Research Paper

Analysis of Sound Field Distribution in Architecturally Diverse Temples

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The results of the research, which aimed to analyze the acoustic properties of selected sacred buildings located in the city of Częstochowa, Poland are presented in the paper. Three architecturally unusual and completely different from each other churches were selected for the study. The churches differed in shape of their buildings, cubic volume, years of construction, interior furnishings, etc. Nine different objective parameters were used to describe the physical properties of acoustical field in the studied churches. Various factors characterizing the acoustic properties of each building were determined, such as the distribution of sound pressure level (SPL), reverberation time T_{30}, definition D_{50}. Next, they were thoroughly analyzed, so as to ultimately obtain distributions of individual acoustic parameters in the space of the tested building. It allowed to evaluate the quality of the received verbal or musical message depending on the place where the listener was. Further research on speech intelligibility and the musical quality of churches was performed by determining the averaged values of next four objective acoustic parameters: centre time T_s, speech clarity C_{50}, music clarity C_{80}, and speech transmission index (STI). A new approach to analyzing the objective physical parameters describing the sound field was presented in Sec. 4. Mean free path length and critical distance were determined for the investigated acoustic fields in each church and they were associated with a general geometric factor characterizing the complexity of the room shape. The final part of the work presents a comparative analysis of the obtained results of acoustic quality tests of the temples, and thus their usefulness in terms achieving a maximum intelligibility of speech and music. The interesting similarities were found in the spatial distribution of individual acoustic parameters characterizing the distribution of the acoustic field in temples with completely different architecture.

Keywords: acoustical field distribution; reverberation time; definition; mean free path; critical distance.

1. Introduction

A common mistake committed when designing and constructing religious buildings is the lack of consultation with professional acoustic engineers. In many cases, this results in very difficult acoustic conditions, often impossible to correct in buildings of this type. This has a direct impact on the intelligibility and quality of speech transmission, which should be a priority in facilities designed for this purpose. Similar reservations can be expressed about musical messages. Acoustic requirements for speech differ essentially from those for organ music. Depending on the main function designed for a sacral building, the recommended reverberation time takes different values (SYGULSKA, 2014).

Optimal acoustic conditions in a church can be defined as a balance between requirements for speech and for music. In the 1980s and 2000s, acoustics were hardly ever taken into account in construction of churches in Poland. Bearing this in mind, the authors decided to carry out an analysis of the actual acoustic conditions prevailing in the three selected, essentially architecturally different temples. The influence of the architecture was analyzed in terms of its influence on acoustic properties of churches in many countries of the world (BERARDI *et al.*, 2009; WRÓBLEWSKA, KULOWSKI, 2007; QUARTIERI *et al.*, 2010; GAGLIANO *et al.*, 2015; CARVALHO, SILVA, 2010; CHU, MAK, 2009; SOETA *et al.*, 2012; ALBERDI *et al.*, 2019). Following the example of several authors who previously pre-

sented synthetic indices to assess the acoustics of performance spaces, BERARDI (2012) proposed a definition of a double synthetic index to the acoustic assessment of churches for two types of sound: music and speech (GIRON *et al.*, 2017). This index was obtained combining the average values of seven objective parameters generally used in the studies of architectural acoustics. The differences between the acoustic requirements for music and speech in churches suggest to take to account different optimal values of the selected parameters for different kinds of sound. Also ENGEL and KOSAŁA (2007) proposed another synthetic factor, called global index of acoustic quality. This index combined partial indices obtained through comparisons of the value of the different acoustical parameters in the church and their optimal values. The authors considered a large number of partial indices: the reverberation index (calculated from the reverberation time T), the music sound quality index (T_S, BR, C_{80}), the external disturbance index (calculated from the sound pressure level), the intelligibility of speech index (ALCONS, RASTI, C_{50}) and the uniformity of the loudness index (calculated from the variations of G). A new method of acoustic assessment of sacred buildings, which involved global index of acoustic quality was described in several papers (ENGEL, KOSAŁA, 2005; 2007; 2013; KOSAŁA, 2014; 2016). The studies also included the impact of the pews and people seated in pews on improvement of acoustic conditions (MARTELLOTTA *et al.*, 2011; DESARNAULDS *et al.*, 2002; CIRILLO *et al.*, 2007; MARTELLOTTA *et al.*, 2009; CARVALHO, PINO, 2012). In the latest publications, the author discussed of the influence of the ceiling structure on acoustics in the contemporary Catholic churches for two types of ceiling structures, i.e. the truss type and the reinforced concrete one (SYGULSKA, 2014; 2019).

A very extensive review of the research on the acoustic properties of churches can be found in the publication (GIRON *et al.*, 2017). This paper presents and analyses the principal achievements in the field of acoustics of Christian churches from the second half of the 20th century to the present day. The authors described research on the acoustics of churches developed in various countries, experimental procedures, measurement results, discussions, theoretical interpretations, and computer simulations methods of sound propagation in these complex buildings.

