

REVERBERATION INDICES IN ACOUSTIC ASSESSMENTS OF SACRAL STRUCTURES

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The proposition of the acoustic assessment of interiors of sacral buildings by means of the single-numbered, global index of acoustic quality was given in this paper. The introduction of a uniform method is justified since none of the available methods addresses to a sufficient degree to the specificity of such interiors. The main partial index – the reverberation index – was discussed and applied to the tests in several catholic churches, where acoustic measurements were performed. The continuation of the research presented here will lead to the development of a new method especially suitable for the acoustic quality assessment of sacral buildings.

1. Introduction

The first sacral structures were erected when human settlements originated. The places of worship enabled people to participate in various religious ceremonies. Sacral buildings had to achieve the adequate acoustic properties and the required capacity. For several years acoustic issues of sacral structures were neglected in Poland, contrary to other European countries where those problems were considered, however, not widely enough.

Investigations performed in many sanctuaries have shown that neither at the designing stage nor at their building or modernisation the need for creation of proper acoustic properties is recognised and appreciated. As the result of such an approach, sacral structures of defective acoustics have often been built. This fact confirms the situation that there is a lack of a proper method, which would allow assessing the acoustic conditions inside churches or temples.

Methods adapted from the Beranek's scale, Ando's scale and the RASTI method as well as impulse methods are used for the assessment of the acoustic performance of interiors of such buildings.

Interiors of sacral structures are characterised by properties resulting from their function and the special requirements of liturgical ceremonies (Fig. 1), architectural and functional designing, furnishing and specific material and constructional solutions.

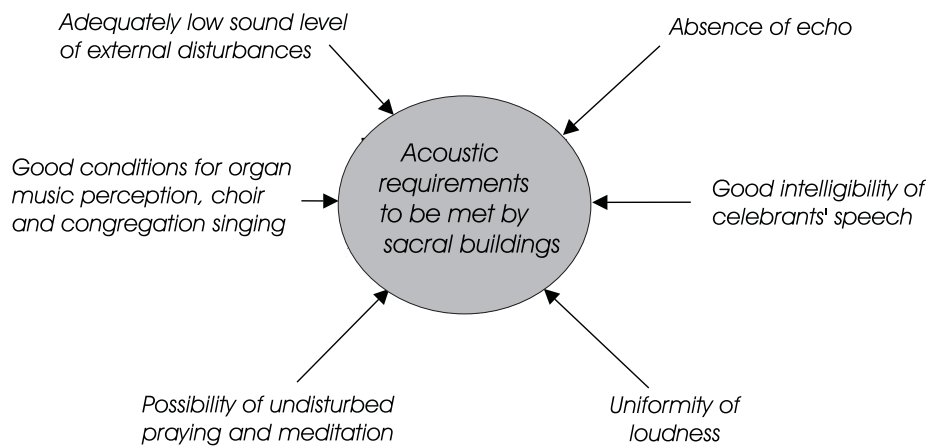


Fig. 1. Acoustic requirements to be met by sacral buildings.

Interiors of places of worship have to meet certain requirements appropriate to the functions of such places. It should be taken into account that sacral structures are often sources of noise themselves, especially churches built near housing districts. The bells on church towers can be quite burdensome from time to time due to their noisiness. The presented paper concentrates entirely on the acoustic performance of interiors of sacral structures and does not include either their surroundings nor the influence on the environment.

The basic functions of any temple are liturgical ceremonies and services. They are accompanied by various sounds: priest's and congregation's singing, speeches, choir and schola singing, organ music. Each religion is characterised by different proportions of those sounds. In catholic churches: music (mainly the organ one), singing and speeches are dominant, in orthodox churches: singing and speeches, in evangelic churches: speeches and music, while in synagogues only speeches. Thus, the interior of the sacral building has to meet simultaneously the requirements of concert halls and of auditoriums.

It should be emphasized that up to the present no uniform criteria determining the acoustic performance of interiors of sacral buildings have been developed. This situation prompted the authors to undertake a study on the index method of the acoustic assessment of sacral structures.

2. Methods of the acoustic assessment of rooms – adapted for interiors of sacral buildings

The creation of proper acoustic conditions inside sacral buildings is a difficult problem since it means the reconciliation of contradictory acoustic requirements (Fig. 1). Different methods that are used nowadays for the assessment of the acoustic performance of sacral buildings will be discussed shortly below.

