Influence of Diffusivity in Room on its Acoustic Response

Dragana Šumarac Pavlović and Milan Petrović

Abstract — **Diffusivity is a geometrical feature of the room which is proportional to the dimension of relief on its interior surfaces. This paper presents the results of analysis which investigates the correlation between diffusivity in a room and parameters calculated from a recorded impulse response. The analysis was performed using a specially prepared physical model of a parallelepipedic room with different combinations of flat and diffusive interior surfaces.**

Keywords — **absorption, acoustic measurement, diffusion, impulse response, physical model.**

I. Introduction

PREDICTION of a sound field in rooms with highest acoustic criteria and acoustic design of such spaces are complex processes. The basic tool in such design is the choice of appropriate characteristics of internal surfaces. Most frequently the global geometry of room is proposed, and the only available tool is the absorption and micro geometry of interior surfaces. The main source of inaccuracy in acoustic design is the lack of knowledge about surfaces characteristics, such as the appropriate values of absorption and diffusion coefficients.

The information about surfaces properties is available on the basis of laboratory measurements in reverberation chambers. The influence the position of absorption materials has on the effective absorption in a room has been analysed in literature. It was discovered that the values of acoustic parameters can vary up to 50% depending on different positions of the same absorption material.

Prediction methods based on sound field software modelling imply the knowledge of the coefficients that describe diffuse properties of the surfaces. Diffuse features of uneven surfaces can be characterized by two parameters. The first is the scattering coefficient representing the ratio between sound energy reflected specularly and total reflected energy. The second parameter is the diffusion coefficient, which gives information about the spatial distribution of reflected energy. Although the methods of measurement of these two coefficients are standardized, in reality there are very few situations when the characteristics of a diffuse surface are known. Experience from various design problems has shown that diffusivity is an efficient tool for control of room acoustic response [1], [2], [3]. Sometimes there are existing diffusive surfaces in a treated room and there is no possibility to move them into laboratory for measurement of diffusive properties.

Haan and Fricke have developed a method for the characterization of irregularities in rooms based on a visual procedure [4]. They defined three categories of diffusivity of surfaces according to their relief depth: a very diffuse surface with a coefficient 1, a medium-diffusivity surface with a coefficient 0.5 and a lowly diffuse one with a coefficient 0. The parameter surface diffusivity index (SDI) is calculated as an average value of diffusivity of all surfaces in a room, but taking into account the contribution of each particular surface in the whole inner surface of the room. Based on the proposed procedure, they analyzed the value of SDI and 31 concert halls. Their conclusion was that halls having the highest acoustic quality have the value of SDI near or equal to 1.

Greater diffusivity of surfaces indirectly involves additional absorption in a room, because any geometrical details of a relief bring about a larger surface. In practice, a real increase of surface and, thus, an increase of absorption cannot be estimated in a simple way.

Three main approaches in sound field prediction in a room are used. Statistical model provides an estimate of the global parameters, of which the most important is reverberation time. The prediction of other parameters calculated from impulse response can be made only on the basis of geometric models, i.e. software simulations, or by measurements in a physical model of the room. This paper deals with an experimental analysis of the influence of diffusivity in a room on parameters calculated from the impulse response. The analysis was performed in a specially designed physical model of a room.

II. Scale Model

The concept of the physical model is based on the principle of dynamically similar systems. This principle means that the two systems can be constructed to be different in their size, but similar in every other way, i.e. with dynamic processes being carried out in the same way [5], [6], [7]. In a non-dispersive medium such as air, the wavelength of sound is inversely proportional to the frequency. Thus, if the scaling factor is $1/n$ the following conditions will be obtained or be required:

- all model dimensions are reduced in the ratio $1/n$;
- the time between reflections will be reduced in the ratio $1/n$, since the transmission medium in the model is air and the velocity of sound remains unchanged;

This paper is a part of the project supported by the Ministry of Science and Technological Development of Serbia, project No 23046.

Dragana Šumarac Pavlović, University of Belgrade, Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia (e-mail: dsumarac@etf.rs).
Milan Petrović, University of Belgrade, Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, Belgrade, Serbia (e-mail: beograd11231@yahoo.com).

