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ACOUSTIC PROPERTIES OF THE SELECTED CHURCHES IN POLAND

SUMMARY

The assessment of the acoustic properties of interiors of sacral buildings was, for many years, done by means of methods developed primarily for assessing concert halls, opera houses or auditoriums adapted for sacral buildings. Those are Beranek's, Ando's, RASTI and impulse methods. The paper provides short description of those methods as well as their verification performed by the authors and graduate students of the Chair of Mechanics and Vibroacoustics AGH in several roman catholic churches in Poland. The analysis of those methods proved that – when applied to sacral objects – they are often not complete and must be supplemented.
Regardless of numerous papers concerning investigations and creation of acoustic conditions in sacral objects, there is a lack of a uniform, specific method which would allow to assess the acoustic quality of such interiors. The new index method, which assesses the acoustic properties of sacral objects by a single-numbered – the global index of acoustic quality – is presented shortly in the paper.
This global index is a function of several partial indices, namely: reverberation index, intelligibility of speech index, uniformity of loudness index, external disturbance index and music sound quality index. The index method was applied and verified in five roman catholic churches in Poland.

Keywords*: acoustics in interiors of sacral structures, assessment indices, acoustic quality of sacral stuctures*

WŁASNOŚCI AKUSTYCZNE WYBRANYCH KOŚCIOŁÓW W POLSCE

Przez wiele lat do oceny akustycznej wnętrz sakralnych stosowano metody adaptowane, przeznaczone do oceny sal koncertowych, operowych i audytoryjnych. Do metod tych zalicza się m.in. metodę Beranka, Ando, RASTI i impulsową. W artykule pokazano skrótowy opis tych metod oraz ich weryfikację przeprowadzoną przez autorów artykułu oraz studentów Katedry Mechaniki i Wibroakustyki AGH w wielu polskich kościołach rzymskokatolickich. Analiza dotychczas stosowanych metod dowiodła iż w zastosowaniu do pomieszczeń sakralnych, są one często niekompletne i muszą być uzupełniane.
Mimo opracowań dotyczących badań i kształtowania warunków akustycznych w obiektach sakralnych dotychczas nie było jednolitej metody pozwalającej w jednoznaczny sposób określić jakość akustyczną tego typu wnętrz. W artykule przedstawiono, w sposób skrótowy, propozycję nowej metody wskaźnikowej, która dokonuje oceny właściwości akustycznych obiektów sakralnych za pomocą jednej liczby – wskaźnika globalnego jakości akustycznej. Globalny wskaźnik jakości akustycznej obiektów sakralnych jest funkcją kilku wskaźników cząstkowych: wskaźnika pogłosowego, wskaźnika zrozumiałości mowy, wskaźnika równomierności nagłośnienia, wskaźnika zakłóceń zewnętrznych i wskaźnika walorów brzmieniowych muzyki. Przedstawiono zastosowanie proponowanej metody wskaźnikowej na pięciu kościołach rzymskokatolickich.

Słowa kluczowe*: akustyka wnętrz sakralnych, wskaźniki oceny, jakość akustyczna obiektów sakralnych*

1. INTRODUCTION

Interiors of sacral objects require adequate conditions for performing functions inherently connected with their destination. The basic functions of any temple are liturgical ceremonies and services. They are accompanied by sounds of various characters: delivery of sermons, singing of priest and congregation, choir and schola singing, artistic soloist songs, instrumental music (including organ music), etc. Due to all that a sacral object has to fulfil simultaneously the requirements of concert halls and auditoriums, which demand very complicated planning of acoustics as well as a careful protection from outside noises.

Wide range of acoustic performances often requires the reconciliation of contradictory acoustic conditions since it is considered that the reverberation time for speeches should be much shorter than for music, especially for the organ one. Obtaining short reverberation time in sacral interiors of large cubic capacity is a very difficult task. Singing and music – on the other hand – require, apart from the longer reverberation time, certain elements such as decorations and furnishing, which will cause multiple wave reflections and good acoustic scattering.

Acoustics problems of sacral structures were, for many years, completely neglected in Poland, contrary to the other European countries where those matters were considered, however, not widely enough. The problem of not adequate acoustic conditions mainly concerns modern sacral buildings where the acoustics matters of interior are left to a sound engineer, who by installing loud-speaking devices has to improve the sound of music quality and intelligibility of speech. Unfortunately, defectively designed interiors make this type of improvement impossible, even by means of very modern loud-speaking appliances. The church ar-

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chitecture is the main factor to which the acoustic quality can be attributed. However, this aspect is usually not taken into account at the designing stage.