2. Experimental apparatus and methodology of investigations

The experimental arrangement used to carry out the measurements consisted of a computer, along with Matlab and AFMG EASERA software, which was responsible for generating signals, saving measurement data, time synchronization and performing calculations. Another element of the measurement arrangement was the analog-digital converter, in which the current waveforms from the omnidirectional microphone were discretized and the discrete signals generated in the computer were converted to current waveforms. Next, they were transmitted to the loudspeaker, which converted the current waveforms into an acoustic signal. The acoustic investigations were conducted using an omnidirectional sound source with a flat characteristic from 100 Hz up to 16 kHz. The loudspeaker was usually placed in the centre of the church chancel. The exact position of the sound source in each temple is indicated by a red dot in the figures below. The next stage involved conversion of the detected acoustic signal back to the current waveform, which was done by means of a microphone, and sending the signal to the transducer. In order to determine the exact position of the microphone at big chamber of the church, a laser distance meter was used. The distances to the walls and characteristic points were measured. Measuring points were selected individually for each examined church, so that the entire area in which the listeners were located could be analyzed. The microphone was placed on a tripod at the height of 1.5 m, and the resolution of the measurement points on a surface parallel to the floor was also 1.5 m. Measurements of acoustic properties were carried out in unoccupied conditions of the temples. Methodology of the investigations was compliant with recommendations available in literature (ENGEL, KOSAŁA, 2007; MARTELLOTTA, 2009; PN-EN ISO 3382-1, 2009). In each church, many measurement points were chosen in the audience plane following the ISO 3382 recommendations (PN-EN ISO 3382-2, 2010). The number of points was large enough to provide analysis of the distribution of individual parameters of the sound field with appropriate accuracy. In order to measure the sound pressure level and the reverberation time, a pink noise method was used, while in case of definition researches a impulse response method was used. The analysis included parameters which are described in literature as basic parameters used to assess acoustic properties of a religious building (GIRON *et al.*, 2017; WRÓBLEWSKA, KULOWSKI, 2007). The measured parameters were compared with values recommended for churches which can be found, inter alia, in literature (BERARDI, 2012; WRÓBLEWSKA, KULOWSKI, 2007; EVEREST, POHLMANN, 2016).

3. Results of sound field distribution measurements

The investigations involved three architecturally different churches located in the city of Częstochowa, Poland. After performing the measurements and thor-

ough analysis of the results, the values of individual acoustic parameters were determined for each of the examined buildings. The end result are three graphs for each of the researched churches, showing distribution of: the sound pressure level (SPL), reverberation time (T_{30}) and the definition (D_{50}) in the horizontal section on the surface located at the height of 1.5 m. These charts allowed to analyze the distribution of individual acoustic parameters in the space of each of the researched churches, and assess the quality of the acoustic field and determine the location of the best and worst places for listeners.

At each point, the values of the reverberation time were determined in octave bands from 125 Hz to 8 kHz, for each band, the mean value from all the points was taken to be the average reverberation time of the church for that band. These averaged values are shown in Table 1. The reverberation times T_{30} shown in the colored distribution charts are the averaged values which were obtained by an averaging process over the frequency range from 100 Hz to 10 kHz. The results are shown in Figs 3, 7, and 11. In addition, mean free path length (BERANEK, NISHIHARA, 2014; HANYU, HOSHI, 2012; KOSTEN, 1960; KUTTRUFF, 2000) and critical distance (KUTTRUFF, 2000; ARAU-PUCHADES, BERARDI, 2015; GLEN, GARY, 2005; ESCOBAR, MORILLAS, 2011) have been determined as important parameters characterizing the acoustic fields in each church. They were associated with a general coefficient describing the room shape complexity (HANYU, HOSHI, 2012).

3.1. St. James's Church

This building was erected in the 1870s, originally as an Orthodox church in the Neo-Byzantine style (*History*, n.d.), Fig. 1. The temple's character was changed from an Orthodox church to a Catholic church in 1918. The church was built on a square setting out plan with a concave, recessed outside niche of the presbytery,

and four powerful pillars, arranged symmetrically in the four corners of the temple. In the middle of the ceiling there is a 25-meter-high dome and smaller domes in the four corners of the temple with arched finishes between them. The ceiling of this temple has a very complex structure focusing sound waves.

The church's cubic volume is 2300 m^3, floor area 230 m^2, and total surface area 1700 m^2. The walls and ceiling are covered with plaster and paint. There is a wooden paneling on the walls and pillars, up to a height of about a meter. The floor is paved with stone and there are wooden benches. The measurements were taken at 30 points, on the right half of the church's surface. It was assumed that the results on the left half will be a mirror image of the right side with respect to the axis passing through the middle of the church, due to the symmetry of the building with respect to this axis.

Measured in the church of St. James's distribution of sound pressure level SPL is shown in Fig. 2. As could be expected, the highest volume of SPL was closest to the loudspeaker (red area). As the distance increases, the values gradually decrease and reach the minimum behind the rear pillars (purple area). In the middle of the surface, a red island can be seen in which a higher SPL was measured. This is due to sound focusing by the large dome situated in the middle of the ceiling.
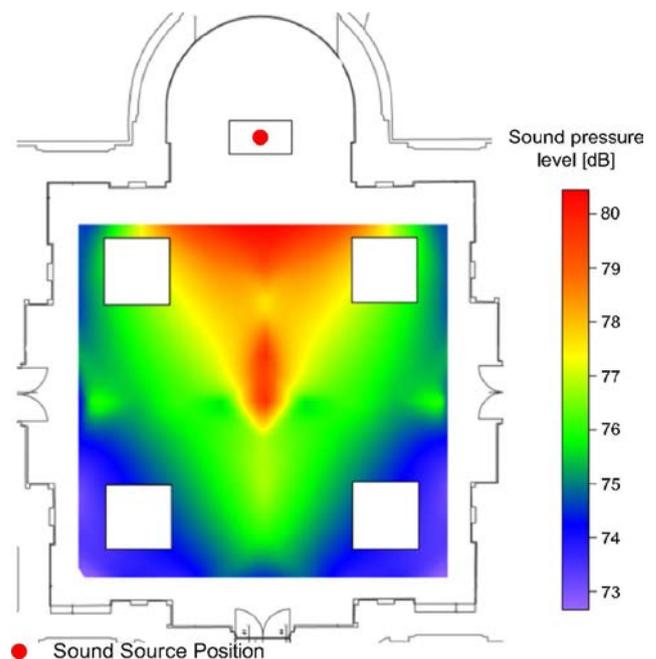
Fig. 2. Distribution of sound pressure level SPL, St. James's Church.

Fig. 1. St. James's Church, north elevation.