- wavelength must be reduced in the ratio $1/n$, therefore, frequencies must be increased by the ratio n;
- the air absorption should have a value n times that applying at original frequencies;
- if the acoustic impedances of the surface of the model over the increased frequency range are made equal to the impedances of the corresponding surfaces in the full size room, over the normal frequency range, it follows that reverberation time will be reduced in the ratio $1/n$ [5];

Working with models is associated with a transposed frequency range and, thus, with non-standard measuring equipment that enables the work on frequencies n times higher than the audio range. The impulse response recorded in the model is returned to the original frequency range with an additional correction of dissipation in the air.

A. Physical model of room designed for this analysis

A physical model of a room with paralellepipedic shape was specially prepared for experimental analysis. The model is scaled 1:10, and its interior dimensions are 80x60x47 cm. The model consists of a strong metal frame and removable sides. Two sets of sides with different characteristics were prepared. The basic set is made as flat panels, which assumes the minimum possible value of the scattering coefficient. An additional set of sides was prepared with diffuse surfaces made of specially made relief. Placing on model the various combinations of sides with different properties introduces changes of room geometrical properties. The model with all flat and with all diffuse sides is shown in figure 1 and 2 (one side is open).

Sides are made of wooden boards with a thickness of 2 cm. The surface is coated with three layers of lacquer to minimize the porosity of wooden surfaces. The relief was formed by placing specially prepared wooden hemispheres of radius 2 cm, for which there is data in the literature about the possible values of the scattering coefficient [8]. The detail of this relief is shown in Figure 3. It has been demonstrated in literature that the scattering coefficient of relief form realized in such a way depends on the density of hemispheres scattered over the surface [8]. With the density at which 50% of the surface is covered with hemispheres the scattering coefficient varies from 0 to about 0.7, depending on frequency. Measured values for scattering coefficient for the surface covered with wooden hemispheres with a density of 50% is shown in Table 1. Values of the frequencies in Table 1 are transposed by ratio 1:10, due to the model scale.

B. Configurations of model

For the experiment, 18 different combinations of sides are realized in the model, as the number and position of diffuse and flat sides were changed. Fig. 2. schematically shows all models. The pattern graphically represents a diffuse surface in the figure, and a six-character symbol represents the combination of flat and diffuse sides. Symbol “0” represents a flat side, and letters L, M and S represent a diffuse surface on the position of large, medium and small sides of the room, respectively.

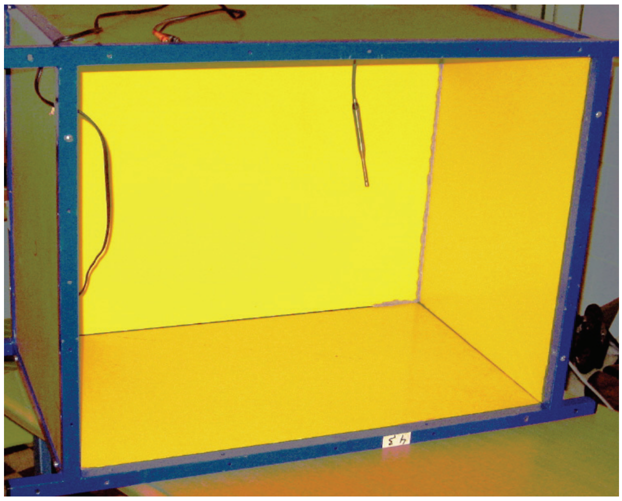

Fig. 1. Physical model of room with mounted flat sides (one side open).

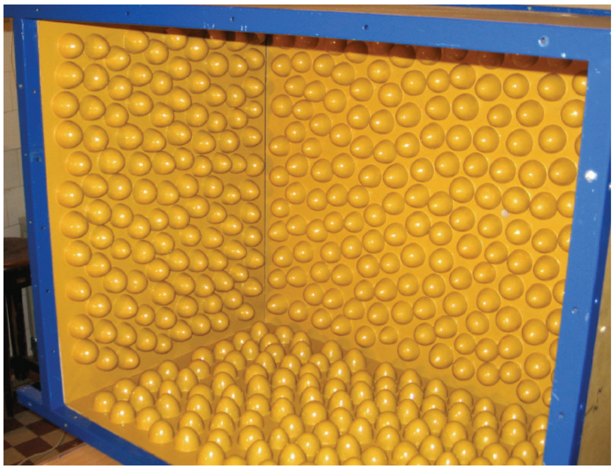

Fig. 2. Physical model of room with mounted diffuse sides (one side open).