Problems encountered in designing can be related to the lack of a specific method allowing to assess acoustic conditions in the interior of worship places – in an explicit way. Until now the methods developed primarily for auditoriums, for verbal-musical events are being adapted for churches. The authors are presenting the new, uniform index method, which can perform the complex assessment of acoustic properties of sacral objects by means of a single-numbered index.

2. INVESTIGATION METHODS

The methods adapted for an application in sacral buildings are:

- Beranek's [3], Ando's method [1],
- RASTI [37],
- impulse methods [24, 25],
- the method based on measuring certain parameters, mainly the reverberation time and comparing them to the preferred values are taken into account [24, 25].

Table 1 presents the comparison of these five methods.

However, the analysis of these methods indicate that none of them considers sufficiently the specificity and uniqueness of interiors of churches or temples [10, 24, 25]. Information are often incomplete, have to be supplemented and do not allow to assess explicitly the acoustic properties of those objects. This was the reason that prompted the authors to develop – on the bases of adapted methods – the uniform index method of the acoustic assessment of sacral buildings.

3. RESULTS OBTAINED IN THE SELECTED CHURCHES

Investigations concerning acoustic qualities of several roman catholic churches have been performed in the Chair of Mechanics and Vibroacoustics for many years. They were the topics of many Master of Engineering Degree Thesis [24, 26, 31, 32, 41, 42, 44], Ph.D. Thesis [25] and several scientific papers [8, 9, 10, 11, 12, 14, 15, 16, 17, 30]. The selected results are presented in this paper.

The reverberation time is the basic parameter for the assessment of acoustic properties of churches. Table 2 presents the measured values of the reverberation time as a function of frequency. The measured values are much higher than the preferred ones (Tab. 2). The longest time (approximately 12 s), several times longer than the preferred value, causes that conditions, both for performing music and for listening to it and to singing, are not good. It also lowers the intelligibility of speech even when loudness improving equipment is used. This is confirmed by the subjective feelings of faithful complaining of non-understandable wording of priest's preaching.

The reverberation time (Tab. 2) was measured in empty churches.

Table 1

Comparison of methods of acoustic assessment of sacral buildings

Method	Assessment	Measurements	Scale	Possibility of assessing		Destination
				At the designing stage	Existing halls	
Beranek's	Subjective	Reverberation time Initial-time-delay gap Assessment of music performers	0–100 points	○	●	Concert and opera halls
Ando's	Objective	Music perception level Early reflections after direct sound Subsequent reverberation time Interaural cross correlation	≤ 0	●	●	Concert and opera halls, auditoria
RASTI	Objective	RASTI coefficient	0–1	●	●	Auditoria
Impulse	Objective	Impulse response	Dependent on optimal values	●	●	Concert and opera halls, auditoria
Traditional: (measuring of acoustic parameters and comparing them with the preferred values)	Objective	Reverberation time Uniformity of loudness Level of external disturbances	Dependent on the preferred values	○	●	Concert and opera halls, auditoria

○ – no, ● – yes

Table 2

Reverberation time measured in several roman catholic churches in Poland

No.	Church, location	Cubic capacity $\times 10^3$ [m^3]	Reverberation time T, s for frequency f, Hz						Average reverberation time $T_{śr}$, s
			125	250	500	1000	2000	4000	
1	St. Mary's Basilica, Gdańsk [44]	100	10.7	11.1	11.4	10.5	6.9	3.7	9.1
2	St. Peter and Paul's Church, Kraków [26]	24	5.4	5.6	5.7	5.3	4	2.5	4.8
3	St. Paul Apostle's Church, Bochnia [25]	22.0	8.3	8.9	9.8	9.3	7.4	4.7	8.1
4	Chryste Lord's Church, Łodź/Retkinia [9]	15.8	11.3	12.5	12.2	11.4	10.1	6.4	10.7
5	St. John Kanty's Church, Kraków [32]	14.5	14.2	12.8	11.6	10.3	–	–	12.2
6	St. Peter and Paul Apostles' Church Trzebinia [42]	12	6.6	5.8	5.9	5.4	5	3.9	5.4
7	St. Maxymilian's Church, Włocławek [9]	9.6	6.8	8.3	7.9	7.7	6.1	4.1	6.8
8	St. Kinga's Chapel, Salt Mine, Wieliczka [8, 31]	7.5	5.7	5.6	5.6	5.3	4.7	2.8	5.0
9	St. Cross Raising Church, Psary [24]	6.8	5.7	5.3	5.1	4.6	3.9	2.8	4.6
10	St. Clemens's Church, Wieliczka [41]	6.4	2.8	3.0	3.2	3.2	2.8	2.1	2.9
11	Holy Cross Church, Dębica [9]	5.9	8.9	10.2	8.8	7.6	5.5	3.3	7.4
12	Reformati Fathers' Church, Wieliczka [44]	4.5	2.9	3.0	3.3	3.1	2.8	2.3	2.9
13	Holiest Sacred Heart's Church, Kraków [25]	2.7	2.7	2.7	3.0	2.9	2.6	2.0	2.6
14	St. Sebastian's Church, Strzelce Wielkie [25]	1.6	1.3	1.4	1.5	1.5	1.4	1.4	1.4