The distribution of the reverberation time T_{30} in this structure is shown in Fig. 3. The average value of the T_{30} determined from all the performed measurements is at the level of 3.0 s. The highest measured
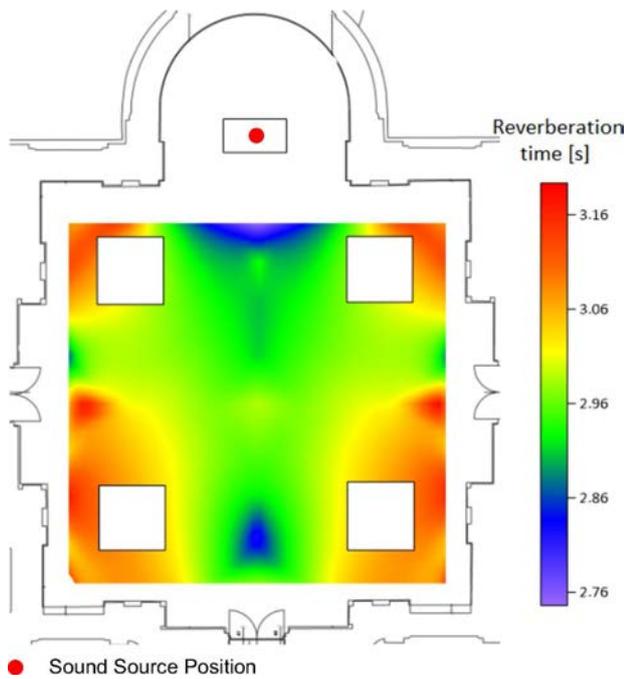
Fig. 3. Distribution of reverberation time T_{30},
St. James's Church.
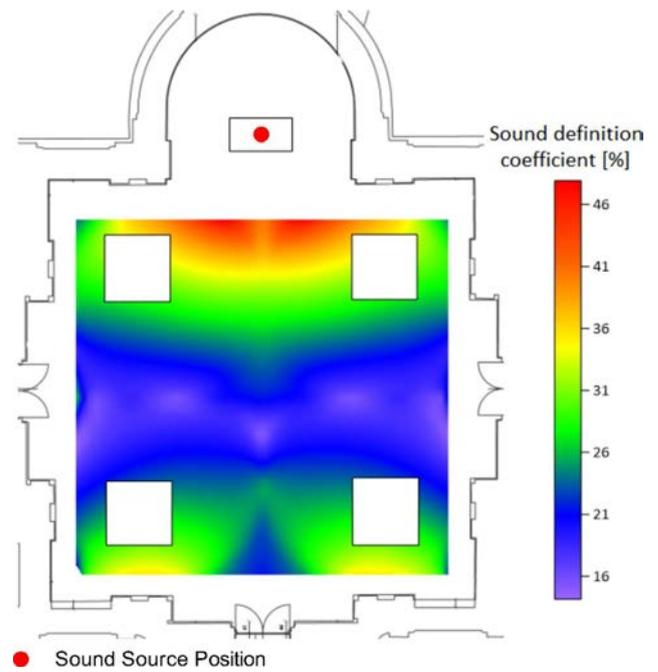
Fig. 4. Distribution of the definition D_{50},
St. James's Church.

value of T_{30} is 3.2 s, while the lowest is 2.7 s. In this cubature of church, the optimal reverberation time for speech should be about 1.2–1.5 s (Everest, Pohlmann, 2016). It is obvious that even the shortest measured value does not qualify as suitable for such a building. It follows that in every point of the room the reverberation time is too long, on average about 1 second, which causes poor quality of the sound received by the listeners. Table 1 presents results of measurements of average reverberation time T_{30} in octave bands, for all investigated churches.

The distribution of the definition coefficient D_{50} measured in this church is shown in Fig. 4. The determined average value of the D_{50} of all the measurements was 26 %, while the deviation from the average value was 9%. The highest measured value of the D_{50} was 52% and the lowest value was 14%. The value of this parameter at the level of 26% was assessed as bad (Engel *et al.*, 2007), and almost half of the area of the church is characterized by values of definition below 26%. Only values above 45% are considered to be acceptable in these rooms, but places with such a coefficient can only be found on a small area of the researched church. In compliance with recommendations, for churches D_{50} irrespective of their internal

volume ranges from 40% to 60%. The relation between D_{50} and the syllable intelligibility has been established by Boré (1956), who indicated that there is indeed a good correlation between the intelligibility and the definition. Speech intelligibility over 85% occurs when $D_{50} = 34\%$ (Cremer, Müller, 1982).

3.2. The Church of St. Hyacinth, O.P.

The temple was built in the 1990s (*Historical view*, n.d.). The building of the church is based on a quarter circle plan, Fig. 5. The narrowest place of the building is the presbytery, and further on, towards the back of the church, the walls are gradually expanding. At the front of the presbytery, there is a convex wall, which disperses the sound, and the rear wall is a concave surface, which focuses the sound, after it is reflected, in a small area along the symmetry axis of the church. The left and right parts of the building are asymmetrical in relation to its axis. On the left side, there is a niche under the choir, while on the right side there is a wall in a symmetrical place.

The cubic volume of the temple is 3600 m^3, floor area 440 m^2, and total surface area 1900 m^2. The ceiling was executed with the drywall system, using plas-

Table 1. Average reverberation time T_{30} in octave bands for all temples.

