# Acoustic Study of a Baroque Church

Anna SYGULSKA
*Poznan University of Technology, Faculty of Architecture,*
*ul. Jacka Rychlewskiego 2, 61 -131 Poznań,*
*anna.sygulska@put.poznan.pl*

**Abstract**

The issue of sonic heritage in sacred historic buildings is gaining popularity and becoming a frequent subject of discussions. The Baroque St Joseph Church of Carmelite Fathers, a minor basilica, is, architecturally and culturally, an exceptional place in Poznań, a city located in western Poland. The church is often used as a concert venue. It underwent an acoustic study with the use of a sound source situated in the presbytery and on the pulpit. The aim of this paper is to present results of acoustic investigations and to compare its acoustic properties with other churches. Acoustic parameters acknowledged as primary values used to assess acoustic properties of a religious building were investigated and then compared with recommended values. Placement of the source in two measurement points rendered it possible to carry out speech intelligibility analyses for a variable position of the sound source, and, in effect, enabled functional assessment of the historic pulpit. Thus obtained results were compared with European Baroque churches whose parameters are available in the literature.

***Keywords:*** church acoustics, architectural acoustics, Baroque church, reverberance

## 1. Introduction

The Catholic Baroque St Joseph Church of Carmelite Fathers in Poznań, a city located in western Poland, has a special place in the city's cultural realm. The building plays an important role in both religious and cultural life owing to classical music concerts that are organized there. The literature reflects an increasing interest in the issues of cultural heritage, which includes historic churches and their distinct aspect of sonic heritage that stems from the unique acoustics of their interiors. The aim of this paper is to present results of acoustic investigations conducted in the St Joseph Church, a valuable object of cultural heritage, and to compare its acoustic properties with other churches that are regarded as highly acclaimed due to their architectural and cultural value. Since the church is also used as a concert venue, it will be necessary to compare the obtained results with other historic Catholic churches that are used for concert needs.

## 2. St Joseph Church

The St Joseph Church of Carmelite Fathers is a three-nave basilica with a transept adjacent to the monastery of Discalced Carmelites. In 2017, Pope Francis designated the church as a minor basilica. The status is granted to churches in recognition of their exceptional historic, liturgical, peregrinative, and missionary values. Erection of the church was commenced in 1644; the designer was Krzysztof Bonadura the Elder, and after his death, Jerzy Catanezzi took over the works. The church went through tempestuous times. At the beginning of the $19^{th}$ century, it was closed down, and the monastery of Discalced Carmelites was resolved. The religious buildings were used as stables as well as hay and straw storage facilities. Devastation of the interior of the church was complete when Napoleon's army passed Greater Poland. In the 1840s, the interior was rebuilt according to the design by Karl Friedrich Schinkl and transformed into a garrison evangelical church. Finally, in 1945, the war-damaged church and the monastery were returned to the Carmelites and then reconstructed. Year 1984 was the beginning of intensive renovation works, and the church was consecrated in 1990. It is built on the rectangular plan; its lunette vault spans over the nave and the presbytery; over the transept there is a barrel vault. In the entrance part of the nave, there is a gallery with the organ. The internal volume of the church is 8 700 m³. Although the style is Baroque, the interior features classic moderation and simplicity. Lesenes and cornices, with decorative niches made the rhythm of the façade [1, 2]. Figure 1a shows the building's façade; Figure 1b shows the building's interior.

a)

b)

Figure 1. a) view of the church; b) church's interior

## 3. Investigations

The acoustic investigations were carried out using an omnidirectional sound source, and DIRAC programme with sound card Brüel & Kjær ZE-0948 USB. E-sweep signal was generated, and the measurements involved parameters that are regarded in the literature as primary to assess acoustic $T_{30}$ properties of a sacred interior: $T_{30}$, EDT, $T_S$, $C_{80}$, $C_{50}$, $D_{50}$, STI and RASTI. A gunshot was an additional sound source, and a control measurement was carried out in selected points. The measured acoustic parameters were compared with values recommended for churches. The sound source was placed in front of the altar (S1) and on the pulpit (S2). The microphones were located in selected points in the pews at the height of 1.1 m. Background noise level in the facility under investigation did not exceed 35 dB. All the investigations were conducted in the absence of people (believers). Figure 2a shows the position of the sound source in front of the altar, Figure 2b the sound source placed on the pulpit, whereas Figure 3 presents a view of the church with marked sound sources S1 and S2, and measurement points, which are marked with digits. The assumed measurement methodology is compliant with recommendations for investigations in churches [3, 4], while the selected acoustic parameters are recommended in the literature to carry out acoustic analyses in church interiors [5].

a) b)

Figure 2. a) Omnidirectional sound source placed in front of the altar;
b) omnidirectional sound source placed on the pulpit.