Table 3

Assessment of the acoustic properties of the selected churches, according to Beranek's scale

	Church					
	St. Peter and Paul's [26]	St. John Kanty's [32]	Chapel of St. Kinga [31]	St. Cross Raising [24]	St. Peter and Paul Apostlets' [42]	Reformati Fathers' [44]
Number of points	**67**	**51**	**67**	**63**	**64**	**64**
Classification (acoustic properties)	**B** (satisfactory to good)	**C$^+$** (satisfactory)	**B** (satisfactory to good)	**B** (satisfactory to good)	**B** (satisfactory to good)	**B** (satisfactory to good)

Assessment – according to the Beranek's scale – was performed for six churches. The results are presented in Table 3. Five out of six churches belong to the B class concert halls, which means that their acoustic properties are contained in the range: from satisfactory to good. The only exception constitutes St. John Kanty's Church, which has only the satisfactory assessment (51 points out of 100 possible). Such low assessment is mainly due to the long reverberation time and related to it sound distortions.

Assessment performed by this method can not be the detailed one, because certain parameters, such as: balance, blend and ensemble can not be precisely determined.

The Ando's method was applied for the assessment of acoustic performance of St. John Kanty's Church [32]. Examples of the obtained results are presented in Figure 1. This assessment confirmed poor acoustic properties inside the church. They concern also low intelligibility of speech. Specialised measurements made by the RASTI method confirmed those findings (see Fig. 2).

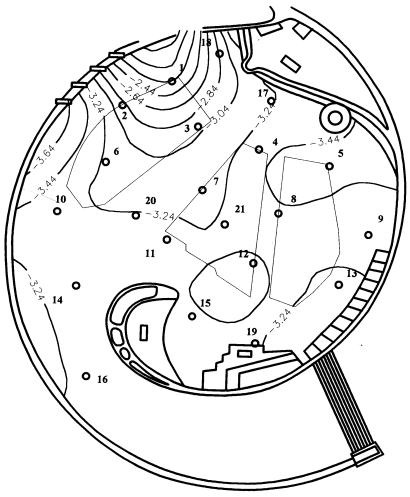

Fig. 1. Isolines of general assessment of the interior of St. John Kanty's Church – acc. to Ando for organ music (octave band of medium frequency 250 Hz)

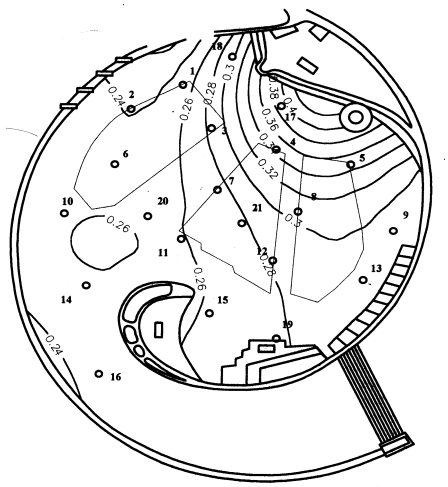

Fig. 2. Isolines of RASTI coefficient for the interior of St. John Kanty's Church