Frequency [Hz]		125	250	500	1000	2000	4000	8000
T_{30} [s]	St. James's	2.95	3.19	3.20	2.96	2.70	2.05	1.34
	St. Hyacinth's	3.83	4.75	5.11	4.70	3.79	2.31	1.38
	VM	6.07	7.53	8.25	8.44	7.03	3.92	1.67
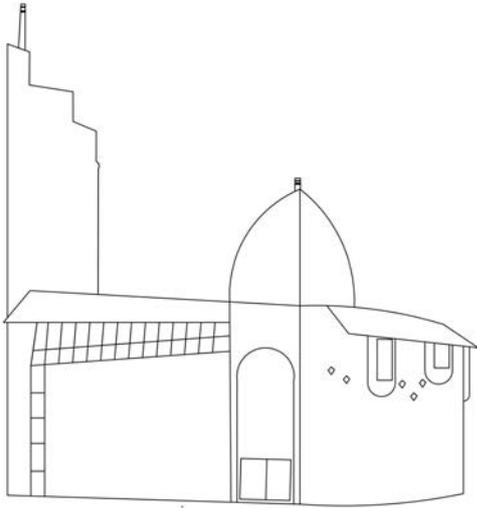
Fig. 5. The Church of St. Hyacinth, west elevation.

Fig. 7. Distribution of reverberation time T_{30},
St. Hyacinth's Church.

terboard panels. The walls were finished with wet plasters and painted. The floor is covered with stone and there are wooden benches on it. The building has a very complex architectural structure of walls of different shapes and curves, and the ceiling, which at the same time disperse, focus and reflect sound waves into the volume of the temple. Measurements were made at 42 points on the entire surface.

The distribution of sound pressure level SPL measured in the church is shown in Fig. 6. The graph shows a significant asymmetry with respect to the axis of the building, this is due to the different geometry of the side walls. At the front, in the middle, there is a red area with a higher SPL. This is due to the concentration of sound waves after they are reflected from the concave rear wall.

average value of T_{30} determined from all measurements is 4.4 s. The highest measured value of T_{30} is 4.62 s, while the lowest is 4.13 s. As shown in the chart, the time of reverberation is the longest in the back corners of the temple (red places). The shortest reverberation times were measured in the middle of the room, at the front. For churches of this volume, the optimal reverberation time for speech is 1.3–1.7 s (Everest, Pohlmann, 2016). Therefore, the measured values diverge the optimal time even more than the one recommended in the first building. The reverberation time is, on average, too long by more than 2 s, which results in a very poor intelligibility of speech received by the listeners. Table 1 shows the reverberation time T_{30} in octave bands for St. Hyacinth's church.

The distribution of the definition coefficient D_{50} measured in the temple is shown in Fig. 8. The deter-

Fig. 6. Distribution of sound pressure level SPL,
St. Hyacinth's Church.

The distribution of the reverberation time T_{30} measured in the building interior is shown in Fig. 7. The
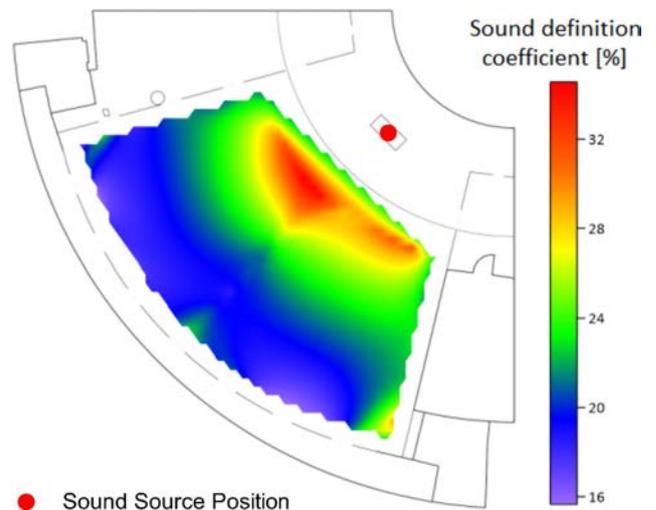
Fig. 8. Distribution of definition D_{50},
St. Hyacinth's Church.

mined mean value of the D_{50} from all measurements is 22%, while the deviation from the average was 5%. The highest value of the D_{50} is 35% and the lowest was 14%. The value of this parameter at the level of 22% was assessed as bad (Engel *et al.*, 2007), and about half of the church's area is characterized by values of definition index below 22%. Only a small area with the D_{50} above 30% deserves to be assessed as poor. The average value and deviation of this parameter are lower than in the St. James's church, which indicates its inferior articulation of the sound, but more evenly spread value on the surface of the temple.

3.3. The Church of the Virgin Mary

The temple was built in the 1980s (*The Church of the Victorious BVM historical view*, n.d.), Fig. 9. It is much larger when compared to the previous two buildings; its cubic capacity is $22\,500$ m^3, floor area 1000 m^2, and total surface area 4800 m^2. The temple has a very interesting and unique architecture due to many planes, directed at different angles, on its walls and ceiling. The building of the church is based approximately on the trapezium plan. The narrowest place is the presbytery, and further towards the rear, there are the expanding walls, which have numerous vertical recesses. The walls and ceiling are finished with plasters and painted. The floor is made of stone and there are wooden benches placed on it. The building has an extremely complex architectural structure of all walls and ceiling, which affect the distribution of acoustic fields in the volume of the interior. Measurements were made at 41 points distributed on the right half of the temple's surface. As in the first case, due to the symmetry of the object with respect to the axis passing through the middle of the church, the left side is a mirror reflection of the right side.
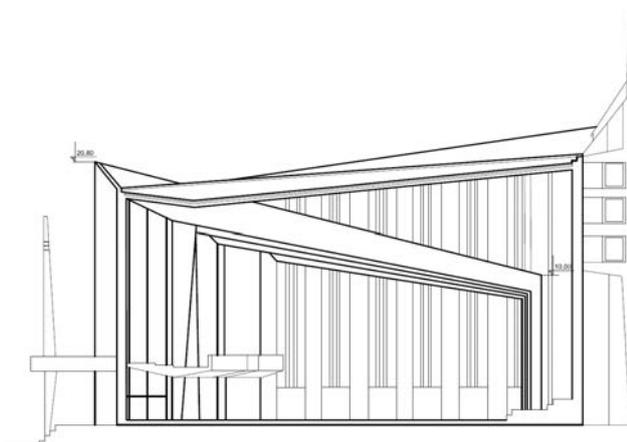
Fig. 9. The church of the Victorious VM, vertical section.