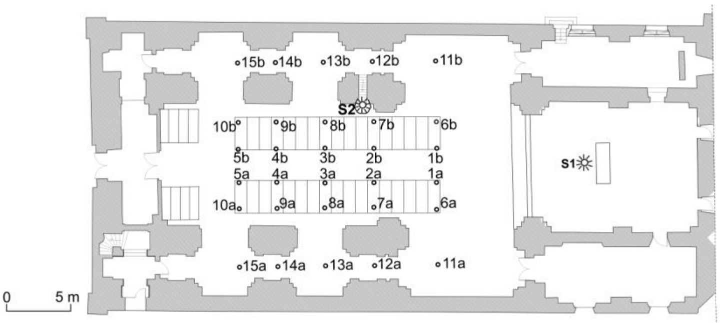


Figure 3. View of the church with marked sound source and measurement points.

## 4. Results of the investigations

Reverberation is quantitatively determined by reverberation time, a primary parameter used to asses acoustic quality of an interior. It is, to a great extent, correlated to numerous acoustic parameters used to assess individual acoustic aspects of an interior. Reverberation time RT is the earliest defined acoustic parameter in an interior. It is the time after which the sound pressure level drops by 60 dB after the continuous sound source is switched off. It is defined on the basis of the sound decay curve. The measurements are made in octave bands. In practice, the measurement involves the range from 5 dB to 35 dB below the initial level and is multiplied by two; it is then defined as $T_{30}$. The average reverberation time $T_{30}$ = 5.8 s, while the recommended $T_{30}$ = 1.5 – 3.3 s [6]. The value of mid-frequency $T_{30}$ is even higher and amounts to $T_{30(500\text{-}1000)}$ = 6.3 s. To compare the church's properties with other Baroque temples, reverberation time as an average of frequencies 500, 1000 and 2000 Hz was also calculated. In the literature, it is defined as $T_m$. In the interior under investigation, $T_m$ = 5.9 s.

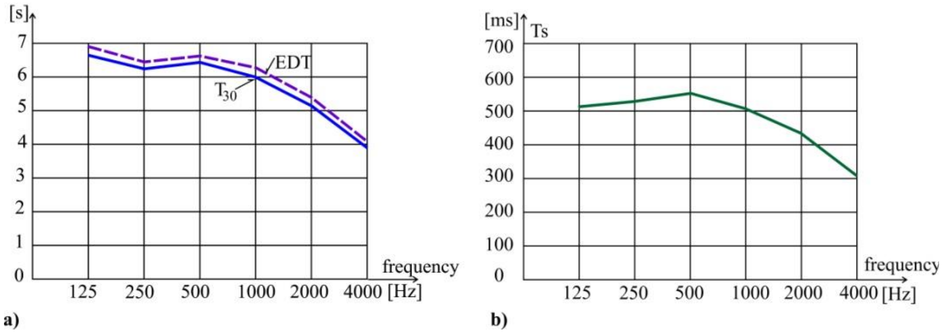


Figure 4. a) frequency characteristic of average reverberation time $T_{30}$ and early decay time EDT; b) center time $T_S$ in frequency function

Early decay time EDT is defined as six times the value of the time after which the sound pressure level drops by first 10 dB after the stationary sound source is switched off. It is determined from the slope of the straight line approximating the time decay curve in the range from 0 to -10 dB. EDT reflects subjectively experienced reverberation of an interior better than RT. Average EDT value equals 6.0 s. Figure 4a presents frequency characteristic for reverberation time and early decay time.
Another parameter, i.e. center time $T_S$ is a coordinate on the time axis of the center of gravity of the echogram. It is used to assess sound clarity of music. Figure 4b shows frequency characteristic of center time; mean $T_S$ = 482 ms, while the recommended $T_S$ = 70 – 120 ms for a liturgical church with the internal volume not exceeding 15 000 $m^3$; the recommended $T_S$ for a concert church with the internal volume over 15 000 $m^3$ ranges from 100 to 180 ms [7].

