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The Evaluation of Certain Acoustic Parameters of the Orthodox Church

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Abstract— This paper describes the evaluation of the acoustic parameters of the orthodox church Saint George in Žitni Potok, Serbia. Those parameters include the reverberation time, the speech transmission index, the index for music, the definition of music in both empty and full church and equivalent sound absorption by person in church . In the first part of this study the formulas for calculating the acoustic parameters are shown, based on the acoustic impulse responses determined by ISO 3382 standard. In the second part of the study the experiment used for the practical measurement of the acoustic impulse responses is described, where the results of the obtained acoustic parameters are shown graphically and in tabular along with their comparative analysis. The obtained results are analysed according to ISO 3382 standard.

Keywords— Room impulse response (RIR), reverberation, acoustic parameters.

I. INTRODUCTION

The acoustic characteristics of facilities whose primary, or one of the primary purposes is listening to a certain sound (speech or music), play an important role in enabling the communication between the source of a sound (the speaker) and the recieiver (the listener) [1].

Since Sabin s measurement of the reverberation time in 1900 untill today, there have been significant findings on the acoustic parameters which describe good acoustics of a facility whether it concerns the speech intelligibility or the quality of the music [1].

The beginning of modern acoustics are characterized by the attempts to define the objective parameters which provide the relation to geometrical and other acoustic characteristics of the facility, and listening experience as well. Within the facility, the direct sound that the listener, is accompanied by a large number of reflections contained in the room impulse response. The early reflections (during the first 50 ms or 80 ms) are particularly significant because the human auditory system integrates them along with the direct sound and thereby they contribute the overall listening experience.

Since the facility may be considered to be an acoustic transmission system, the acoustic impulse gives an overall description of the alteration of a sound signal (bearer of musical or voice communication) which occurs on its way, and by its analysis it is possible to obtain almost all objective and subjective acoustic parameters of the facility: reverberation time, temporal focus, definition, clarity, speech intelligibility, etc.[1].

From the aspect of acoustic treatment in ortodox churches , as a part of the sound components there are three distinctive forms of audio information: a) chanting of a priest, b) polichronic chanting of a priest and a choir and c) the sermons [2]. The acoustic design of a church must meet the requirements of all three sound forms, i.e. the most important parameters: a) the reverberation time due to the aesthetic demands on polichronic music, b) *IACC* (*Inter Aural Cross Correlation*) due to spatial effects which is also an important aesthetic element od a sound image and c) the relation between the direct sound and the reflected components within the response due to the speech intelligibility.

This study describes the analysis of the estimated values for some of the acoustic parameters for both empty and full church. First the measurements of the impulse responses for several different positions of a microphone have been done. Then, using software packages EASERA and Matlab and algorithm the evaluation of the following acoustic parameters: a) for the empty church: the indexes for music $C_{80unocc}$, the definition for music $D_{80unocc}$, the mean value of clarity for music $\overline{C_{80_{unocc}}}$ and the mean value of definition $\overline{D_{80_{unocc}}}$ and b) for the full church: the reverberation time RT_{30occ} , indexes of the speech transmission STI_{occ}, the clarity for music C_{80occ}, the definition for music D_{80occ}, the mean value of reverberation time per octaves bands for measured points $\overline{RT_{30occ,MP}}$, the mean value of reverberation time per octaves bands for all measurement points $\overline{RT_{30occ}}$, the mean value of reverberation time per measurement points for all octave bands $\overline{RT_{30occ,f}}$, the mean value of the speech transmission index $\overline{STI_{occ}}$, the mean value of clarity for music $\overline{C_{80_{occ}}}$, the mean value of the definition for music $\overline{D_{80_{occ}}}$, the mean value of equivalent sound absorption of the person per octaves bands for measured points $\overline{A_{pers,MP}}$, the mean value of equivalent sound absorption of the person per octave bands for all the measured points $\overline{A_{pers}}$ end the mean value of equivalent sound absorption by person by the measurement points for all octave bands $\overline{A_{pers,f}}$. The standard deviations are calculated: a) the reverberation time for the empty and the full church by the measurement points for all octave bands ($\sigma_{RT_{30unocc,f}}$, $\sigma_{RT_{30occ,f}}$) and b) the mean value of equivalent sound absorption by person by the measurement points for all octave bands $\overline{A_{pers,f}}$. The obtained values of these parameters are analysed in relation to the standard values and certain conclusion is given.

Further study organizattion is as follows: in Section 2 the acoustic impulse response and some acoustic parameters are analysed and the algorithms for their evaluation are shown. In Section 3 the experimental results along with results analysis for the acoustically processed church. Section 4 is the conclusion.

II. THE ROOM IMPULSE RESPONSE

The *Acoustic Impulse Response*, (AIR)) is defined as the alteration of sound impact at the time and at the location of the receiver in the room which occurs at the incentive signal of the room [3].

The acoustic impulse response contains all information about the acoustic characteristics of the room between the position of the source and the position of the receiver. During the sound transmission from the source to some of the receiving points in the room, the existing reflected sonic energy is the basic characteristic of the room as the acoustic transmission system.

