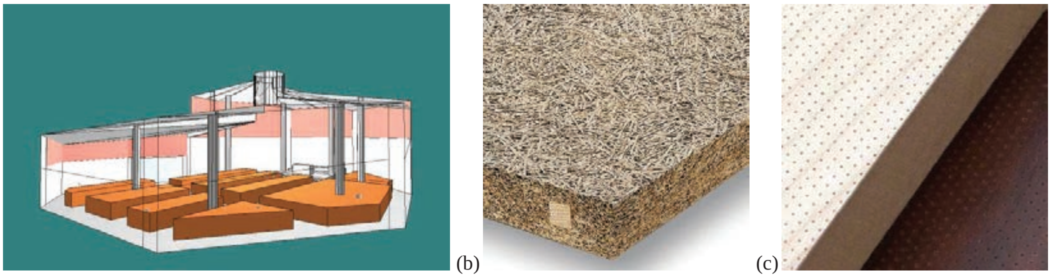

(a) (b) (c)

Fig. 3. (a) Area of intervention for acoustic correction (pink) (b) Wood Wool panel (c) Micro-Perforated Panel

The main features of the two acoustic treatments are shown in Table 1.

Table 1. Main features for Wood Wool Panel and Micro-Perforated Panel absorbers

Treatment Name	Material	Description	Absorption Coefficients α					
			125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
WWPT	Wood Wool Panel	Porous absorber Panel thickness 25 mm Distance from wall ≥ 24 mm	0.12	0.11	0.48	0.72	0.51	0.82
MPPT	Micro-Perforated Panel	Panel thickness 2.0 mm Hole diameter 0.2 mm Hole repeat distance 1.0 mm Distance from wall 70 mm	0.21	0.54	0.84	0.74	0.29	0.19

The absorption coefficients, reported in table 1, were obtained from the data sheet of the producer, while the absorption coefficients of the Micro-Perforated Panel were calculated using the equations proposed in [15].

Figure 4 shows the comparison between calculated and measurements values for the two treatments.

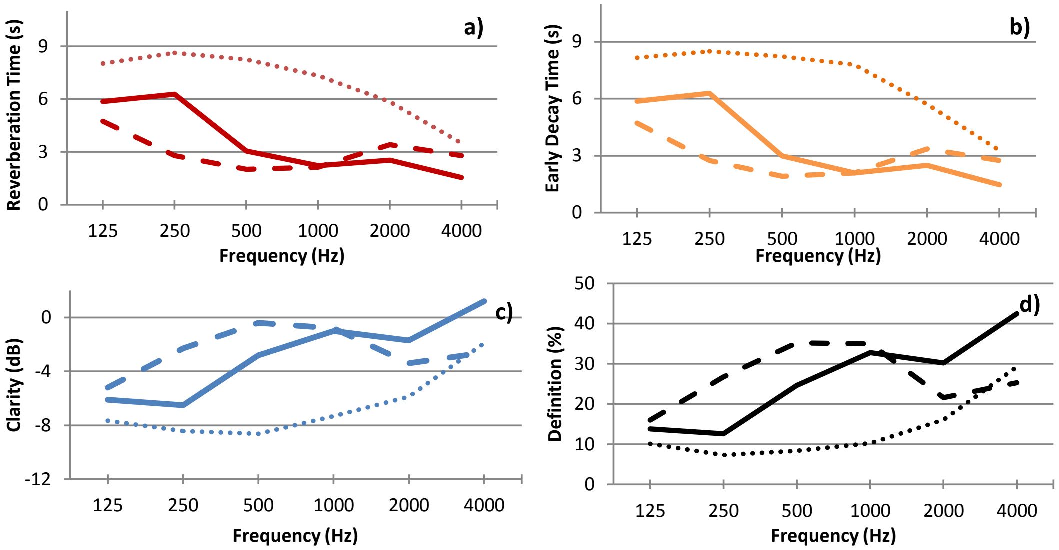


Fig. 4. Average indices values after acoustic correction: Measured (dot), WWPT (continuous), MPPT (dash).
(a) Reverberation Time T_{30}; (b) Early Decay Time *EDT*; (c) Clarity C_{80}; (d) Definition D_{50}.

RT_{60} and *EDT* values mainly improved at mid and high frequencies, according to absorption coefficient trend.

WWPT system has a worse behavior than the MPPT in low frequencies and this cause a great difference in whole spectrum reverberation balance. However, in both case optimum values of reverberation for churches at 500 Hz were achieved, ranging from 3.0 to 4.0 s for a 3500 m^3 hall.

C_{80} and D_{50} values are improved significantly in comparison to measured values: this means that absorbing area lets energy to stay more in early reflection than before. It is possible to notice differences in spectrum balance: WWPT improves mostly high frequencies (speech), while MPPT leads to a more balanced frequency spectrum.

The proposed treatments increase the speech intelligibility, but do not allow reaching the expected objectives (at least 50%). However, this result is referred to the empty hall: *STI* could improve in the case of occupied seats, because of audience sound absorption in speech frequencies. Average values of *STI* are 41% for WWPT treatments and little bit worse when the MPPT treatment is chosen (39%), since it affects less the high frequencies reflections.

5. Conclusions

The acoustic survey carried out on a contemporary catholic church has revealed that reverberation time, clarity, definition and speech intelligibility index values are very far from acceptable values for this kind of environments, e.g. RT_{60} and EDT of about 7.3 sec at 1 kHz.

A 3D computer model was set up in CATT-Acoustic software to simulate the acoustic field within the church. This computer model was validated and calibrated, finding no more than 5% error in values matching. Once defined the surfaces where the absorbing materials could be inserted, two different treatments were proposed for acoustic correction of the hall: the first is a porous absorber made of wood wool; the second is a micro-perforated panel, based on the principle of Helmholtz Resonator. The simulations carried out revealed that the two proposed acoustic interventions allow achieving significant improvements for each acoustic index (e.g RT_{60} of about 2.5 sec at 1000 Hz and STI of about 40%).

Both results lead to a good achievement, because all parameters have been measured and predicted in empty hall condition. The scope of the acoustic treatment in a church is to reduce the acoustic quality variability related to audience presence, which mostly affects the mean sound absorption of the hall.

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