Sound Propagation in a Reverberation Chamber

Martina Kreuzbichler, Jamilla Balint, Gerhard Graber

Signal Processing and Speech Communication Laboratory, Graz University of Technology

8010 Graz, Email: m.kreuzbichler@student.tugraz.at, balint@tugraz.at, graber@tugraz.at

Introduction

The laboratory reproducibility of sound absorption measurements in reverberation chambers is still unsatisfactory [1]. The main requirement for measuring the absorption coefficient in a reverberation chamber is a diffuse sound field. Annex A of ISO 354 [2] states that the sound field in the chamber becomes more diffuse with an increasing amount of diffusers. The ideal amount of diffusers is reached, when the measured mean sound absorption coefficient in the frequency range from 500 Hz to 5000 Hz approaches a maximum value and remains constant with an increasing number of diffusers. Although this procedure is very common, a lot of different approaches for investigating the diffusivity of the sound field exist. Some of the approaches are described briefly in the following paragraphs.

Remmers at al. described the diffusivity of sound fields in [3] inter alia with the principle of a spatial constant energy density distribution. The square of the sound pressure values are proportional to the energy density and therefore the sound pressure level in third octave bands was measured. Their measurement results for the energy density with and without diffusers in a reverberation chamber were similar. The differences in the sound pressure level with and without diffusers are very low at high frequencies and increase slowly towards low frequencies.

Nolan et. al. [4] tried to verify the reverberation room's diffuse field conditions with measurements of the equivalent sound absorption area of an absorptive sample and the diffuse field factor. Low values of this factor indicate a high degree of diffusion. They performed their measurements for different diffuser settings including panel and spherical diffusers and discovered that the equivalent sound absorption area is rather sensitive to the change in the diffusivity but the diffuse field factor does not constitute an accurate indicator and can only be used for rough estimations.

Nutter et al. demonstrated in [5] that total acoustic energy density may be beneficially used in reverberation chamber measurements. They assumed that the velocity in the diffuse field is not exactly zero and calculated the total energy density impulse response by taking the squared pressure impulse response and the squared velocity magnitude impulse response. Nutter et al. showed with their measurements that using the total energy impulse response, T_{60} measurements and sound absorption calculations provide greater spatial uniformity.

Although many different investigations regarding the diffusivity of the sound field in a reverberation chamber were carried out, up to this point it is still not known how diffuse a sound field can get. When measuring the reverberation time and calculating the absorption coefficient of a sample in a reverberation chamber, values of $\alpha > 1$ in the entire frequency range appear. With the so called edge effect, some of these high values can be explained [6]. This research evaluates the influence of the panel diffusers regarding the energy distribution in a reverberation chamber. Diffusers redirect the sound rays to the absorbent sample and are a barrier to the sound waves. Depending on the wave length the sound waves are either reflected or diffracted. As a consequence high frequencies are reflected and low frequencies are diffracted. In [7] the hypothesis was set up that the panel diffusers decrease the volume in a reverberation chamber and therefore the absorption coefficients are overestimated.

This paper investigates if this is a valid assumption and how the energy distribution around a diffuser looks like after excitation. We measured the impulse response around a diffuser in 70 positions and show how the sound waves propagate after the excitation.

Fundamental relations

The energy E of a discrete time signal with N samples is defined as:

$$E = \sum_{n=0}^{N-1} |x(n)|^2 \tag{1}$$

If we apply Parseval's theorem, the broadband signal energy E is equal to the summation of the energy spectrum across all frequencies:

$$\sum_{n=0}^{N-1} |x(n)|^2 = \frac{1}{N} \sum_{k=0}^{N-1} |X(k)|^2 \tag{2}$$

where $x(n)$ is equal to the amplitudes of the measured impulse response - sound pressure values. $X(k)$ is the fast Fourier transform of $x(n)$ and N is the number of samples. The square of the sound pressure values is proportional to the energy density. Therefore these terms are not multiplied by the volume V of the reverberation chamber to get the energy. Moreover they are not normalized by the speed of sound c and the air density ρ and are used for comparison among themselves but not as absolute values.

Measurements

The measurements were carried out in the reverberation chamber of the Laboratory for Structural Engineering (Laboratory of Building Physics), Graz University of Technology. The reverberation chamber with sound hard, parallel walls has the dimensions of 8.34 m by 5.99 m and a height of 4.90 m. The total volume of the chamber is 244.79 m^3. The room is equipped with panel diffusers according to ISO 354 [2].

Figure 1 shows the measurement setup in the reverberation chamber. A panel diffuser, made out of a 4 mm thick chipboard, with the size of 1 x 1.5 m, was bended along the length and positioned in the middle of the room. The microphone positions were distributed around it.

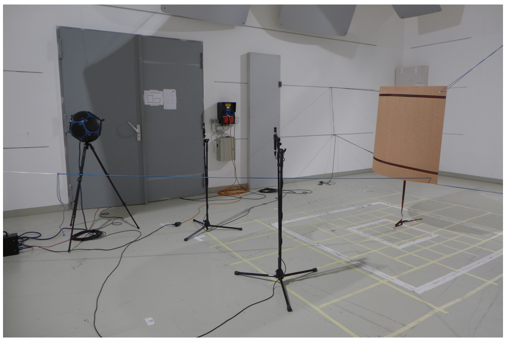

Figure 1: Measurement setup in the reverberation chamber

We measured the impulse response in 70 measurement points (see fig. 2) at a height of 1.3 m. For the integrated impulse method the room was excited by an MLS Signal. The distance between the microphone positions close to the diffuser was 0.25 m and 0.5 m resp. 0.75 m in the more distant area.

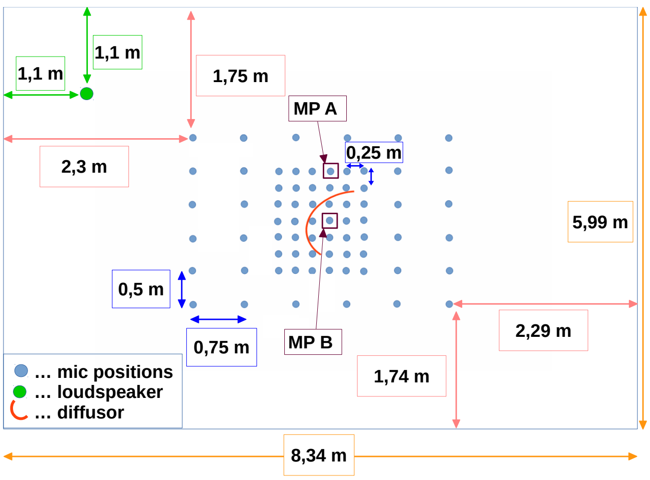

Figure 2: Floorplan of the reverberation chamber: The distance between the measurement points close to the diffuser was 0.25 m. The far-off points were placed with an interval of 0.5 m in the width and 0.75 m in the length.

Measurement results

In figure 3, the impulse responses from measurement point A and B are shown (the microphone positions are marked in fig 2). The measurement positions are 0.75 m apart from each other and separated by the diffuser.

At measurement point B behind the diffuser (lower picture of fig. 3), no direct sound arrives and the first reflections hit the microphone at approx. 8 ms after the direct sound arrived at measurement position A. At measurement point A the direct sound is visible as a clear peak at the beginning of the impulse response. After that time frame the sound field can be regarded as diffuse. At measurement point B most of the energy arrives between 35 ms and 50 ms. At this stage the sound waves hit the entire surfaces of the reverberation chamber and were reflected at least once. From these observations we conclude that it takes up to 40 ms longer until a diffuse sound field builds up behind the diffuser. In this fig. 3 the delay between the sound source and the microphone positions, which has a length of 10 ms ($\triangleq$ 3.3 m), is not considered.

In figure 4 the decay curves from measurement point A and B are shown. No remarkable difference can be seen in this normalized curves. So the decay process in front of and behind the diffuser is equal and very homogeneous.

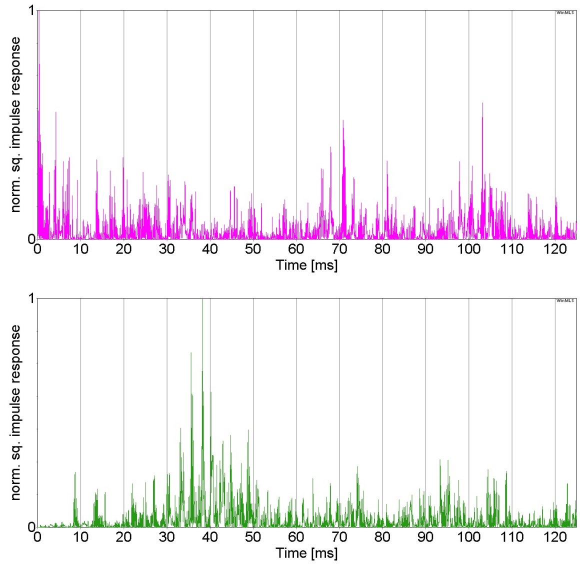

Figure 3: Squared impulse response for 2 measurement points, pink: measurement point A in front of the diffuser, green: measurement point B behind the diffuser

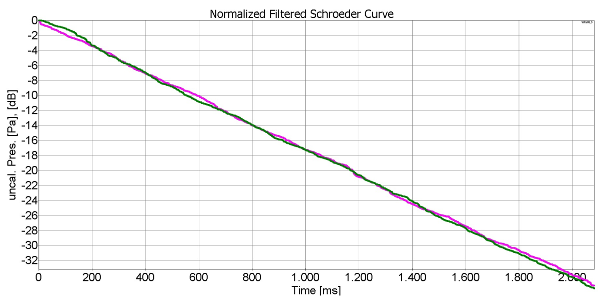

Figure 4: Decay curves for 2 measurement points at the third octave band of 2000 Hz, pink: measurement point A in front of the diffuser, green: measurement point B behind the diffuser

For a better understanding of the structure of the sound field around the diffuser, a visualization of the sound propagation was generated. The visualizations were animated over time and video clips were made. We created video clips for a broadband propagation and for six different third octave bands, the animations can be watched online and downloaded. The required link is given at the end of the paper. Certain time periods of the animation are shown in the following paragraph and will be discussed.

In figure 5 the energy propagation is displayed for the time period of 5 ms after excitation for the frequency range of 63 Hz to 8 kHz. The white area in the middle of the plot represents the bended diffuser. The measurement area covers all the microphone positions shown in fig. 2. The grey area represents the floor area of the reverberation chamber.

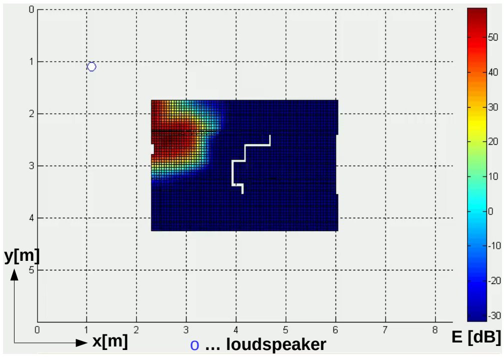

Figure 5: Energy distribution in the reverberation chamber at 5 ms after excitation for the frequency range of 63 Hz to 8 kHz

We displayed the energy propagation for the time periods of 8 ms, 11 ms, 16 ms, and 35 ms (see fig. 6 and 7). For better visibilty of the results only the measurement area is shown. The colorbar from fig. 5 is also valid for fig. 6 and fig. 7. After a time period of 8 ms to 11 ms which corresponds to a distance of 2.7 m to 3.7 m referred to the loudspeaker, parts of the energy are visible behind the diffuser but it takes up to 35 ms until the energy is distributed almost equally over the measurement area. Up to 29 ms the level behind the diffuser is slightly lower (- 10 to -12 dB) compared to the area which is facing the sound source. At 11 ms the yellow area on the left side is due to a measurement error and the star shaped edge is because of the distance between the microphone positions and the interpolation in-between.

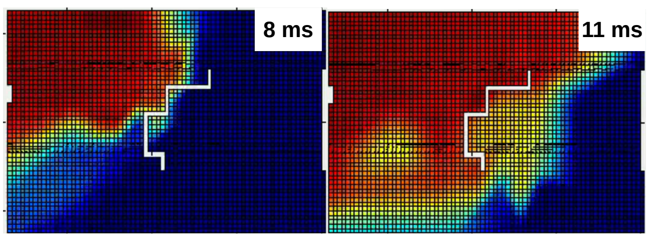

Figure 6: Energy distribution in the reverberation chamber at 8 ms and 11 ms after excitation for the frequency range of 63 Hz to 8 kHz. For colorbar see fig. 5.

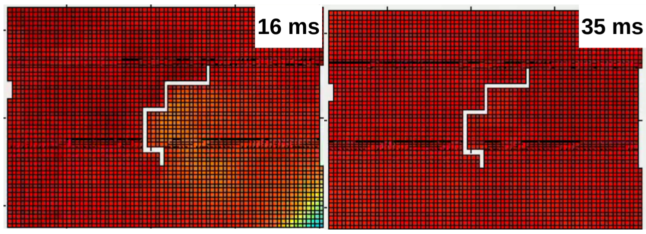

Figure 7: Energy distribution in the reverberation chamber at 16 ms and 35 ms after excitation for the frequency range of 63 Hz to 8 kHz. For colorbar see fig. 5.

In fig. 8 to 10 the energy distribution is shown for the third octave band of 2 kHz. The difference between the energy level behind the diffuser and in front of is clearly visible for the time frame of 16 ms after excitation. For the time periods of 19 ms, 24 ms, 29 ms, and 35 ms the energy still fluctuates for small time instances and is not completely equal everywhere in the room. The colorbar from fig. 8 is also valid for fig. 9 and 10

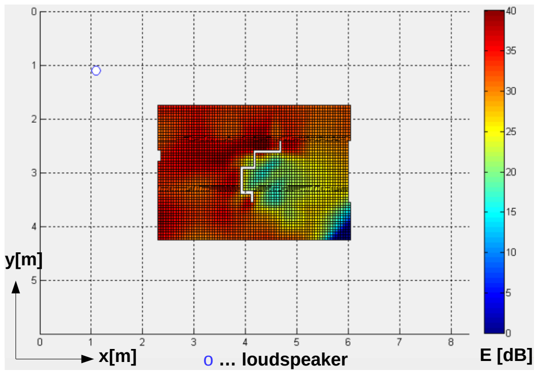

Figure 8: Energy distribution in the reverberation chamber at 16 ms after excitation for the third oktave band of 2 kHz

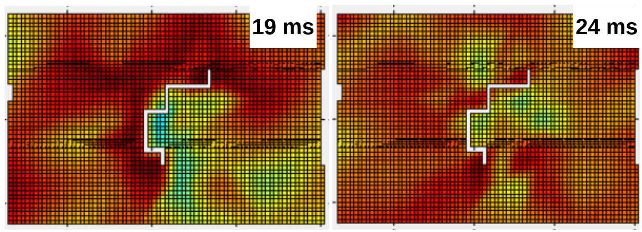

Figure 9: Energy distribution in the reverberation chamber at 19 ms and 24 ms after excitation for the third oktave band of 2 kHz. For colorbar see fig. 8.

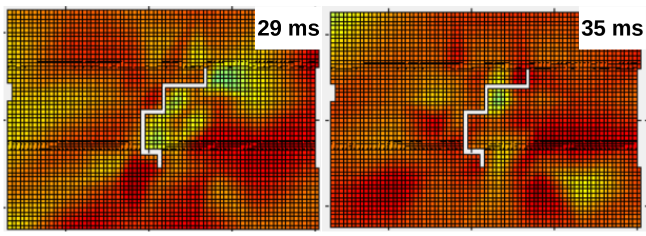

Figure 10: Energy distribution in the reverberation chamber at 29 ms and 35 ms after excitation for the third oktave band of 2 kHz. For colorbar see fig. 8.

When analyzing the lower third octave bands the fluctuations of the sound field are quite big for the entire decay process and are larger than for high frequencies. Therefore the effectivity of the diffusor is limited. Figure 11 shows a 3D - Plot at 237 ms for the 63 Hz third octave band. The measurements in this specific reverberation room are only valid above the Schroeder frequency calculated by

$$f_g = \sqrt{\frac{T}{V}} \cdot 1000 \tag{3}$$

where T is the reverberation time and V the total volume of the reverberation chamber. Below the Schroeder frequency f_g individual room modes can appear. The development of an diffuse sound field is not possible because the amount of room modes is too small. ISO 354 [2] gives no general indication for f_g but points out that is could be hard to get accurate measurement results for the low frequency range. The Schroeder frequency for this reverberation chamber is $f_g = 148.5Hz$ when calculated with a reverberation time of $T = 5.4$ s. The fluctuation of the sound field is visible in fig. 11.

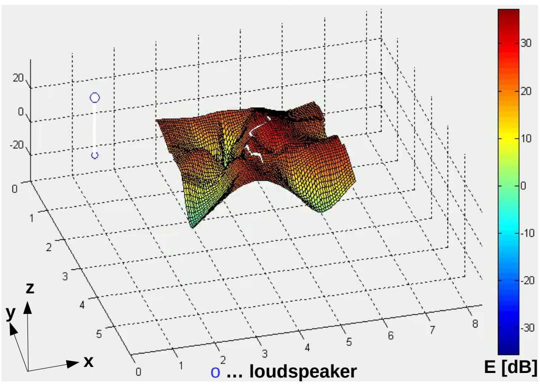

Figure 11: Energy distribution in the reverberation chamber at 237 ms after excitation for the third octave band of 63 Hz

Discussion and Conclusion

In this research we investigated the energy distribution around a panel diffuser in a reverberation chamber after excitation. We placed a diffuser in the middle of the chamber and looked at the energy level in the area behind the diffuser and compared it to the area in front of it which was facing the sound source.

We animated the measurement results of the energy distribution over time to illustrate the different energy levels in the reverberation chamber from the point of excitation through the entire decay process. Our measurements showed that the energy level of the broadband signal in front of the diffuser is higher up to a time frame of 35 ms after excitation. At around 35 ms the reflections from the reverberation chamber's surface start to weight in. After this time, the energy is distributed almost equally in the entire measurement area and the difference between the measurement positions reach a minimum value.

For low frequency bands the density of room modes is very low and the energy distribution in the room is unequal, therefore large fluctuations appear. This can be seen in the animations for 63 Hz and 125 Hz. For frequency bands above 125 Hz the energy is distributed almost equally after 35 ms after excitation.

Reverberation chambers are usually equipped with more than one diffusers. Although the energy in the reverberation chamber in our research is almost equally distributed after 35 ms above the Schroeder frequency, it is questionable how the energy distribution looks like when the sound field around more than one diffuser is analyzed. Usually the diffusers are cascaded in the upper half of the reverberation chamber. Therefore it could take longer until equal energy levels are reached. Moreover the panel diffusers could reduce the volume and be one of the reasons why the measured absorption coefficients differ so much in each reverberation chamber. This has to be evaluated in future research.

Webpage for Animations

The generated animations can be watched online: `www.spsc.tugraz.at/student_projects/soundpropagation`

References

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