An impulse response can be obtained in several ways. One of them is using a diagram of waveform signal from the output of the measuring microphone at room impulse using several acoustic sources which produce a shot signal (Dirac impulse which is subjectively sensated as a shot, a gun, firecracker, piercing of the inflated balloon, electric spark etc.) [4]. Other ways are based on more sophisticated methods of measuring impulse response which are more precise and fully meet the requirements of the ISO 3382 standard [5]. These are methods which are based on the emission of complex incentive signals. Most frequently these are [1]: broadband, deterministic and recurring signal, e.g. Maximum Length Sequence MLS for system impulse which is believed to be linear and time-invariable and sinusoidal signal with frequency which changes exponentially, logarithmic sweep signal (SineSwap), for system impulse which is not linear and also for time variable systems.

A. Calculation of Certain Parameters Based on the Impulse Response

The following parameters which describe the room acoustically can be derived from the impulse response [5, 7]:

1) **Reverberation Time** RT_{60} (*s*), is the time necessary for decreasing of the sonic energy of a room , after turning off the sound source, to one millionth of its value compared to the study state. Respectively, it is the time necessary for decreasing of the sound level, after turning off the sound source to 60 dB compared to the sound level in steady state.

RT_{60} is the same at all points of the room, does not depend on either the position of the sound source or the receiver in the room, but it depends on the volume of the room and the total absorption in it, the geometry of the space and it is the dimension which depends also on the frequency.

Reverberation Time RT_{60} (s), is defined in accordance to Sabin's formula [4]:

$$RT_{60} = \frac{0.16V}{A}, \tag{1}$$

and Eyring's formula:

$$RT_{60} = \frac{0.16V}{-S\,ln\left(1-\overline{\alpha}\right)}, \tag{2}$$

where: V (m^3) is the total volume of a room; $A = \overline{\alpha}\, S$ (m^2) is the equivalent absorption area in a room; S (m^2) is the sum of all areas in a room; $\overline{\alpha}$ is the mean coefficient of the absorption. Sabin's formula is applicable for the rooms with the approximate diffuse sound field where RT_{60} > 0.8 s, while Eyring's formula states more precise results for the rooms with RT_{60} < 0.8 s.

During the measuring procedure it is not possible to achieve the dynamics of decrease of the sound level in a room to 60 dB, so that the reverberation is determined according to the decrease of the sound level at 20 dB, (RT_{20}), 25 dB, (RT_{25}) and 30dB, (RT_{30}).

Duration of the impulse response must be longer than the reverberation time. The dynamics of the measured impulse response must be at least 20 dB, but it is recommended, for the sake of objectivity, that the dynamic range is at least 30 dB [7].

2) **Early Decay Time** *EDT*, is [8] defined as the time necessary for the sound level to decrease by 10 dB, starting from -5 dB compared to the maximum level. It depends on room geometry. If *EDT* significantly deviates from the reverberation time, it is shown that it is most important for the subjective perception of a room reverberation.

3) **Centre Time** T_C, is a dimension which shows the discrete divides the impulse response into an early and a late period. [9]. Along the timeline of the impulse response the values of this dimension give the information about equal energy of the initial part of the impulse response and the energy of the rest of the impulse response:

$$T_C = \int_0^\infty t h^2(t)dt \Big/ \int_0^\infty h^2(t)dt\,. \tag{3}$$

4) **Clarity** is the parameter which characterizes the time distinguishing tones which appear simultaneously despite the existing reverberation. The objective measure of the clarity is index C (dB).The parameters C_{50} and C_{80} are defined as logarithmic relation of the early acoustic energy (the one which reaches the certain spot in the room for the first 50 ms or 80 ms of impulse response) to the remaining subsequent acoustic energy (the energy which appears after a defined moment in time):

$$C_{t_e} = 10 log\left(\int_0^{t_e} h^2(t)dt \Big/ \int_{t_e}^{\infty} h^2(t)dt \right), \quad (4)$$

t_e is 50 ms or 80 ms. The parameter C_{50} is used for speech, and a C_{80} is used for music.

5) **Definition** D_{50}, and D_{80}, represents the relation between The early acoustic energy (first 50 ms or 80 ms of the impulse response) and the total acoustic energy ranging ($0 - \infty$):

$$D_{t_e} = \int_0^{t_e} h^2(t)dt \Big/ \int_0^{\infty} h^2(t)dt \quad . \quad (5)$$

D_{t_e} also measures the share of the energy of a direct wave and early reflections within the total signal. It can be also shown as a percentage. The definition of the higher percentages provides better listening conditions, and significantly influences the intelligibility. The connection between the parameters D_{t_e} and C_{t_e} is achieved by the following relation:

$$C_{t_e} = 10 log \frac{D_{t_e}}{1 - D_{t_e}} \Rightarrow D_{t_e} = \frac{10^{C_{te}/10}}{1 + 10^{C_{te}/10}} . \quad (6)$$

6) **Degree of speech intelligibility** is performed using the objective parameters: AL_{cons} (*Articulation Loss of Consonants*), *STI* (*Speech Transmission Index*) and RASTI (*Rapid Speech Transmission Index*) which qualify the subjective feeling of speech intelligibility. Peutz [8] explained that the percentage of indistinct consonants AL_{cons}. AL_{cons} depends on relation between the direct and the reflected sound, reverberation time, and the relation signal/noise in a room.

RASTI and *STIPA* (*Speech Transmission Index for Public address*) methods represent the condensed *STI* methods [6]. They are obtain by reducing the number of modulation frequences and the number of octave bands in which *STI* is calculated i.e. measured. *STIPA* is sensitive to the distortion in the system, and *RASTI* is focused on direct speech communication and it includes the impact of the environment.

