Can we use the standard deviation of the reverberation time to describe diffusion in a reverberation chamber ?

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Introduction

The random incidence absorption coefficient is measured in a reverberation room according to the international ISO 354 [1] or national standards such as the ASTM C423 – 09a [2]. It is known that the inter laboratory reproducibility of these results is still not very well (see e.g. [3],[4],[5]).

A diffuse field is one of the most important requirements of the reverberation chamber measurement method. Although effort is taken to obtain a diffuse field, it is still questionable if the sound field in a reverberation chamber is sufficient diffuse. The sound absorption of a highly absorptive sample will be about twice as much as the total sound absorption of the empty room which just fulfils the minimum required reverberation time. The non-equal distribution of this added absorption results per definition in a non-diffuse field.

In addition to this, it is assumed that the differences in diffuse field conditions between laboratories are the main cause of the poor inter laboratory reproducibility. So improving the diffuse field conditions of reverberation chambers should lead to a better reproducibility of the absorption measurement method.

Generally a certain degree of diffuse field is obtained by application of non parallel walls and convex curved panels suspended from the ceiling and/or rotating diffusers. ISO 354 prescribes a method to increase the amount of panels until the measured absorption coefficient does not increase any more. The risk of this method of diffusion is that parts of the room, above the diffusers, are decoupled from the room. The effective volume is smaller than the geometrical volume and the absorption is overestimated. Another issue might be that underneath the diffusers a horizontal field may arise between the four walls, especially when these are all vertical walls. So the method of increasing the number of diffusers until a maximum absorption is reached may not end up with the right absorption. All this implies that there is a need for better diffusion and a reliable method to describe it. In [6] suggestions are given to improve the diffuse field by using diffusers attached to two walls and the ceiling. The volume behind these diffusers is closed and subtracted from the room volume. The total area of the diffusers is much higher than the area that can be obtained with panel diffusers. Scale model research showed an improved diffuse field in the room with these type of diffusers [6]. The improvements were promising enough to carry out 1:1 measurements in our reverberation room.

The second issue is that there needs to be a descriptor for the diffuse field conditions, to be able to evaluate the alternatives and possibly to define requirements for the diffuse field conditions in the laboratory in the standard. Generally a sound field is considered diffuse if the energy density and the direction of the energy is uniform at all positions. Several attempts to describe the sound field (e.g. with correlation techniques or sound intensity) are made, but do not seem to be sufficiently reliable nor practical and there is no consensus on a measurement method. A rather practical method is based on evaluation of the standard deviation of measured decays. This method is actually incorporated in the American standard for sound absorption measurements in the reverberation chamber, the ASTM C423 [2] and e.g. applied in [10]. This method will be used to describe and evaluate alterations we made to the reverberation chamber of Peutz in Mook, Netherlands.

Variance of the reverberation time

The 'stationary' sound field in a room is not a constant, but fluctuates with time and place. So measurements based on energy balance considerations (such as measurements of the sound absorption in a reverberation chamber, of the sound insulation between two rooms and of the sound power in a reverberation room) use a time and place average of the sound field. The fluctuations in time domain of the sound pressure level will also occur during the decay of the sound field after a sound source is interrupted. These fluctuations during statistical independent time intervals will result in a (statistical) variation of the reverberation time. The theory on the variation of the reverberation time is described in publications by J. Davy (e.g. [7] and [8]) and will be summarized here shortly.

The $\mathrm{var}_e(T_{60})$, the ensemble variance of the reverberation time, is the variance of measured reverberation times for a specific combination of (point) source and microphone.
The variance of the (average) reverberation times of different source-microphone combinations is called spatial variance $\mathrm{var}_s(T_{60})$. The theoretical value for $\mathrm{var}_s(T_{60})$ is:

$$\mathrm{var}_s(T_{60}) = T_{60}\left(\frac{10}{\ln 10}\right)^2\left(\frac{720}{BD^3}\right)F\left(D\frac{\ln 10}{10}\right) \qquad (1)$$

$$F(x) = 1 - 3\frac{\left(1+e^{-x}\right)}{x} - 12\frac{e^{-x}}{x^2} + 12\frac{\left(1-e^{-x}\right)}{x^3} \qquad (2)$$

With:B the statistical bandwidth, generally 20% larger than the nominal bandwidth; for one third octave bands: $B \approx 1{,}2 \cdot 0{,}23 \cdot f_c$, with f_c is the centre frequency.
D dynamic range over which the reverberation time is evaluated [dB]

Filling in the constants, using third octave bands, will result in:

D=20 dB: $$\mathrm{var}_s(T_{60}) = 2{,}80\frac{T_{60}}{f_c} \tag{3}$$

D=30 dB: $$\mathrm{var}_s(T_{60}) = 1{,}09\frac{T_{60}}{f_c} \tag{4}$$

Measurements (e.g.[9]) show that the actual values are relatively close to these theoretical ones, generally slightly lower for the middle and high frequencies and larger for the low frequencies.

These theoretical values for the spatial variance are derived with a few assumptions e.g. that within the bandwidth, the decay times for different frequencies (modes) are equal.

The actual conditions might be different resulting in other values. The hypothesis that is to be investigated in this research is that, if the sound field is less ‘diffuse’, the actual spatial variance will increase, relative to the theoretical values and if it is more diffuse, it will decrease.

A diffuse field factor f_d will be introduced, being the ratio of the measured spatial standard deviation (index m) to theoretical one (index t):

$$f_d^{\,2} = \frac{\mathrm{var}_{m,s}(T_{60})}{\mathrm{var}_{t,s}(T_{60})} \tag{5}$$

For the derivation of formula (1) a sufficient modal overlap is assumed (above Schroeder frequency). In [8] an extension of the theory is presented with a correction factor for low frequencies. For the purpose of this research it is sufficient to realize that the theoretical variance for low frequencies will be higher than predicted with (1) and formula (1) will just be used as the reference for the diffuse field factor.

ASTM standard

In Annex A3 of [2] tests are described to qualify the reverberation room. This qualifying procedure is more elaborate than in [1]. A3.3 describes the measurement of the variation of the decay rate, using the relative standard deviation of the decay rate, which is standard deviation of decay rate s_M divided by average decay rate d_M. Note that the decay rate is inversely proportional to the reverberation time: $d = 60/T_{60}$, directly resulting in:

$$\frac{s_M}{d_M} = \frac{\sqrt{\mathrm{var}(T_{60})}}{T_{60}} \tag{6}$$

The ASTM defines requirements for s_M/d_M for the situation without and with a sample, the latter being the average of three possible positions on the floor. The requirements are listed in the table below.

		125			**250**			**500**	
Without	0,11	0,07	0,04	0,03	0,03	0,03	0,03	0,02	0,02
With	0,07	0,04	0,04	0,04	0,03	0,03	0,03	0,02	0,02
		1k			**2k**			**4k**	
Without	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
With	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02

Table 1. Requirements for the relative standard deviation of decay rate according to table A3.1 of [2]

This requirement suggests that the relative standard deviation is a value independent from reverberation time. From formula (1) however can be seen that it is not the relative standard deviation but $\mathrm{var}(d)/d$ (or $std(d)/\sqrt{d}$) that is independent from reverberation time. The theoretical value of the relative standard deviation of the decay rate still depends on the decay rate or reverberation time:

$$\frac{s_M}{d_M} = \frac{\sqrt{\mathrm{var}_s(T_{60})}}{T_{60}} = \frac{1}{\sqrt{T_{60}}}\left(\frac{10}{\ln 10}\right)\sqrt{\left(\frac{720}{BD^3}\right)F\left(D\frac{\ln 10}{10}\right)} \tag{7}$$

This makes the use of the relative standard deviation, as in the ASTM, less appropriate for the purpose of setting requirements for laboratories. It is therefore proposed to use the diffuse field factor f_d, because it’s independent of the value of the reverberation time.

Reverberation room

The reverberation room used for the investigation is the reverberation room of Peutz in Mook, Netherlands. This room has volume of 214 m^3 and has in the standard situation curved diffusing panels, suspended from the ceiling. The walls are vertical, non parallel and the ceiling is tilted. Floor and ceiling are made of concrete, walls of heavy brickwork, plastered and finished with a polyurethane coating.

Measurement Procedure

There are three microphones and four dodecahedron sound sources, which results in 12 independent source-microphone combinations. The reverberation time measurements were performed with the interrupted noise method and with the integrated impulse method

Interrupted Noise Method

Using the interrupted noise method, for each source-microphone combination, 18 registrations of the sound decay were recorded and analysed. The measurements were performed for one-third octave band frequencies from 100 to 5000 Hz. From the measurements the ensemble variance $\mathrm{var}_e(T_{60})$ is calculated for each source-microphone position and the result is averaged for the 12 source-microphone positions and denoted as $\overline{\mathrm{var}}_e(T_{60})$. The total variance $\mathrm{var}(T_{60})$ is calculated from the 12 ensemble averages of the reverberation time. The spatial variance is obtained by subtracting the variance of the ensemble average:

$$\mathrm{var}_s(T_{60}) = \mathrm{var}(T_{60}) - \overline{\mathrm{var}}_e(T_{60})/18 \tag{8}$$

Integrated Impulse Method

For the integrated impulse method one registration for each source-microphone combination was made. The measurements were performed with a Maximum Length Sequence (MLS) signal. Each registration consists of two ranges and 16 averages in time domain for each range. The range had an upper frequency of 3 kHz for the third octave band from 100 Hz to 2500 Hz, the second range has an upper frequency of 6 kHz, resulting in third octave bands from 3150 to 5 kHz.

ISO 354 requires backward integration of the (filtered) impulse response, before evaluating the reverberation time from the decay curve. Since the measurement time is finite, there is always a part of the decay signal that is not recorded, or there is noise biasing the backward integration. To solve that, the signal has to be truncated before background noise starts and for the missing part an 'optional' correction factor is indicated in formula (4) of the standard. The correction factor applied in this research is:

$$C = p^2(t_1)\frac{T_{60}}{13,82} \qquad (9)$$

The pressure at truncation point t_1 and the reverberation time T_{60} are estimated values based on a first least squares fit of the (non integrated) decay.

The impulse response measurement is deterministic so there is only one registration needed for each source-microphone position. The measured variance over the 12 source-microphone positions is the spatial variance.

Situations to be measured

Measurements in the reverberation room will be performed in three modes:

a) the standard standard situation (with panel diffusers);
b) without panel diffusers;
c) with circular diffusers on two walls and ceiling (fig.1).

The panel diffusers consisted out of six convex plexiglas elements suspended from the ceiling and two tilted straight panels attached to the walls. The circular diffusers were made of polyester. The weight of the wall suspended diffusers was increased at the inside with a 3 cm mixture of sand and harsh. The diameter of the diffusers is 2,2 m, the volume taken by each diffuser approx. 0,8 m^3, the total volume to be subtracted from the room volume is approx. 14 m^3. Due to this subtraction, these diffusers will be indicated as volume diffusers in this research.

Figure 1. Reverberation room at Peutz with circular diffusers

Figure 2 shows the reverberation time in the empty room in the three modes. Due to the low surface weight the volume diffusers did not fulfil the minimum requirement of ISO 354 for the low frequencies. The purpose of this requirement is to have sufficient accuracy for low absorbing samples. Since the sample measured in this study is highly absorptive, the adverse effects due this excess of room absorption is limited.

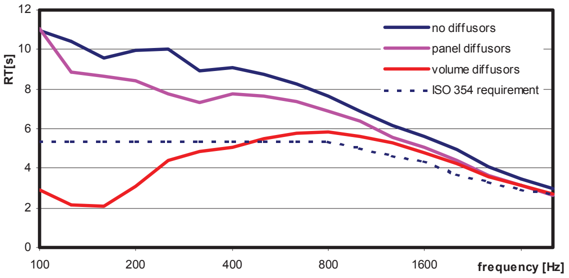

Figure 2. Reverberation time of the empty room in three modes; also indicated is the ISO 354 requirement (for 214 m^3)

Depending on the room mode, the room was measured:

1. without sample;
2. with a sample in the middle of the floor;
3. with a sample on the floor in one of the corners;
4. with a sample attached to one of the walls.

The sample used consisted out of 15 elements of mineral wool (Rockwool type 211, thickness 100 mm and density of ca. 44 kg/m3) in a wooden casing (1,2*0,6m), covered with a non woven fleece (Lantor type 3103HO) and an open wire mesh for protection. The back is made of a 3 mm hardboard.

Measurement results

The measured absorption absorption coefficients in the three modes (interrupted noise, sample in the middle of the floor) are given in figure 3. The error bars indicate ±2 standard deviations, calculated from the error propagation of the variation of the reverberation time.

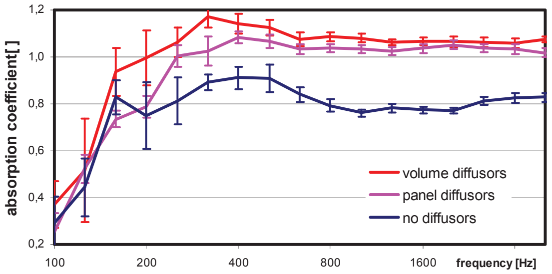

Figure 3. Measured absorption coefficient in the three modes.

For the standard situation with convex panels, the ISO procedure was followed, thereby increasing the absorption from the situation without diffusers to the situation with panel diffusers. It is remarkable that the absorption with the volume diffusers is higher than the standard situation and clearly exceeds 1,0 even for the high frequencies. The differences are statistically significant ($p<0,07$) for half the

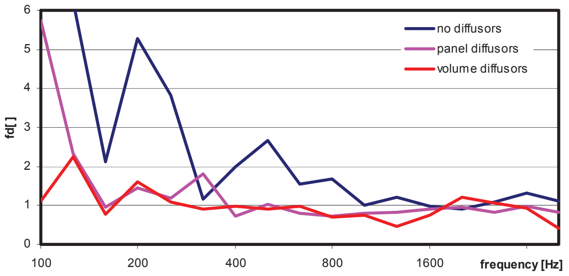

Figure 4. Diffuse field factor f_d with (5), with sample.

third octave bands.

Figure 4 shows the diffuse field factor f_d in the three modes, with sample at the middle of the floor. The high value for the room without diffusers clearly indicates that the spatial variation of the RT is an indicator of the non-diffuse field situation, which is evident in this situation. However the differences between panel diffusers and volume diffusers are rather small, although figure 3 showed a clear difference in measured absorption. From this it can be concluded that the use of the standard deviation is not a sufficiently tool to use to characterise the diffuse field conditions of the reverberation room.

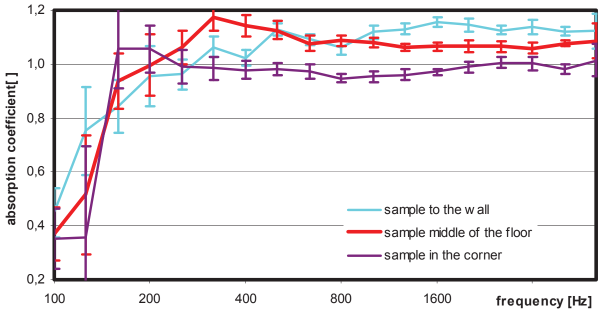

Figure 5. Measured absorption coefficient for three positions of the sample, room with volume diffusers.

The influence of the position of the sample in the reverberation room on the absorption coefficient is shown in figure 5 (volume diffusers) and figure 6 (panel diffusers). Figure 5 shows that at high frequencies, the absorption is higher with the sample mounted to the wall. This indicates that there still is a horizontal sound field in the room.

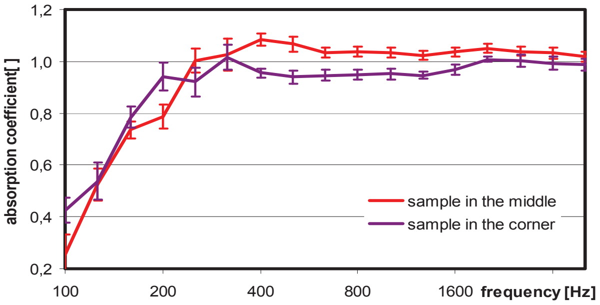

Figure 6. Measured absorption coefficient for two positions of the sample, room with panel diffusers

The absorption with the sample positioned on the floor, in the corner of the room is significantly lower, except at 160 and 200 Hz where room modes dominate the sound field.

Measurements were also performed with the integrated impulse method. Repeated measurements for a single source-microphone position showed very low deviations, as expected. However, the average RT's show small differences (1-2%) between the methods and the spatial variation of the reverberation turned out to be larger with integrated impulse than with interrupted noise. The influence on the diffuse field factor is shown in figure 7.

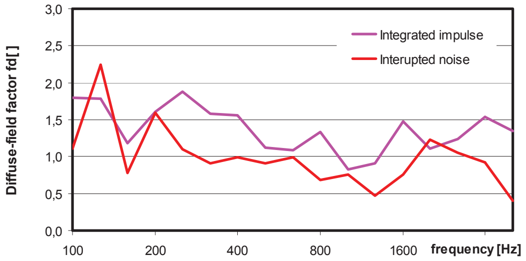

Figure 7. Measured diffuse field factor (volume diffusers, sample in the middle of floor) with interrupted noise and with integrated impulse

Discussion and Conclusion

The measurements with the volume diffusers have shown that a further increase of sound absorption by increased diffusion is possible. The standard deviation of the reverberation time proved to be not a sufficient indicator for this. At this point the only way to improve the inter laboratory variation is to use a reference absorber [4] for qualification of the laboratory. Other positions of the sample in the reverberation room may give significantly different results. Also for this purpose a reference absorber may be used, possibly with a correction procedure.

The integrated impulse methods shows a larger spatial variation. The cause of this is not clarified, but it might be expected that this is due to inaccuracies in the measurement or evaluation method. Requirements on the standard deviation of reverberation time could be useful to prevent these unnecessary deviations.

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