Sound Field Diffusivity in a Small Reverberation Room

Dejan Ćirić, Kristian Jambrošić, Marko Janković

Abstract—**Diffuse sound field is one of the most important prerequisites for various measurements in a reverberation room. Unfortunately, it is rather complex to have such a sound field in the whole frequency range of interest. This is especially valid at low frequencies, and for some rooms of inadequate characteristics like inadequate shape or small volume. Another topic is how to evaluate the diffusivity of the sound field. There is no direct measure to assess this property, instead various indirect descriptors are used for that purpose. This paper deals with assessment of sound field diffusivity of a small reverberation room. Focus is on energy decay curves and their deviation from the target ones. Two indirect descriptors – standard deviation of decay rate and linearity of energy decay curves are used here to investigate the sound field diffusivity. The effects of having diffusers in the room are also considered.**

Index Terms—**Reverberation room; diffuse sound field; energy decay curve; diffusivity descriptors.**

I. Introduction

REVERBERATION rooms (chambers) are used for various acoustical measurements such as random incidence absorption coefficient of materials, source power level and transmission loss. Although there are other measurement methods, like impedance tube method [1,2], the reverberation room method has been preferred for a number of applications and long continued to be used successfully. Measurement of absorption coefficient in a reverberation room is based on the relation between volume, absorption and sound decay [3]. An important assumption related to this measurement is diffuse sound field present inside the room. Such a sound field is very challenging to be implemented, especially at low frequencies.

It has been reported in various studies that there are significant differences among sound absorption performance data from different laboratories [4]. Several factors are identified for such a large spread of the absorption coefficient results. They include the diffusion conditions in the reverberation room, its volume and shape, type and area of diffusers, the edge-effect, the installation area of the tested sample [4] and the value of sound absorption coefficient.

The lack of a diffuse field is specified as the main reason for differences in absorption coefficient results in a number of reports [5]. The sound field in a room can be considered to consist of a horizontal and vertical sound field [5]. The vertical field can be strongly damped especially when a highly absorptive sample is placed in the room. On the other hand, the horizontal sound field is much less affected by the absorption. Depending on which sound field is dominant, the measurement results for absorption performance can differ. In case of dominant horizontal sound field, the absorption will be underestimated [5].

One of common discrepancies found in the absorption performance measurement is the absorption coefficient greater than 1. The reasons for this phenomenon include [6]:

- edge diffraction effect (the edge occurs mainly at the lower frequencies from 200-500 Hz [5]),
- non-diffuseness that causes non even time and space distribution of the sound pressure level across the reverberation room,
- Sabine formulation that should not be applied when the mean absorption value is > 0.4 (if this is not satisfied, an overestimation of the absorption can be obtained [5]),
- effect of diffusers (reduction of the mean free path - MFP) is not accounted in the calculation of the absorption.

For quite some time, there has been shown interest in extending the frequency range of the absorption measurement towards low frequencies (below 100 Hz). The main reason why it is difficult to do this is the low modal density at low frequencies [7]. It is worth noting that the room modal behavior depends on the room geometry.

The sound diffusion in a reverberation room and the method to realize diffuse sound field have been topics of a number of investigations so far. However, the relationship between the measurement accuracy of sound absorption coefficient and the sound field in a reverberation room is still an important problem [8]. In addition, quantification of sound field diffusivity (diffuseness) is still on open issue. This is why this paper sheds some light on this matter from a perspective of energy decay curves (EDCs). These curves are used to calculate two descriptors of sound field diffusivity, that is, standard deviation of decay rate and linearity of EDCs. The diffusivity of sound field of a small reverberation room is thus analyzed in third-octave bands by investigating the mentioned descriptors. Besides, the analysis includes the effects of diffusers, too.

II. Reverberation Room and Its Acoustics

Reverberation room design is defined in different standards

Dejan Ćirić is with the University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia (e-mail: dejan.ciric@elfak.ni.ac.rs).

Kristian Jambrošić is with the University of Zagreb, Faculty of Electrical Engineering and Computing, Unska 3, HR-10000 Zagreb, Croatia (e-mail: Kristian.Jambrosic@fer.hr).