B. The Evaluation of the Parameters for the Full Room

1) The evaluation of the reverberation time for the full room RT_{occ} can be carried out using the following formula [10]:

$$RT_{occ} = RT_{unocc} - DT , \quad (7)$$

where RT_{unocc} is estimated reverberation time for the empty room, and *DT* is Shulc's diffusiion time which is calculated using the equations from the Table 1 [10].

TABLE I
SHULC'S ESTIMATED VALUES FOR *RT*.

***f* (Hz)**	***DT* (s)**
125	0.510*RT*-0.708
250	0.605*RT*-0.867
500	0.668*RT*-0.929
1000	0.696*RT*-0.935
2000	0.694*RT*-0.889
4000	0.652*RT*-0.752

Just noticeable difference of the reverberation time values detected by the listeners is 1 JND=5% [5].

2) The evaluation of the speech intelligibility parameters for the full room STI_{occ} can be carried out using [11]:

$$STI_{occ} = STI_{unocc} + \Delta STI . \quad (8)$$

STI_{unocc} is the index of the speech transmission for the empty room and ΔSTI je the value which is calculated using the following formula:

$$\Delta STI = 0.45 ln \frac{RT_{unocc}(2kHz)}{RT_{occ}(2kHz)} + 0.012 , \quad (9)$$

where RT_{unocc} is the reverberation time of the empty room and RT_{occ} is the reverberation time of the full room. These values are taken at f=2 kHz [11].

3) The evaluation of the music clarity in the room can be carried out using Baron's theory of sound decreasing in which the direct sound follows an exponential decrease in sound energy [12, 13]. Propagation time of the direct sound from the source to the receiver at the distance *r* is $t_D=r/c$, where *c* is the speed of sound.

For the room of the volume *V* integrated acoustic energy *l* for the time $t \geq t_D$, where $t \to \infty$, at certain location in the room is:

$$l(t) = 31200 \frac{RT}{V} e^{-\frac{13.82t}{RT}} , \quad (10)$$

where *RT* is thw reverberation time.

The evaluation of music clarity parameters in the room, C_{80}, includes three components of the received sound at the receiver position: the direct sound *d* (Eq. 11), the early reflected sound *e* with the delay less than 80 ms (Eq. 12) and the late reflected sound *l* with the delay of more than 80 ms (Eq. 13):

$$d = \frac{100}{r^2}, \tag{11}$$

$$e = 31200\frac{RT}{V}e^{-\frac{0.04r}{RT}}\left(1-e^{-\frac{1.11}{RT}}\right), \tag{12}$$

and

$$l = 31200\frac{RT}{V}e^{-\frac{0.04r}{RT}}e^{-\frac{1.11}{RT}}. \tag{13}$$

where *r* is the distance between the receiver and the source. The estinated parameter of the sound clarity in the room C_{80} is:

$$C_{80} = 10\,log\frac{\int_{t_0}^{t_0-0.08} p^2(t)dt}{\int_{t_0+0.08}^{\infty} p^2(t)dt} = 10\,log\frac{d+e}{l}. \tag{14}$$

4) The calculation of the equivalent sound absorption by person (A_{pers} in m^2) can be done starting from the Sabine equation [11]:

$$A_{pers} = \frac{0.16V}{N}\left(\frac{1}{RT_{occ}} - \frac{1}{RT_{unocc}}\right), \tag{15}$$

where *N* is the number of persons, *V* is the volume of the room, RT_{occ} and RT_{unocc}, the reverberation time values in the full and empty room, respectively. The values for sound absorption by person who is standing (with a coat and without a coat) are given in [14].

III. THE EXPERIMENTAL RESULTS AND THE ANALYSIS

The evaluation of the acoustic parameters has been carried out for the ortodox church ‘Sveti Đorđe’ in Žitni Potok, Serbia, which is shown in the Fig. 1.

Fig. 1 The church Saint George in Žitni Potok

After the measurements of the impulse responses, the evaluation of the acoustic parameters for both empty and full church has been carried out using software packages EASER and Matlab and the theoretical models as well. The process of recording, as well as the parameters evaluation is performed in accordance with the ISO 3382 standard [5]. The results obtained are shown both in graphical and tabular presentation.

For the purpose of the acoustic calculations, the mean values of certain parameters such as (the reverberation time, the clarity for music, the definition of music, the speech transmission index, the equivalent sound absorption by person, the standard deviations) are required at measuring locations and the level of all measuring locations within the analysed room. Therefore, in the following part of this paper (Eq. 16-18) we have defined the formulas for calculating the mean values, where x stands for any of the above mentioned acoustic parameters.