Clarity $C_{80}$ is used to assess the sound quality of music and defines ability to differentiate between details of a received piece of music. In the logarithmic measure, it is the ratio of sound energy which arrives at the measurement point within the first 80 ms to the sound energy arriving there after 80 ms. In accordance with the guidelines available in the literature, $C_{80}$ was averaged for 0,5; 1; 2 kHz. Also, following guidelines for investigations of religious buildings [5], $C_{80}$ was determined for the first and the last rows. Table 1 shows a comparison of thus obtained results for the parameter $C_{80}$. In the interior under investigation, clarity reaches negative values from -6.7 to -14.9 dB. The results show that the interior exceeds recommended values that are favourable for symphonic and oratorio music, while in some measurement points, the values were favourable for organ music. According to the guidelines for churches, $C_{80}$ values for the first and the last rows should be positive (above 0). In the investigated church, the mean value of the parameter in the first rows is -8.9 dB, while in the last rows, it amounts to -12.5 dB.

Table 1. Comparison of the parameter $C_{80}$

| $C_{80}$ [dB] | | | | |
|---|---|---|---|---|
| first row | recommended | last row | recommended | general recommendations |
| -9.0<br>-8.3<br>-8.9<br>-9.2 | 3 to 8 | -11.9<br>-11.8<br>-13.4<br>-12.8 | 0 to 5 | -8 to -3<br>organ music<br>-3 to 6<br>symphonic and oratorio music |

Speech intelligibility is a crucial issue related to reverberation of an interior. In churches, this particular issue is currently the most serious acoustic problem which thwarts or even renders it impossible for believers to become fully engaged in liturgy. $C_{50}$, STI, RASTI, and $D_{50}$ are parameters that are used to evaluate speech intelligibility.
Clarity $C_{80}$. Measurements are used to calculate the weighted value of clarity $C_{50}$. Octave bands 0,5; 1; 2; 4 kHz are multiplied by the weighting factor that is equal to 0,15; 0,25; 0.35; 0.25 for each band respectively, and thus obtained results are added up. It is recommended that thus calculated $C_{50}$> -2 dB for speech without an amplifying system. According to [8], when $C_{50}$ ranges from -7 to -2 dB, it indicates poor speech intelligibility, while $C_{50}$ < -7 dB indicates bad speech intelligibility.

Within the scope of analysis of the parameters used to measure speech intelligibility, the investigations also involved the sound source placed on the pulpit (Figure 2b). In historic churches without an amplifying system, the pulpit was used to give sermons. This structure was located close to the listeners in the nave, usually on the left, to facilitate speech intelligibility. The current pulpit in the basilica was mounted in 1962, assembled from Baroque elements from churches in Obrzycko and Maciejowa near Jelenia Góra [1]. The investigations were used to compare the values of speech intelligibility parameters for the sound source placed near the altar and on the pulpit. In relation to the sound source located near the altar, speech intelligibility is greatly improved. The mean value of the parameter $D_{50}$ for the sound source placed on the pulpit (S2) is 0.23, while for source placed near the altar (S1), it is 0.08. For the pulpit, the most favourable speech reception is in points 8b and 3b. The values for $D_{50}$ are 0.45 and 0.4 respectively, which mainly results from the sound amplified by the corner of the pillar behind the sound source. Such position of reflective surfaces enabled the reflected wave to be directed onto these points. The worst results for source S2 were registered in points 11b and 12b, which are in the acoustic shade. In contrast, for the source located near the altar (S1), points 11a and 11b registered the most favourable values, with the parameter $D_{50}$ equal to 0.135 and 0.150. This is caused by sound amplification due to smooth reflective walls behind the receivers. The poorest performance was registered in points 15a and 15b, which are located in the considerable acoustic shade; the value of $D_{50}$ for these points amounts to 0.027 and 0.02. The values of the RASTI parameter are analogous to the $D_{50}$ parameter, reaching the highest value 0.44 in point 3b for source S2, and the lowest value of RASTI = 0.15 in points 14a and 15b for source S1. The STI parameter gives similar results. In points 14a and 15b, STI for male and female is 0.18, which means that speech intelligibility is bad, while in point 3b for S2, STI(female) = 0.46, and STI(male) = 0.45, which denotes fair speech intelligibility. Table 2 shows results for parameters $D_{50}$, STI and RASTI.

