The Estimation of Acoustic Suitability of the Amphitheater for Lecturing

Violeta Stojanović [1] and Zoran Milivojević [2]

Abstract – **This paper presents the acoustic analysis of the amphitheater provided for lecturing. In the first part of paper we describe the experiment which measures the acoustic impulse response and show the calculated acoustic parameters. The results are shown both graphically and tabular. In the second part of this paper we analyse the parameters for the empty amphitheater and their accordance to ISO 3382 standard.**

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

I. INTRODUCTION

The analysis of the acoustic parameters of a room can determine its suitability for certain purposes. Namely, for auditoriums, i.e., amphitheaters, the important parameters are Reverberation Time, *RT,* and Speech Intelligibility. The empirical equation for estimation of *RT* was given by C. W. Sabine in 1922 [1]. The estimation of *RT* is based on the analysis of the volume, the dimensions and wall absorption coefficients for a certain room. Further, there were several empirical equations where the estimated and measured *RT* showed consistency within the smaller reverberation rooms in relation to Sabin's prediction. The most significant one is Norris - Eyring equation which was presented in 1930 [2]. When a wall absorption coefficients are considerably different, the best results are obtained by Milingtone Sette equation which was presented in 1933 [3]. In 1965 Schreder proposed the algorithm estimations of *RT* using RT_{60} acoustic parameter, which is calculated by analysing of the acoustic Room Impulse Response, RIR [4]. Early Decay Time, *EDT*, was defined by Jordan in 1970 [5]. Centre Time, T_C, was defined by Cremer and Curer in 1971 [6]. In 1971, Peutz suggested the parameter referring to Articulation Loss of Consonants, Al_{cons} [7]. Abdel Alim and Reichard suggested the parameter Clarity C_{50} and C_{80} for speech and music in 1974 [8]. In 1985 Houtgast and Steeneken suggested the acoustic parameter Speech Transmission Index, *STI*, within the room [9].

This paper analyses the acoustic suitability of the amphitheater by analysing some of the acoustic parameters. For the purpose of the analysis, measuring of RIR was done at 9 measuring points. After that, using RIR analysis, some of the acoustic parameters were calculated along with their mean values and standard deviations as follows *EDT*, T_{R10}, T_{R20}, and T_{R30}, T_C, C_{50}, D_{50}, AL_{cons}, *STI*, Just Noticable Difference in acoustic parameters' values detected by listeners, *JND*, was also calculated. The obtained values of these parameters were analysed in relation to the values defined by ISO 3382 standard [10]. Finally, we drew the conclusions concerning the acoustic suitability of the amphitheater. Recording of RIR and the analysis of the acoustic parameters was done using software package EASERA and Matlab.

The organization of this paper is as follows. In the section II the experiment is explained and the results are shown. In the section III, the analysis of the results of the analysed amphitheater is shown. The section IV is the conclusion.

[1] Violeta Stojanović is with the College of Applied Technical Sciences of Niš, 20. Aleksandra Medvedeva, St, 18000 Niš, Serbia, e-mail: violeta.stojanovic@vtsnis.edu.rs

[2] Zoran Milivojević is with the College of Applied Technical Sciences of Niš, 20. Aleksandra Medvedeva, St, 18000 Niš, Serbia.

II. EXPERIMENTS

The estimation of the acoustic suitability of the amphitheater at The College of Applied Technical Sciences in Niš (Serbia) is shown in Figure 1. The dimensions of the amphitheater are X = 11.5 m, Y = 11.25 m, H = 5 and the volume V = 646.875 m^3. The amphitheater capacity is $9 \times 17 = 153$ students. The reflexive coefficients of walls, ceilings and floor are 0.95, 0.85, 0.88, 0.88, 0.85 and 0.88 respectively. The air temperature is t = 20 ºC. Measuring of the impulse response is carried out using incentive log sweep signal with the duration of 6 s sampling frequency is f_S = 44.1 kHz. 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.

A. The Basis

The data base is consisted of wav files obtained by measuring of RIR at 9 measuring points, marked with circles with ordinal numbers (Fig. 1.). There were 10 measurements for each measuring points which is total of 90 files.