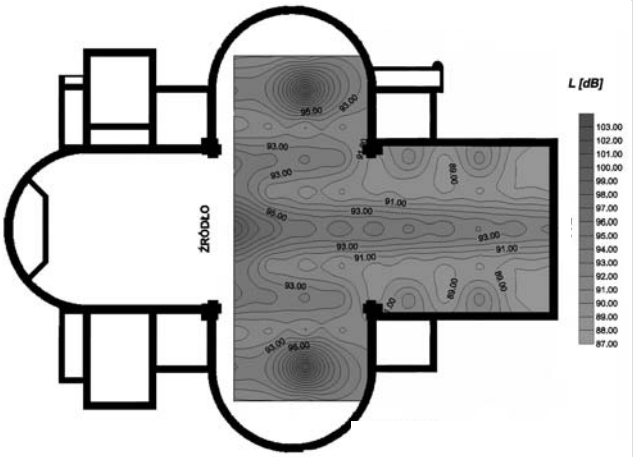

Fig. 3. Distribution of acoustic pressure level for 500 Hz octave band in the St. Peter and Paul Apostles' Church

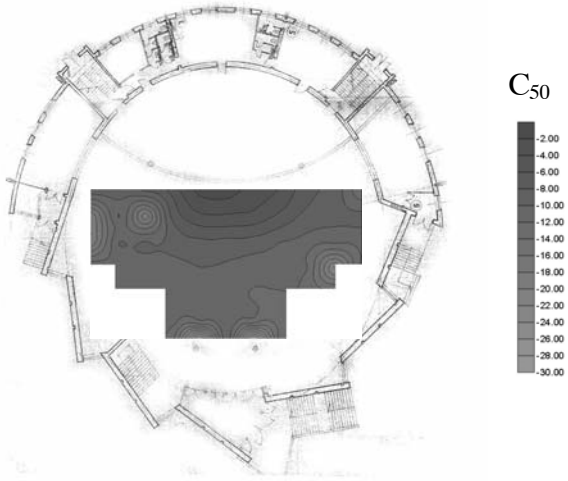

Fig. 4. Distribution of isolines of C_{50} coefficient in the St. Paul Apostle's Church in Bochnia

Uniformity of loudness is also a parameter being determined in interiors of sacral objects.

Figure 3 presents the selected results of the distribution of acoustic pressure level for 500 Hz frequency octave band for St. Peter and Paul Apostlets' Church in Trzebinia.

Investigations of RASTI, STI, ALCONS, C_{50}. parameters are applied for measuring the intelligibility of speech – C_{50} for St. Paul Apostle's Church in Bochnia, Figure 4.

4. INDEX METHOD OF ASSESSMENT

4.1. Global Index of Acoustic Quality of Sacral Objects

The proposed index method was developed on the bases of analysis of factors decisive for acoustic properties of interiors and analysis of methods adapted for the acoustic assessment of worship sites [24, 25]. Investigations were preceded by acoustic measurements in several churches [8, 9, 12, 24, 25, 26, 31, 32, 41, 42, 44]. Acoustic properties are determined in a complete way by means of just one number – index of acoustic quality of sacral objects W_{JAS}.

The global index W_{JAS} as the function of several partial indices is determined by the formula

$$W_{JAS} = \frac{\sum_{i=1}^{n} W_i \eta_i}{\sum_{i=1}^{n} \eta_i} \tag{1}$$

where:

W_i – partial index,

η_i – weight of the i-th partial index.

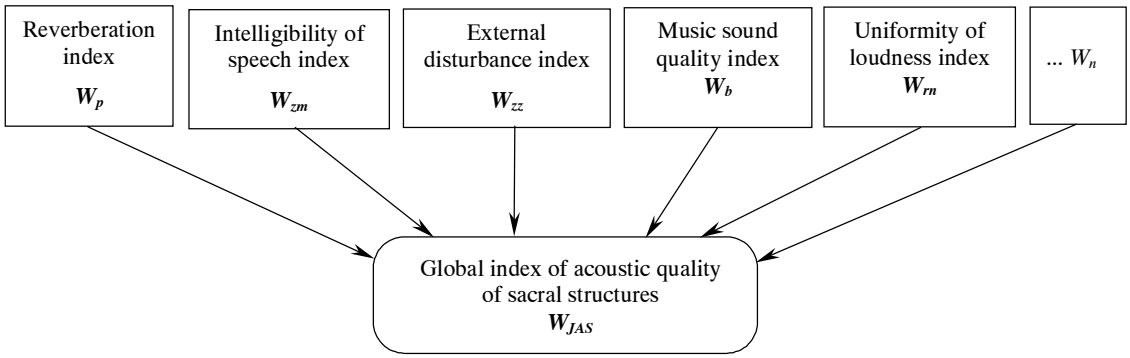

Fig. 5. Global index of acoustic quality of sacral objects

Five partial indices presented in Figure 5 have been proposed for the assessment of sacral objects. However, the possibility of introduction of new indices is not excluded.