One of the first methods was the Beranek's scale based on a comparison of the acoustic characteristics of more than fifty concert and opera halls in the world. This type of assessment concerns mainly the suitability of concert and opera halls for selected types of music. In this method the points are allocated for various properties such as: reverberation time at given frequency bands, initial-time-delay gap, volume of the hall, distance between the listener and the singer or the conductor. Remaining features are estimated according to the perception of persons taking part in the assessment procedure. The sum of those points classifies the concert hall into a certain category. This is an entirely subjective method since the music perception of persons assessing the acoustic quality is not adequate to the impressions of common listeners.

The method proposed by Y. Ando is an example of a modern method of assessment. It is based on the subjective preference scale. The following four independent parameters were selected by Ando: listening level, early reflections after direct sound, subsequent reverberation time and interaural cross correlation. The Ando's scale of the acoustic quality of concert halls is nowadays the most compact one and takes into consideration acoustic parameters, which probably are most important for the music reception by human beings. However, for performing the measurements and establishing the preferred values, the application of very sophisticated measuring tools is necessary, which causes that the method is not widely used.

An advantage of the Ando's method is the possibility of application not only to already existing buildings but also at the stage of designing, while the Beranek's method is applicable only for existing structures.

The RASTI method (Rapid Speech Transmission Index) is supplementing above methods in the field of the intelligibility of speech. It is based on the connection between the transmission function of the system modulation and the intelligibility of speech. The RASTI index and the subjective assessment of the intelligibility of speech are linked by corresponding formulations [20, 31].

The impulse method, based on the determination of the impulse response of the interior of the hall followed by the calculation of parameters essential for the acoustic performance of that interior, is also sometimes utilized. The parameters are, among other things: reverberation time, expressiveness, expressiveness index, early decay time. Comparing the corresponding measured values with the optimal ones, we can assess the intelligibility of speech (RASTI and STI indices) and the conditions for music perception.

The assessment of the acoustic performance of a sacral structure can be also performed in a traditional way by measuring the reverberation time, uniformity of loudness and the level of external disturbances.

The comparison of available methods is given in Table 1. The analysis of all those methods shows that none of them addresses to a sufficient degree to the specificity and uniqueness of the interior of sacral buildings. This is not surprising since those methods were developed either for the acoustic assessment of concert and opera halls (Beranek's method), or for subjective preferences (Ando's method), or for the estimation of the

intelligibility of speech (RASTI method). The impulse method is also only partially applicable and must be supported by other methods.

Table 1. Comparison of the methods of acoustic assessment of sacral structures.

Method	Kind of assessment	Measurements	Scale	Assessment possibility		Destination
				At the designing stage-	Existing halls	
Beranek's	Subjective	– Reverberation time – Initial-time-delay gap	0 – 100 points	○	●	Concert and opera halls
Ando's	Objective	– Listening 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 (measurements of acoustic parameters and comparison with preferred values)	Objective	– Reverberation time – Uniformity of loudness – Level of external disturbances	Dependent on preferred values	○	●	Concert and opera halls, auditoria

All mentioned above deficiencies of the available methods indicate clearly that there is a need for developing a special method suitable for the acoustic estimation of specific interiors of sacral buildings taking into account their furnishing and constructional materials.

3. Proposal of the index method for the acoustic assessment of sacral structures

The authors suggest hereby the introduction of the universal index method for the acoustic assessment of sacral structures.

The proposed method was developed on the basis of the analysis of parameters influencing the acoustic properties of interiors as well as on the analysis of the methods adapted to the acoustic assessment of sites of worship.

The index method concerns catholic and evangelic churches and synagogues of the interior volume V_s [m³] being in the range $600 \leq V_s \leq 40000$. The introduced method can be applied for interiors in which the measured reverberation time, corrected for the presence of the congregation, is smaller than 7 seconds. The method is more suitable for single-structure churches than for churches with large side chapels, which act as coupled spaces and as such constitute a separate acoustic problem not discussed in the present paper.

The acoustic assessment, performed by means of this new method, has been done in the interiors of places of worship when all sound transmitting electroacoustic equipment installed there was switched off.

The single-numbered global index of acoustic quality of sacral structures, W_{JAS} , provides the complex description of their acoustic properties.