The mean value of the acoustic parameters of *j*-th measuring location for N_{oct} octaves is as follows:

$$\overline{X_{a,j}} = \frac{1}{N_{oct}}\sum_{i=1}^{N_{oct}} X(f_c(i)), \qquad 1 \le j \le MP, \tag{16}$$

where: f_c are the central frequency of the i - th octave band ($f_c \in \{125, 250, 500, 1000, 2000, 4000\}$), N_{oct} number of the octave bands analysed, *MP* the total number of measured points, and *X* stands for some of the above listed acoustic parameters. The mean values of acoustic parameters for all measuring points are calculated using:

$$\overline{X} = \frac{1}{MP}\sum_{j=1}^{MP}\overline{X_{a,j}} . \tag{17}$$

The mean values of acoustic parameters for *i*–th octave bands with the central frequency f_c for the whole church are calculated using:

$$\overline{X_i} = \frac{1}{MP}\sum_{j=1}^{MP} X_j(f_c(i)), \qquad 1 \le i \le N_{oct} . \tag{18}$$

The standard deviations of the acoustic parameters for *i*–th octave bands with central frequency f_c for the whole church are calculated using:

$$\sigma_{X_i} = \sqrt{\frac{\sum_{j=1}^{MP}(X_j(f_c(i)) - \overline{X_i})^2}{MP-1}} . \tag{19}$$

By the comparative analysis of the obtained parameters values for the full church, and the same values for the empty church and the values obtained by ISO 3382 standard, we can draw the conclusion on the effects to the speech and music intelligibility in the church along with its acoustic suitability.

The measurements and the calculations are carried out in accordance to ISO 3382 standard [5]: a) the minimum distance between two measuring locations is 2 m; b) the distance between each measuring locations and the closer reflecting superficies (including the floor) is approximately 1 m; c) the minimum distance between the measuring location and the sound source is defined by the term:

$$d_{\min} = 2\sqrt{\frac{V}{cRT}} , \tag{20}$$

where *V* is the volume of the room, *c* is the propagation speed of the sound in the room, *RT* is the estimated reverberation time; d) the height of the sound source is 1.5 m above the floor; e) the height of the microphone is 1.2 m above the floor (the height of an ear of a person in the sitting position).

The optimal reverberation time is calculated for f = 500 Hz je [15]:

$$RT_{opt} = 0.55 \log V - 0.14 . \tag{21}$$

The diagrams for the empirical determination of the reverberation time with respect to the volume of the room in accordance to ISO 12001 standard are given in [16, 17].

A. The Experiment

The process of measuring the acoustic impulse response is carried out in the Orthodox church with its volume V = 2163 m^3, inner area S = 167 m^2, at the temperature t = 25 ^{o}C. The interior walls and the ceilings covered with plaster (the coefficient of absorption α = 0.02). The floor with the ceramic tiles (the coefficient of absorption α = 0.015). The church capacity of about 80 people.

The equippment used for the experiment as follows: (a) an omnidirectional microphone (PCB 130D20), having a diaphragm diameter of 7mm; (b) a B&K omnidirectional sound source type 4295 (dodecahedron loudspeaker); (c) a B&K audio power amplifier, rated at 100W RMS, stereo, type 2716-C; (d) a laptop, incorporating a Soundmax Integrated Digital Audio sound card from Analog Devices. Measuring of the impulse response is carried out using incentive log sweep signal with the duration of 5 s sampling frequency is f_S = 44.1 kHz. The recording of the acoustic impulse responses is carried out at the measured points positioned as in the Fig. 2.

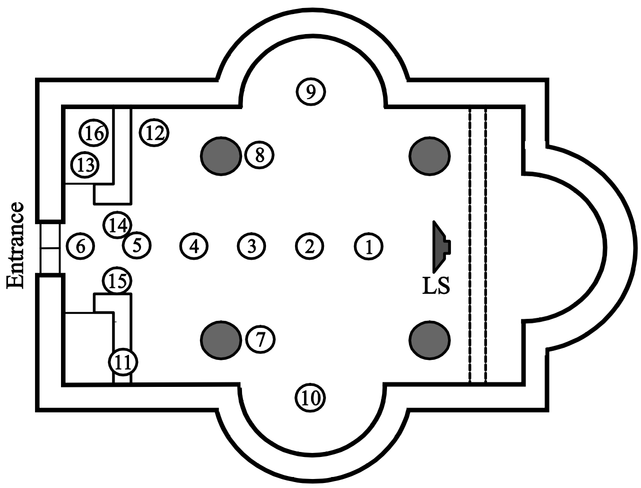

Fig.2 The church where the impulse response is measured: LS the location of the sound source, 1-16-measured points.

The position of the sound source, *LS* is located near the altar. The measurement are carried out at *MP*=16 measured points. Three of the measured points are located on the balcony (measured points 14, 15 i 16). The minimum distance from the microphone to the loudspeakers is d = 3.54 m. There are a small number of seats in the church, so that the measurements are also carried out with the microphone 1.5 m above the floor.

B. The Results

The calculated values of the reverberation time for both empty and full church are shown in the Table 2 and Table 3, respectively. In the Table 4 shows the values of a) the reverberation time $RT_{30unocc}$ (1 kHz, 2 kHz), the speech transmission index STI_{unocc}, the clarity for the music $C_{80unocc}$ and definition for music $D_{80unocc}$; b) the reverberation time RT_{30occ} (1 kHz, 2 kHz), the speech transmission index STI_{occ}, the clarity for the music C_{80occ} and definition for music D_{80occ} for the full church. Table 6 shows the estimated values a) of equivalent sound absorption by person for the measured points A_{pers}, b) the mean equivalent sound absorption by person for by the octave bands for measured points $\overline{A_{pers,MP}}$ and c) the estimated mean value of the equivalent sound absorption by person $\overline{A_{pers}}$ for the church. Table 5 and Table 7 show the mean value and the standard deviation $RT_{30unocc}$ and RT_{30occ} according to frequency for the empty and full church and the mean values and the standard deviation A_{pers} by the measurement points for all octave bands, respectively. . The changes in the mean values of the reverberation times $RT_{30unocc}$ and RT_{30occ}, the speech transmission indexes STI_{unocc} i STI_{occ} and the clarity for the music $C_{80unocc}$ i C_{80occ} at the measuring locations for both empty and full church are shown in the Fig. 3, the Fig. 4 and the Fig. 5, respectively. Equivalent sound absorption by person by the octave bands for all measurement points and by the measurement points for all octave bands are shown in Fig. 6 and Fig. 7, respectively.