The global index W_{JAS} for five partial indices, developed so far, is given by the formula [15, 25]

$$W_{JAS} = \frac{W_p\eta_1 + W_{zm}\eta_2 + W_{zz}\eta_3 + W_{rn}\eta_4 + W_b\eta_5}{\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5} \tag{2}$$

where:

W_p – reverberation index,
W_{zm} – intelligibility of speech index,
W_{zz} – external disturbance index,
W_{rn} – uniform loudness index,
W_b – music sound quality index,
$\eta_1 \ldots \eta_5$ – weights of partial indices [25].

4.2. Partial indices

4.2.1. Reverberation index

The reverberation time is the main parameter determining the acoustic quality of interiors, including interiors of sacral buildings [15]. The reverberation index W_p, which is the function of several auxiliary indices $W_{p1} \ldots W_{p3}$ plays very important role in the index method proposed by the authors. The main reverberation index is determined according to the diagram shown in Figure 6 and given by the formula

$$W_p = W_{p1} \cdot \beta_1 + W_{p2} \cdot \beta_2 + W_{p3} \cdot \beta_3 \tag{3}$$

where:

W_p – reverberation index,
W_{p1} – reverberation – volume index,
W_{p2} – reverberation index for organ music,
W_{p3} – reverberation index for speech,
$\beta_1 \ldots \beta_3$ – weights for auxiliary indices $W_{p1} \ldots W_{p3}$.

Index W_p takes values from 0 to 1. The most favourable conditions – according to the reverberation time – occur when $W_p = 1$ and the worst when $W_p = 0$. To each of the auxiliary indices (W_{p1}, W_{p2}, W_{p3}) the adequate weight is ascribed. The weights depend on the cubic capacity of sacral object and the type of the sound event in the church. The weight values $\beta_1 \ldots \beta_3$ are described in [15, 25].

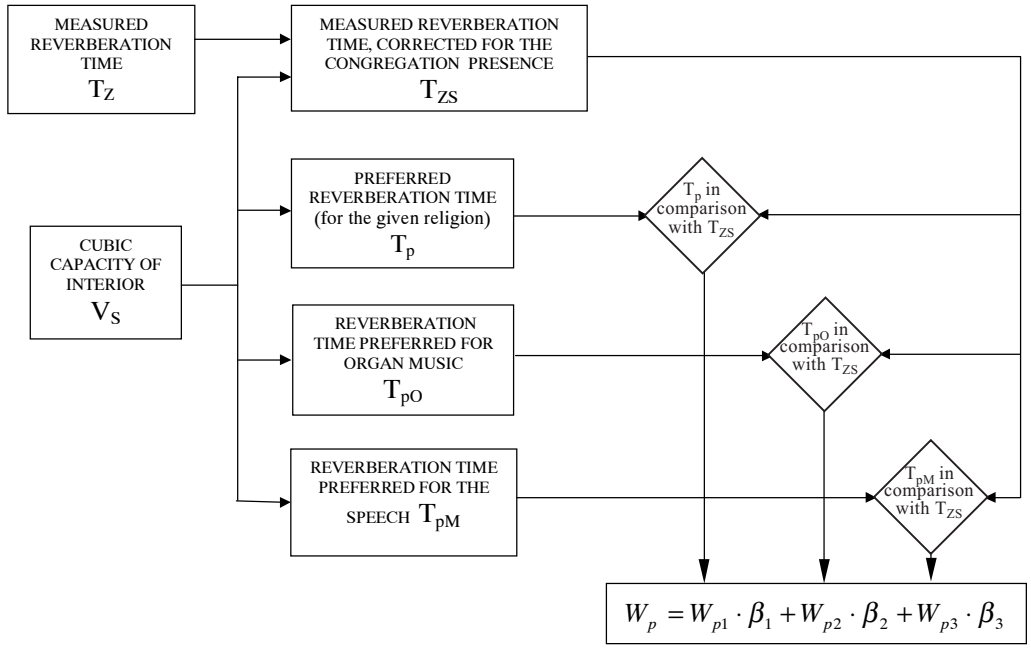

Fig. 6. Diagram of the estimation of the reverberation time index W_p

In order to estimate the main reverberation index W_p the cubic capacity of the interior of the sacral interior V_s and the reverberation time T_z – corrected for the presence of the congregation – should be measured. The corrected reverberation time is estimated by the procedure given in [15] and [25].