The global index W_{JAS} (1) is a function of several partial indices:

$$W_{JAS} = f(W_1, W_2, W_3, \dots, W_n), \quad (1)$$

where W_{JAS} – index of the acoustic quality of sacral structures, $W_1 \dots W_n$ – partial indices. Thus, the global index W_{JAS} can be determined by the formula:

$$W_{JAS} = W_1 \cdot W_2 \cdot W_3 \cdot \dots \cdot W_n. \quad (1a)$$

The partial indices W_1 to W_n , similarly to the global index W_{JAS} , assume values from 0 to 1. The partial indices give information on: the reverberation time, intelligibility of speech, level of external disturbances and the uniformity of loudness. However, the possibility of introduction of other indices is not excluded (Fig. 2).

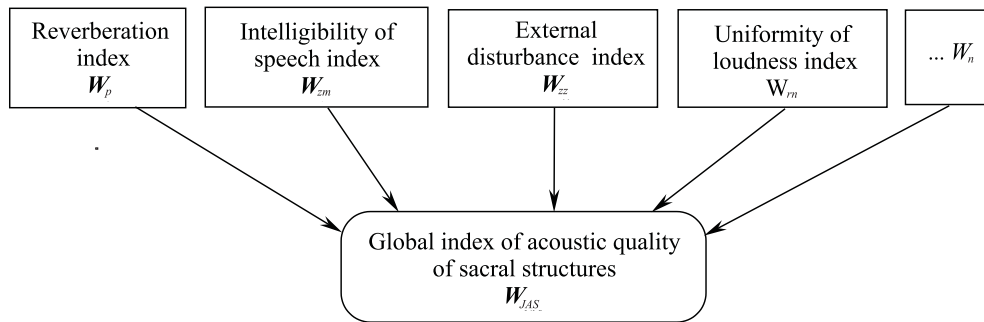


Fig. 2. Global index of acoustic quality of sacral structures.

The performing of measurements of the reverberation time (when the congregation is present in the church), intelligibility of speech, external disturbances (acoustic back-

ground), and the acoustic pressure level connected with the uniformity of loudness is necessary for the determination of the relevant partial indices and their weights (Fig. 3).

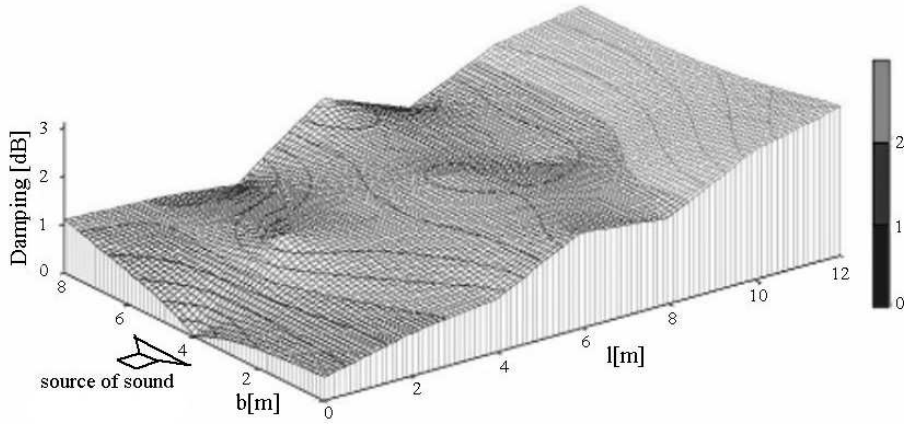


Fig. 3. The distribution of the acoustic pressure level recalculated into damping (in dB) in relation to the maximal pressure level for the octave band of medium frequency $f = 1000$ Hz ; results obtained for the church in Psary (Kościół Podwyższenia Krzyża Św.); l, b [m] – length and width of the measurement surface, respectively.

The reverberation index, W_p , one of the acoustic partial indices, is presented in the paper.

Problems dealing with the directivity and the diffusion of the acoustic energy are omitted here since they will be considered when discussing other acoustic indices. They are very important phenomena influencing the acoustic quality of churches, which can sometimes secure the proper acoustic performance regardless of the not adequate characteristics and the reverberation time value [30, 32].

4. Reverberation indices

The reverberation time is the main parameter determining the acoustic quality of rooms including interiors of sacral buildings. In the index method proposed here, the reverberation index plays a very important role. This index W_p is a function of several auxiliary indices $W_{p1} \div W_{p3}$. The main reverberation index is determined according to the diagram given in Fig. 4 and can be presented by the following formula:

$$W_p = W_{p1} \cdot \beta_1 + W_{p2} \cdot \beta_2 + W_{p3} \cdot \beta_3, \quad (2)$$

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

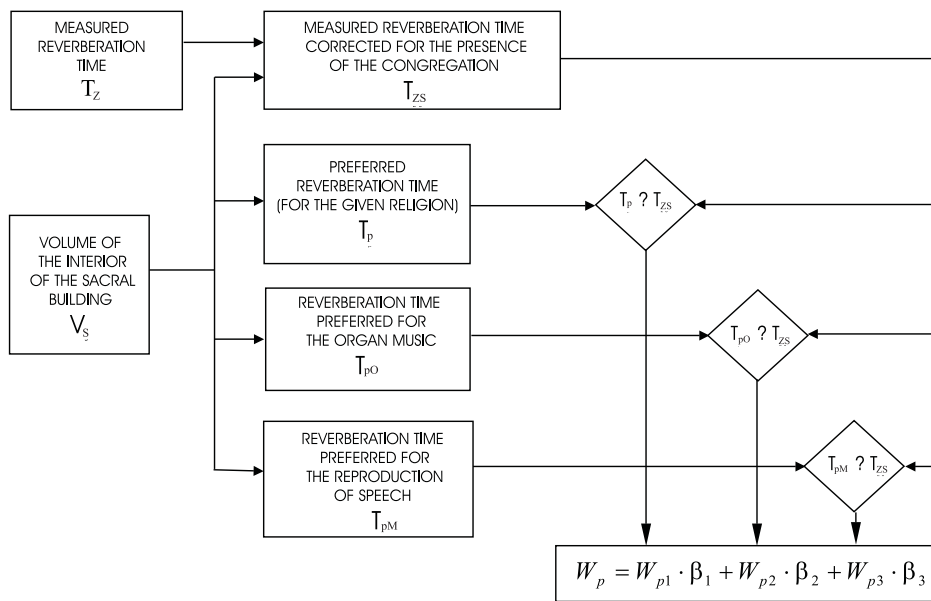


Fig. 4. Diagram of the estimation of the reverberation time index, W_p .

The W_p index assumes values from 0 to 1. The conditions are most favourable when $W_p = 1$, and are the worst ones when $W_p = 0$. There is an adequate weight ascribed to each of the auxiliary indices (W_{p1} , W_{p2} , W_{p3}). It depends on the volume of the interior and the kind of the acoustic event. The weight values $\beta_1 \div \beta_3$ are given in Table 2.

It is impossible to obtain a reverberation time, which would provide simultaneously good conditions for the music perception and for the intelligibility of speech. These are mutually contradicting requirements since a long reverberation time favours the music perception, while a short one is needed for good understanding of speech. Therefore in small buildings is the intelligibility of speech better and the weights of the β_3 coefficients are the biggest ones. In case of organ music, its better resounding is provided by a longer reverberation time. Therefore in buildings of a large volume the weight β_2 attains a maximal value, while in small buildings a minimal one. Since organ music is not used in synagogues, the weight β_2 is in those buildings equal to 0. The weight β_1 of the reverberation-volume index has an identical value for various sacral structures of different volumes. This weight is the biggest one since the W_{p1} index is the basic parameter of the reverberation index W_p .

To estimate the main reverberation index W_p , the volume of the interior of the sacral building as well as the reverberation time T_z , which should be corrected for the presence of the congregation, are needed. The corrected reverberation time is compared (by means of adequate dependencies) with the reverberation time preferred for the particular type of the sacral structure due to the religion cult and with the reverberation time preferred for the sound reproduction of the organ music and speech.

Table 2. Weights of the auxiliary parameters for the specified type of sacral building.

		Sacral building			
Volume of the interior V_s [m ³]		$600 < V_S \leq 1500$	$1500 < V_S \leq 15000$	$15000 < V_S \leq 40000$	
Type of building		small	medium	large	
Weights of auxiliary parameters	β_1	Catholic churches	0.6	0.6	0.6
		Protestant churches			
		Synagogues			
	β_2	Catholic churches	0.1	0.2	0.3
		Protestant churches			
		Synagogues			
	β_3	Catholic churches	0.3	0.2	0.1
		Protestant churches			
		Synagogues	0.4	0.2	0

The reverberation – volume index, W_{p1} , is determined from the equation:

$$W_{p1} = 1 - \frac{|T_{ZS} - T_p|}{5}, \quad (3)$$

where T_p – reverberation time preferred for the specified sacral building and its volume [s], T_{ZS} – measured reverberation time corrected by the presence of the congregation [s].

The reverberation time preferred, T_p , depends on the volume of the sacral building V_S . The value of this time can be determined from the graph presented in Fig. 5 [5].

More accurate values can be determined on using the following formulae:

- Catholic churches:

$$T_p = 0.24 \ln(V_S) - 0.24 \text{ [s]}; \quad (4)$$

- Protestant churches:

$$T_p = 0.17 \ln(V_S) + 0.12 \text{ [s]}; \quad (5)$$

- Synagogues:

$$T_p = 0.14 \ln(V_S) + 0.08 \text{ [s]}; \quad (6)$$

where V_S – volume of the sacral building [m³].

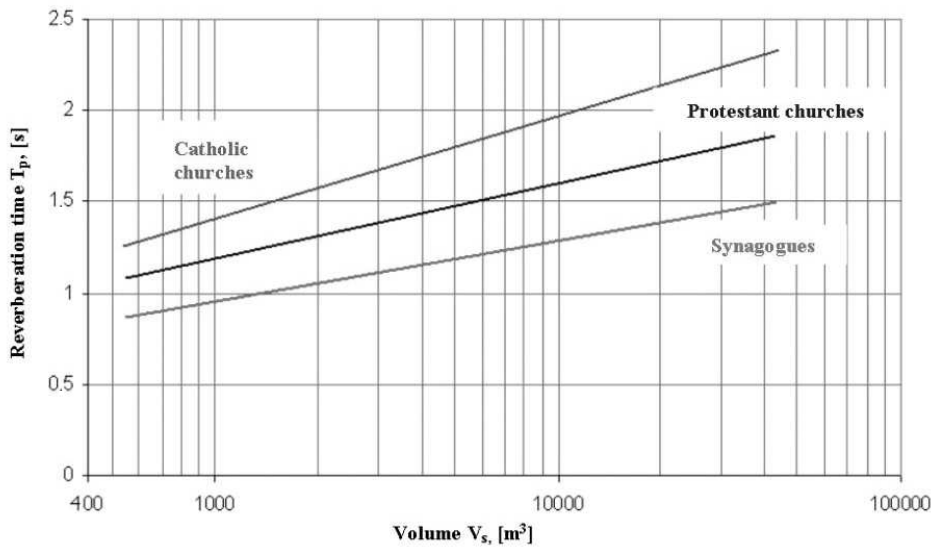


Fig. 5. Preferred optimal reverberation time for different sacral buildings [5].

The index W_{p1} (Eq. (3)) takes the values $0 \div 1$ on the assumption that $T_{ZS} \leq T_p + 5$.

When $T_{ZS} = T_p$, $W_{p1} = 1$; that means the investigated sacral building has excellent acoustic properties.

When $T_{ZS} = T_p + 5$, the index $W_{p1} = 0$ that is tantamount to bad acoustic properties.

When $T_{ZS} > T_p + 5$, Eq. (3) renders negative values and the W_{p1} index should be assumed to be 0. That means that the reverberation time corrected for the presence of a congregation exceeds the preferred reverberation time by more than 5 seconds.

The auxiliary index W_{p2} for the organ music can be estimated from the formula:

$$W_{p2} = 1 - \frac{|T_{ZS500} - T_{pO}|}{5}, \quad (7)$$

where T_{pO} – preferred reverberation time for organ music for the octave band of medium frequency 500 Hz, s, T_{ZS500} – measured and corrected reverberation time for the octave band of medium frequency 500 Hz, s.

The preferred reverberation time for organ music T_{pO} depends on the volume of the building. It can either be estimated from the graph shown in Fig. 6 or calculated from the following formula:

$$T_{pO} = 0.73V_s^{0.15} [s], \quad (8)$$

where V_s – volume of the sacral building [m³].

The values of the preferred reverberation time for organ music, T_{pO} , are referred to the octave band of the medium frequency 500 Hz.

The index W_{p2} (Eq. (7)) assumes values $0 \div 1$ on the assumption that $T_{ZS500} \leq T_{pO} + 5$.