TABLE 1. MEASURED VALUES OF SCATTERING COEFFICIENT FOR SURFACE 50% COVERED WITH WOODEN HEMISPHERES OF RADIUS 2 cm (FREQUENCIES ARE TRANSPOSED BY RATIO 1:10, DUE TO THE MODEL SCALE)

f **(Hz)**	**200**	**250**	**315**	**400**	**500**	**630**
scattering	0.15	0.2	0.37	0.4	0.47	0.51
f **(Hz)**	**800**	**1000**	**1250**	**1600**	**2000**	
scattering	0.57	0.56	0.5	0.71	0.7	

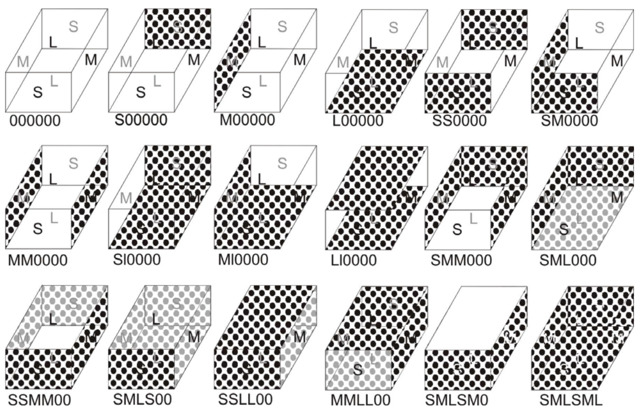

Fig. 3. Schematic presentation of all 18 combinations in model with symbols representing positions of sides with relief.

The amount of diffuse surfaces in the model for different configurations is described by SDI. For two types of sides a flat surface was assigned a scattering coefficient 0, and a diffusive surface 1. The value of SDI is calculated for each analyzed configuration presented in Fig. 3. By changing the configurations of the model a relatively evenly distributed diffusivity index ranging from 0 to 1 was obtained. Diffusivity index 0 has a model with all flat surfaces and the index 1 model with all diffuse surfaces. Changing the configurations, the relative uniform distribution of SDI values in the interval from 0 to 1 was obtained. The calculated values of SDI for all combinations of surfaces in the model are presented in Table 2.

TABLE 2. SDI FOR DIFFERENT MODEL CONFIGURATIONS

Model	*coefficient*	*model*	*coefficient*
000000	0	LL0000	0.42179
S00000	0.1239	SMM000	0.45431
M00000	0.1652	SML000	0.5
L00000	0.2109	SSMM00	0.57821
SS0000	0.2478	SMLS00	0.6239
SM0000	0.2891	SSLL00	0.6696
MM0000	0.3304	MMLL00	0.7522
SL0000	0.3348	SMLSM0	0.7891
ML0000	0.3761	SMLSML	1

The scattering coefficient of relief applied to model sides has different values at different frequencies, depending on the wavelength to hemispheres dimension ratio. However, the relative ratio of individual diffusivity indexes for all configurations will remain unchanged. That is why only the relative ratio between different configurations was considered.

C. Recording of impulse response in model

The model was excited with an impulse generated by an electrical spark generator [9]. The generator is specially designed for measurements in physical models with the spectrum wide enough for measurement in the model scaled 1:10. The model was always excited at one point, and the impulse response was recorded at two different points. The positions of these were precisely defined, providing conditions for a relative comparison of the results obtained for different model configurations. Impulse response was recorded by a standard measuring microphone appropriate for measurement in physical models. Its upper frequency limit is about 80 kHz. The signals were recorded with a sampling frequency of 192 kHz. By restoring the original frequency domain and compensating the dissipation in the air, conditions were provided for the analysis of impulse response in the range up to 1/3 octave band at 6.3 kHz.

III. ANALYSIS OF REVERBERATION TIME

The analysis of reverberation time was performed in 18 different configurations of the model, all presented in Fig. 3. The reverberation time was measured form recorded impulse responses.