Marko Janković is with the University of Niš, Faculty of Electronic Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia (e-mail: marestudio2004@gmail.com).

[7,9]. Thus, there are specifications related to room dimensions saying that there should be no two dimensions equal to each other, and that the largest dimension should be at least two times greater than the smallest one. Strong preference is given to highly irregular room shapes as they are able to continuously redistribute the energy in all possible directions [10]. Each standard typically prescribes the minimum volume of the room [11]. Then, in order to facilitate the least absorption, the room should be constructed of heavy materials. Diffusers are also mentioned in the standards. Hanging randomly in the room volume, they should increase the sound diffusivity [3].

One of the major assumptions related to the absorption measurements is that the sound field in the reverberation room is diffuse. According to definition, this means that sound field is the same in every point of the room, that is, sound waves are incident from all directions with equal intensity and random phase at any position in the room [1]. In other words, characteristics of the ideal diffuse sound field are spatial uniformity of acoustic energy density and the isotropy of acoustic energy flow everywhere in the sound field [8].

In spite of requirements for achieving diffuse sound field, significant deviations from the target diffuseness have been reported in a number of studies [11]. Thus, it is well-known that in reality the standing waves are present in reverberation rooms, especially at low frequencies, and the sound pressure distribution within the rooms considerably varies from point to point. Several important factors are identified affecting the diffusion state inside the reverberation chamber, among which shape of the chamber and the size of the space stand out [4]. Besides, the sound field diffusivity in the empty chamber and when a specimen with high absorption performance is present could be very different.

A. *Effects of Diffusers*

Diffusivity of the sound field inside a reverberation room can be improved by placing a certain number of diffusers. These objects scattered over the room's walls and ceiling disrupt acoustic standing waves [1]. Usage of diffusers is also specified in the relevant standards including ISO 354 [9]. Unfortunately, the specification found in ISO 354 is not very precise stating that the diffusion plates shall be installed in the room until there is no further enhancement of the sound absorption performance of the specimen [4,9]. In this standard, more diffusers (more than one) with different sizes are recommended. An adequate diffuser can be a plate of plywood that can be slightly curved, and whose thickness can be only few millimeters and an area between 0.8 and 2 m^2.

Regarding the total diffuser surface area, different data can be found in the literature, from the recommendation that diffusers should occupy between 15% and 25% of the total surface [4] up to the one saying that total area should be approximately equal to the floor surface [10]. In some of the previous studies, it is shown that addition of diffusers does not necessarily provide an optimal diffuse sound field [4]. It is also found that the quantity of diffusers has little influence on the measured absorption performance below 250 Hz, while its influence is larger in medium to high frequency range [10].

When diffusers are installed in a reverberation room, reverberation time of the empty room gets smaller [7]. This behavior can be attributed to the reduction of the MFP of the acoustic waves and to the low frequency dissipation of energy [7]. Change of the MFP depends on the type, number and orientation of the diffusers [10]. What can be problematic here is that the formula for the calculation of the equivalent absorption area specified in the standard ISO 354 does not take into account this change of the MFP.

III. Descriptors of Sound Field Diffusivity

There are no direct ways to characterize sound field diffusivity in a reverberation room and consequently there is no direct objective measurement to be used for that purpose [11]. This is why diffusivity of sound field in a reverberation room is evaluated using various indirect descriptors or quantifiers. They include cut-off-frequency, number of modes, spatial uniformity of reverberant sound field, standard deviation of reverberation time, accuracy of measured reverberation time, linearity of EDCs, accuracy of measured absorption coefficient (α_{rev}) and number of peaks of the impulse response [4,5]. Focus here is on standard deviation of reverberation time or decay rate and linearity of EDCs. In addition, cut-off-frequency is briefly explained and calculated for the used reverberation room.

A. *Cut-off frequency*

A low frequency limit is defined as a tentative criterion for existence of diffuse sound field in a reverberation room. There are two types of definition of the low frequency limit – the first one is related to modal overlap (where overlap factor of 3 is typically applied), while another one is statistically based related to modal count in a given frequency range. The first definition yields the Schroeder's frequency known to be rather restrictive. This frequency should actually represent a transition from modal behavior to uniformly diffuse field. For a room of volume around 220 m^3 and reverberation time in the frequency range from 100 Hz to 5 kHz of 11.3 s, it is 454 Hz. From theoretical point of view, the sound field in a reverberation room below the Schroeder frequency is not diffuse. However, it is reported in a number of studies that the sound field is not diffuse enough even well above the Schroeder frequency [10]. According to the second definition of the low frequency limit, this limit typically corresponds to a modal count of 20 in a given frequency band. For a third-octave band, the cut-off limit is obtained as

$$f_c = \frac{343}{\sqrt[3]{V/4}}, \tag{1}$$

where V is the room volume.

B. *Standard deviation of reverberation time (decay rate)*

Another indicator of the sound field diffusivity is based on the reverberation time (decay rate), actually on standard deviation of the reverberation time according to the microphone location inside a reverberation chamber. A particular reverberation room is evaluated to have a diffuse sound field if the standard deviation of the measured reverberation time is smaller than the standard deviation of the theoretical reverberation time. The specification of the maximum allowable displacement of the decay rate depending on the location of the microphone is given in the ASTM C 423 standard [12]. The decay rate can be calculated as

$$d_i = \frac{60}{T_i} - m_{iso}\, c \log(e), \tag{2}$$

where d_i is the decay rate measured at the i-th microphone, T_i is the reverberation time at the *i*-th position, m_{iso} is the air attenuation coefficient calculated according to ISO 9613-1 [4], c is the speed of sound and e is the base of natural logarithm. The standard deviation of decay rate among the N microphone positions in a third-octave band (S) can be calculated as

$$S = \left(\frac{1}{N-1} \sum_{i=1}^{N} \left(d_i - \overline{d} \right)^2 \right)^{\frac{1}{2}}, \tag{3}$$

where $\overline{d}$ represents the decay rate averaged over all microphone positions. Since the contribution of the second term in (2) - $m_{iso}c\log(e)$ is small, especially after subtraction in (3), the decay rate here is calculated as $60/T_i$. The relative standard deviation of decay rate (S_{rel}) used as the sound field diffusivity indicator is calculated as $S_{rel} = S/\overline{d}$. Better diffusion conditions exist if the relative standard deviation of decay rate has a lower value.

C. *Linearity of energy-decay curve*

EDCs can also be used as an indicator of sound field diffusivity. It is known that in perfectly diffuse sound field, energy decay versus time on dB scale represents straight line, or, in other words, it represents a linear function. Thus, a measure of nonlinearity of EDC can be used as an indirect quantifier of the sound field diffusivity. Quantification of the curvature of the EDCs can be done by means of a correlation coefficient, *r*, between the predicted decay curve and the best-fitted straight line [11]. Another option for an effective measure of the curvature (κ) is to magnify the deviation from perfect correlation

$$\kappa = 1000\left(1 - (r)\right). \tag{4}$$

IV. Investigation Method

The measurements whose results are given here were carried out within the COST Action 15125, where a round robin experiment related to measured absorption coefficient variability is performed. In that regard, the variability is caused by reverberation room, equipment, signal processing and team doing the measurements. Some details are already given in [13]. What is especially interesting here is that reverberation room of the Faculty of Electronic Engineering in Niš where the measurements were carried out is rather small – its volume is 65.05 m^3. The room has an irregular shape, there are no parallel walls, the largest and the smallest dimensions of the floor are 4.08 m and 3.67 m, respectively. The highest point of the ceiling is 4.33 m, while the smallest height is 3.87 m.

In order to improve the room diffusivity, there are 5 diffusers of the area from 0.8 m^2 to 2 m^2, hanging from the ceiling, see Fig. 1. The positions and orientations of diffusers are random. This is in accordance with the standard ISO 354 [9]. The measurements in empty room were carried out with and without diffusers, while the measurements with test specimens were carried out only with diffusers. In addition, the measurements with diffusers are repeated having different number of them placed in their positions, from all 5 to none of them.

Fig. 1. Reveberation room of the Faculty of Electronic Engineering in Niš with all 5 diffusers.