The distribution of sound pressure level SPL measured in the church of the VM is shown in Fig. 10. The SPL is the highest in places closest to the loudspeaker

Sound Source Position
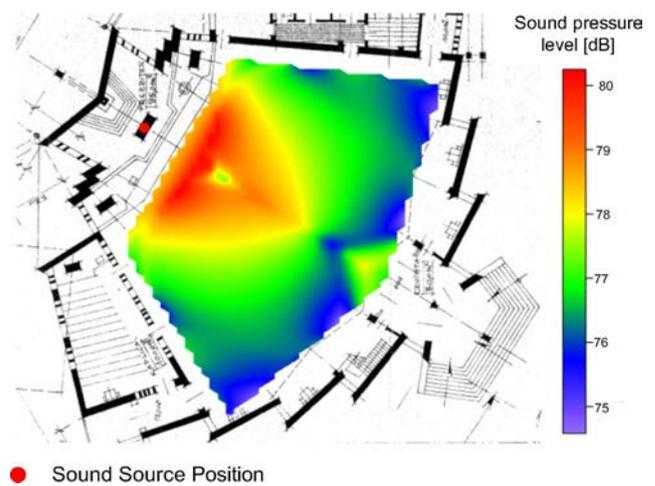
Fig. 10. Distribution of sound pressure level SPL, the church of the VM.

(red area). The lowest SPL values can be heard near the rear wall (blue areas), with the exception of the middle of the church, where increased SPL (the green island) was measured. This can be explained by complicated wall and ceiling arrangement, which causes the acoustic energy is directed and focused in that area.

The reverberation time T_{30} profile measured in the temple is shown in Fig. 11. The average value of T_{30} determined from all measurements is 7.4 s. The highest measured T_{30} is 8.2 s, while the lowest is 6.9 s. As shown in the graph, the T_{30} is the shortest in the front of the church in the middle, while the longest one is in the back corners of the interior. The optimal value of reverberation time for speech and a room with such a cubic capacity is 1.5–2.0 s (Everest, Pohlmann, 2016). As a result, the measured actual values differ significantly from the recommended standard, even more than in the previous two cases. The average value of this parameter is four times greater than the recom-

Sound Source Position
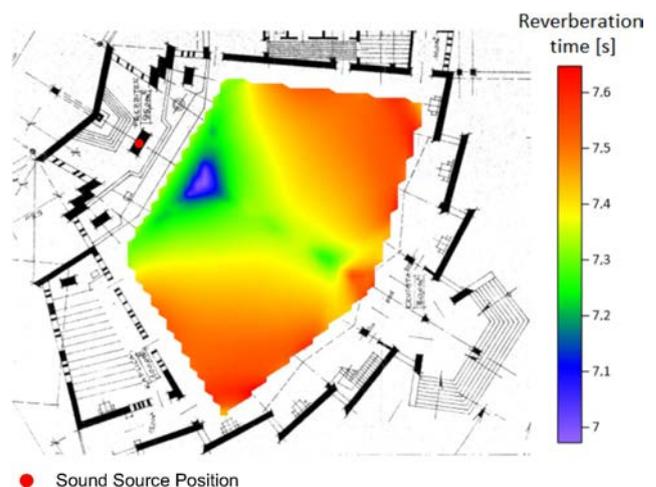
Fig. 11. Distribution of reverberation time T_{30}, the church of the VM.

mended value, which must cause a very poor intelligibility of speech and simultaneously quality of music received by the listeners. Table 1 shows the reverberation time T_{30} in octave bands for this church.

Distribution of the definition D_{50} measured in the temple is shown in Fig. 12. The obtained mean value of the D_{50} determined from all measurements is 21%, while the deviation from the average is 9%. The highest measured value of the D_{50} was 42% and the lowest was 7%. By far, the best area, similar to the previous churches, is the part of the surface located at the front of the church, closest to the loudspeaker (the red area). Then, the values of this D_{50} decrease successively until the minimum in the central part near the rear wall (the purple area) is reached. The value of this parameter at the level of 21% was rated as bad, and slightly more than half of the chamber's surface is characterized by values of D_{50} below 21%. Only a small area with a D_{50} above 40% can be considered as sufficient or poor (above 30%) (ENGEL et al., 2007).
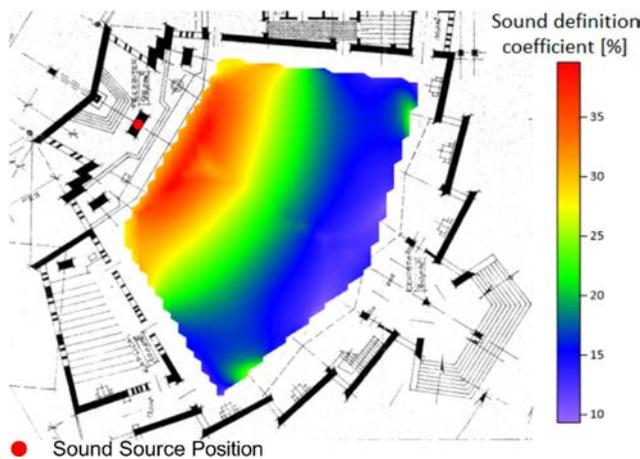
Fig. 12. Distribution of the definition coefficient D_{50}, the church of the VM.

It should be noted, that the values of both parameters the sound pressure level and the definition, given in the article, were determined for a specific geometry of measurements, i.e. the position the loudspeaker and the measuring microphone. While in the case of reverberation time when the position of the loudspeaker was changed at particular points, no significant changes in its length were noted, which is largely influenced by the applied measurement method.