Relief surfaces, besides diffusivity, introduce also some additional absorption in the model. Increased absorption has a consequence on all parameters calculated from impulse response. Effects of increased absorption are superpositioned to the effect the diffuse surfaces have on a sound field through the redistribution of sound energy flow. To split these two effects, measured values of the reverberation time are normalised to a statistically expected value. According to the reverberation time value measured in the model with configuration 000000, the Sabine formula was used to calculate the absorption coefficient of lacquered wooden surface in the model:

$$T = \frac{0.16V}{\overline{\alpha}S + 4mV} \qquad \overline{\alpha} = \frac{0.16V}{TS} - \frac{4mV}{S} \tag{1}$$

A measurable factor indicating the additional absorption is the increase of surface due to the presence of relief. The relief increases the surface and decrease the total volume in the model (understandable in Fig. 2). Considering that the relief surfaces are made of the same material as flat surfaces and has the same absorption coefficient as calculated from configuration 000000, one can introduce in formula (1) a surface and volume correction due to the number of wooden hemispheres present in the model. Reverberation time correction is determined by the equation:

$$T_{kor} = \frac{0.16V \cdot k_v}{\overline{\alpha}S \cdot k_s + 4mV \cdot k_v} \tag{2}$$

where k_v and k_v represent the calculated corrections of total volume and interior surface for each configuration of model due to the present relief.

To quantify differences between measured and statistically expected values of reverberation time, the parameter R is observed:

$$R = \frac{T_{measured} - T_{Sabine}}{T_{Sabine}} [\%] \tag{3}$$

where R is the deviation of reverberation time, T_{Sabine} is reverberation time calculated by formula (2), and $T_{measured}$ is reverberation time measured in the model. Value $R = 0$ represents the measured value identical to the statistically estimated.

The values of R as a function of SDI for all 18 configurations of the model and for different 1/3 octave bands are shown in Figs. 4 and 5. Each curve represents a deviation in one 1/3 octave band for all configurations of model sides. In lower frequency bands there are evident deviations for different configurations of diffusivity. According to statistical theory, some configurations should have nearly the same reverberation time, if they have nearly the same total interior surface. Model configurations LL0000 and SMM000 have nearly the same surface of relief, but their measured reverberation times are about 50% different. Although they have the same number of diffuse elements (hemispheres), their position in space is not such as to give the same general diffusivity. With increasing frequency these differences in configurations are reduced, as presented in diagrams from Fig. 5.

The results of reverberation time measurements reveal that relief at room interior surfaces influences the flow of energy through the room in a more complex way than can be simply explained by the increase in total interior surface. With an increasing total diffusivity, i.e. increasing frequency, these phenomena are more pronounced. There is also important influence of relief position inside the room. This causes the configurations with similar SDI and thus, with similar statistically expected reverberation times, to have a noticeable difference in measured values.

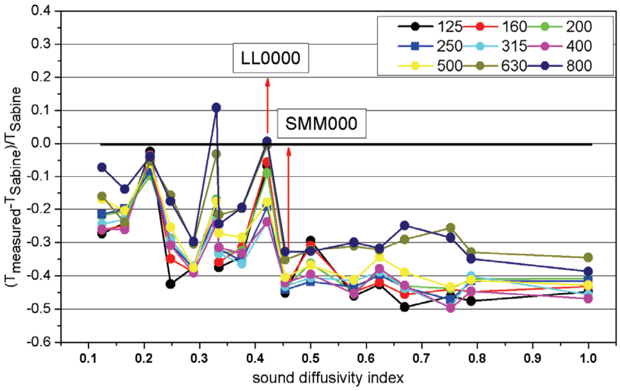

Fig. 4. Deviation of measured reverberation time compared to statistically expected by Sabine formula (in 1/3 octave band from 125 Hz to 800 Hz).