B. The Results

The mean values and standard deviations of the acoustic parameters for 9 measuring points are shown Table I, Table II, Table IV and Table V. The mean values and standard deviations of these parameters for the amphitheater (for all measuring points) are shown in Table III and Table VI respectively. The mean values of the acoustic parameters and their standard deviations at frequencies f = 500 Hz, 1000 Hz are shown in Table VII and Table VIII respectively. In Fig. 2. the mean values and standard deviations for RT_{30}, C_{50}, *STI* and

AL_{cons} at measuring points are shown at all measuring points. The Fig. 3. shows the regression line for *STI* and RT_{10}.

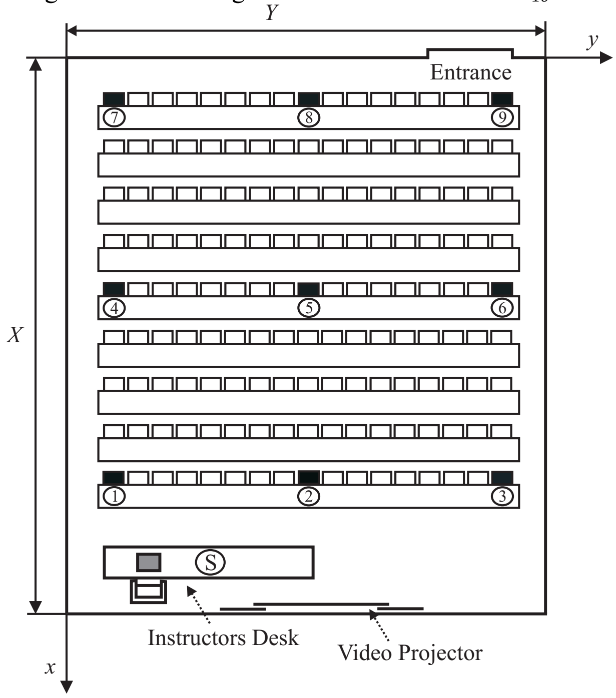

Fig. 1. The show of the room where the impulse response is measured: S - the location of the sound source, 1 - 9 - the location of the receiver.

TABLE I
THE MEAN VALUES OF THE ACOUSTIC PARAMETERS FOR THE MEASURED POINTS.

MP	$\overline{EDT}(s)$	$\overline{RT_{10}}(s)$	$\overline{RT_{20}}(s)$	$\overline{RT_{30}}(s)$
1	1.393	1.747	2.262	2.613
2	1.637	1.828	2.311	2.807
3	1.737	1.966	1.984	1.783
4	1.61	1.906	2.06	1.894
5	1.689	1.956	1.957	1.832
6	1.83	2.144	2.071	1.912
7	1.856	2.023	1.991	1.808
8	1.837	2.1	2.128	1.98
9	1.83	2.058	2.16	1.975

TABLE II
THE MEAN VALUES OF ACOUSTIC PARAMETERS FOR THE MEASURED POINTS.

MP	$\overline{T_C}(ms)$	$\overline{C_{50}}(dB)$	$\overline{STI}$	$\overline{AL_{cons}}(\%)$
1	56.944	4.14	0.551	8.61
2	71.21	3.13	0.53	9.665
3	131.261	-2.86	0.436	16.167
4	80.518	2.14	0.51	10.716
5	91.25	1.22	0.488	12.109
6	129.542	-2.07	0.422	17.337
7	109.148	-0.01	0.47	13.341
8	113.187	-0.43	0.449	14.921
9	129.381	-2.11	0.429	16.658

TABLE III
THE MEAN VALUES OF THE ACOUSTIC PARAMETERS FOR ALL MEASUREMENT POINTS.

	$\overline{EDT}(s)$	$\overline{RT_{10}}(s)$	$\overline{RT_{20}}(s)$	$\overline{RT_{30}}(s)$
MP	1.713	1.97	2.103	2.067
	$\overline{T_C}(ms)$	$\overline{C_{50}}(dB)$	$\overline{STI}$	$\overline{AL_{cons}}(\%)$
MP	101.382	0.35	0.476	13.28

TABLE IV
THE STANDARD DEVIATION OF ACOUSTIC PARAMETERS FOR THE MEASURED POINTS.