4.2.2. External Disturbance Index

30 dB of sound A level was assumed as the permissible level of disturbing noises. When sound A level $L_A \leq 30$ dB, it means that the permissible level of external disturbances is not exceeded for the given sacral building and $W_{zz} = 1$. However, when $L_A > 30$ dB the external disturbance index has to be calculated by the formula [16, 25]

$$W_{zz} = \frac{3}{L_A - 27} \tag{4}$$

where L_A – sound A level of external disturbances inside the church, dB.

4.2.3. Music Sound Quality Index

Out of several parameters describing the properties of interiors from the point of view of music perception four factors were hereby selected. Those are:

- two subjective factors introduced by L.L. Beranek (1962) i.e. liveness T_{mid} and sound warms BR,
- the clarity index C_{80} introduced by Reinchardt,
- the centre of gravity time T_S proposed by Kürer (1969) and developed by Cremer (1982).

Thus, the music sound quality index W_b is a function of four auxiliary indices W_{b1}, W_{b2}, W_{b3}, W_{b4}.

$$W_b = f(W_{b1}, W_{b2}, W_{b3}, W_{b4}) \tag{5}$$

where:

W_{b1} – auxiliary index concerning acoustic liveness inside the sacral object T_{mid} , $0 < W_{b1} \leq 1$;
W_{b2} – auxiliary index describing the sound warmth BR, $0 < W_{b2} \leq 1$;
W_{b3} – auxiliary index describing the clarity index C_{80} inside the sacral building, $0 < W_{b3} \leq 1$;
W_{b4} – auxiliary index describing the centre of gravity time T_S, $0 < W_{b4} \leq 1$.

Music sound quality index as well as auxiliary sound quality indices take values: $0 < W_b \leq 1$. Index W_b is determined by the equation [25]

$$W_b = \sqrt{\frac{W_{b1}^2 + W_{b2}^2 + W_{b3}^2 + W_{b4}^2}{4}} \tag{6}$$

Values of individual auxiliary indices W_{b1}, W_{b2}, W_{b3}, W_{b4}, can be estimated from nomograms presented in [25].

4.2.4. Intelligibility of Speech Index

The application of three indices: ALCONS (Percentage Articulation Loss of Consonants), RASTI (Rapid Speech Transmission Index) and C_{50} (Clarity Index) has been proposed for the assessment of the auxiliary intelligibility of speech indices and the main index of the intelligibility of speech W_{zm}. All three indices can be assessed from the impulse response of the interiors of sacral objects.

On the bases of the dependencies in between the measured subjective and objective indices of the intelligibility of speech given in [6], nomograms presented in [25] were used for the estimation of the auxiliary indices W_{z1}, W_{z2}, W_{z3}, on the bases of ALCONS, RASTI and C_{50} coefficients. The intelligibility of speech index W_{zm}, being the partial index of the global index of the acoustic assessment of sacral objects W_{JAS}, is a function of auxiliary indices of the intelligibility of speech W_{z1}, W_{z2}, W_{z3} and is expressed as

$$W_{zm} = \sqrt{\frac{W_{z1}^2 + W_{z2}^2 + W_{z3}^2}{3}} \tag{7}$$

where W_{z1}, W_{z2}, W_{z3} – auxiliary indices of the intelligibility of speech, which assume values in the range from 0.1 to 1.

4.2.5. Uniformity of Loudness Index

The distribution of the acoustic pressure level decisive for the uniformity of loudness can be determined from the measurements of the acoustic pressure level in the measuring points [17, 25]. The conversion of the measured acoustic pressure levels into their decrease Δ_L, in dB, related to the maximum measured acoustic pressure level $L_{P_{\max}}$ is expressed by the formula

$$\Delta_L = \left| L_{p_{\max}} - L_{p_i} \right| \tag{8}$$

where:

$L_{P_{\max}}$ – maximum of the acoustic pressure level, dB,
L_{P_i} – acoustic pressure level in the given measuring point, dB.

Loudness contours (isophone lines) of the decrease of the pressure level plotted in the distribution diagram will show the value, by which the acoustic pressure level decreased in the given area.

The uniformity of loudness index is being determined for each j-th frequency octave band from the following formula [17, 25]

$$W_{R_j} = \frac{\sum_{1=1}^{n} \kappa_j \cdot S_{\Delta L}}{S_c} \tag{9}$$

where:

κ_j – coefficient of the decrease of the acoustic pressure level for the j-th frequency octave band, (j = 125; 250; 500; 1000; 2000; 4000 Hz),

S_c – surface area on which the uniformity of loudness is investigated, m^2,

$S_{\Delta L}$ – surface area between two neighbouring isophones in which the decrease Δ_L, m^2 occurs.