4. Dependence of the mean free path and critical distance in acoustical field on the church shape complexity

BERANEK and NISHIHARA (2014) proved that the well-known formula for the mean free path between reflections may be considered valid in most of the rooms, except for halls of unusual shapes. The room shape also plays an important role over the diffusiveness of the sound field.

ARAU-PUCHADES and BERARDI (2015) discussed a new concept of the critical distance, also known as reverberation radius, in rooms with non-uniformly distributed sound absorption and investigated it in some real rooms. In earlier works, ARAU-PUCHADES (2012) found that, in a highly reverberant room (short r_{max}) the reverberated field is perceived almost instantly; reversely, in the chamber with short reverberation time (long r_{max}), it takes longer to hear the reverberated sound field. This phenomenon can be interpreted through considering that at shorter distances than the reverberation radius, the direct sound dominates, and at longer distances than the reverberation radius, the diffuse sound field dominates.

In this research mean free path length and critical distance were determined for the investigated acoustic fields in each church. They were associated with a coefficient describing the complexity of the temple shape. The room shape complexity can quantitatively be evaluated using a objective geometric factor h which have been defined as (HANYU, HOSHI, 2012):

$$h = \frac{S^3}{64 \cdot V^2},\tag{1}$$

where V is room volume, and S is total surface area.

This coefficient is a dimensionless number that becomes larger as total surface area of interior increases relative to volume, that is, as the room shape complexity increases. For similar room shapes, even if the interior volumes are different, the h values will be the same. Thus, this coefficient can be used as a measure of the complexity of the room shape. On the basis of the factor h, the density of reflected sounds and the sound power can also be calculated for a given room volume.

The mean free path length of the acoustic field can be expressed as the following relationship using the interior volume V and room shape complexity (HANYU, HOSHI, 2012)

$$I_{MFP} = \sqrt[3]{\frac{V}{h}}.\tag{2}$$

This physical parameter indicates that the mean free path length becomes shorter when the room shape complexity increases and longer when the chamber volume increases.

The critical distance (also called the critical radius) is the distance from the sound source to that place of the acoustical field at which the sound pressure level of the direct and reverberant sound are equal. If the source is directional, the sound pressure level as a function of distance between source and listener varies with their relative position, so that for a particular room and source the set of points where direct and reverberant sound pressure are equal constitutes a some surface. The critical distance for a diffuse approximation

of the reverberant field can be expressed as the following relation (GLEN, GARY, 2005):

$$r_{\max} = \frac{1}{4} \cdot \sqrt{\frac{\gamma V}{6\pi T}} \quad [\text{m}], \tag{3}$$

where V is volume of the space [m³], T is reverberation time of room [s], and γ is is the degree of directivity of the source ($\gamma = 1$ for an omnidirectional and point source).

This parameter of the acoustic field can be another expressed as the following relationship using the interior volume V and room shape complexity h:

$$r_{\max} = \frac{1}{2} \cdot \sqrt{\frac{\gamma \alpha_{\text{mean}} \sqrt[3]{V^2 h}}{\pi}} \quad [\text{m}]. \tag{4}$$

This formula explicit shows that the length of critical distance is dependent on the shape complexity and absorption properties of the space in which the acoustic waves propagate. At reverberant room, a critical distance is shorter and in acoustically good interior this distance is a longer.

All above discussed parameters: room shape complexity, mean free path and average critical distance determined for the three investigated churches are shown in the Table 2. The values of the average critical distance determined from the formula (3) on the basis of the reverberation time measurements were marked as $r_{\max}^{(3)}$ and the values calculated from the relation (4) on the basis of the mean absorption coefficient were marked as $r_{\max}^{(4)}$.

Table 2. Acoustical field objective parameters: mean free path and critical distance related to the shape complexity of the churches.

Church	V [m³]	S [m²]	h	I_{MFP} [m]	$r_{\max}^{(3)}$ [m]	$r_{\max}^{(4)}$ [m]
St. James's	2300	1730	15.3	5.32	1.58	1.50
St. Hyacinth's	3600	1867	7.9	7.71	1.63	1.52
VM	22500	4831	3.5	18.63	3.14	2.83

As can be seen from the comparison, the highest value of the room shape complexity factor has St. James church and it is above four times greater than for the VM church. This relations can be explained by the complex structure of the church interior, which is described in Subsec. 3.1. The obtained length of the mean free path determined on the basis of measurements varies in the investigated churches in the range from 5 to 18 m. This objective parameter describing the general properties of acoustic field, as can be seen from formula (2), depends not only on the room volume but also on the church shape complexity. Analysis of the issue critical distance of the acoustical field was carried out on the basis of investigations in three architecturally diverse temples.The

obtained values of the average critical distances determined from both relations (3) and (4) are summarized in Table 2. Their values are correspondingly close to each other but the difference between them increases as the church volume increases. It should be remembered that the calculations were made assuming that the sound source is point and omnidirectional. As expected from relation (3), the critical distance for the individual churches depends on reverberation time. Because all the investigated temples are of poor acoustic quality and have a long reverberation time it can explain why the critical distance is short for all of them.

The critical distance, also known in the literature as the reverberation radius, whether the critical radius is a very useful parameter in many areas of acoustics. Some examples of the applications of this parameter are given below. The critical distance may be used to calculate diffuse sound energy in the revised theory of sound decay (BARRON, LEE, 1988), where the lower limit of integration of the diffuse sound energy is assumed equal to the time needed for an acoustic wave to travel a critical distance. The critical distance is highly useful in assessing the reverberance of a room. This distance is an important parameter for the sound perception as by knowing the distance of the listener from a source and the length of critical radius of the room, it is then possible to assess whether the direct or diffused acoustic filed prevails. One can to express liveliness of sound in the room as the ratio of the direct and diffuse energy density, using the critical radius concept. In this way, the comparison of the critical distance with the room dimensions allows an easy estimation the subjective feelings of listeners. In the electroacoustics field, investigations proved that microphones must be located at a distance from the sound source shorter than the the critical distance during recording (MIJIĆ, MASOVIC, 2010).