Table 2. Speech parameters $D_{50}$, STI and RASTI - the best and the worst points for sources S1 and S2

| **Sound source** | **Measurement point** | $\mathbf{D_{50}}$ | **STI** | | **RASTI** |
|---|---|---|---|---|---|
| | | | **female** | **male** | |
| S1 | 11a | 0.135 | 0.27 (Bad) | 0.27 (Bad) | 0.23 (Bad) |
| | 11b | 0.150 | 0.29 (Bad) | 0.28 (Bad) | 0.23 (Bad) |
| | 14a | 0.037 | 0.18 (Bad) | 0.18 (Bad) | 0.15 (Bad) |
| | 15a | 0.027 | 0.19 (Bad) | 0.19 (Bad) | 0.18 (Bad) |
| | 15b | 0.020 | 0.18 (Bad) | 0.18 (Bad) | 0.15 (Bad) |
| S2 | 3b | 0.402 | 0.46 (Fair) | 0.45 (Fair) | 0.44 (Poor) |
| | 8b | 0.448 | 0.45 (Fair) | 0.45 (Fair) | 0.43 (Poor) |
| | 11b | 0.042 | 0.25 (Bad) | 0.24 (Bad) | 0.22 (Bad) |
| | 12b | 0.063 | 0.25 (Bad) | 0.25 (Bad) | 0.22 (Bad) |

Table 3. $C_{50}$ for sound sources S1 and S2

| Sound source | $\mathbf{C_{50}}$ [dB] | | |
|---|---|---|---|
| | Mean value | range | recommended |
| S1 | -11.6 | -7.1 to -17.3 | >-2 |
| S2 | -5.5 | -1.3 to -13.5 | > -2 |

The parameter $C_{50}$ achieves much better results for the sound source located on the pulpit (S2) than on the altar (S1). For sound source S1, the value is no greater than -7 dB in each of the measurement points, which means that speech intelligibility is bad. The mean value is -11.6 dB, and in point 15b reaches the value of -17.3 dB. For sound source S2, the mean value is -5.5 dB, which means that speech intelligibility is poor. Some measurement points reach values in line with recommendations, i.e. greater than -2 dB. Table 3 presents values of the $C_{50}$ parameter for sources S1 and S2.

## 5. Discussion

The St Joseph Church is undoubtedly a part of architectural heritage as its Baroque construction is a vital element of Poznań's urban architecture. Acoustically, the building is characterised by long reverberation time $T_m$ = 5.9 s. The finishes of the walls are marble and cement-lime plaster; the vaults are covered with plaster, while the flooring is made of stone tiles. These materials are characterised by low sound absorption coefficient. The pews are wooden and they are not upholstered, which would ensure sound absorption. In addition, the vast internal volume of the church promotes long reverberation time. The decrease of reverberation time seen on the graph (Figure 4a) for high frequencies is related to the sound absorbed by air. In comparison to other Baroque churches investigated in Europe, this temple belongs to the group of churches with the highest reverberation levels. Figure 5 shows a comparison of European Baroque Catholic churches whose reverberation time $T_m$ and the internal volume are available in the literature [9]. Out of twenty-seven churches, fourteen have reverberation time $T_m$ equal to or greater than 5 s, and nine of them have longer reverberation time than the St Joseph Church, i.e. their $T_m$ takes values between 6.10 to 9.90 s. The St Joseph Church's internal volume is 8 700 $m^3$. Baroque churches with internal volumes similar to the building under investigation have average reverberation time $T_m = 4.0$ s. In terms of its internal volume, the church under investigation belongs to a group of medium-size temples. Longer reverberation time of the investigated church is affected by sparse use of the architectural detail. Frequently, Baroque churches are home to a great number of sculptures and decorations of sculptural nature, which influence sound diffusion and decrease reverberation. Despite the fact that the St Joseph Church features the Baroque style, it boasts few of such details. What is more, many churches are carpeted, especially in the presbytery area, and the pews are upholstered. These materials have sound absorptive properties, while the investigated church does not have such absorbers.

The St Joseph Church is readily used for concert needs. Apart from organ music concerts, also oratorio concerts and choir concerts are held here. The church is also occasionally used for solo performances. The acoustics of the church have positive reviews, and the excessive reverberation time does not raise reservations, which is confirmed by an observation in the works of a few authors [10, 11, 12] that church interiors are expected to have longer reverberation time than concert halls. Also, the accepted range of reverberation level is broader than in halls that are dedicated solely for music performance. What is more, most Catholic churches in Poland have long reverberation time. Thus, the audience's custom is related to their expectations of distinct reverberation in a historic church interior. Long reverberation time results in poor reception of speech, objectively being an acoustic defect but undoubtedly an asset that creates an acoustic ambience of an interior, which is typical of vast temples and cathedrals, promoting spiritual atmosphere. It is also evident that the use of the pulpit in the past for reading the Word of God and giving sermons rendered it easier for the believers to understand speech. The position of the sound source closer to the audience as well as reflective surfaces behind the sound source have an impact on noticeable improvement of speech intelligibility parameters.