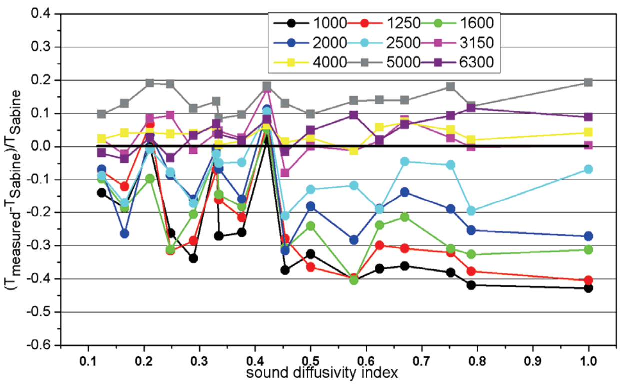

Fig. 5. Deviation of measured reverberation time compared to statistically expected by Sabine formula (in 1/3 octave band from 1000 Hz to 6300 Hz).

IV. Analysis of Total Absorption

The deviations of measured reverberation time from the statistically expected value are presented in Figs 4 and 5. The absorption in room and the reverberation time are related by the Sabine formula (1). The deviation of room response compared to that expected from statistical theory can also be expressed as an issue of absorption. The effective (achieved) absorption calculated from measured reverberation time by the Sabine formula can be compared to the value obtained as a product of interior surface and the mean absorption coefficient of wall material. That absorption coefficient was calculated according to the results of measurement realised in the model with all flat sides (configuration 000000).

Expected absorption for different configurations was calculated taking into account the increase of total surface due to the relief. From both achieved and expected absorption in room the equivalent absorption coefficients were calculated. The normalised values of achieved coefficient as a function of SDI in room are presented in Figs. 6 and 7. The effective absorption in room increases with increase of diffusivity.

For larger values of SDI the effective absorption in room is larger. For SDI of the room larger than 0.5, its deviation from the statistically expected is more than 50%. Only for the highest observed frequencies (in 1/3 octave band at 3150 Hz and higher), the effective absorption in room has values near, or even lower than, statistically expected.

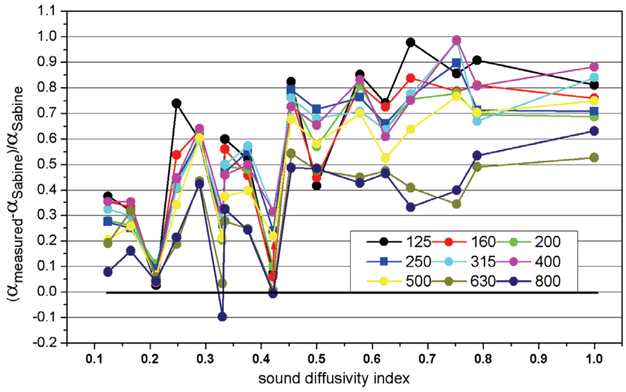

Fig. 6. Deviation of achieved absorption coefficient compared to expected value according to increased total surface in room (in 1/3 octave band from 125 Hz to 800 Hz).

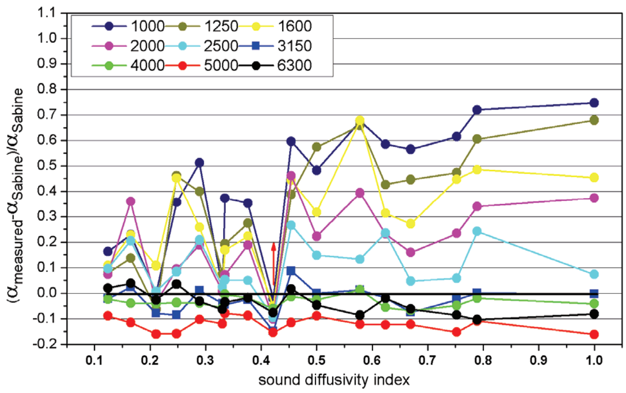

Fig. 7. Deviation of achieved absorption coefficient compared to expected value according to increased total surface in room (in 1/3 octave band from 1000 Hz to 6300 Hz).

V. Analysis of Room's Broadband Response

The influence of diffusivity in room was also tested for a broadband impulse response. During all measurements the positions of source and receivers have been kept constant for all configurations of the model. That enabled the comparison of parameters measured in the model with different configurations. The measured values of parameters [10] T20, EDT, Ts, C80 and D50 for a wideband signal are presented in Figs. 8, 9, 10, 11 and 12, respectively. The parameters are presented in diagram as a function of SDI (i.e. for different configurations in the model).

