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THE ACOUSTICALLY EFFECTIVE AIR VOLUME OF A REVERBERATION CHAMBER EQUIPPED WITH SUSPENDED DIFFUSORS

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Abstract: *It is known, that the reproducibility of measurements of the absorption coefficient in reverberation chambers show large deviations over the full frequency range. [2][5] Starting point of this research is the measurement of the absorption coefficient of a high absorbing sample in a reverberation chamber according to ISO 354 with 0, 4, 9 and 12 suspended diffusers. The standard deviation of the measured reverberation time between the different microphone positions is calculated with and without diffusors. Resulting in only slight differences, the hypothesis is set up that the increasing number of diffusers does not improve the sound field diffusity and thus rises the absorption coefficient of the sample but has an impact on the acoustically effective volume of the reverberation chamber which declines with increasing number of diffusors. This is proven by the derivation of Sabines formula and by evaluating the energy density distribution in the room. A method for calculating the acoustically effective air volume of a reverberation chamber equipped with diffusors is suggested. Since the volume will be lower than supposed until now, also the absorption coefficient will decrease. Further consequences of this hypothesis are discussed which seem to be able to solve a few well known conflicts in room acoustics.*

Key words: reverberation chamber, sound field diffusity, suspended diffusors, sound pressure, reverberation time, Sabine, absorption coefficient, ISO 354

1. INTRODUCTION

The absorption coefficient of the same sample measured in different reverberation chambers show large deviations over the entire frequency range. [2] Over the last decades severel round robin tests have been carried out but the issue has not been resolved until now. [5] So far the attempt was to improve the diffustiy of the sound field, which is defined by the constant spacial energy density distribution inside a closed surface, in order to enhance the inter laboratory reproducibility. Mostly this was achieved by mounting suspended diffusors inside the reverberation chamber according to ISO 354 [7]. The standard states that the optimal diffusity is reached, when the equivalent absorption area of a sample reaches a maximum value. The calculation is carried out with Sabines formula by measuring the reverberation time.

To be able to evaluate the sound field in detail, a high measuring point density of 333 points was chosen. A closer look at the spacial variance of the reverberation time with and without diffusors installed in the room gives an overview on how the sound field behaves over a frequency range from 100 Hz to 10 kHz.

2. MEASUREMENTS

The investigated reverberation chamber has a total volume of 243 m^3 and a total surface area of 234 m^2 with non parallel, sound hard walls. The reverberation time was measured with and without diffusors installed in the room with each 333 microphone positions from 100 Hz to 10 kHz with the swept sine method. The microphone positions were equally distributed at three different heights with each 111 measurement points. To be able to look at the non disturbed diffusity of the sound field, no absorbers or any samples were placed in the room. For calculating the spacial variance of the sound field, the rel. standard deviation of the reverberation time between the microphone positions was evaluated.

When the diffusity according to ISO 354 was verified, the reverberation time for two different source positions and eight microphone positions was measured for the case when 0, 4, 9 and 12 diffusors were added to the room. The sample used was 12 m^2 of mineral wool with $\alpha > 0.9$. The rel. standard deviation of the reverberation time for those setups was calculated.

3. RESULTS

The reverberation time measurements indicate that the overall reverberation time with diffusors in the room declines. But according to the rel. standard deviation of the reverberation time the diffusity of the sound field above 300 Hz is not improved, since the rel. standard deviation almost stays the same with and without the diffusors (see fig. 1). Knowing that the diffusity of the sound field is disturbed when an absorber is placed inside the room, the rel. standard deviation of the reverberation time was evaluated with and without the absorber. The results show that the sound field is less diffuse with the absorber placed on the ground, no matter if there are diffusors in the room or not (see fig. 2 and 3). Also, the standard deviation of the reverberation time with an absorber placed on the ground with 0, 4, 9 and 12 diffusors was evaluated (see fig. 4). There is no tendecy with increasing number of diffusors, the rel. standard deviation fluctuates around the same values.

4. THE IMPACT OF SUSPENDED DIFFUSORS

From a wave theoretical point of view, suspended diffusors represent a barrier to the sound waves. Depending on the wave lenght, the sound wave is either reflected or diffracted. Taken into consideration that the diffusors have an onesided surface area of 0.8 m^2 to 3 m^2, frequencies approx. $>$ 300 Hz are reflected. In conclusion, the volume behind the diffusors is acoustically effective in a different way. Based on those consideration, a hypotheses is derived that the diffusors change the effective volume of the reverberation chamber.

5. HYPOTHESIS

PART 1: The equivalent absorption area A_T
The entire further considerations affect the frequency range $>$ 300 Hz. The formula for calculating A_T of a sample is given by:

$$A_T = A_2 - A_1 = 55,3 \cdot V \left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1} \right) - 4 \cdot V(m_2 - m_1) \quad (1)$$

The measurements show that the reverberation time decreases with diffusors installed in the room. Looking at equ.1, the only two parameters wich are variable are A_T and the volume V of the room, when the meteorological influences are minimized or compensated with regard to ISO 9613 [8]. Since the diffusors are sound hard, the absorption of them can be ruled out. Until now the assumption was made that A_T of a sample rises due to the increased diffusity of the sound field. But this is not reasonable since the diffusors are sound hard and the sample stays physically the same. On the assumption that A_T is constant, the only variable parameter left in eq. 1 is the volume V of the reverberation chamber.

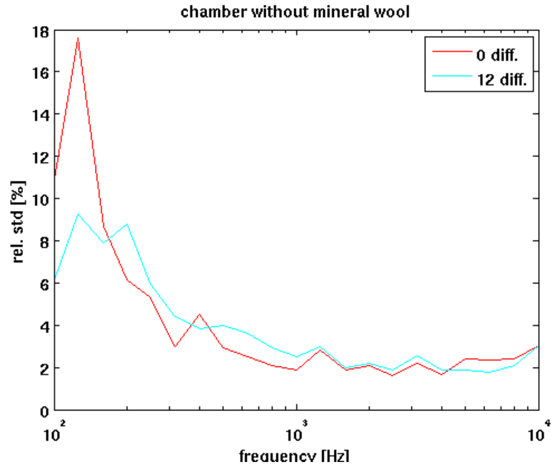

Figure 1: Standard deviation of R_T with 0 and 12 diffusors

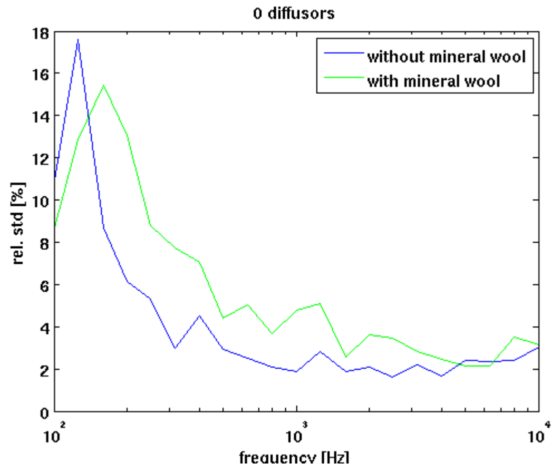

Figure 2: std. of R_T with 0 diffusors, with and without mineral wool

PART 2: Sabines Formula
Eq. 1 is Sabines formula for the reverberation time. For further assumptions it is necessary to derive this equation. The origin of Sabines formula lies within the observation of the power balance in the room based on the assumption of an ideal diffuse sound field and can be described as:

$$\underbrace{P}_{source\ power} - \underbrace{\frac{V \cdot E}{\tau}}_{powerloss} = \underbrace{V \cdot \frac{dE}{dt}}_{power\ density\ in\ the\ room} \quad (2)$$