MP	$\sigma_{EDT}(s)$	$\sigma_{RT_{10}}(s)$	$\sigma_{RT_{20}}(s)$	$\sigma_{RT_{30}}(s)$
1	0.013	0.008	0.008	0.018
2	0.005	0.008	0.012	0.031
3	0.046	0.109	0.205	0.183
4	0.013	0.023	0.046	0.061
5	0.08	0.178	0.275	0.269
6	0.011	0.025	0.042	0.041
7	0.076	0.0166	0.25	0.236
8	0.08	0.0163	0.041	0.064
9	0.009	0.0193	0.031	0.086

TABLE V
THE STANDARD DEVIATION OF ACOUSTIC PARAMETERS FOR THE MEASURED POINTS.

MP	$\sigma_{T_C}(ms)$	$\sigma_{C_{50}}(dB)$	σ_{STI}	$\sigma_{AL_{cons}}(\%)$
1	0.3	0.052	0.0006	0.031
2	10.202	0.067	0.0008	0.032
3	1.882	0.334	0.0009	0.074
4	1.78	0.165	0.0011	0.066
5	3.912	0.042	0.0006	0.03
6	0.451	0.048	0.001	0.077
7	3.494	0.032	0.0007	0.05
8	0.574	0.082	0.0008	0.064
9	0.684	0.057	0.001	0.082

TABLE VI
THE STANDARD DEVIATION OF ACOUSTIC PARAMETERS FOR ALL MEASUREMENT POINTS.

	$\sigma_{EDT}(s)$	$\sigma_{RT_{10}}(s)$	$\sigma_{RT_{20}}(s)$	$\sigma_{RT_{30}}(s)$
MP	0.149	0.149	0.181	0.379
	$\sigma_{T_C}(ms)$	$\sigma_{C_{50}}(dB)$	σ_{STI}	$\sigma_{AL_{cons}}(\%)$
MP	26.432	2.35	0.0442	3.031

TABLE VII
THE MEAN VALUES OF THE ACOUSTIC PARAMETERS FOR ALL MEASUREMENT POINTS AT CERTAIN FREQUENCIES.

f(Hz)	$\overline{EDT}(s)$	$\overline{RT_{10}}(s)$	$\overline{RT_{20}}(s)$	$\overline{RT_{30}}(s)$
500	2.496	2.357	2.134	2.002
1000	2.242	2.214	2.001	1.857
f(Hz)	$\overline{C_{50}}(dB)$	$\overline{STI}$	$\overline{T_C}(ms)$	
500	-3.586	0.475	182.157	
1000	-3.212	0.475	163.285	

TABLE VIII
THE STANDARD DEVIATION OF ACOUSTIC PARAMETERS FOR ALL MEASUREMENT POINTS AT CERTAIN FREQUENCIES.

f(Hz)	$\sigma_{EDT}(s)$	$\sigma_{RT_{10}}(s)$	$\sigma_{RT_{20}}(s)$	$\sigma_{RT_{30}}(s)$
500	0.1166	0.18	0.238	0.334
1000	0.094	0.145	0.262	0.351
f(Hz)	$\sigma_{C_{50}}(dB)$	σ_{STI}	$\sigma_{T_C}(ms)$	
500	2.059	0.046	28.593	
1000	1.515	0.046	17.414	

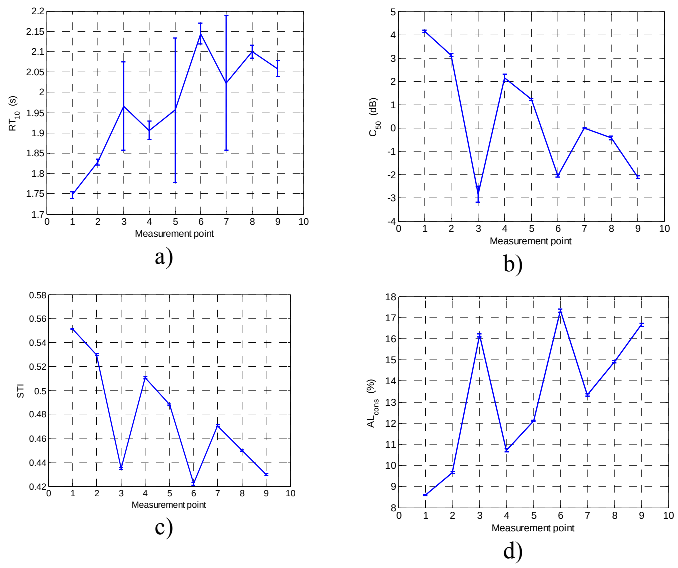

Fig. 2. The mean values and standard deviations at all measuring points for: a) RT_{10}, b) C_{50}, c) *STI* and d) AL_{cons}.