5. Discussion

The sound energy distribution in churches does not decay according to the "revised" theory proposed by (BARRON, LEE, 1988). They found that the sound level decay was linear soon after the direct sound in large rooms and the reflected sound level decreased with increasing source-receiver distance. The lack of accuracy of the revised theory when applied to churches was pointed out by different researchers (SENDRA et al., 1999; ZAMARREÑO et al., 2007). The authors attributed a loss of energy to the geometrical complexity of churches. Different models have been proposed to show why the sound energy is not homogenous and in churches there are zones with more focusing, standing waves and coupling sounds fields. A wide review of these models with an analysis in different churches were reported in the papers (BERARDI et al., 2009; GIRON et al., 2017).

The μ model, which was originally defined with reference to Mudejar-Gothic churches by Zamarreño *et al.* (2008), was first generalized by showing that church-specific μ values, could be grouped according to typological characteristics. A typological classification was proposed using an incremental approach, so that any given architectural feature determines a corresponding increment of μ. This approach was then extended on the parameter k in the modified theory by Cirillo and Martellotta (2005) and Martellotta (2009). The authors showed how the typological classification, that is valid for both the μ model and modified theory, should be applied as a function of architectural features. This modified model also maintains the same separation of energy as Barron's model as well as the exponential decay distance dependence for early and late acoustic energy.

In order to generalise the μ model Berardi *et al.* (2009) compared the predictions from the revised model by Barron and Lee, the modified model by Cirillo and Martellotta, and the μ model by Zamarreno with the experimental results of 24 Italian churches differing in style, typology, and location. Some analogies should be noted between the μ and k typological parameters and the objective geometric factor h used in this work.

The investigations made in frame of this work allowed to draw clear conclusions concerning the influence of architecture of the churches on their acoustic properties. Nine different objective parameters were used to describe the physical properties of acoustical field in the studied churches. To compare the acoustic properties of the three studied temples, the results of measurements are summarized in Tables 2–4. Table 3 shows results of measurements of average, minimum, and maximum values of the reverberation time T_{30} and the values recommended for speech and for music in the professional literature (Everest, Pohlmann, 2016) for a given volume of the church are also included.

The mean values of the sound absorption coefficient α_{mean} in each of the studied churches were determined by inserting the measured values of reverberation times into the Knudsen relation:

$$T = \frac{0.161V}{-S \cdot \ln(1 - \alpha_{\mathrm{mean}}) + 4mV} \quad [\mathrm{s}], \qquad (5)$$

where S is the total surface area of the room [m^2], α_{mean} is the mean absorption coefficient, m is the attenuation coefficient of the air [m^{-1}].

Knudsen's formula for reverberation time is more accurate for large chambers because it takes into account sound attenuation in the air. The determined in this way absorption coefficients are shown in the last column of Table 3. A comparison of their values with the sound absorption coefficient for a wall made of cement plaster, for a wave frequency of 1 kHz, $\alpha = 0.03$, shows that for the St. James's and St. Hyacinth's churches they are twice as greater while for the VM church it is about three times greater. Characteristics of reverberation time as a function of sound wave frequency were determined for each temple. Figure 13 shows a comparison of the results for all investigated churches.
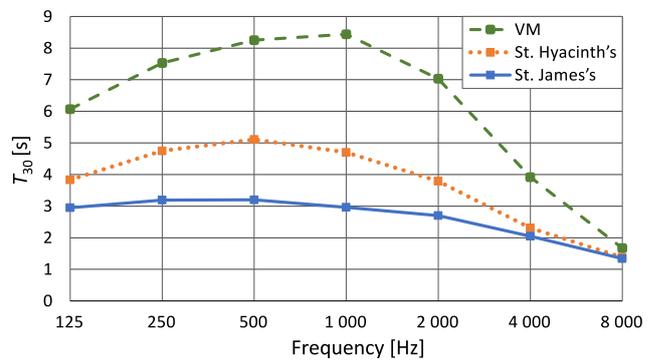
Fig. 13. Average reverberation time T_{30} as a function of frequency in the investigated temples.

It can be observed that for low frequencies – below 1000 Hz, the T_{30} increases as the sound frequency increases. This is characteristic of churches with reinforced concrete covers (Sygulska, 2019). Over 1000 Hz, T_{30} rapidly decreases *vs* frequency, which is mainly caused by absorption of acoustic waves energy by the air. The product $4mV$ which is in the denominator of the Knudsen formula (5) shows that a big internal volume of an interior will cause greater sound absorption by air.

Table 4 presents results of measurements of average, minimum and maximum values definition index D_{50} and the values recommended for each church are also included (Cremer, Müller, 1982; Giménez, Marín, 1988). In all examined churches, the rever-

Table 3. Results of measurements of reverberation time T_{30} in the temples.

Church	Volume [m^3]	Reverberation time [s]					α_{mean}
		Average	Minimal	Maximal	Recommended for speech	Recommended for music	
St. James's	2300	3.0	2.7	3.2	1.2–1.5	1.5–2.5	0.065
St. Hyacinth's	3600	4.4	4.1	4.6	1.3–1.7	1.7–2.6	0.062
VM	22500	7.4	6.9	8.2	1.5–2.0	2.0–3.3	0.083

Table 4. Results of measurements of the definition coefficient D_{50} in the examined churches.

Church	Definition [%]			
	Averege	Minimal	Maximal	Recommended
St. James's	26	14	52	>34
St. Hyacinth's	22	14	35	>34
VM	21	7	42	>34

Table 5. Comparison of the acoustic objective parameters: clarity (C_{50} and C_{80}) in the temples.