The reverberation times are measured and EDCs are generated using the *swept sine* technique and interrupted noise technique. In this paper, only the results obtained by the former technique are presented. Logarithmic *swept sine* signal of length of 30 s and frequency range from 20 Hz to 11 kHz sampled at 44.1 kHz repeated twice with the silence in between of 30 s is used as an excitation signal.

The excitation is emitted by the omni-directional spherical sound source having 12 loudspeakers in dodecahedral distribution, see Fig. 2. The responses are recorded by the 1-inch measurement microphone Bruel & Kjaer, type 4144. The measurement equipment also contains an audio amplifier, external sound card, microphone power supply and laptop.

As defined in the instructions for the *round robin* test, 12 regular combinations of source and microphone positions are used for the measurements. Two additional combinations include 2 microphone positions in the room corners for a particular sound source position. This gives 14 combinations in total, obtained for 4 positions of the sound source and 3 positions of the microphone plus two corner positions for the microphone. Regular positions for the sound source and microphone are chosen in accordance to the standard ISO 354. Every source and microphone position has its own height of the transducer. For every test sample, the measurements are repeated twice (with and without the sample).

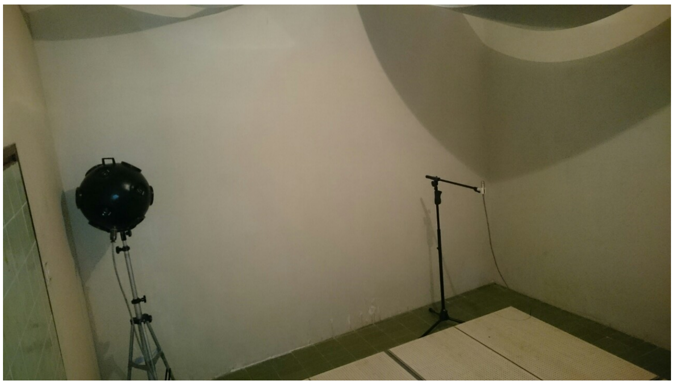

Fig. 2. Measurement setup showing omni-directional sound source and measurement microphone in the reverberation room.

V. Results

The repeatability of EDCs obtained by the Schroeder backward integration from 5 repeated measurements in the same points is illustrated in Fig. 3. The EDCs from repeated measurements coincide very well to each other, especially in broadband and EDCs filtered in third-octave bands at high and mid frequencies. Somewhat larger deviations among the curves appear in the EDCs at low frequencies. The only case where the differences among the EDCs are larger is the third-octave band at 100 Hz, see Fig. 3(d). The cause of the mentioned (in the majority of cases small) differences among the EDCs can be the positioning of the source/microphone. Since these positions are no strongly fixed by a hard construction, but instead by using markers and measuring distances from the reference walls and floor, there is a possibility of having a slight change of source/microphone positions from measurement to measurement.

Changing the positions of the sound source and microphone leads to certain changes of the EDCs. These changes for broadband EDCs are illustrated in Fig. 4(a). EDCs for different combinations of source and microphone positions have somewhat different shapes. Thus, regular decay curve shape (linear main decay), but also multi-rate decay and concave shapes of the decay curves can be found.

The changes in EDCs in third-octave bands caused by changes of sound source and microphone positions depend on frequency band. At higher and mid frequencies (above several hundred Hz), the differences among EDCs for different combinations of source and microphone positions are rather small. A representative case where EDCs coincide very well with each other is shown in Fig. 4(b).

Observing EDCs in third-octave bands at lower frequencies, more prominent differences in the main decay among the EDCs begin to appear mainly from 315 Hz downwards. In the frequency bands from 315 Hz to 200 Hz, the EDCs have a rather regular shape, and different decay rate, see Fig. 5. From 160 Hz towards the lower frequencies, in addition to different decay rate, there are different shapes of the EDCs, too. As mentioned above, these different shapes are related to regular linear main decay, multi-rate decay, concave shape and some other irregular shapes.

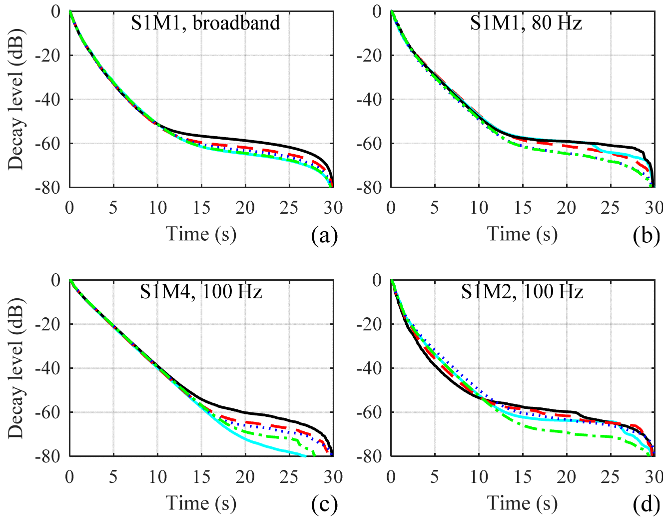

Fig. 3. EDCs from five repeated measurements for source position S1 and microphone positions M1, M4 and M2.

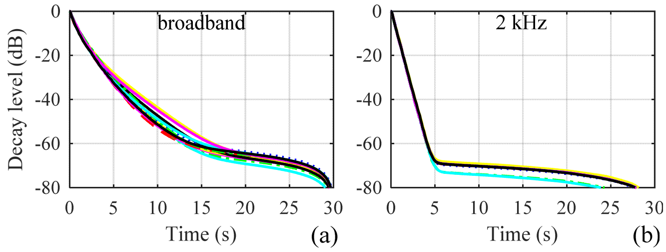

Fig. 4. (a) Broadband EDCs and (b) EDCs in third-octave band at 2 kHz obtained for all 14 combinations of sound source and microphone positions.

Two special cases of EDC differences at low frequencies are presented in Fig. 6. The first one given in Fig. 6(a) is related to regular shape of EDC with linear main decay, where the differences caused by changing the source and microphone positions are reflected in differences in the decay rate. These decay rate differences are even not that large comparing to similar differences in other frequency bands. The second special case shown in Fig. 6(b) is related to the largest differences among the EDCs at 100 Hz. Here, in a single frequency band, several different shapes of EDCs are present (the regular one, multi-rate decay and concave shape).

Placing diffusers inside the reverberation room should improve the diffusivity of the sound field. Here, opposite effects of removing the diffusers from the room are observed. Previously presented results are obtained having all five diffusers hanging from the ceiling. Then, these diffusers are removed one by one and the measurements are repeated for one combination of sound source and microphone position. The broadband EDCs for these six cases (including the one without diffusers) are presented in Fig. 7(a), while EDCs in third-octave bands are given in Fig. 7(b) to 7(d).

By increasing the number of diffusers, broadband EDC becomes steeper in the main decay part. This will reduce the decay rate, although the differences are not that large. Similar effect is noticed in the EDCs in third-octave bands. Here, the largest changes are observed at mid frequencies of several hundred Hz. In these frequency ranges, the EDCs have regular shape, and the effects of diffusers can be tracked in an easier way. This is not the case at lower frequencies, below 160 Hz, where the EDCs are typically irregular, see Fig. 7(d).

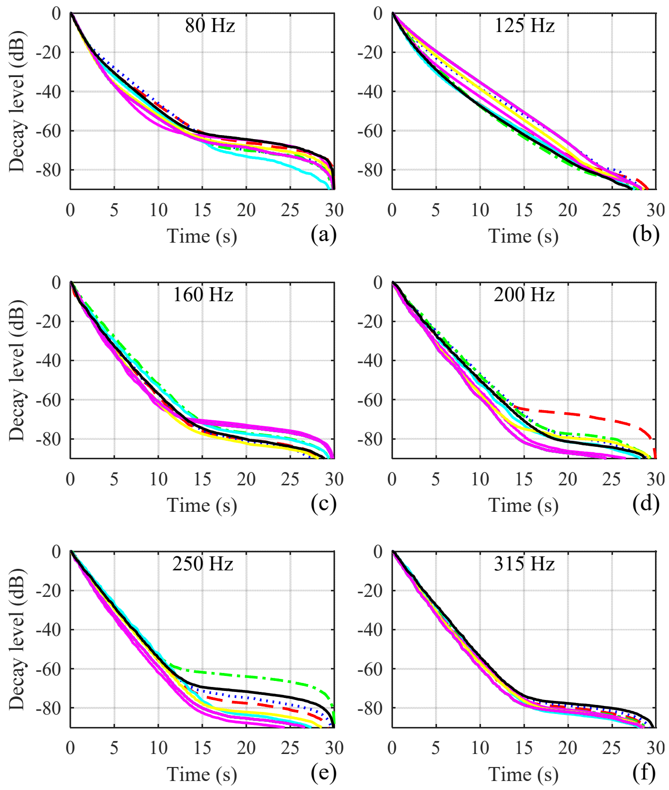

Fig. 5. EDCs in third-octave bands at low frequencies for all 14 combinations of sound source and microphone positions.

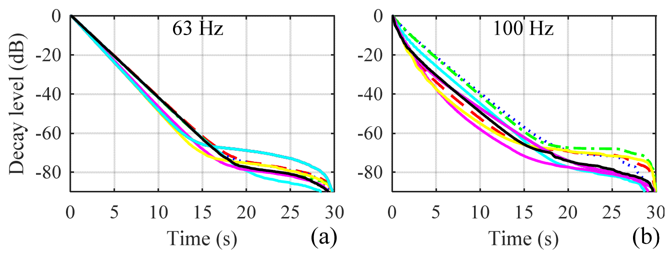

Fig. 6. Special cases of EDCs differences in third-octave bands at low frequencies for all 14 combinations of sound source and microphone positions.

Reverberation time (RT) is calculated from the obtained EDCs using the default range from -5 dB to -35 dB, except for the EDCs at 50 Hz, where RT is calculated in the range from -5 dB to -30 dB due to reduced dynamic range available in this frequency band. At lower frequencies (up to 315 Hz), changing the source and microphone position leads to more prominent change of RT, see Fig. 8(a). By increasing the frequency, this change of RT becomes smaller, and the curves presenting RT values for all 14 source/microphone positions become closer to straight lines, as shown in Fig. 8(b).

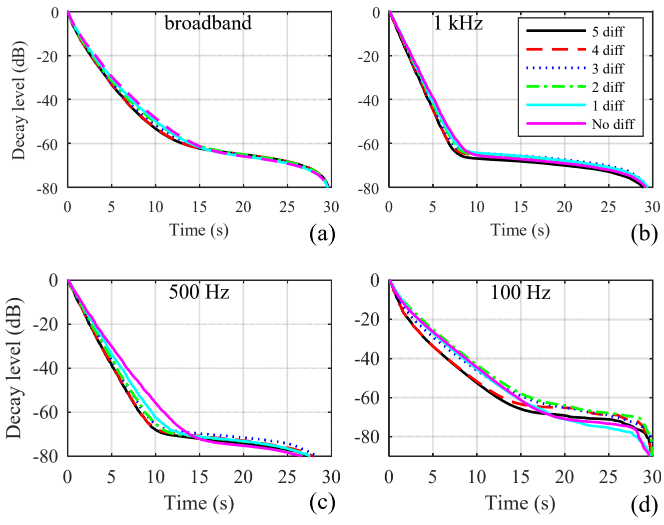

Fig. 7. (a) Broadband EDCs and (b) to (d) EDCs in third-octave bands obtained having different number of diffusers in the reverberation room and without diffusers for sound source position S1 and microphone position M2.

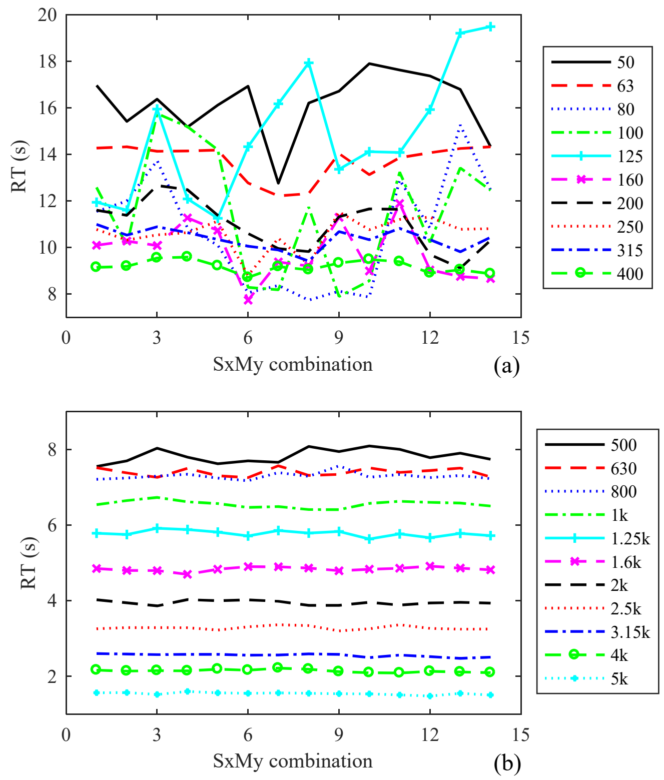

Fig. 8. Reverberation time (RT) calculated from EDCs in third-octave bands for different combinations of sound source (Sx) and microphone (My) positions (14 in total) for one set of repeated measurements.

These RT values are used for calculation of relative standard deviation of decay rate (S_{rel}). This diffusivity descriptor for one set of the measurements in the reverberation room is shown in Fig. 9. The standard deviation is larger at lower frequencies. The greatest value is obtained for 100 Hz. The most prominent differences among EDCs caused by both repeating the measurements and changing the source/microphone position exist in this frequency band.

Somewhat smaller values of standard deviation of decay rate exist at 50 Hz and 63 Hz. This could be a consequence of smaller dynamic range used for RT calculation at the former frequency, and rather regular EDCs with large dynamic range of the main decay at the latter frequency.

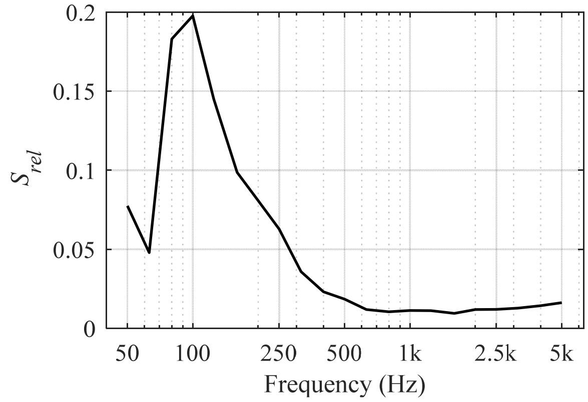

Fig. 9. Standard deviation of decay rate (S_{rel}) calculated using RT values in third-octave bands for one set of repeated measurements from Fig. 8.

Another descriptor of sound field diffusivity calculated here is related to correlation coefficient between the obtained EDCs and the best-fitted straight lines, that is, the effective measure of the curvature (κ). This descriptor for one of the repeated set of measurements is given in Fig. 10. The shape of this descriptor is very similar to the shape of standard deviation (S_{rel}) from Fig. 9. Similar as with S_{rel}, this descriptor (κ) has larger values at low frequencies. The greatest value is in the frequency band at 100 Hz, and the reasons are those already mentioned above. It is interesting to note that the value of κ in the frequency band at 65 Hz is very close to 0, meaning that the main decays of EDCs in this band are the closest to the straight lines.

VI. Conclusion

Diffuse sound field is one of the most important requirements for acoustical measurements such as the ones of absorption performance of test material in a reverberation room. Achievement of completely diffuse field in the whole frequency range of interest is a rather difficult task. Diffusivity of sound field in a small reverberation room of volume of about 65 m^3 is investigated in this paper. For that purpose, EDCs obtained from repeated measurements and for different combinations of sound source and microphone positions are observed. Besides, two indirect descriptors, standard deviation of decay rate and linearity of EDCs are used for that purpose. Based on these results, it can be considered that the sound field is diffuse in third-octave frequency bands at 315 Hz and above. In the bands at 250 Hz and 200 Hz, deviations from diffuse sound field are acceptable, while in the bands at and below 160 Hz significant deviations from diffuse conditions are present. It is also noticed in this research that adding the diffusers in the room leads to a steeper main decay of the EDC.

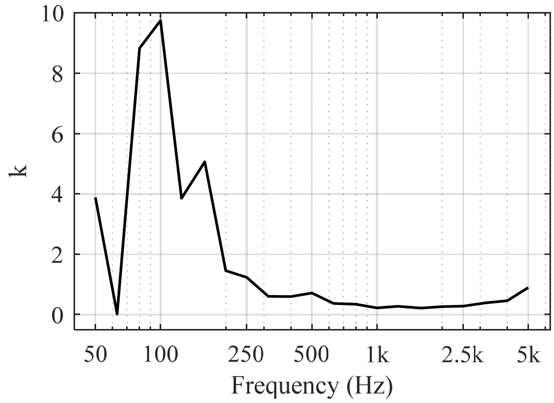

Fig. 10. Effective measure of the curvature (κ) calculated based on the correlation coefficient obtained in third-octave bands for one set of repeated measurements from Fig. 8.

Acknowledgment

This work has been supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

References

[1] W. O. Hughes, A. M. McNelis, "Examination of the measurement of absorption using the reverberant room method for highly absorptive acoustic foam," 29th Aerospace Testing Seminar, Los Angeles, CA, USA, 27 October, 2015.

[2] K. V. Horoshenkov, A. Khan, F.-X. J. Becot, et al., "Reproducibility experiments on measuring acoustical properties of rigid-frame porous media (round-robin tests)," *J. Acoust. Soc. Am.*, vol. 122, no. 1, pp. *345-353,* July, 2007.

[3] M. Vercammen, M. Lautenbach, "Non diffuse sound field in the reverberation room," Proc. 22nd Int. Congress on Acoustics, Buenos Aires, Argentina, 5-9 September, 2016.

[4] K. H. Kim, J. Y. Jeon, "Effect of diffusion conditions on absorption performance of materials evaluated in reverberation chamber," *Sustainability*, vol. 11, no. 23, pp. *6651 (16 pages),* 2019.

[5] M. L. S. Vercammen, "Improving the accuracy of sound absorption measurement according to ISO 354," Proc. Int. Symp. Room Acoust. ISRA 2010, Melbourne, Australia, 29-31 August 2010.

[6] T. J. Cox, P. D'Antonio, *Acoustic Absorbers and Diffusers,* 2nd ed. New York, USA: Taylor & Francis, 2009.

[7] E. A. Piana, N. B. Roozen, C. Scrosati, "The DENORMS round robin test: measurement procedure and post-processing of time data," Proc. 26th Int. Congress Sound and Vib. ICSV26, Montreal, Canada, 7-11 July, 2019.

[8] E. Toyoda, S. Sakamoto, H. Tachibana, "Effects of room shape and diffusing treatment on the measurement of sound absorption coefficient in a reverberation room," *Acoust. Sci. & Tech.*, vol. 25, no. 4, pp. *255-266,* 2004.

[9] *Acoustics—Measurement of Sound Absorption in a Reverberation Room*, ISO 354, 2003.

[10] C. Scrosati, F. Scamoni, M. Depalma, "On the diffusion of the sound field in a reverberation room," Proc. 26th Int. Congress Sound and Vib. ICSV26, Montreal, Canada, 7-11 July, 2019.

[11] M. M. Hasan, M. Hodgson, "Effectiveness of reverberation room design: Room size and shape and effect on measurement accuracy," Proc. 22nd Int. Congress Acoustics ICA, Buenos Aires, Argentina, 5-9 September, 2016.

[12] *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*, ASTM C423-17, 2017.

[13] D. Ćirić, K. Jambrošić, N. Stojković, "Energy decay curves obtained in reverberation chamber during measurements of absorption coefficient," (in Serbian), Proc. 63rd ETRAN, Silver Lake, Serbia, 3-6 June, 2019.