The problem of excessive reverberation is common to churches. To improve acoustic conditions, a variety of acoustic treatments is applied, consisting in application of sound absorptive materials or systems. In churches of highly acclaimed cultural value, application of permanent acoustic treatment that changes the historic character of the interior is unacceptable. The assumed solutions should respect the value of cultural heritage; therefore, a temporary acoustic treatment that can be easily dismounted is the most common choice. This type of treatment is used mostly for concert needs, including sliding folding sound absorptive panels, wall absorbers or solutions using a variety of sound absorptive textiles. For example, in the Seville Cathedral, the proposed application involved using velvet draperies not to interfere with the historic interior [12]. In the 1970s in the Saint Mary Magdalene Church in Lviv, whose erection dates back to the

17th century, a suspended plywood ceiling filled with mineral wool was proposed within the project of acoustic adjustment of the interior for concert needs. It was intended to be mounted in the entrance area of the nave, and suspended on a steel structure. The structure was to cover part of the Baroque vaults. The plan was not put into practice since the assumption was faulty as it would affect the aesthetics of the interior. Another project assumes introduction of movable acoustic sound panels that could be used only during concerts. This solution ensures alteration of acoustic properties by improving mutual audibility of the performers on the stage without a destructive impact on the church's architecture [13]. The above examples show that simple solutions can create an acoustically functional interior without compromising the original architectural concept. This can be a cue for prospective attempts to decrease reverberation in an interior in order to create conditions closer to those in a concert hall.

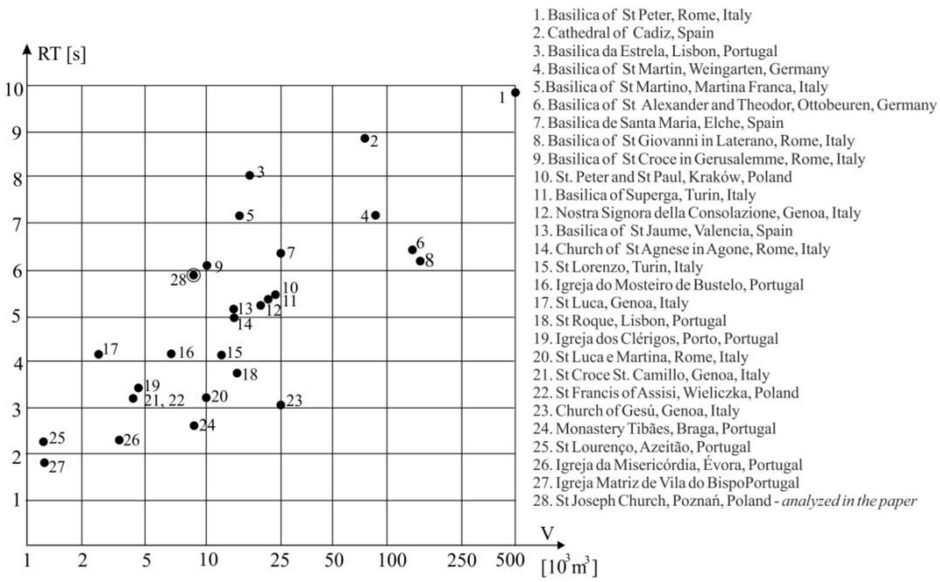


Figure 5. Catholic Baroque churches in Europe [9], reverberation time depending on the object volume

**6. Conclusion**

Acoustics of religious spaces is given more and more attention, but, in comparison with the number of investigations conducted in concert halls, they are still scarce. The investigation under discussion involved the St Joseph Church, a building of high architectural and cultural value belonging to Discalced Carmelites.

The results of the acoustic investigations reveal that the interior is characterized by long reverberation time. Speech intelligibility is low. Additional investigations involving placement of the sound source on the historic pulpit gave better results for speech intelligibility parameters, which indicates its good functionality in the past. The church is often used for concert needs. High reverberation properties of the interior go down well with the audience. In terms of the length of reverberation time, in comparison with other churches from the same historical period, the values are in the upper range of medium values. In terms of the internal volume, reverberation time is considerably longer that in churches of similar internal volumes. It can also be observed that in terms of acoustic treatment, temporary solutions in historic churches are applied with due regard for the architecture. Against other Baroque European churches, it can be noticed that acoustics as a sonic space is a characteristic element of cultural heritage. Sonic ambience featured by big historic churches is perceived as atmosphere of the sacred. Therefore, historic churches analysed mainly for their architectural values also hide acoustic heritage of great scientific value.

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