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The Comparative Analysis of Acoustic Properties of Roman Catholic Churches Using the Index Method

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Development of the index method for acoustic assessment of Roman Catholic churches is presented in the article. The current version of the global index was developed on the grounds of studies conducted in 8 churches and was based on 4 partial assessment indices: reverberation, music sound, speech intelligibility, and external disturbances. The use of sound strength as another partial index for global assessment is proposed in the article. A new formula of the global index for assessment of the acoustic quality of Roman Catholic churches is proposed. The computational procedure of the global index which uses analytical tools such as singular value decomposition (SVD) and comparative multivariate analysis (CMA) resulted from studies and analyses performed on an index observation matrix that was larger than before. Verification of index assessment was carried out for a sample of 12 Roman Catholic churches.

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1. Introduction

Despite numerous research works concerning church interiors, no complete method for assessment of the acoustic quality of this type of interior has been developed to date. In the methods of Beranek [1] and Ando [2] for assessment of concert halls, the total assessment of a building's acoustic properties is the weighted sum of uncorrelated partial indices thanks to which it is possible to assess various aspects of the acoustic field. Due to the wide range of acoustic production that is present in temples, particularly in Roman Catholic churches, any synthetic assessment of correlated acoustic parameters is difficult. An attempt to develop a unified method of acoustic assessment of churches has been undertaken by Berardi [3] who has proposed a double index for separate synthetic assessment of acoustic properties related to music and speech.

Acoustic studies in religious buildings are usually carried out using an interior's impulse response from which acoustic parameters are obtained. The impulse response of interiors of religious buildings is also used in listening tests conducted in subjective studies utilizing the convolution technique [4, 5].

Another approach, based on synthesis of the assessment of the acoustic parameters of a church interior into one number, is the subject of many years of studies and analyses conducted by the author, especially in [6] and [7]. The results of studies presented in this article are the continuation of work on improving the proposed index method of acoustic assessment of Roman Catholic churches. Until now, the complete assessment of the acoustic properties of churches of this type using the global index was a function of four proposed partial indices: reverberation R, music sound M, speech intelligibility S, and external disturbances D. The three correlated indices R, M, and S were replaced with one index using the method of Singular Value Decomposition (SVD) of an index observation matrix with dimensions of 8x3 (8 churches, 3 indices). Currently, the SVD method is proposed to be used in order to reduce the number of correlated indices using linear transformation performed on a larger index observation matrix than before, containing 12 studied buildings. It is also proposed to increase the number of partial indices and to introduce the sound strength index S_T to the global assessment.

2. The studied churches

12 Roman Catholic churches were studied: St. Sebastian's Church, Strzelce Wielkie (SE); St. Andrew's Apostle Church, Gilowice (AA); St. Joachim's Church, Krzyżanowice (JO); The Holiest Sacred Heart's Church, Cracow (NS); St. Clemens Church, Wieliczka (KL); The Holy Cross Increase Church, Psary (PK); The Jesuits Fathers Church, Cracow (JE); St. Peter and Paul Apostles' Church, Trzebinia (AP); St. John the Baptist Church, Cracow (JC); St. Joseph's Church, Cracow (JF); St. Paul Apostle Church, Bochnia (PA); Sanctuary of the Divine Mercy, Cracow (BM), including historical (in that number some wooden) and modern buildings, with cubature ranging from 1102 to 41378 m^3, with differing floor shapes and interior furnishing appropriately to the architectural style in which they were built (Fig. 1). The churches have wooden pews, stained glass windows, floors made of marble or ceramic tiles, and organs located on the gallery over the church main entrance. Apart from three historical wooden churches — SE, JO, and AA (Fig. 1), the wall finishing in churches is cement-lime plaster coated with emulsion paint.