When the uniformity of loudness indices in frequency octave bands W_{R125} ... W_{R4000} are determined, the averaged uniformity of loudness index can be calculated from the formula

$$W_{rn} = \frac{\sum_{j=1}^{6} W_{Rj}}{6} \tag{10}$$

where W_{Rj} – the uniformity of loudness index for the j-th frequency octave band.

4.3. Application of the Proposed Index Method for the Acoustic Assessment of Sacral Buildings

Verification of the proposed method was performed in five roman catholic churches of the schematic lay-out presented in Figure 7.

The measurements of the impulse responses were performed in the measuring points of the tested interiors [25]. The measurements of the external disturbance levels as well as of the acoustic pressure levels for the sound source being placed near the altar were also accomplished. The acoustic parameters were estimated from the impulse response. On these bases the values of individual partial parameters were assessed for each church. The data are presented in Table 4 and in Figure 8.

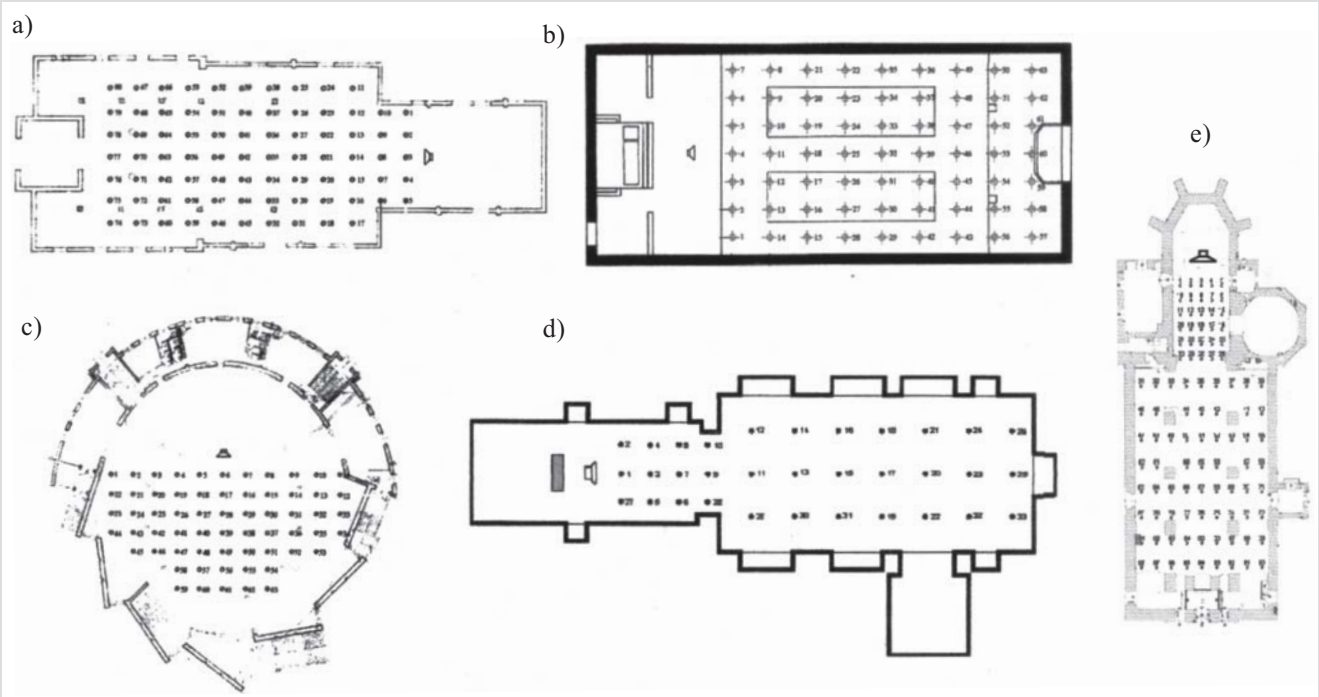

Fig. 7. General lay-outs of: a) St. Sebastian's Church in Strzelce Wielkie; b) the Holiest Sacred Heart's Church in Kraków; c) St. Paul Apostle's Church in Bochnia; d) the Reformati Fathers' Church in Wieliczka; e) St. Clemente's Church in Wieliczka

Table 4

Comparison of acoustic properties of sacral objects by means of partial indices and the global acoustic index