Church	C_{50} [dB]	Recommended C_{50} [dB]	C_{80} [dB]	Recommended C_{80} [dB]
St. James's	−4.5	speech > −2	−2.9	(−3–6) oratorio music < −3 organ music
St. Hyacinth's	−5.5	speech > −2	−4.3	(−3–6) oratorio music < −3 organ music
VM	−5.8	speech > −2	−5.6	(−3–6) oratorio music (−8–3) organ music

Table 6. Comparison of the acoustic objective parameters: centre time (T_s) and speech transmission index (STI) in different churches.

Church	T_s [ms]	Recommended T_s [ms]	STI	Recommended STI
St. James's	217	60–100 speech 120–180 organ music	0.45	>0.6
St. Hyacinth's	318	60–100 speech 120–180 organ music	0.42	>0.6
VM	535	120–180	0.41	>0.5

beration time and definition index did not reach recommended values. It was at its closest to the recommended value in St. James's church, while it was particularly unfavourable in the rear part of VM church.

Further research on speech intelligibility and the musical quality of churches was performed by determining the next four objective acoustic parameters: centre time (T_s) (Barron, 2005), speech clarity (C_{50}) (Anhert, Schmidt, 1980), music clarity (C_{80}) (Kuttruff, 2000), and speech transmission index (STI) (Hougast, Steeneken, 1973). To asses the clarity of music sound, the centre time and C_{80} index are applied. Speech intelligibility was determined from physical factors C_{50} and STI. All these averaged factors for the three investigated churches are shown in Tables 5 and 6. Comparison of these parameters values with some recommendations is also shown in these tables. The recommended values were taken from the following papers: centre time (Wróblewska, Kulowski, 2007; Fasold *et al.*, 1994), clarity (Wróblewska, Kulowski, 2007; Marshall, 1996; Kulowski, 2011; Gade, 1994), and speech transmission index (PN-EN ISO 9921, 2005; *RASTI Technical Review*, 1995).

Some conclusions can be made on the basis of the results presented here. The clarity C_{50} and speech transmission indexes did not reach recommended values – they are too small in all investigated churches. Since the average STI values were lower than 0.6 for of the temples interiors, speech intelligibility could not be considered as good in all cases.

Centre time occurred close to the recommended values but only in St. James's church and only for organ music. Based on the results of measurements of music clarity index C_{80} and in accordance with the recommendations given in the literature it can be stated that the investigated churches have sufficient conditions suitable for organ music.

6. Conclusions

The observed interesting similarities in the spatial distribution of individual acoustic parameters characterizing the distribution of the acoustic field in researched temples with completely different architecture deserve particular attention. The distribution of sound pressure level in the first and third church has a similar shape – which can be illustrated by isosceles triangles whose heights are the axis of symmetry of the church.

Based on theoretical considerations, it was found that either through the theoretical linear model (Barron, Lee, 1988), or through the multi-rate decay

model (Martellotta, 2009), the acoustic energy density depends on source-receiver distance r and can be expressed through the parameters V, S, T, α, δ, and the typological parameter ρ or k.

The distribution of the definition in all three churches has a similar character – illustrated in the form of a system of stripes that are perpendicular to the church's symmetry axis. This indicates an approximately uniform decrease in definition factor alongside the church. However, the reverberation time in each of the researched buildings has a different and very complicated distribution.

The description of the acoustic properties of the entire room using only one averaged value of the parameter, as can be seen from the above analysis, is only an inaccurate approximation. At each point of the space of the churches, the parameters describing the sound field are different and show different geometry of distribution. To get an accurate description of the acoustic field, it should to use the parameters, the values of which on the one side depend on the frequency of the sound waves and on the other side also on the location of the receive point in the volume of the room.

A new approach to analyzing the distribution of the sound field in the volume of the room was presented. Objective physical parameters describing the sound field have been connected with a geometric factor characterizing the complexity of the church shape. In this research, mean free path length and critical distance were determined for the investigated acoustic fields in each temple. Based on formulas (2) and (4), it can be stated that the change of these objective factors in architecturally diverse churches depends on the volume and shape complexity of the room in which the sound propagates.

Some authors (Mijić, Masovic, 2010; Arau-Puchades, Berardi, 2015) confirmed how difficult it is to accurately estimate the critical distance and suggest further research in this field. The investigation of the mean free path and critical distance in real rooms with non-diffuse sound field and non-rectangular shape remains an important area of research.

The following conclusions can be drawn based on the analysis of the results of nine researched parameters describing the acoustic field in temples. These parameters, averaged over wave frequencies and measurement points, can be divided into two groups. To the first of them belong the factors whose values differ significantly (from 200% to 350% between the examined churches. This group includes reverberation time, centre time, mean free path and critical distance. The second group consists of indexes whose values differ slightly (from 10% to 50%) between the investigated buildings. This group consisted of the definition, clarity C_{50} and C_{80}, speech transmission index. It should be emphasized that the churches were very different in volumes, sizes and geometrical shapes.

Nine acoustic characteristics were considered for the evaluation of the speech intelligibility and music quality separately. The differences between requirements for music and speech in churches suggest to consider different optimal values of the selected parameters for different kinds of sound. The performed measurements and their analysis made it possible to conclude that none of the studied religious buildings provides good acoustic conditions for speech intelligibility. In each case, the values of the measured speech parameters are significantly worse than the values recommended for them in the literature. The measurements of music indices allow to assess that the investigated churches had sufficient conditions suitable but only for organ music.

After analyzing the obtained results, it is possible to state that no acoustic adaptation has been made in any church, either at the construction stage or when preparing their design. Moreover, it is evident that the temple built more than one hundred years earlier than the other two is characterized by better parameters defining the acoustic quality. This, of course, results in later problems in the correct reception of the verbal and musical message.

Acknowledgements

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