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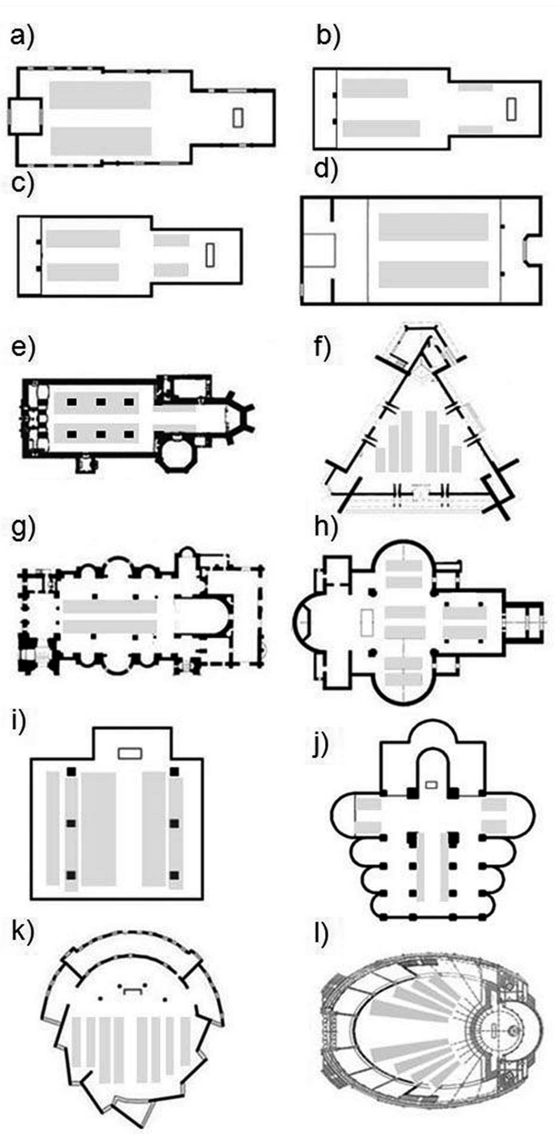

Fig. 1. Ground plan with pew zone (shaded area) for the 12 churches surveyed: a) St. Sebastian's Church, Strzelce Wielkie (SE); b) St. Andrew's Apostle Church, Gilowice (AA); c) St. Joachim's Church, Krzyżanowice (JO); d) The Holiest Sacred Heart's Church, Cracow (NS); e) St. Clemens Church, Wieliczka (KL); f) The Holy Cross Increase Church, Psary (PK); g) The Jesuits Fathers Church, Cracow (JE); h) St. Peter and Paul Apostles' Church, Trzebinia (AP); i) St. John the Baptist Church, Cracow (JC); j) St. Joseph's Church, Cracow (JF); k) St. Paul Apostle Church, Bochnia (PA); l) Sanctuary of the Divine Mercy, Cracow (BM).

3. Results of experimental studies

Acoustic measurements in 12 churches were carried out in accordance with standard ISO-3382 [8], according to the measurement technique described in [7]. Studies where based on determination of a room's impulse response from which the values of acoustic parameters were calculated, such as: T_{30} (reverberation time), C_{80} (music clarity index), rapid speech transmission index (RASTI), L_{Aeq} (equivalent sound A level of external disturbance inside the church), and G (sound strength). The values of these parameters, averaged over measuring points and octave frequency bands in the range 125–8000 Hz, are shown in Table I. The exception was G_{mid} which was averaged over octave bands with a mid-band frequency of 500 Hz and 1000 Hz. The measured average values of T_{30}, increasing with the cubature of churches, ranged from 1.4 to 8.1 seconds.

TABLE I

Acoustic parameters of 12 Roman Catholic churches surveyed

Church	vol. [m^3]	T_{30} [s]	C_{80} [dB]	*RASTI*	L_{Aeq} [dB]	G_{mid} [dB]
SE	1102	1.4	2.5	0.53	27.3	5.2
AA	1215	1.6	1.3	0.52	35.1	3.8
JO	1770	1.6	0.8	0.49	22.9	2.4
NS	2750	2.6	–1.9	0.37	34.6	5.8
KL	6380	2.8	–2.7	0.35	32.2	2.8
PK	6800	4.1	–4.0	0.31	33.4	4.3
JE	9120	6.0	–4.3	0.27	32.3	9.3
AP	12000	5.5	–6.6	0.27	39.6	0.3
JC	14360	7.4	–6.8	0.25	32.1	2.3
JF	16962	6.1	–8.8	0.26	29.6	1.0
PA	22000	8.1	–6.5	0.17	26.3	4.9
BM	41378	7.6	–6.5	0.21	28.8	–0.5

4. The index method in acoustic assessment of churches

The index method of acoustic assessment of churches proposed in [9] and modified in later studies is based on a single-number global index of acoustic quality that is a function of several partial indices. The global index constitutes an approximate general assessment, whereas partial indices provide more precise information about acoustic parameters related to their generally accepted preferred values. All indices assume values from 0 to 1. The 1 value signifies very good acoustic properties. Such a value of an acoustic parameter corresponds to the preferred acoustic quality represented by this parameter. The 0 value of an index signifies bad properties that significantly deviate from the preferred acoustic feature represented by this parameter. Assessment using the index method applies to unoccupied churches and buildings with their sound amplification system switched off.