The statistically expected values of T20 were also calculated by equation (2) for all room configurations. As for the analysis in 1/3 octave bands, the mean value of broadband absorption coefficient for material in the model was calculated from reverberation time obtained for configuration (000000). These values are shown in Fig. 8 (red dots and red line).

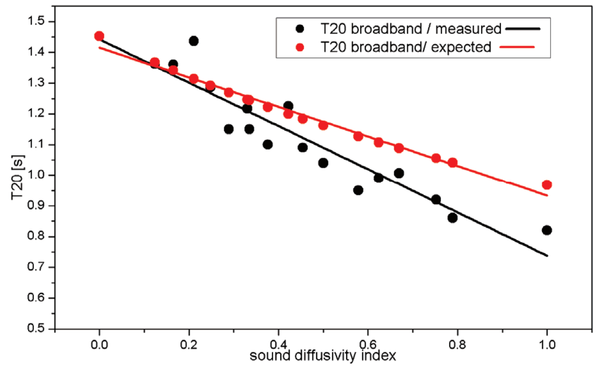

Fig. 8. Broadband T20 as a function of SDI..

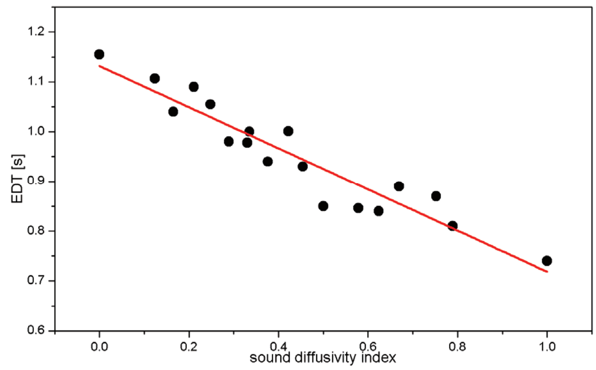

Fig. 9. Broadband EDT as a function of SDI.

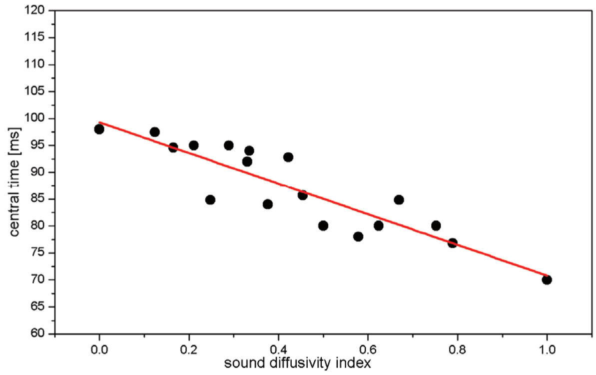

Fig. 10. Ts as a function of SDI.

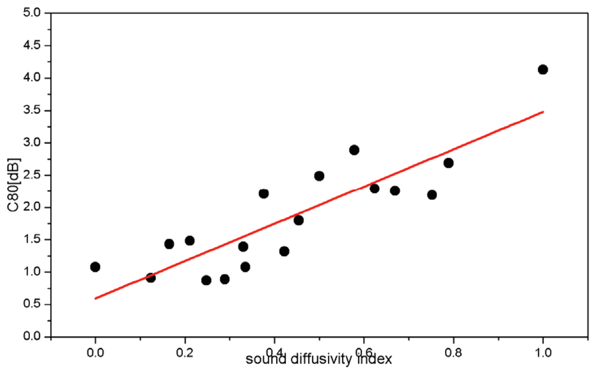

Fig. 11. Broadband C80 as a function of SDI.

The results reveal that diffusion on interior surfaces makes the measured value of T20 to be smaller than that calculated by the Sabine equation. The difference between measured values and statistically estimated values is larger for higher diffusivity in room (larger value of SDI).

In contrast to the reverberation time, which can be predicted in a simple way by the statistical model, other numerical parameters calculated from impulse response and presented in Figs 9, 10, 11 and 12 have no simple calculation procedure. Parameters EDT and central time Ts show the same trend as T20, i.e. monotonically decrease when diffusivity in room rises. This can be explained by the higher amount of energy in the beginning part of impulse response if diffusivity in room is higher. This circumstance gives a constant rise of C80 and D50 as a function of SDI.