Another definition of the powerloss is given by the ab-

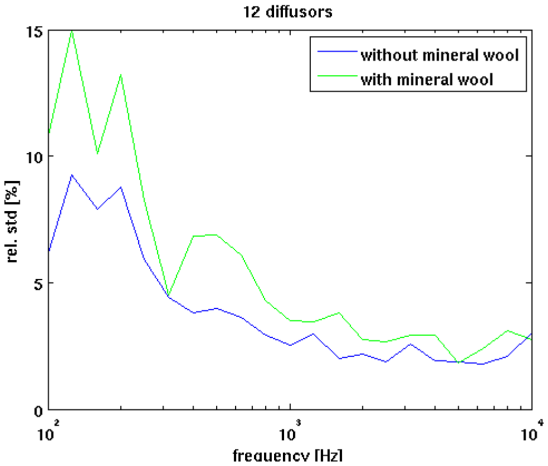

Figure 3: std. of R_T with 12 diffusors, with and without mineral wool

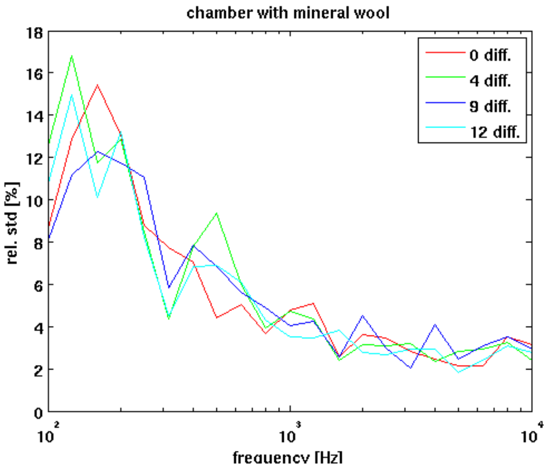

Figure 4: std. of R_T with 0, 4, 9, 12 diffusors, with mineral wool

sorbed power due to the room surfaces:

$$P_\alpha = \frac{1}{4} \cdot E \cdot c \cdot A_{tot} \tag{3}$$

Both equations can be set equal:

$$P_\alpha = \frac{1}{4} \cdot E \cdot c \cdot A_{tot} \stackrel{!}{=} \frac{V \cdot E}{\tau} \tag{4}$$

With the basic assumption of statistical room acoustics the energy density is equally distributed in the entire room, eq. 4 is reduced to:

$$A_{tot} = \frac{4 \cdot V}{c \cdot \tau} \quad \text{with} \quad \tau = \frac{T}{6 \cdot ln10} \tag{5}$$

With the definition of the reverberation time and the decay time Sabines formula follows:

$$T = 0.161 \cdot \frac{V}{A_{tot}} \tag{6}$$

The essential step of the derivation is the assumption of the *equally distributed energy density in the entire room*. Only in that case it is possible to eliminate the energy density in eq. 4 and to derive Sabines formula.

PART 3: Energy Density

In a reverberation chamber with no diffusors installed, the energy density E_0 will be equally distributed in the entire volume V_{tot} (see fig. 5, le.). But when diffusors are installed, the situation changes. As mentioned in section 4, the sound waves at higher frequencies will be reflected by the diffusors and at lower frequencies they will be diffracted. The energy density distribution will not be the same at every point in the room rather than several different energy levels E_i in the upper part of the room will occur (see fig. 5, ri.).

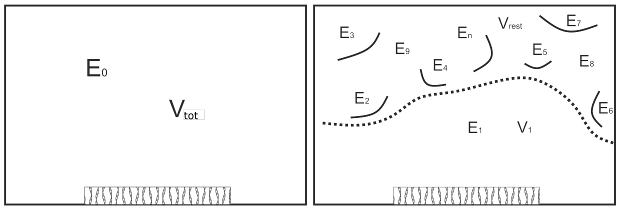

Figure 5: Energy density distribution without and with diffusors

Based on the assumption that many different energy levels are present in the room, the total energy inside can be written as:

$$E_1 \cdot V_1 + \sum_{i=2}^{n} E_i \cdot V_i \tag{7}$$

Assuming an averaged energy distribution E_m in the upper half of the room with a residual volume V_{res}:

$$\sum_{i=2}^{n} E_i \cdot V_i = E_m \cdot V_{res} \quad \text{with} \quad V_{tot} = V_1 + V_{res} \tag{8}$$

When the same energy is brought into the room in both cases with and without diffusors, eq. 7 becomes:

$$E_0 \cdot V_{tot} = E_1 \cdot V_1 + E_m \cdot V_{res} \tag{9}$$

$$E_1 > E_0 > E_m \tag{10}$$

Since the energy density has to fullfill the condition that it is equally distributed in the room in order to be able to derive Sabines formula, it is necessary to deal with the unequal energy densities E_1 and E_m in eq. 9. Therefore, the *unknown* is extracted from the energy densities and put into the modified volume $V_{1,e}$ and $V_{res,e}$:

$$E_1 \cdot V_1 = E_0 \cdot V_{1,e} \quad \text{and} \quad E_m \cdot V_{res} = E_0 \cdot V_{res,e} \tag{11}$$

Now the energy density in the room can again be written as:

$$E_0 \cdot V_{tot} = E_0 \cdot V_{1,e} + E_0 \cdot V_{res,e} \tag{12}$$

When E_0 is eliminated, both cases for the volume are true:

$$V_{1,e} + V_{res,e} = V_{tot} \quad \text{and} \quad V_1 + V_{res} = V_{tot} \tag{13}$$

But it can also be concluded:

$$V_1 \neq V_{1,e} \text{ and } V_1 < V_{1,e} \tag{14}$$

$$V_{res} \neq V_{res,e} \text{ and } V_{res} > V_{res,e} \tag{15}$$

$$\Rightarrow V_{1,e} < V_{tot} \tag{16}$$

PART 4: Reverberation Time
According to eq. 10, the energy density E_m in the upper half of the room is smaller than E_1 in the lower half. When the power source is turned off, corresponding to the law of entropy, an energy compensation will occur and the energy from the lower half will flow to the upper part of the room with less energy. In conclusion, for the volume V_1, not only the surface respectively the absorber is responsible for the absorption in the room but also the energy compensation between V_1 and V_{res}. Therefore the reverberation time should decline with diffusors as the measuremt shows.

PART 5: The equivalent volume V_e
The consequence of part one to four is that the total volume of the reverberation chamber decreases and this has to be considered in Sabines formula for the reverberation time.

The hypothesis is set up that the equivalent absorption area of a sample stays constant and does not increase with raising numbers of diffusors but instead the equivalent volume of the reverberation chamber declines and becomes frequency-dependent.

When the equivalent absorption area of a sample is measured in the empty room with no diffusors installed, the real absorption coefficient can be calculated. This is done in every reverberation chamber equipped with suspended diffusors when the diffusity according to ISO 354 is verified. The values obtained for A_T when all the diffusors are mounted, stay the same. Eq. 1 has to be reversed and the equivalent volume V_e of the reverberation chamber has to be calculated as follows:

$$V_e = \frac{A_T}{55,3 \cdot \left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right)} \tag{17}$$

This procedure was performed for the investigated reverberation chamber. The results show a frequency-dependent, decreased volume above 300 Hz (see fig.6).

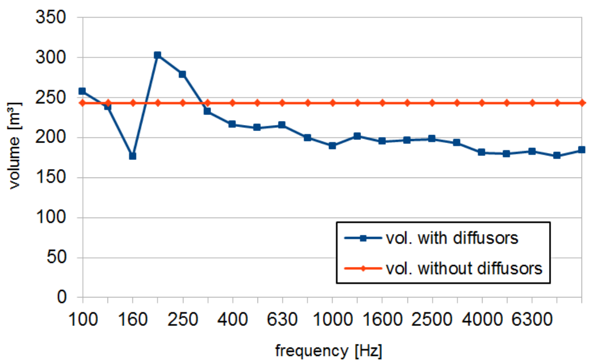

Figure 6: The reduced volume of the reverberation chamber

6. CONSEQUENCES

The equivalent volume V_e of every reverberation chamber equipped with suspended diffusors has to be calculated again. If the measurement procedure has been followed according to ISO 354 guidelines, the equivalent absorption area of the sample in the empty room can be used. All the absorption coefficients α which have been calculated up to that time, have to be newly calculated with the reduced equivalent volume V_e. Since α is directly proportional to the volume, α will also decrease. So far, acoustical design of rooms has been done with overestimated α of the surfaces. This fact has been proven by measurements of the reverberation time after the constructions have been completed. Finally the Annex A of ISO 354 would have to be revised.

7. CONCLUSION

From a physical point of view, the rel. standard deviation of the reverberation time is a good indicator for the diffusity of the sound field. A closer look at the rel. standard deviation of the reverberation time with and without diffusors installed in the room leads to the conclusion that the diffusity of the sound field is not improved by the diffusors. The equivalent absorption area of a sample is non-varying with regard to the number of diffusors installed in the room. The hypothesis was set up, that the volume of the reverberation chamber with suspended diffusors cannot be assumed with the total volume of the room, instead it declines in the frequency range > 300 Hz. The diffusity of the sound field < 300 Hz as well as the volume < 300 Hz requires further investigation.

Future work deals with the evaluation of the different energy density distributions in front of the diffusors and behind them. Sound pressure measurement respectively particle velocity measurements should provide information about the energy density in the reverberation chamber.

8. ACKNOWLEDGEMENTS

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