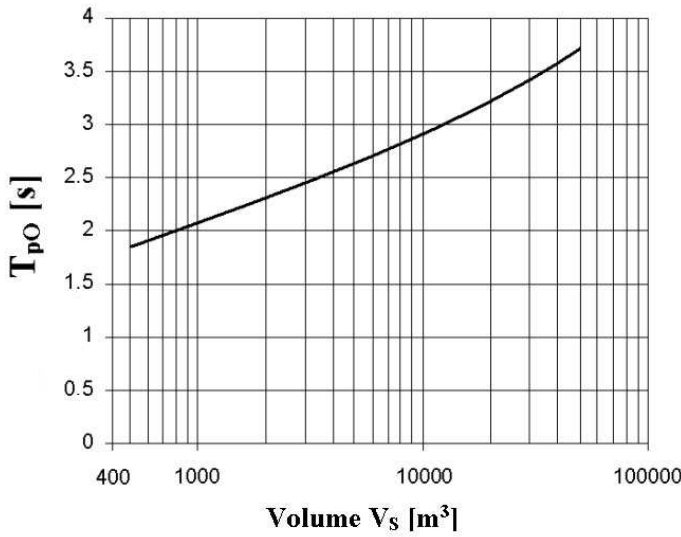


Fig. 6. Preferred reverberation time for organ music in sacral buildings [5].

When $T_{ZS500} = T_{pO}$, the index $W_{p1} = 1$, i.e. the investigated building has the best properties for the organ sound reproduction.

When $T_{ZS500} = T_p + 5$, the index $W_{p1} = 0$; this indicates that there is a difference of 5 seconds between the corrected measured time and the preferred one. It is tantamount to bad acoustic qualities of the building.

When $T_{ZS500} > T_p + 5$, Eq. (7) renders negative values; in this case the W_{p1} index should be assumed to be equal to 0. Thus means that the reverberation time corrected for the presence of the congregation exceeds the reverberation time preferred by more than 5 seconds.

The auxiliary reverberation index for speech, W_{p3} , is estimated from the formula:

$$W_{p3} = 1 - \frac{|T_{ZS} - T_{pM}|}{5}, \quad (9)$$

where T_{pM} – permissible reverberation time for interiors destined for the speech reproduction, s, T_{ZS} – corrected measured reverberation time, s.

The permissible reverberation time for the speech reproduction, T_{pM} , depends on the volume and can be estimated either from the graph given in Fig. 7 or from the formula:

$$T_{pM} = 0.17 \ln(V_S) - 0.43, \quad (10)$$

where V_S – volume of the sacral building, [m³].

Equation (9) takes the values from 0 to 1 on the assumption that $T_{ZS} \leq T_{pM} + 5$. When $T_{ZS} = T_{pM}$, $W_{p3} = 1$. When $T_{ZS} < T_p$, it is assumed that $W_{p3} = 1$. The index $W_{p3} = 0$ when $T_{ZS} = T_{pM} + 5$, i.e. when the difference between T_{ZS} and T_{pM} equals 5 seconds. When $T_{ZS} > T_{pM} + 5$, it should be assumed that $W_{p3} = 0$.

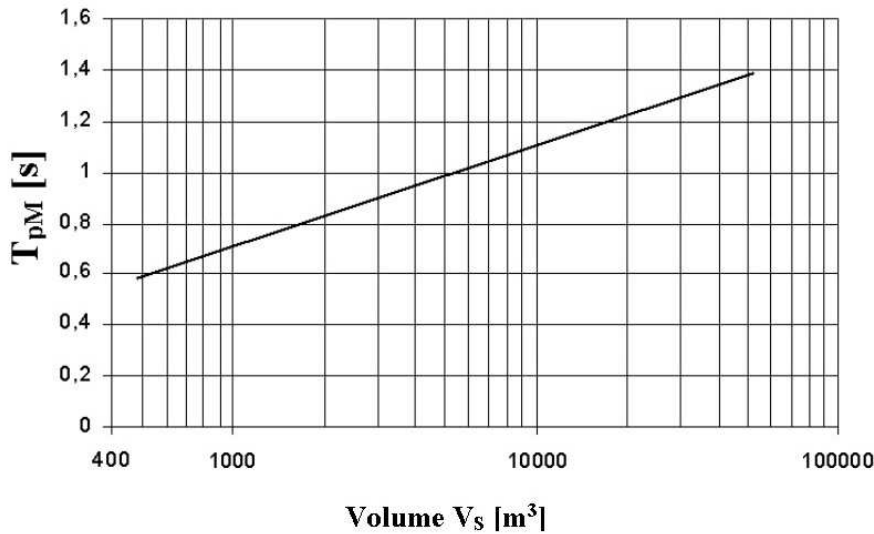


Fig. 7. Permissible values of the reverberation time in buildings of various volumes destined for the reproduction of signals of speech [18].

The measured reverberation time corrected for the presence of the congregation, T_{ZS} , is estimated from the following formula [20]:

$$T_{ZS} = \frac{0.161V_S}{(S - S_1 - S_2)\alpha_p + S_1\alpha_1 + S_2\alpha_2}, \quad (11)$$

where α_p – average reverberation absorption coefficient, V_S – volume of the interior of the sacral building, m³, S – surface area of surrounding surfaces, m², S_1 – surface area filled by seating congregation, m², S_2 – surface area filled by standing congregation, m², α_1 – absorption coefficient for a seating person, α_2 – absorption coefficient for a standing person.

The average reverberation absorption coefficient is estimated from the equation:

$$\alpha_p = \frac{0.161V_S}{T_Z}, \quad (12)$$

where V_S – volume of the interior of the sacral building, m³, T_Z – measured average reverberation time, s.

Equation (11) is an approximate relationship based on the Sabine's equation. The accuracy of the reverberation time assessment performed on the basis of this equation depends, among others things, on the estimation of the volume of the interior. In certain churches, the latter might be quite difficult due to their complicated shape, "sculpturing" and a sophisticated arrangement of the design.

The absorption coefficients for seating and for standing person, α_1 and α_2 , respectively, are given in the references [20] and [32].

The comparison of the average values of the measured reverberation time in empty churches with the calculated ones corrected for the presence of the congregation is illustrated in Fig. 8.

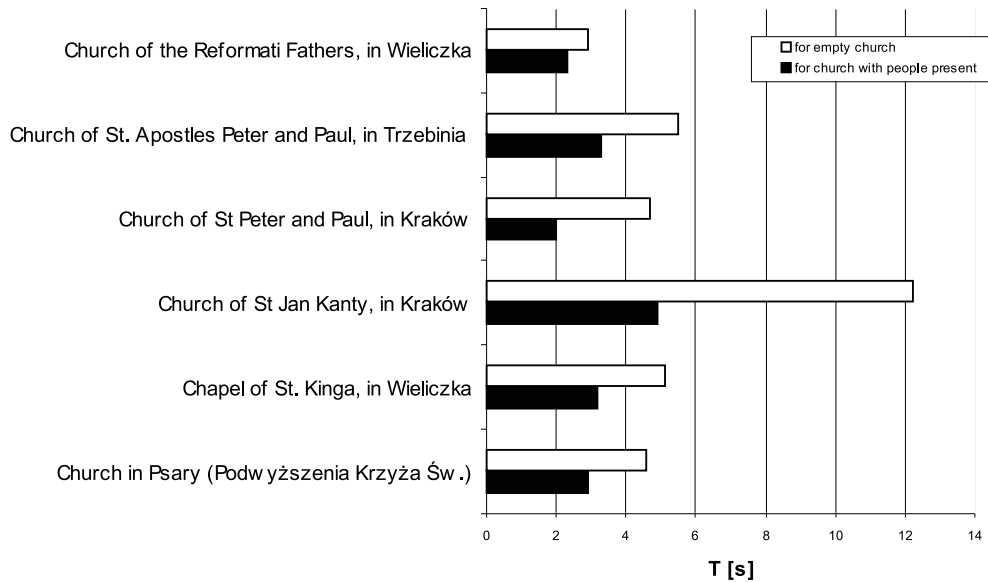


Fig. 8. Comparison of the average reverberation times estimated for empty churches and for churches with the congregation present.

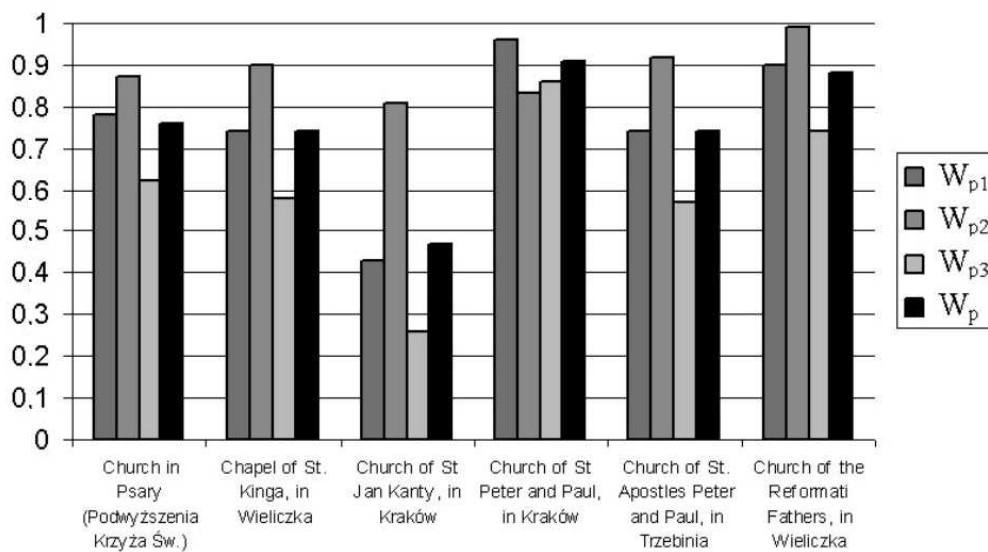


Fig. 9. Comparison of several churches by means of the reverberation indices.

Table 3 presents the results of the measurements of the reverberation time performed in several churches within the research program of the Department of Mechanics and Vibroacoustics. The methods and techniques of measurements used to obtain the measured values presented in Table 3 are described in references [10, 13, 20, 21, 26] and [27].

A comparison of the same churches using the reverberation indices is presented in Fig. 9.

Table 3. The reverberation index values, W_p , estimated for several catholic churches.

Church	V_S [m ³]	n_w	T_Z [s]	T_{ZS} [s]	T_{ZS500} [s]	W_{p1}	W_{p2}	W_{p3}	W_p
Church in Psary (Podwyższenia Krzyża Świętego)	4308	300	4.6	2.9	3.2	0.78	0.87	0.62	0.76
Chapel of St. Kinga in Wieliczka	7500	500	5.13	3.2	3.3	0.74	0.9	0.58	0.74
Church of St. Jan Kanty in Kraków	14500	1200	12.2	4.9	2.12	0.43	0.81	0.26	0.47
Church of St. Peter and Paul, in Kraków	24000	300 2000 4000	4.7	4.3 2.8 1.98	4.6 3.0 2.5	0.58 0.88 0.96	0.74 0.93 0.83	0.4 0.7 0.86	0.61 0.88 0.91
Church of St. Apostles Peter and Paul, in Trzebinia	12000	900	5.5	3.3	3.4	0.74	0.92	0.57	0.74
Church of the Reformati Fathers in Wieliczka	4450	300	2.9	2.3	2.5	0.90	0.99	0.74	0.88

V_S – volume of the interior of the church; n_w – number of persons present in the church; T_Z – average reverberation time measured in the empty church; T_{ZS} – measured reverberation time corrected for the presence of the congregation; T_{ZS500} – measured reverberation time corrected for the presence of the congregation for the octave band of medium frequency 500 Hz; $W_{p1} \div W_{p3}$ – auxiliary reverberation indices; W_p – reverberation index.

5. Conclusions

In this paper, a proposition of the acoustic assessment of sacral buildings by means of the reverberation indices is given. Currently available methods adapted to the acoustic assessment of sacral buildings were shortly discussed. The analysis of Beranek's scale, the Ando's method, the RASTI method and the impulse method shows that none of them considers the specificity of interiors of churches of different religion in a sufficient way. Those methods were developed either for the assessment of acoustic performance of concert and opera halls or for the estimation of the intelligibility of speech. Thus, their application should be supplemented by other methods.

The index method introduced by the authors is based on the previous analysis of existing methods and other parameters essential for the acoustic properties of a building.

The index method can be used for sacral objects of volumes ranging from 600 m³ to 40000 m³, in which the reverberation time, corrected by the presence of the congregation, is smaller than 7 s.

Problems connected with the directivity and diffusion of the acoustic energy are omitted in this paper since they will be discussed when introducing other acoustic indices.

In the paper, one of the main partial indices, the reverberation index, W , was discussed. This index was applied in practice for the assessment of several churches in that acoustic tests were performed.

Further investigations in this field are necessary in order to define other indices and to develop uniform criteria of the acoustic quality assessment.

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