TABLE II
THE VALUES OF: A) THE REVERBERATION TIME FOR THE MEASURED POINTS $RT_{30UNOCC}$, B) THE MEAN REVERBERATION TIME FOR THE MEASURED POINTS $\overline{RT_{30unocc,MP}}$ AND C) THE MEAN REVERBERATION TIME $\overline{RT_{30unocc}}$ FOR THE EMPTY CHURCH.

***f* (Hz)**	**MP**															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
125	2.39	2.58	2.76	2.84	2.88	2.80	2.41	2.96	2.71	2.60	3.50	2.79	3.29	2.47	2.15	2.43
250	2.44	2.62	2.16	2.49	2.20	2.67	2.43	2.46	2.68	2.92	2.16	2.45	2.49	2.47	2.11	2.31
500	2.36	1.90	2.33	2.28	2.16	2.30	2.36	2.63	1.88	2.16	2.38	2.43	2.56	2.14	2.30	1.97
1000	2.29	2.25	2.25	2.23	2.12	2.29	2.46	2.51	2.54	2.44	2.25	2.17	2.19	2.28	2.34	2.27
2000	2.12	2.12	2.08	2.06	2.05	2.11	2.23	2.21	2.13	2.02	2.03	2.08	2.07	2.09	1.98	2.02
4000	1.91	1.91	1.85	1.78	1.81	1.82	1.88	1.90	1.86	1.78	1.80	1.86	1.83	1.80	1.75	1.82
$\overline{RT_{30unocc,MP}}$ (s)	2.25	2.23	2.24	2.28	2.20	2.33	2.30	2.45	2.30	2.32	2.35	2.30	2.41	2.21	2.11	2.14
$\overline{RT_{30unocc}}$ (s)	2.28															

TABLE III
THE ESTIMATED VALUES: A) OF THE REVERBERATION TIME FOR THE MEASURED POINTS RT_{30OCC} , B) THE MEAN REVERBERATION TIME FOR THE MEASURED POINTS $\overline{RT_{30occ,MP}}$ AND C) THE ESTIMATED MEAN VALUE OF THE REVERBERATION TIME $\overline{RT_{30occ}}$ FOR THE FULL CHURCH.

***f* (Hz)**	**MP**															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
125	1.88	1.97	2.06	2.10	2.12	2.08	1.89	2.16	2.04	1.89	2.46	2.07	2.32	1.92	1.76	1.89
250	1.83	1.90	1.72	1.85	1.74	1.92	1.83	1.84	1.93	2.02	1.72	1.83	1.85	1.84	1.70	1.78
500	1.71	1.56	1.70	1.69	1.65	1.69	1.71	1.80	1.55	1.65	1.72	1.74	1.78	1.64	1.69	1.58
1000	1.63	1.62	1.62	1.61	1.58	1.63	1.68	1.70	1.71	1.68	1.62	1.59	1.60	1.63	1.64	1.62
2000	1.54	1.54	1.52	1.52	1.52	1.54	1.57	1.56	1.54	1.51	1.51	1.52	1.52	1.53	1.49	1.51
4000	1.42	1.42	1.40	1.37	1.38	1.38	1.41	1.41	1.40	1.37	1.38	1.40	1.39	1.38	1.36	1.38
$\overline{RT_{30occ,MP}}$ (s)	1.67	1.67	1.67	1.69	1.66	1.71	1.68	1.75	1.69	1.69	1.73	1.69	1.74	1.66	1.61	1.63
$\overline{RT_{30occ}}$ (s)	1.68															

TABLE V
THE MEAN VALUE AND THE STANDARD DEVIATION $RT_{30UNOCC}$ AND RT_{30OCC} ACCORDING TO FREQUENCY FOR THE EMPTY AND FULL CHURCH.

***f* (Hz)**	**125**	**250**	**500**	**1000**	**2000**
$\overline{RT_{30unocc,f}}$ (s)	2.72	2.44	2.26	2.30	2.09
$\sigma_{\overline{RT_{30unocc,f}}}$ (s)	0.342	0.219	0.215	0.122	0.066
$\overline{RT_{30occ,f}}$ (s)	2.04	1.83	1.68	1.63	1.53
$\sigma_{\overline{RT_{30occ,f}}}$ (s)	0.177	0.086	0.071	0.038	0.020

TABLE IV

THE VALUES OF THE PARAMETERS A) THE REVERBERATION TIME $RT_{30UNOCC}$ (1 KHZ, 2 KHZ), THE SPEECH TRANSMISSION INDEX STI_{UNOCC}, THE CLARITY FOR MUSIC $C_{80UNOCC}$ AND DEFINITION FOR MUSIC $D_{80UNOCC}$ FOR THE EMPTY CHURCH AND B) THE ESTIMATED VALUES OF THE REVERBERATION TIME RT_{30OCC} (1 KHZ, 2 KHZ), THE SPEECH TRANSMISSION INDEX STI_{OCC}, THE VALUES OF THE CLARITY FOR THE MUSIC C_{80OCC} AND DEFINITION FOR MUSIC D_{80OCC} FOR THE FULL CHURCH.