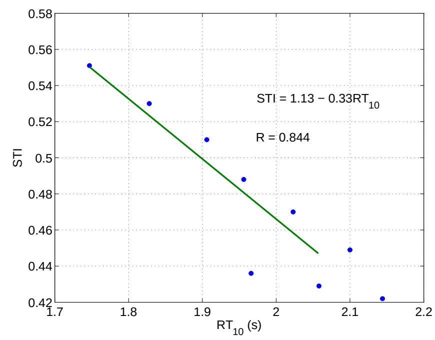

Fig. 3. The regression line for *STI* and RT_{10}.

III. RESULTS ANALYSIS

Based on the results shown in the Tables (I-VIII) and the Figures 2.and 3. the following can be concluded:

a) the values $\overline{RT_{10}}$ for the measuring points and for all measuring points within the amphitheater ($\overline{RT_{10}}$ = 1.747 – 2.144 s and $\overline{RT_{10}}$ = 1.97 s) in relation to the values $\overline{RT_{20}}$ and $\overline{RT_{30}}$, have the least standard deviations: $\sigma_{RT_{10}}$ = 0.08 – 0.109 s and $\sigma_{RT_{10}}$ = 0.149 s. $\overline{RT_{10}}$ is higher than the value of the optimal reverberation time RT_{opt} = 1.55 s which is proposed by ISO 12001 standard for auditoriums of certain volumes. The permitted range of values *RT* for the auditoriums for general purposes (both speech and music) determined by standard is 1.4 – 1.9 s. The value $\overline{RT_{10}}$ = 1.97 s for all points within the amphitheater is the most proximate to the upper limit of this range with the least standard deviation ($\overline{RT_{20}}$ = 2.103 s, $\sigma_{RT_{20}}$ =0.181 s and $\overline{RT_{30}}$ = 2.067 s, $\sigma_{RT_{30}}$ = 0.379 s). The value $\overline{RT_{30}}$ (1000 Hz) = 1.857 s is also at the upper limit of this range, though $\sigma_{RT_{30}}$ (1000 Hz) = 3.77 *JND*. For $\overline{RT_{20}}$ (500 Hz) = 2.134 s and $\overline{RT_{20}}$ (1000 Hz) = 2.001 s are $\sigma_{RT_{20}}$ (500 Hz) = 2.23 *JND* and $\sigma_{RT_{20}}$ (1000 Hz) = 2.62 *JND*. The least standard deviations have $\overline{RT_{10}}$ (500 Hz) = 2.357 s and $\overline{RT_{10}}$ = 2.214 s: $\sigma_{RT_{10}}$ (500 Hz) = 1.53 *JND* and $\sigma_{RT_{10}}$ (1000 Hz) = 1.31 *JND*.

b) the values of $\overline{EDT}$ for measuring points are $\overline{EDT}$ = 1.61 – 1.856 s; their standard deviations have the values σ_{EDT} = 0.005 – 0.08 s. For all measuring points $\overline{EDT}$ = 1.713 s and σ_{EDT} = 0.149 s. These values significantly deviate from the defined range for both music and speech. However, the values of $\overline{EDT}$ at the medium frequencies belong to the range for music: 2.1 – 4.2s: $\overline{EDT}$ (500 Hz) = 2.496 s and $\overline{EDT}$ (1000 Hz) = 2.242 s. Their standard deviations are lower than 1 *JND*: σ_{EDT} (500 Hz) = 0.93 *JND* and σ_{EDT} (1000 Hz) = 0.84 *JND*.

c) the values $\overline{T_C}$ for the measuring points and their standard deviations are: $\overline{T_C}$ = 56.944 – 131.261 ms, σ_{T_C} = 0.3 – 10.202 ms. For all measuring points is $\overline{T_C}$ = 101.382 ms and σ_{T_C} = 26.432 ms. At measuring points 1,2 and 3, the values for $\overline{T_C}$ correspond to determined values for speech (60 – 80 ms) and at measuring points 4, 5, 6, 7, 8 and 9 are consistent to determined values for music (70 – 150 ms). At medium frequencies only the lower limit is $\overline{T_C}$ (1000 Hz) ≈ 150 ms, but other values are higher. The standard deviations don't exceed 1 *JND* (σ_{T_C} (500 Hz) = 0.2 *JND*, σ_{T_C} (1000 Hz) = 0.15 *JND*)

d) for the measuring points $\overline{C_{50}}$ and their standard deviations are $\overline{C_{50}}$ = -2.86 – 4.14 dB, $\sigma_{C_{50}}$ = 0.052 – 0.334 dB. For all measuring points are $\overline{C_{50}}$ = 0.35 dB and $\sigma_{C_{50}}$ = 2.35 dB. These values are consistent to determined values for speech (C_{50} ≥ -2 dB) but also meet the requirements determined for music ($C_{80} = 0 \pm 1.6$ dB, for singers: C_{80}=1 – 5 dB). At medium frequencies the values of this parameter exclusively characterize the speech: $\overline{C_{50}}$ (500 Hz) = -3.586 dB, $\overline{C_{50}}$ (1000 Hz) = -3.212 dB. These values are consistent to standard deviation higher than 1 *JND*: $\sigma_{C_{50}}$ (500 Hz) = 2 *JND*, $\sigma_{C_{50}}$ (1000 Hz) = 1.5 *JND*.

e) the obtained values for *STI* are equable and confirm the acceptable speech intelligibility (0.45 – 0.6). For the measuring points of medium values standard deviations of this parameter are: $\overline{STI}$ = 0.422 – 0.55, σ_{STI} = 0.0006 – 0.0011 whereas for all measuring points $\overline{STI}$ = 0.476, σ_{STI} = 0.0442. At medium frequencies the values of this parameter are the same $\overline{STI}$ = 0.475 and σ_{STI} =0.046. Strong negative correlation between $\overline{RT_{10}}$ and $\overline{STI}$ (r = - 0.9189, R = 0.844), shown in Figure 3., provides as for the RT_{opt} estimated value for $\overline{STI}$ = 0.618, which confirms good speech intelligibility.

f) the obtained values for the parameter AL_{cons} for all measuring points are within the range of permitted values which show good speech intelligibility (7 – 15 %): $\overline{AL_{cons}}$ = 13.28%, $\sigma_{AL_{cons}}$ = 3.031%. Such standard deviation indicates bad speech intelligibility at certain measuring points. Those points are 3, 6 and 9. The best intelligibility is shown at the measuring point 1. The mean values of this parameter and their standard deviations are $\overline{AL_{cons}}$ = 8.61 – 17.337 %, $\sigma_{AL_{cons}}$ = 0.03 – 0.082.

Based on the performed analysis of the empty amphitheater it is concluded that $\overline{RT_{10}}$, $\overline{RT_{20}}$ and $\overline{RT_{30}}$ higher than RT_{opt}. The estimated values of the reverberation time for the full amphitheater can be obtained using reverberation time for the empty amphitheater and Schulc's diffusion time [11]. At medium frequencies they are: $\overline{RT_{30occ}}$ (500 Hz) = 1.59 s, $\overline{RT_{30occ}}$ (1000 Hz) = 1.5 s, $\overline{RT_{20occ}}$ (500 Hz) = 1.64 s, $\overline{RT_{20occ}}$ (1000 Hz) = 1.54 s, $\overline{RT_{10occ}}$ (500 Hz) = 1.68 s, $\overline{RT_{10occ}}$ (1000 Hz) = 1.61 s. All these values are within the range of values for auditoriums for general purposes and $\overline{RT_{20occ}}$ (1000 Hz) is the most proximate to the optimal reverberation time RT_{opt} = 1.55 s which is recommended by ISO 12001 standard [12] for the auditoriums of the volume which the analysed auditorium has. Strong negative correlation between $\overline{RT_{10}}$ i $\overline{STI}$ (r = - 0.9189), shown in Figure 3, gives the estimated values for $\overline{STI_{occ}}$ (500 Hz) = 0.576 ≈ 0.6 and $\overline{STI_{occ}}$ (1000 Hz) = 0.6 which are now limiting values of acceptable good speech intelligibility.