Church of:	V m^3	W_p	W_{zm}	W_{zz}	W_{rn}	W_b	W_{JAS}	Assessment of acoustic properties
Reformati Fathers, in Wieliczka	4450	0.88	0.33	0.37	0.26	0.48	**0.56**	Satisfactory
Holiest Sacred Heart, in Kraków	2750	0.94	0.34	0.4	0.53	0.6	**0.66**	Good
St. Sebastian, in Strzelce Wielkie	1650	0.88	0.49	1	0.2	0.67	**0.71**	Good
St. Paul Apostle, in Bochnia	22000	0.39	0.21	1	0.78	0.21	**0.47**	Bad
St. Clemente, in Wieliczka	6380	0.94	0.32	0.57	0.21	0.49	**0.62**	Satisfactory

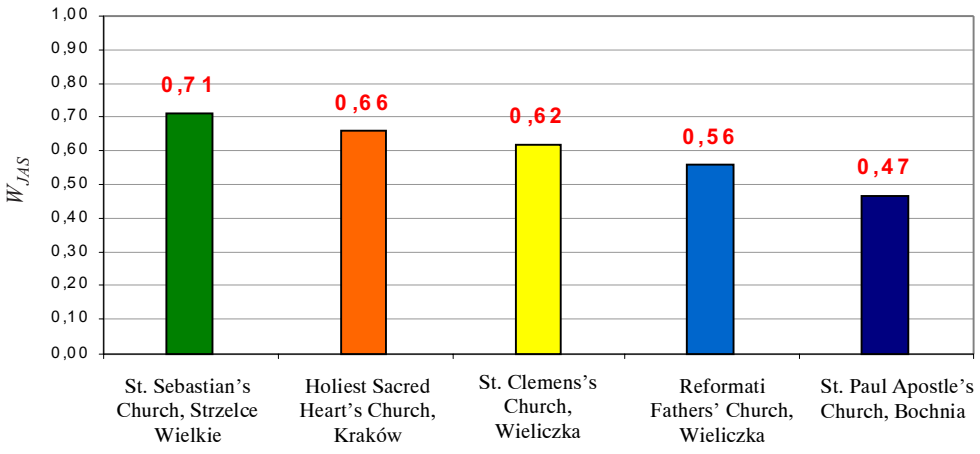

Fig. 8. Comparison of an acoustic performance of five roman catholic churches assessed by means of the global index W_{JAS}

The global index was calculated for each church. They were also classified according to the tentative scale developed in [25].

The best acoustic performance among the tested churches characterises – according to the index method – the Holiest Sacred Heart's Church in Kraków and the wooden, antique St. Sebastian's Church in Strzelce Wielkie, while the worst – the modern St. Paul Apostle's Church in Bochnia.

5. CONCLUSIONS

The results of investigations concerning acoustic properties of the selected Polish churches are presented in the paper. The results obtained by means of methods adapted for this type of interiors are also given. They do not supply the complete results and must be often supplemented. It should not be surprising since they were primarily developed for an acoustic assessment of concert halls or auditoriums and not specifically for the places of worship. Then, the proposal of the new method of acoustic assessment of sacral buildings – the index method was given. The method developed by the authors allows to hope that in future, after considerable development, it will help in designing interiors of greatly improved acoustic performances. The index method is destined for a certain group of sacral buildings such as: roman catholic and evangelical churches and synagogues of a cubic capacity from 600–40 000 m^3 and of straight shapes. The method is not – at present – suitable for interiors of acoustically coupled spaces. They require further research. The tentative assessment is being done in a complex way by means of a single-numbered index. In addition, the partial indices allow to estimate individual properties of the sacral object: reverberation time, intelligibility of speech, music sound quality, external disturbance level and uniformity of loudness level. The proposed index method allows for a better estimation of the acoustic properties and performance of the sacral object than the presently used adapted methods.

The measurements of impulse responses in the measuring points inside the given object as well as the acoustic pressure level and external disturbances level are needed for the global assessment. On the bases of those measurements the values of individual acoustic parameters, e.g. reverberation time, C_{80}, C_{50}, ALCONS, RASTI indices and the centre of gravity time are estimated. Then, the parameters are used for the calculation of partial indices as well as the global index of acoustic qualities of sacral building.

The verification of the proposed method was performed in five selected roman catholic churches, which were classified into groups of sacral objects of certain acoustic properties, by means of the proposed tentative scale.

The application of the index method will allow to create the data base of objects of similar acoustic properties, which might contribute to improvements in designing, building and furnishing of sacral buildings.

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