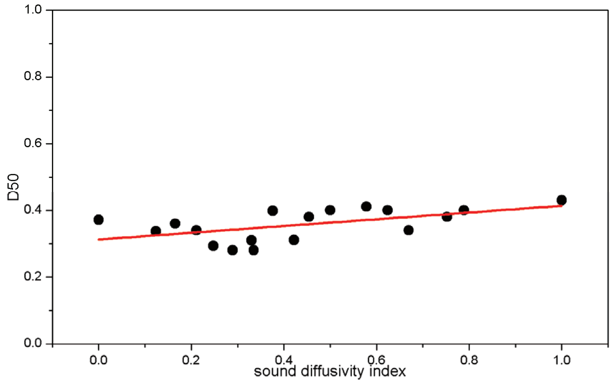

Fig. 12. Broadband D50 as a function of SDI.

VI. Characteristic Cases LLOOOO and SMMOOO

The performed analysis shows a trend of changes of acoustical parameters with the increase of sound diffusivity index. In some of room configurations, acoustical parameters were divergent from the global trend. Two models with a similar SDI but opposite acoustical responses were observed: model LL0000 (SDI 0.42) and model SMM000 (SDI 0.45). These two configurations have nearly the same amount of diffuse element and expected values of acoustic parameters in them are the same. Model SMM000 fits the global trend of dependence and acoustic response in LL0000 significantly deviates from the global trend.

Frequency characteristics of the reverberation time (expected and measured values) in two selected models are presented in Fig 13. Expected values are almost the same.

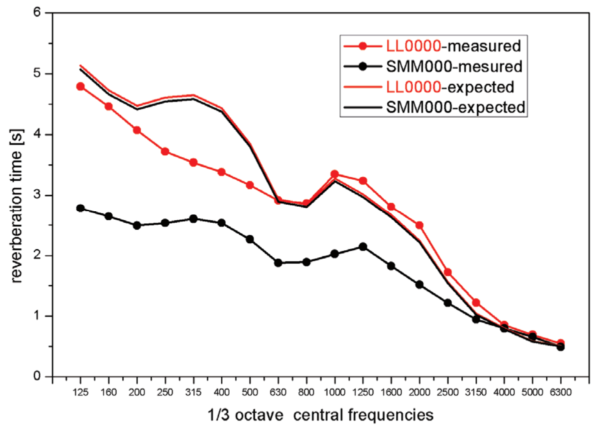

Fig. 13. Dependence of measured EDT values as a function of diffusivity index.

The difference in measured values of reverberation time has a consequence on other acoustical parameters. Higher values of RT cause a reduction of D50 and C80. At the same time the values of D50 and C80 are influenced by the way of energy arrival in the initial part of the impulse response, which is affected by the spatial distribution of diffusivity. The influence of these effects cannot be accurately described mathematically. Frequency dependences of D50 and C80 for two selected models are presented in Figs 14 and 15.

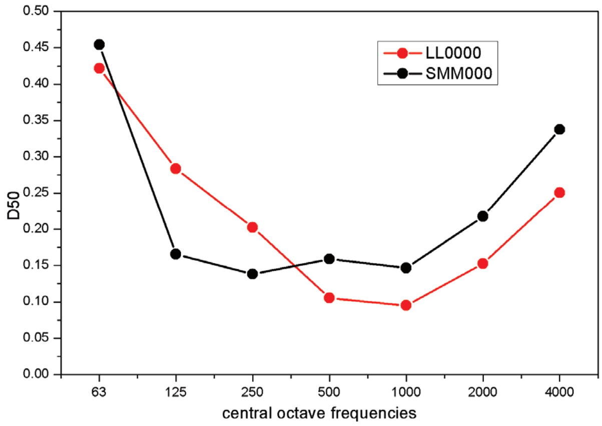

Fig. 14. Frequency dependence of D50 parameter for two selected models.