The acoustic analysis of the full amphitheater will be the issue of further studies.

IV. Conclusion

This study presents the acoustic parameters of the amphitheater calculated according to measured impulse responses. Measuring of the impulse responses was performed in the empty amphitheater.

Based on both measured and calculated acoustic parameters for the empty amphitheater, it is concluded that $\overline{RT_{10}}$ = 1.97 s (with the lowest standard deviation $\sigma_{RT_{10}}$ = 0.149 s) is the most proximate to the upper limit of the values recommended by ISO 12001 standard for the auditoriums for general purposes (both speech and music). The mean values of the acoustic parameters which are characteristic for speech transmission in an empty amphitheater confirm acceptable good speech intelligibility: $\overline{STI}$ = 0.476, $\overline{AL_{cons}}$ = 13.28%. Based on the estimation for the full ampfitheater, it is concluded that $\overline{RT_{occ}}$ (500 Hz) = 1.59 – 1.68 s i $\overline{RT_{occ}}$ (1000 Hz) = 1.5 – 1.61 s also include the optimal reverberation time which is recommended by ISO 12001 standard for the auditoriums of certain volume. The reduction of the reverberation time value resulted in expected increase of the value of the *STI*: $\overline{STI_{occ}}$ (500 Hz) ≈ 0.6 and $\overline{STI_{occ}}$ (1000 Hz) = 0.6 that confirmed acceptably - good speech intelligibility of the full amphitheater.

Based on the previous analysis, it is concluded that the analysed amphitheater for lecturing is suitable for its purpose, but for the sake of acoustic improvement, additional acoustic treatment can be performed.

References

[1] Sabine, W. Collected Papers on Acoustics (1922). (Harvard University Press.Reimpresión Dover, 1964).

[2] Eyring, C.F. “Reverberation Time in “Dead” Rooms”, J. ACOUST. SOC. AM., Vol. 1 217-241, 1930.

[3] Sette, W. H. “A New Reverberation Time Formula”, J. ACOUST. SOC. AM., Vol. 4, pp 193-210, 1933.

[4] Schroeder, M.R.: New method of measuring reverberation time JASA 38 (1965), S. 329 and 40, S. 549.

[5] Jordan, V.L., 1970. "Acoustical Criteria for Auditoriums and Their Relation to Model Techniques", - JASA, Vol. 47, No. 2 (Part 1), pp. 408-412.

[6] Kürer, R.: Einfaches Messverfahren zur Bestimmung der Schwerpunktzeit“raumakustischer Impulsantworten (A simple measuring procedure for determining the "center time" of room acoustical impulse responses), 7th INTER. CONGRESS ON ACOUSTICS, Budapest 1971.

[7] Peutz, V.M.A- Articulation Loss of Consonants as a criterion for Speech Transmission in a Room - J. AUDIO – ENG. SOC. Vol. 19, p. 915-919, 1971.

[8] Abdel Alim, O.: Abhängigkeit der Zeit - und Register-durchsichtigkeit von raumakustischen Parametern bei Musikdarbietungen (Dependence of time and register definition of room acoustical parameters with music performances) Dissertation, TU Dresden 1973.

[9] Steeneken, H. J. M. – A Physical Method for measuring Speech Transmission Quality - J. ACOUST. SOC. AM., Vol. 19, 1980.

[10] ISO 12001:1998, Acoustics Noise emitted by machinery and equipment, Rules for the drafting and presentation of a noise test code, 1998.

[11] M. Topa, N. Toma, B. Kirei, I. Saracut and A. Farina, Experimental Acoustic Evaluation of an Auditorium, HINDAWI PUBLISHING CORPORATION ADVANCES IN ACOUSTICS AND VIBRATION, Volume 2012.

[12] ISO 12001:1998, Acoustics Noise emitted by machinery and equipment, Rules for the drafting and presentation of a noise test code, 1998.