It is currently proposed in the index method that the new global index of assessment of the acoustic quality of Roman Catholic churches, *GI*, is a function of five partial indices: reverberation R, music sound M, speech intelligibility S, external disturbances D, and sound strength S_T. The computational procedures for the case of four indices: R, M, S, and D have been shown in [7]. The sound strength index S_T was proposed in [10] where it was used in studies that simulated a church with defective acoustics. The correlated indices R, M, and S are reduced using the SVD technique to the single-number RMS index. Next, the weights of each of the uncorrelated indices, RMS, D, and S_T, are calculated using the method of Comparative Multivariate Analysis (CMA) described in [11].

4.1. Assessment using partial indices

For the 12 studied churches, the values of 5 partial indices, averaged over all measuring points, were determined, as shown in Fig. 2. Three historical wooden churches (SE, JO, AA) have very good reverberation conditions ($R = 1$) which favors good speech intelligibility ($S \approx 0.5$) and good music sound ($M = 1$). Churches with large cubature have the worst parameters (JF, JE, PA, JC, and BM). Their reverberation indices are near or equal to 0. Speech intelligibility in these churches is bad ($S < 0.3$). One of the churches mentioned above (JE) is distinguished by good conditions for listening to music ($M = 0.6$). Only 5 among the 12 studied buildings have good conditions for undisturbed prayer or meditation ($D = 1$). Two churches, BM and AP, have sound strength indices $S_T = 0$.

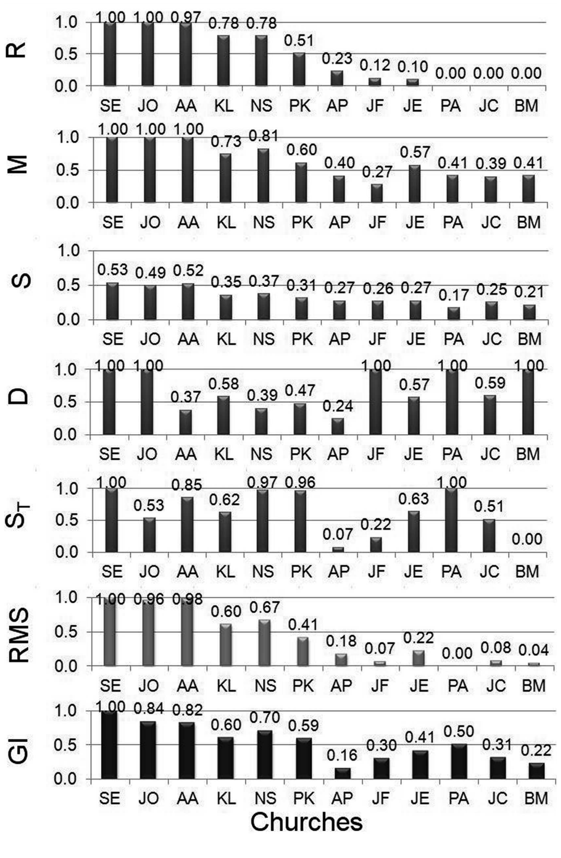

Fig. 2. Comparison of the acoustic properties of 12 churches using: partial indices R, M, S, D, S_T; reduced RMS; and the global index GI.

4.2. Global assessment of churches

4.2.1. Reduction of the number of correlated partial indices using SVD

In order to reduce partial indices that are correlated with each other, the Singular Value Decomposition technique, known as SVD, was used. Among many applications of SVD, dimensional reduction of matrices, data compression, and analysis of relationships between variables should be enumerated. For many years, SVD has been applied in problems of multi-dimensional machine diagnostics [12].

Analysis of the linear correlation of three partial indices, R, M, and S, showed that they are strongly correlated with each other. Their linear correlation coefficients are: $R \leftrightarrow M$: 0.947, $R \leftrightarrow S$: 0.941, $M \leftrightarrow S$: 0.938. On the basis of the values of three partial indices, R, M, and S, determined in 12 churches, observation matrix $\boldsymbol{A}$ was created (with dimensions of 12x3) and was subjected to SVD after prior standardization of every column vector. Three matrices were obtained [7]:

$$\boldsymbol{A} = \boldsymbol{U}\Sigma\boldsymbol{V}^T, \tag{1}$$

where $\boldsymbol{U}$ is an orthonormal matrix $m \times m$, Σ is a diagonal matrix $m \times n$, and $\boldsymbol{V}^T$ is an orthonormal matrix $n \times n$. The columns of matrix $\boldsymbol{U}$ are called the left singular vectors $\boldsymbol{u}_i = [u_{1i}, u_{2i}, u_{3i}, \ldots u_{mi}]^T$. The rows of $\boldsymbol{V}^T$ contain elements of the right singular vectors $\boldsymbol{v}_i = [v_{1i}, v_{2i}, v_{3i}, \ldots, v_{ni}]$. The elements of Σ are non-zero on diagonals and are called the singular values. Matrix $\boldsymbol{V}$ was used for linear transformation, and matrix $\boldsymbol{B}$ was obtained:

$$\boldsymbol{B} = \boldsymbol{A}\boldsymbol{V} = \boldsymbol{U}\Sigma. \tag{2}$$

Matrix $\boldsymbol{B}$, with dimensions of 12×3, contains uncorrelated column vectors $\boldsymbol{b}_i = [b_{1i}, b_{2i}, b_{3i}, \ldots b_{12i}]^T$. The first vector, $\boldsymbol{b}_1$, provides the most important information. This results from the fact that the first singular component σ_1 usually has the largest value in comparison to the others, σ_2 and σ_3. The percentage shares of clarification of information by successive singular components are equal to 78%, 12%, and 10%. Thus, vectors $\boldsymbol{b}_2$ and $\boldsymbol{b}_3$ can be discarded, and the number of indices will be reduced to a single vector, $\boldsymbol{b}_1$, in this way. The single-number index RMS is obtained after normalization of vector $\boldsymbol{b}_1$to the range from 0 to 1.

The single number RMS index is very strongly correlated with indices R, M, and S. Linear correlation coefficients are equal to: $RMS \leftrightarrow R$: 0.982, $RMS \leftrightarrow M$: 0.981, $RMS \leftrightarrow S$: 0.979. The values of the RMS index, calculated for 12 churches, are shown in Fig. 2.

4.2.2. The global index as a synthesis of uncorrelated indices

The global index GI is the weighted sum of uncorrelated partial indices: RMS, D, and S_T. The linear correlation coefficients between indices are equal to: $RMS \leftrightarrow D$: –0.087, $D \leftrightarrow S_T$: –0.087, and $S_T \leftrightarrow RMS$: 0.488. Finally, after calculating the weights of each of the uncorrelated indices, the global index of the acoustic quality of Roman Catholic churches was obtained, determined by the formula

$$GI = 0.5RMS + 0.2D + 0.3S_T. \quad (3)$$

The values of the global index GI, calculated for the 12 studied churches, are shown in Fig. 2. Among the studied buildings, only one church (SE) had a very good acoustic quality. Two further are close to such an assessment (JO and AA, with a $GI = 0.8$). Churches AP and BM have the lowest global index values.

5. Summary and conclusions

The new approach, which uses the SVD technique to obtain a single number index reduced from three other correlated indices using linear transformation performed on a greater observation matrix for 12 buildings, turned out to be effective in the sense of showing a very strong linear correlation of the reduced index with the three partial indices ($r = 0.98$).

The conducted studies and analyses showed that an index description of the acoustic properties of Roman Catholic churches may be formulated in the form of a single number, also with consideration for a fifth partial index related to sound strength. The weight values of uncorrelated indices obtained from studies conducted on 12 buildings using the CMA statistical method are proposed for assessment of any Roman Catholic church that has a cubature within the range 1100–41000 m^3.

The global assessment determined from measured values of selected parameters averaged over space and frequency, which gives an approximate assessment of the acoustic climate of a church, is, first of all, intended for people who who are not familiar with acoustics. More accurate information on individual acoustic properties is provided by partial indices which can also be determined for each measuring point, so that their spatial distribution is obtained. Both global and partial index assessment may be a helpful tool for persons concerned with the assessment, study, design, modernization, or adaptation of acoustics in churches.

The method shown in the article is worked out for analysis and assessment of the acoustic properties of the specific multifunctional interiors, such as Roman Catholic churches, characterized by a wide range of acoustic production. Religious objects are distinguished, among the other public utility objects, by two factors: *sacrum* and emotional. Taking into account the culture and symbolic virtues in the assessment procedure of acoustic quality of the churches is a very difficult task.

The index method, in the form shown in the article, for the sake of specific calculation procedure, taking into consideration both reverberation requirements for Roman Catholic churches and their range of acoustic production, should not be applied either to another type of religious buildings (synagogues, Orthodox churches) or to other multifunctional interiors (theatres, multipurpose rooms, operas).

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