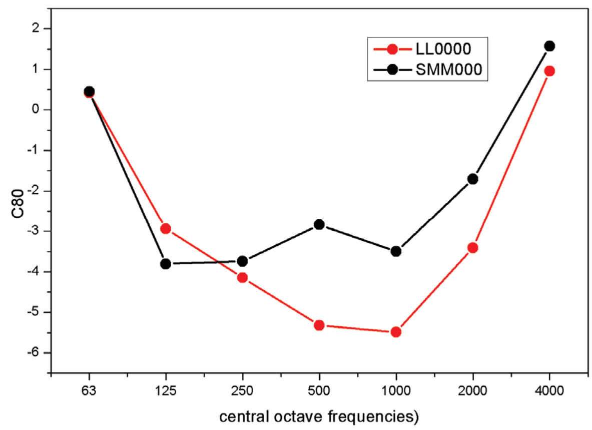

Fig. 15. Frequency dependence of C80 parameter for two selected models.

Although the measured reverberation time in the configuration LL0000 is longer than in SMM000 for all observed frequency bands, the variations of parameters D50 and C80 reveal that diffusive elements on interior surfaces in some way change the flow of sound energy in room. This is why there is no clear correlation between all measured parameters, and thus their values cannot be predicted from the reverberation time.

A cumulative function of energy at the same place in the room, but for two different relief configurations, is presented in Fig. 16. Although a longer reverberation time makes in theory the value of cumulative energy higher, the diagram reveals that higher diffusivity in configuration SMM000 makes the energy approaching the receiver point higher.

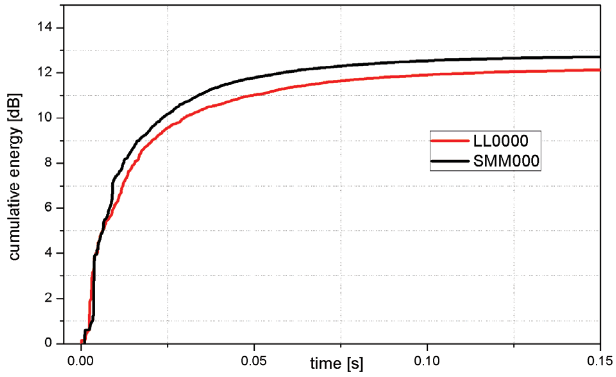

Fig. 16. Cumulative energy increment in one receiver position for two models.

VII. Conclusion

Surfaces with relief in a room influence its acoustical response in a complex way. To quantify the diffusivity in this paper, the surface diffusivity index is used as a numerical indicator of relief amount. The analysis of acoustical parameters based on impulse responses recorded in 18 different configurations of the model reveal some trends the acoustical parameters manifest as a function of SDI. But, there are some configurations of relief surfaces when a deviation of common trends was found. One can conclude that such a feature is a result of complex mechanisms of sound energy traffic. The results have shown the possibility to change the character of room response by a different diffuse surface arrangement.

References

[1] P. D'Antonio, T. J. Cox, "Diffusor application in rooms," *Applied Acoustics*, Vol. 60, 2000.

[2] B. Dalenback, M. Klenier, P. Svensson, "A Macroscopic View of Diffuse Reflection," *J. Audio Eng. Soc*., Vol. 42, No 10, October 1994.

[3] T. J. Cox, P. D'Antonio, "Acoustic Absorbers and Diffusers-theory, design and application," *Spon Press*, 2004.

[4] C. H. Haan and F. R. Fricke, "Surface diffusivity as a measure of the acoustic quality of concert halls," *Proceedings of Conference of the Australia and New Zeland Architectural Science Association*, Sydney, 1993, pp 81-90.

[5] H. D. Harwood, A. N. Burd, "Acoustic scaling: General outline," BBC Research Department Report No. 1970/13, April 1970.

[6] M. Mijić, D. Šumarac-Pavlović, "20 godina tradicije u upotrebi fizičkih modela u akustičkom projektovanju i istraživanju u Laboratoriji za akustiku ETF," TELFOR, 2007.

[7] D. Šumarac-Pavlović, M. Mijić, "Analiza uticaja geometrijskih karakteristika prostorije na njen akustički odziv – merenja na fizičkim modelima," LII Konferencija za ETRAN, 2008.

[8] M. Vorlander, E. Mommertz, "Definition and measurement of random-incidence scattering coefficients," Applied Acoustics 60, 2000.

[9] M.Mijić, D.Šumarac Pavlović, "Jednostavan impulsni izvor za merenja u fizičkim modelima," ETRAN 2009, Proceedings.

[10] ISO 3382: "Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters".