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ENERGY DECAY CURVE DEVIATION IN THE ABSORPTION COEFFICIENT MEASUREMENT IN A SMALL REVERBERATION ROOM

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ABSTRACT

A recent trend in absorption coefficient measurements in a reverberation room is to extend the frequency range of interest to low frequencies. In these measurements, there are certain conditions related to the reverberation room required to be fulfilled. One of the most important prerequisites is to have a diffuse sound field. However, some reverberation rooms do not have the pre-defined characteristics such as shape or required volume. It is worthwhile to know how reliable results can be obtained in such rooms. In this work, the absorption coefficient of several sets of rock mineral wool materials was measured in a small reverberation room of a volume of 65 m^3. The focus is on the sound energy decay curves (EDCs) in the third-octave bands from 50 Hz to 5 kHz in both conditions with and without test sample. The deviation of these EDCs from the ideal straight-line is analyzed. For quantifying the observed effects, the standard deviation of decay rate and nonlinearity of EDCs are used. Some interesting effects found include the concave shape of the EDCs with test samples at frequencies of several hundred Hz and specific irregular EDC shapes at particular low frequencies both with and without test sample.

Keywords: *absorption coefficient, energy decay curve, reverberation room, diffuse sound field.*

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1. INTRODUCTION

In measurements of the absorption coefficient in a reverberation room, the reverberation time (RT) is estimated without and with test material placed in the room according to the requirements defined in the relevant standard, e.g., ISO 354 [1]. It is assumed that the measured energy decay curve (EDC) is a straight line (single slope exponential decay) when plotted on a logarithmic graph, that is, when the decay levels are given in dB. For such an EDC, the RT can be estimated by fitting a linear regression to the main decay of the EDC where reverberation energy is dominant over noise [2].

EDCs measured in real spaces can have a single slope decay, but also multiple slope or multi-exponential decay. The latter is typically related to the coupled spaces [3,4], but it can be found in single spaces, too. Some illustrative examples can be found in [2,5-7]. The EDCs that deviate significantly from the straight lines are presented in the study of non-diffuse sound field decay in a model of rectangular parallelepiped room with two non-parallel absorbing walls [7]. These EDCs at the frequency of 4 kHz have concave shape with large deviation from the straight line especially in the case without scattering elements in the room. The curvature of the EDCs depends significantly on the source-receiver location.

Curvature of the EDCs measured in different rooms including reverberation chambers has been a research topic more than several decades. As potential causes of the curved decays, "not diffuse sound field, feedback of energy from an adjacent room with a longer RT, or working to close to the bakcground noise" are stated in [8]. The largest curvatures in this study are found at low frequencies, although the curved EDC are seen at mid and high frequencies, too. In [9], it is reported that the measured EDCs are more bent than the respective theoretical ones. Significant deviation of the absorption characteristics in real reverberation rooms from the uniform wall admittance (assumed in theoretical consideration) is indicated as the most probable reason for this lack of agreement. It is also observed that the curvature is increased when a plane concentrated absorbent is added to one of the walls [9]. The EDC curvature depends on the source position, where some source positions give lower curvature than some other positions. Another interesting observation is that almost perfectly linear EDCs are obtained when the small samples of low frequency absorbents are randomly placed in the room [9].

The measurements of absorption coefficient in a very small reverberation chamber with the unlined volume of 2.86 m^3 and unlined surface area of 12.4 m^2 are analyzed in [10]. It is concluded that such a small chamber can give the absorption coefficient estimates that are suitably close to those obtained from either the reverberation room or impedance tube over the entire frequency range (from 100 Hz to 4 kHz).

Taking into account what has been presented in the literature, it can be concluded that the curved EDC is a known phenomenon that can appear even in large reverberation rooms. On the other hand, reverberation rooms of different volumes (belonging to a wide range from several m^3 to a few hundreds of m^3) and shapes are used for the absorption coefficient measurements. A question that can be raised is what results can be expected to be obtained in a small reverberation room and how reliable these results can be. This study provides some results that shade light from a particular perspective to the raised question.

To achieve the defined goal, the absorption coefficient of several sets of rock mineral wool was measured in the small reverberation room of the volume of 65 m^3. Special attention is paid to the curvatures of EDCs obtained in the empty reverberation room and when the test absorption material is placed in the room. Illustrative examples of the curved EDCs are identified, analyzed and presented here. The deviation from the straight line is quantified by the standard deviation of decay rate and nonlinearity of EDCs.

2. NON-EXPONENTIAL DECAY CURVES

Multi-exponential decays represent a phenomenon that is typically associated with coupled spaces. Here, estimation of the decay rate is often done by approximating such decays by a sum of multiple decays having different decay rates [3,4]. However, it is presented in the literature that multi-exponential decays in a particular frequency band can be present in a single space, too, [5,11]. The EDC in this frequency band is a sum of exponential decays of individual modes. Consequently, if the rates of these decays are not the same, the frequency band EDC will be curved or multiple-sloped instead of being a single exponential decay [5].

The mentioned multiple-sloped decays can appear throughout the frequency range, that is, in the low, mid and high frequency bands. Typically, a special attention is paid to low frequencies, below so-called Schroeder frequency [12,13], as the overlap of individual modes is low here. In these frequency bands, the axial and tangential modes are dominant, and they decay slower than the oblique modes. Thus, the different decay rates of the modes cause the decays at low frequencies to be curved [5,9]. Non-straight decay raises a question how to estimate the RT and other parameters such as absorption coefficient.

By placing the microphone in a corner of a room, the measured sound pressure level is greater than the average level in the room by 3 dB, 6 dB and 9 dB for the axial, tangential and oblique modes, respectively [14]. This level increase is the result of the effects of interference. Similar interference effects are present when a sound source is placed in a room corner having significance influence on the balance between the modes.

An interesting phenomenon is mentioned in the literature appearing at mid and high frequencies when distribution of absorption in a room is uneven leading also to multi-exponential decays [5], that is, to decays that deviate from the Sabine's law. In a scenario found in the measurement of absorption coefficient in a reverberation room, one surface is partly covered with a highly absorbing material while the other surfaces are highly reflective. Here, the rapid decays of non-grazing modes and slower decays of grazing modes can lead to the curved energy decays. Such a phenomenon is reported in the literature for rectangular rooms [15].

It is worth mentioning that curved EDCs do not automatically mean that the sound field in a room is non-diffuse [5]. However, there is no unique approach how to deal with these decays. Moreover, it is one of the most important causes of differences in results of absorption coefficient measurements done in different laboratories.

It is published in the literature that the mean of all excited modes in a room is contained in the beginning of the EDC [5]. Opposite situation is present in the late part of the EDC containing only the modes that decay slower. In that regard, a proposal is given to take only the initial part of the EDC for calculating the absorption coefficient. In this way, smaller values of the RT are obtained in comparison to those that can be expected. However, such results are

considered to be better than those obtained using 20 dB or 30 dB of decay range [5]. A solution how to handle the multi-sloped decay curves can be not to use a single decay rate, but instead several decay terms can be applied, e.g., from two to seven [5].
In a reverberation chamber, it is expected to have a single exponential decay. However, certain deviations from such decay have been reported even in reverberation chambers [5]. In these circumstances, determination of RT depends on the applied estimation method and the used decay range. The curvature of sound decay in a reverberation chamber, the effects of diffusers and setup of absorbing material are analyzed in [5]. It is found that slight curvature exists in the low frequency one-third octave band (500 Hz) in the empty reverberation chamber. When the absorption material is placed on the floor, the EDC exhibits a multi-sloped decay due to the uneven distribution of absorption. This is valid in the whole frequency range - at low frequencies as well as at mid and high frequencies, although it seems that the effect is more prominent at low frequencies. The curvature is decreased after mounting six diffusers on the ceiling, where the effect is less prominent at low frequencies.

3. ACOUSTICS OF A REVERBERATION ROOM

The uniform distribution of sound absorption in a reverberation room would allow a diffuse sound field, where the measured EDC would have a single-sloped decay. However, when the absorption coefficient is measured in a reverberation room, the tested material is typically placed on a floor violating the uniformity of absorption distribution.
The sound field in a room can be represented as a sum of normal modes having their own single exponential decays and specific damping constants [9]. Since in the absorption coefficient measurements, the decay signal is filtered in octave or third-octave bands, the decay process in such bands can be given as [2,16]

$$p(t) = \sum_{i=1}^{N} a_i \, e^{\delta_i t} \cos\left(\omega_i t - \phi_i\right), \qquad (1)$$

where N is the number of modes present in the observed band, $p(t)$ is the sound pressure in a certain point in the room, a_i and δ_i are the amplitude and decay constant (related to decay rate) of each of the existed modes, while ϕ_i is their phase. When the number of modes is large, the mean squared sound pressure becomes [2,16]

$$\overline{p^2(t)} = \frac{1}{2} \sum_{i=1}^{N} a_i^2 \, e^{2\delta_i t} \, . \qquad (2)$$

As a consequence of large number of modes, their interference is cancelled and varying decay constants result in a discrete distribution. If various dominating modes have nearly the same damping constants, the energy decay is exponential and EDC is linear [9]. In the opposite case of different constants, the decay shows a convex curvature.
In order to illustrate the effect of having multiple modes with varying decay constants, only three such modes are included in Eqn. (2), and the result is presented in Fig. 1. These modes have different decay constants leading to the decay rates of 70 dB/s, 40 dB/s and 20 dB/s, representing an extreme example used here to enable better visibility of the multi-sloped EDC. As stated in [2,16], the early decay of the EDC represents the weighted mean of the decay constants, where the weight is related to the decay rate distribution.

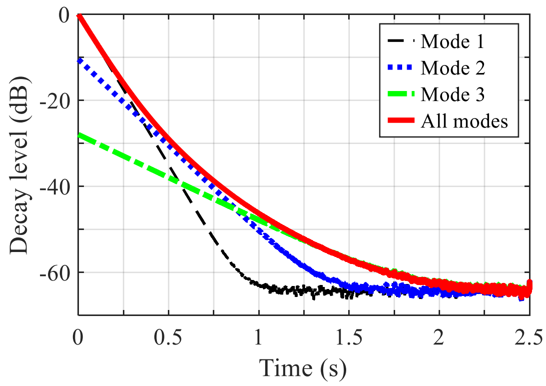

Figure 1. Decay of individual modes and sum of the three individual modes according to Eqn. (2).

4. METHOD OF INVESTIGATION

4.1 Measurements and EDC calculation

The absorption coefficient was measured in the reverberation room of the Faculty of Electronic Engineering in Niš, Serbia having a volume of 65.05 m^3. The room has an irregular shape with non-parallel walls. The side walls have the following dimensions at the floor level: 3.92 m, 3.67 m, 4.08 m and 3.97 m, while the corner heights are 4.33 m, 4.32 m, 3.88 m and 3.87 m.
To analyze the effects of increasing the room diffusivity, five diffusers of area from 0.8 m^2 to 2 m^2 were added to

hang from the ceiling, as shown in Fig. 2. In accordance with the standard ISO 354 [1], the positions and orientations of diffusers were randomly chosen. The EDCs of the empty room were obtained without and with diffusers, where they were added one by one. On the other hand, the EDCs with test samples were calculated only with all five diffusers.

Figure 2. Five diffusers placed on the ceiling of the reverberation room.

The EDCs were extracted from the measurements of room impulse responses carried out by applying the swept sine technique. In that regard, logarithmic swept sine signal of duration of 30 s and frequency range from 20 Hz to 11 kHz repeated twice with the silence in between of 30 s was used as an excitation signal. The sampling frequency was 44.1 kHz.

The transmitting part of the measurement system consisted of the dodecahedron speaker (sound source) NTi Audio, type DS3 and amplifier Art Pro Audio, type SLA-1, while the receiver was the 1-inch measurement microphone NTi Audio, type M2230. The measurement equipment also contained external sound card Focusrite, type Scarlet and laptop.

As defined in the standard ISO 354 [1], 12 combinations of source and microphone positions were used for the measurements. These included four source positions, and for each of them three microphone positions, see Fig. 3. Sound source and microphone were placed at regular positions in accordance with the standard ISO 354. Both source and microphone had a particular height for every position. The measurements were carried out twice for each of the test samples. Rock minearal wool was used as test absorbing material, and there were 8 test samples related to different sets of this material. The area of all these test samples was 3 × 2.4 m. This is large area in comparison to the floor size, since app. 45 % of the floor was covered with the absorbing material.

Figure 3. Measurement setup a) in the empty reverberation room, and b) when the test sample was placed in the room.

4.2 Quantification of sound field diffusivity

Sound field diffusivity can be quantified in different ways. One of the indicators that can be used for this purpose is based on the RT (decay rate), that is, on standard deviation of the RT according to the source and microphone locations inside a reverberation room [17]. The specification of the maximum allowable displacement of the decay rate depending on the locations of the source-microphone is given in the ASTM C 423 standard [17]. The decay rate d_i measured for the i-th source-microphone location can be calculated using the RT obtained in that position T_i by

$$d_i = \frac{60}{T_i} - m_{iso}\, c \log(e), \tag{3}$$

where the second term is related to sound attenuation in air described by the air attenuation coefficient m_{iso} calculated according to ISO 9613-1 [17], the speed of sound c and the base of natural logarithm e. Having N source-microphone positions, the standard deviation of decay rate in a third-octave band (S) can be calculated as

$$S=\left(\frac{1}{N-1}\sum_{i=1}^{N}\left(d_i-\bar{d}\right)^2\right)^{\frac{1}{2}}, \qquad (4)$$

where $\bar{d}$ is the decay rate averaged over all source-microphone positions. As the contribution of the sound attenuation in air term in Eqn. (3) is small, especially after its inclusion in Eqn. (4), the decay rate here is calculated as $60/T_i$. As a sound field diffusivity indicator, the relative standard deviation of decay rate (S_{rel}) can be used, which is calculated by dividing S with $\bar{d}$ ($S/\bar{d}$). Lower values of S_{rel} indicate better diffusion conditions.

Sound field diffusivity can also be evaluated using EDCs. In a perfectly diffuse sound field, EDC on dB scale should be a straight line. In that regard, a measure of EDC nonlinearity can be used as an indirect quantifier of the sound field diffusivity. Curvature of the EDCs can be calculated by the correlation coefficient r between the decay curve and the best-fitted straight line [17]. In this study, the EDC curvature is measured by applying an indicator κ that magnifies the deviation from perfect correlation

$$\kappa = 1000\left(1-(r)\right). \qquad (5)$$

5. RESULTS

5.1 Effects of diffusers

The strongest effects of diffusers are seen at frequencies below 1 kHz. Installation of diffusers in the reverberation room lead to two main effects - reduction of decay rate (making the EDCs steeper) and reduction of irregularity of the EDC shape. Regarding the latter effect, the diffusers make the EDCs less curved, that is, less concave in shape. Some illustrative examples in third-octave bands are shown in Fig. 4. In that regard, there are bands where the effects of diffusers are prominent, as the band at 315 Hz, see Fig. 4.a), but also bands with smaller effects of diffusers, as the band at 160 Hz given in Fig. 4.b). By increasing the number of diffusers in the room, the mentioned effects become more prominent. Here, the larger differences are seen by placing up to three diffusers, and smaller differences are observed for further increase in number of diffusers.

The EDCs shown in Fig. 4 are generated using the impulse responses measured by the equipment described in [17]. Comparison of the EDCs generated using these responses and the responses measured by the equipment described in this paper is presented in Fig. 5. It can be concluded that the repeatability of the results is quite good.

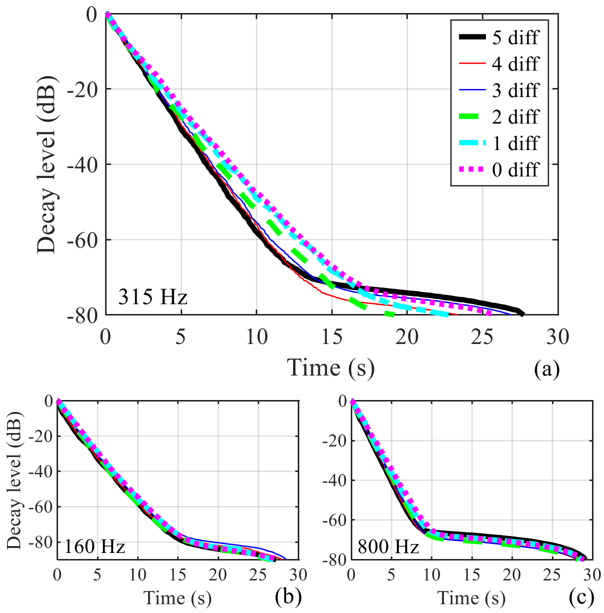

Figure 4. EDCs in third-octave bands at a) 315 Hz, b) 160 Hz and c) 800 Hz obtained without (0 diff) and with diffusers (from 1 diff to 5 diff).

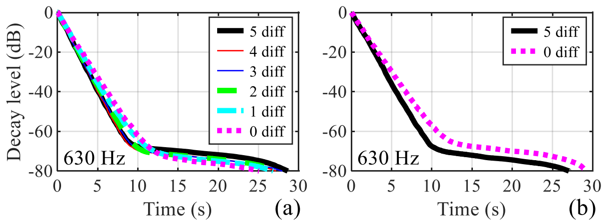

Figure 5. EDCs in third-octave band at 630 Hz obtained without (0 diff) and with diffusers (1 diff to 5 diff) measured using two different measuring equipments: a) from [17] and b) from this paper.

5.2 Quantification of sound field diffusivity

The EDCs obtained in two conditions – empty reverberation room (without test material) and with test material placed on the floor are analyzed here. In order to calculate the relative standard deviation of decay curves, the RTs in third-octave bands from 50 Hz to 5 kHz are estimated from the EDCs by the linear interpolation method. Here, the largest possible dynamic range of the EDCs is employed, from -5 dB of decay up to a point shifted for at least 15 dB upward from the background noise level, as defined in the standard [1]. This dynamic range was typically greater than 30 dB, but in significant number of cases it was close to that number used for estimation of the RT known as RT30 or T30. The RTs for one set of measurements without test material are presented in Fig. 6. Change of source or microphone position causes larger difference in the RTs at lower frequencies (up to several hundreds of Hz), as shown in Fig. 6.a). These differences become rather small at frequencies above 1 kHz.

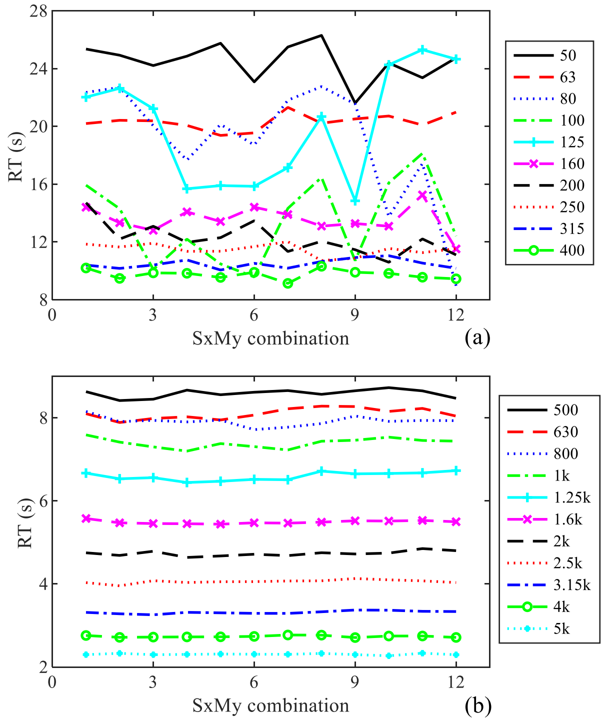

Figure 6. RT of the empty reverberation room calculated from EDCs in third-octave bands for all 12 combinations of sound source (Sx) and microphone (My) positions.

The relative standard deviation of decay rate (S_{rel}) of the empty room calculated by using the RTs from Fig. 6 has the greatest values at low frequencies, that is, at 80 Hz, 100 Hz and 125 Hz, as shown in Fig. 7. Such a result was also obtained in the previous measurements presented in [17]. Obtaining less diffuse sound field at low frequencies is well aligned with what can be expected in reverberation rooms. The situation is somewhat changed when the sound absorbing material (rock mineral wool) is placed in the room, see Fig. 7. Now, larger values of S_{rel} are present in a wider frequency range, almost to 1 kHz.

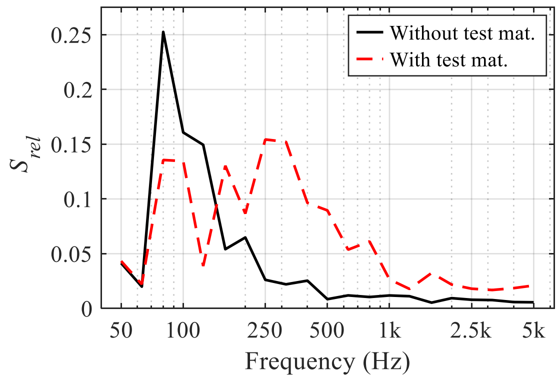

Figure 7. Relative standard deviation of decay rate (S_{rel}) of the empty reverberation room (calculated using RTs from Fig. 6) and with test material (the first specimen of rock mineral wool).

Another indicator of the sound field diffusivity based on the curvature (nonlinearity) of the EDCs (correlation between the EDC and the best-fitted straight line - κ) for both measurement conditions without and with test material is shown in Fig 8. Larger curvatures of the EDCs of the empty room are present at low frequencies, between 80 Hz and 160 Hz. On the other hand, the EDC curvatures are significantly larger when the absorbing material is placed in the room. This is especially valid for the EDCs in the third-octave bands from 250 Hz up to 800 Hz.

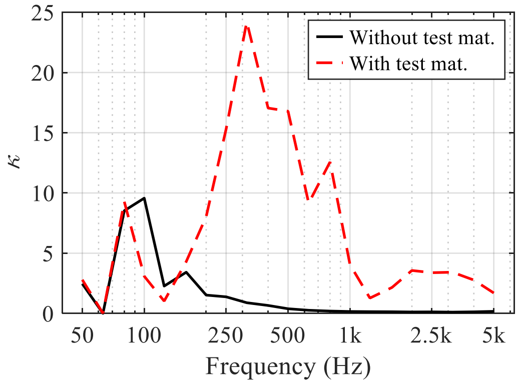

Figure 8. Effective measure of curvature of EDCs (κ) measured without and with test material (the first specimen of rock mineral wool).

5.3 EDCs obtained without and with test material

Considering the EDCs of the empty reverberation room, the most significant irregularities of EDC shape are seen at low frequencies, especially at 80 Hz and 100 Hz, as shown in Fig. 9.a) and 9.b), respectively. Depending on particular source and microphone position, these irregularities can be either double slope or multiple slope EDCs represented also as a concave decay curve. In such cases, the decay rate is larger in the beginning of the EDCs, and smaller in later parts of the decay. An interesting situation is seen in EDCs in the third-octave band at 200 Hz, Fig. 9.c), where the EDCs have rather regular shape, but different decay rates that depend on particular sound source and microphone positions. For the third-octave band at 315 Hz, Fig. 9.d), and upward, the EDCs are very close to each other having very similar decay rates.

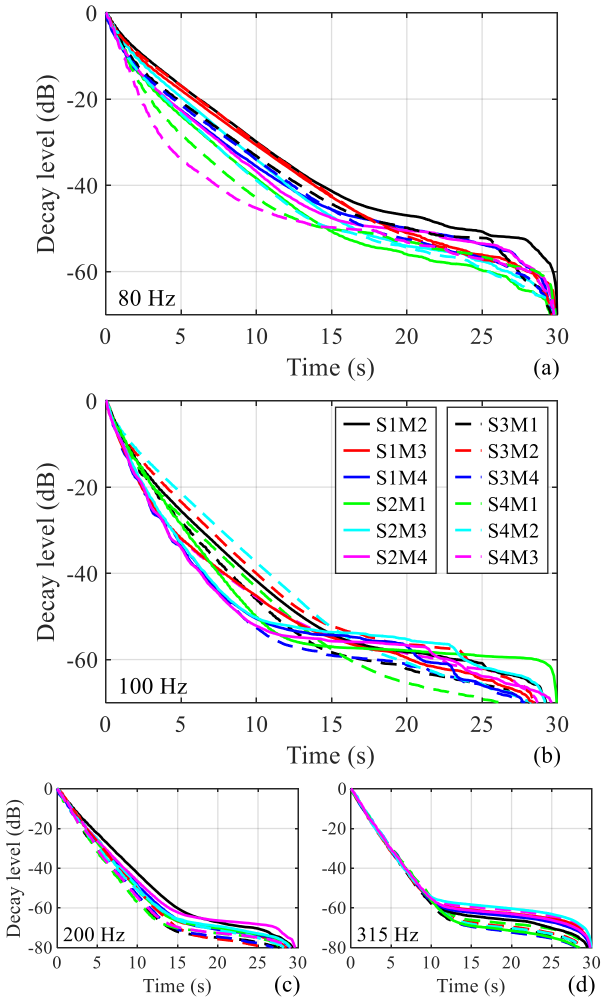

Figure 9. EDCs in third-octave bands obtained in the empty reverberation room for all 12 combinations of sound source (Sx) and microphone (My) positions.

With regards to the curvature of the EDCs, the situation is changed when the test sample (the rock mineral wool material) is placed in the room. The most significant effect is related to concave shape of the EDCs, which is present in a number of EDCs in third-octave bands at low frequencies, but also at frequencies of several hundreds of Hz and even close to 1 kHz. Some illustrative examples are shown in Fig. 10.

It is interesting to note that there are frequency bands where the EDCs are almost coincident regarding the reverberation decay (the difference can be seen in the background noise levels), but the EDC shape is rather concave, as presented in Fig. 10.a). Another example is shown in Fig. 10.b) presenting different EDC shapes – regular (single slope), double and multiple slope decays. Dependence of the EDC curvature on the sound source and microphone positions is seen in the third-octave band at 200 Hz, see Fig. 10.c), where both single slope and strong double slope decays can be distinguished. There are also bands where the EDCs have single slope decay, but different decay rates, similar to the case presented in Fig. 9.c) for the empty room. Such a situation with test material is found at 100 Hz, not shown here.

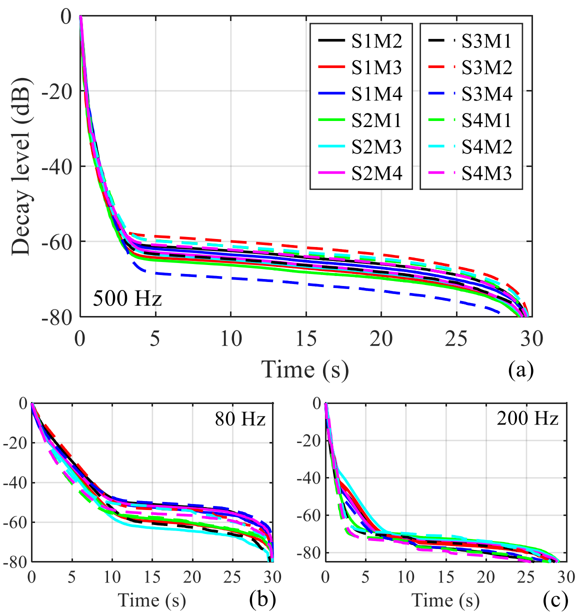

Figure 10. EDCs in third-octave bands obtained in the reverberation room with test material (the first specimen of rock mineral wool) for all 12 combinations of sound source (Sx) and microphone (My) positions.

6. CONCLUSIONS

The EDCs obtained in the small reverberation room without and with test specimen (rock mineral wool material) are analyzed in the study. Two indicators of sound field diffusivity show that the strongest deviation from diffuse conditions exists at low frequencies (below 160 Hz) when the measurements are carried out in the empty room. In third-octave bands at these frequencies, various shapes of EDCs can be found – single slope of the same and different decay rates, double or multiple slope decays having a concave shape. By placing the absorbing material on the floor surface occupying rather large area of the floor (close to 45%), the concave shape of the EDCs is observed in a number of EDCs both at low frequencies and frequencies of several hundreds of Hz or even close to 1 kHz. The strongest curvatures are seen at frequencies of several hundreds of Hz, e.g., from 250 Hz to 800 Hz. This is confirmed by the indicator showing the effective correlation between the EDC and the best-fitted straight line.

7. ACKNOWLEDGMENTS

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