MP	$RT_{30unocc}$ (1 kHz) (s)	RT_{30occ} (1 kHz) (s)	$RT_{30unocc}$ (2 kHz) (s)	RT_{30occ} (2 kHz) (s)	STI_{unocc}	STI_{occ}	$C_{80unocc}$ (dB)	C_{80occ} (dB)	$D_{80unocc}$ (%)	D_{80occ} (%)
1	2.29	1.63	2.12	1.54	0.49	0.64	-0.14	1.62	49	59
2	2.25	1.62	2.12	1.54	0.45	0.60	-0.67	1.06	46	56
3	2.25	1.62	2.08	1.52	0.42	0.57	-0.1	0.70	49	54
4	2.23	1.62	2.06	1.52	0.39	0.54	-1.24	0.46	47	53
5	2.12	1.58	2.05	1.52	0.41	0.56	-1.35	0.47	42	53
6	2.29	1.63	2.11	1.53	0.42	0.57	-1.67	0.18	41	51
7	2.46	1.68	2.23	1.57	0.54	0.69	-0.91	0.98	45	56
8	2.51	1.70	2.21	1.56	0.53	0.68	-1.29	0.80	43	54
9	2.54	1.71	2.13	1.54	0.47	0.62	-0.92	0.96	45	55
10	2.44	1.68	2.02	1.51	0.44	0.59	-0.96	0.94	44	55
11	2.25	1.62	2.03	1.51	0.38	0.53	-1.63	0.04	46	50
12	2.17	1.60	2.08	1.52	0.40	0.55	-1.53	0.32	41	52
13	2.19	1.60	2.07	1.52	0.37	0.52	-1.9	-0.04	39	50
14	2.28	1.63	2.09	1.53	0.37	0.52	-1.46	0.37	41	52
15	2.34	1.65	1.98	1.49	0.38	0.53	-1.25	0.37	42	52
16	2.27	1.63	2.02	1.51	0.40	0.55	-1.1	0.30	47	52
	$\overline{RT_{30unocc,MP}}$ (1 kHz) (s)	$\overline{RT_{30occ,MP}}$ (1 kHz) (s)	$\overline{RT_{30unocc,MP}}$ (2 kHz) (s)	$\overline{RT_{30occ,MP}}$ (2 kHz) (s)	$\overline{STI_{unocc}}$	$\overline{STI_{occ}}$	$\overline{C_{80unocc}}$ (dB)	$\overline{C_{80occ}}$ (dB)	$\overline{D_{80unocc}}$ (%)	$\overline{D_{80occ}}$ (%)
	2.3	1.64	2.09	1.53	0.43	0.58	-1.13	0.60	44	53

TABLE VI

THE ESTIMATED VALUES A) OF EQUIVALENT SOUND ABSORPTION BY PERSON FOR THE MEASURED POINTS A_{PERS}, B) THE MEAN EQUIVALENT SOUND ABSORPTION BY PERSON BY THE OCTAVE BANDS FOR MEASURED POINTS $\overline{A_{pers,MP}}$ AND C) THE ESTIMATED MEAN VALUE OF THE EQUIVALENT SOUND ABSORPTION BY PERSON $\overline{A_{pers}}$ FOR THE CHURCH.

	MP															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
f (Hz)	A_{pers} (m^2)															
125	0.49	0.52	0.53	0.54	0.54	0.53	0.49	0.54	0.52	0.62	0.52	0.54	0.55	0.50	0.46	0.51
250	0.59	0.63	0.51	0.60	0.52	0.64	0.58	0.59	0.63	0.66	0.51	0.60	0.60	0.60	0.49	0.56
500	0.70	0.50	0.69	0.66	0.62	0.68	0.70	0.76	0.49	0.62	0.70	0.71	0.74	0.62	0.68	0.54
1000	0.77	0.75	0.75	0.75	0.70	0.76	0.82	0.82	0.83	0.80	0.75	0.73	0.73	0.76	0.79	0.76
2000	0.77	0.77	0.77	0.75	0.74	0.76	0.81	0.82	0.78	0.72	0.74	0.77	0.76	0.76	0.72	0.72
4000	0.78	0.78	0.75	0.73	0.75	0.76	0.77	0.79	0.76	0.73	0.73	0.76	0.75	0.73	0.71	0.76
$\overline{A_{pers,MP}}$ (m^2)	0.68	0.66	0.67	0.67	0.64	0.69	0.69	0.72	0.67	0.69	0.66	0.68	0.69	0.66	0.64	0.64
$\overline{A_{pers}}$ (m^2)	0.67															

TABLE VII

THE MEAN VALUES AND THE STANDARD DEVIATION A_{PERS}. PER THE MEASUREMENT POINTS FOR ALL OCTAVE BANDS.

f (Hz)	125	250	500	1000	2000	4000
$\overline{A_{pers,f}}$ (m^2)	0.52	0.58	0.65	0.77	0.76	0.75
$\sigma_{\overline{A_{pers,f}}}$ (m^2)	0.342	0.219	0.215	0.122	0.066	0.049

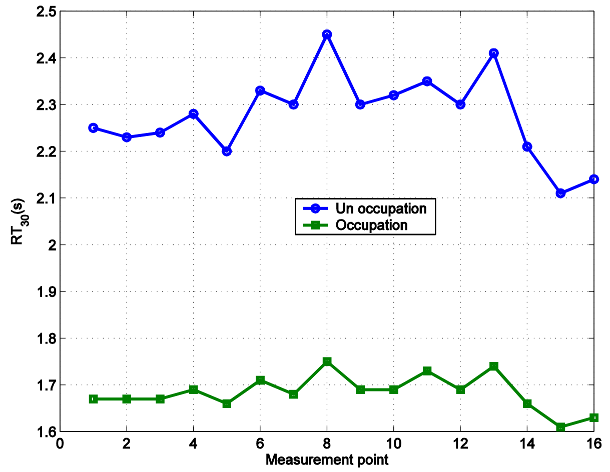

Fig. 3 The mean values of the reverberation time at the measured points for both empty and full church.

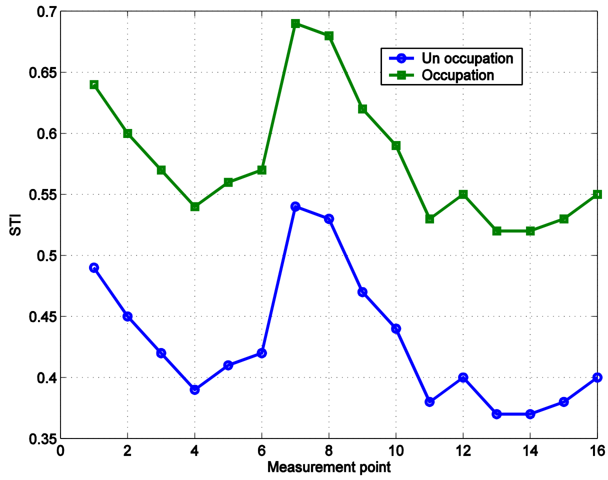

Fig. 4 The values of the speech transmission index at the measured points for both empty and full church.

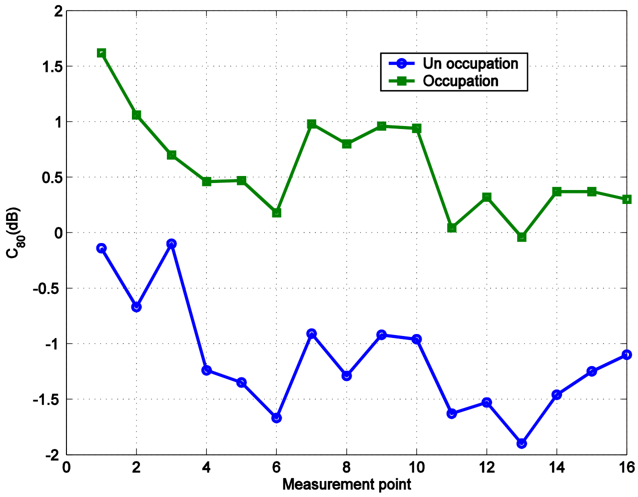

Fig.5 The values of the clarity for the music at the measured points for both empty and full church.

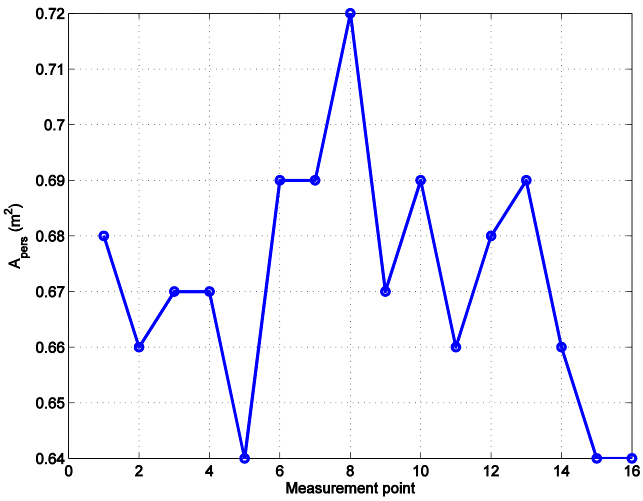

Fig. 6 Equivalent sound absorption by person by the octave bands for all measurement points

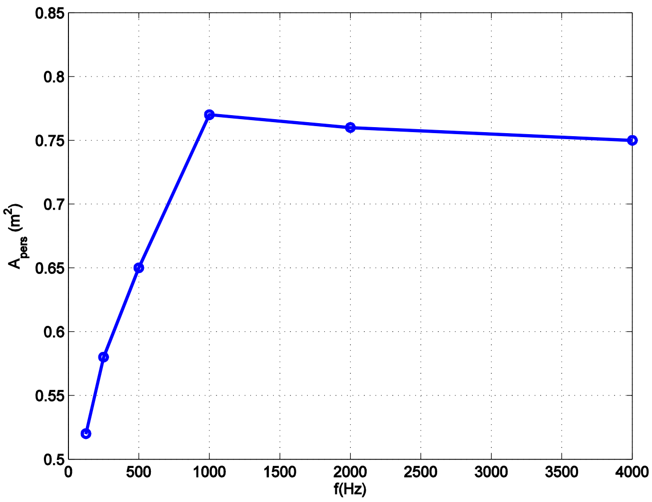

Fig.7 Equivalent sound absorption by person by the measurement points for all octave bands.

C. Comparative Analysis

Based on the results shown in the Table (3 - 8) and the Fig. 3 and Fig. 7 we can draw the following conclusion:

a) The presence of people in the church causes the fall of the reverberation time, $\overline{\Delta RT_{30}}$ = 0.6 s, which can be expected beacause of the additional audio absorption they cause.

b) The fall of the reverberation time at the frequencies which are approximate and equal to the frequency f = 1 kHz, $\overline{\Delta RT_{30}}$ (1 kHz) = 0.66 s is particularly important because these frequencies are the most important for the quality of the speech intelligibility.

c) The values of the standard deviation RT_{30} at midrange frequency for full church ($\sigma_{RT_{30occ,f}}$ = 0.071 – 0.038s) are smaller than the values of the standard deviation at midrange frequency for the empty church ($\sigma_{RT_{30unocc,f}}$ = 0.215 – 0.122s). At midrange frequency the standard deviation for the full church is $\sigma_{RT_{30occ,f}}$ < 1 JND, ($\sigma_{RT_{30occ,f}}$ = (0.84 – 0.47 JND)), and for the empty church $\sigma_{RT_{30unocc,f}}$ > 1 JND, ($\sigma_{RT_{30unocc,f}}$ = (1.9 – 1.06 JND)).

d) The calculated optimal reverberation time RT_{opt} = 1.69 s is also recommended by ISO 12001 standard for the auditoriums of specified volumes.

e) The value RT_{opt} = 1.69 s is within the range of the specified values of the optimal reverberation time for the church RT = (1.4 – 8.1) s.

f) The decrease of the reverberation time causes the expected increase of the values of the speech transmission index, $\overline{\Delta STI}$ = 0.15.

g) The estimated mean value of the speech transmission index for the empty church $\overline{STI_{unocc}}$ = 0.43 is approximate to the specified values which can be accepted as the reasonable speech intelligibility: 0.45 - 0.6.

h) The estimated mean value of the speech transmission index for the full church $\overline{STI_{occ}}$ = 0.58 is approximate to the specified values which can be accepted as good speech intelligibility: 0.6 - 0.75.

i) The estimated mean value of the clarity for the music at all measured positions in both ($\overline{C_{80unocc}}$ = - 1.13 dB), and full church ($\overline{C_{80occ}}$ = 0.60 dB),are within the range of the optimal values C_{80opt}= 0 ± 1.6 dB.

j) The estimated mean values of the clarity for the music meet the criteria of the optimal values for the orchestral music, (0 - -3) dB and the singers (1 - 5) dB.

k) The negative values of the clarity for the music in the empty church at all measured positions confirm that the delay of the sound energy is dominant and thus the music perception is less clear. The positive values of the clarity for the music in the full church at all measured positions confirm that the inicial sound dominates and the impression of clarity is stronger. The alteration of the values of the clarity parameters is $\overline{\Delta C} = 1.73\,dB$.

l) Due to increase of the values of the clarity for the music, the music definition also increased for $\overline{\Delta D} = 10\%$.

m) The estimated mean values of the definition index for music in both empty ($\overline{D_{80unocc}}$ = 43 %), and full church ($\overline{D_{80occ}}$ = 53 %), are within the range of the optimal values D_{80opt} = (30 - 70) %.

n) The mean value of equivalent sound absorption of the person per octaves bands for measured points is 0.64 – 0.72 m2. The value equivalent sound absorption per person by the measurement points at the midrange frequency (average at 500 Hz and 1000Hz) are 0.65 ± 0.215 m2 and 0.77 ± 0.122 m2, respectively. These values belong to the values of the sound absorption person who is standing: 0:59 - 0.98 m^2.

Based on the analysis of the results we can draw the conclusion that the reduced values of the reverberation time due to the presence of the people in the church have the positive influence on the acoustic parameters related to speech and music. Their estimated values, which satisfy the conditions determined by ISO 3382 standard which refers to the speech and music can confirm that. In the study [2] it is pointed out that "the reverberation time in the ortodox church mustn't be longer than 3 s, and the aesthetic optimum is undoubtly closer to the value of 2 s.".The values obtained from this experiment for the reverberation time for both empty and full church, $\overline{RT_{30unocc}}$ = 2.28 s, $\overline{RT_{30occ}}$ = 1.68 s meet this criteria.

IV. CONCLUSIONS

This paper describes the results of the experiment carried out in the ortodox church Sveti Đorđe in Žitni Potok, Serbia. The parameters for the evaluation of the acoustic suitability of the church are defined. The reverberation time is determined based on the measured impulse responses of the church, and afterwards the evaluation of the acoustic parameters for the speech and music in the full church is carried out. The presence of the people caused the expected decrease in the mean value of the reverberation time for $\overline{\Delta RT_{30}}$ = 0.6 s, the increase in the mean value of the speech transmission index for $\overline{\Delta STI}$ = 0.15, the increase in the mean values of the clarity for the music for $\overline{\Delta C} = 1.73\ dB$ and the increase in the mean value of the definition index for the music for $\overline{\Delta D} = 10\ \%$. By the analysis of the estimated values of the acoustic parameters, we can draw the conclusion that the church Sveti Đorđe in Žitni Potok, Serbia, meets all the acoustic requirements defined by ISO 3382. standard.

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