2pAAa7. Can we use the standard deviation of the reverberation time to describe diffusion in a reverberation chamber?

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It is generally assumed that the non-diffuse field properties of reverberation rooms, especially with a strongly sound absorbing sample, is the main reason for the poor reproducibility values for the sound absorption between laboratories. Reverberation rooms should be made much more diffuse to reduce the inter laboratory differences. Although there are practical ways to achieve this, it is most important that there will be a requirement in the ISO 354 standard on the diffusing quality of the sound field. One possibility is to use the standard deviation of the reverberation time for different source-microphone combinations in the reverberation room. To investigate the influence of different settings of a reverberation room on the standard deviation of the reverberation time, measurements are performed, compared to the theoretical standard deviation. This is done with the interrupted impulse method and the integrated impulse method. The results will be shown in the presentation. The usefulness of this qualification method for the ISO standard will be discussed.

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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 sample can be twice as much as the total sound absorption of the empty room. 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 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 under 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.

While making the preparations for the alterations in the laboratory and thinking through the measurement setup and program, several aspects are encountered which are of interest in their own right. These aspects will be described in this article and basically handle the discussion on how to define requirements on the diffuse field conditions.

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 and 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].

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 \( \text{var}_e(T_{60}) \), the ensemble variance of the reverberation time is the variance of measured reverberation times for a specific combination of (point) source and microphone. The theoretical value for \( \text{var}_e(T_{60}) \) is [8]:
\[ \text{var}(T_{60}) = T_{60}\left( \frac{10}{\ln10} \right)^2 \left( \frac{720}{BD^3} \right) F \left( \frac{D\ln10}{10} \right) \]  

(1)

with:

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

(2)

and:  

\( B \) the statistical bandwidth, generally 20\% larger than the nominal bandwidth;  

for one third octave bands: \( B = 1,2 \cdot 0,23 \cdot f_c \), with \( f_c \) is the centre frequency.  

\( D \) dynamic range over which the reverberation time is evaluated [dB]  

\( \gamma \) the ratio of the reverberation time of the room to the decay time (over 60 dB) of the exponential averaging device.

The variance of the (average) reverberation times of different source-microphone combinations is called spatial variance \( \text{var}_s(T_{60}) \). The theoretical value for \( \text{var}_s(T_{60}) \) is:

\[ \text{var}_s(T_{60}) = T_{60}\left( \frac{10}{\ln10} \right)^2 \left( \frac{720}{BD^3} \right) F \left( \frac{D\ln10}{10} \right) \]  

(3)

This is almost the same as the ensemble variance, but now \( \gamma = 1 \).

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

\( D = 20 \text{ dB} \):

\[ \text{var}_s(T_{60}) = 2,80 \frac{T_{60}}{f_c} \]  

(4)

\( D = 30 \text{ dB} \):

\[ \text{var}_s(T_{60}) = 1,09 \frac{T_{60}}{f_c} \]  

(5)

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):

\[ f_d = \frac{\text{var}_m(T_{60})}{\text{var}_t(T_{60})} \]  

(6)

In [8] an extension of the theory is presented with a correction factor using the statistical modal overlap (product of statistical bandwidth and modal density). For the purpose of this research it is sufficient to realize that the theoretical variance for low frequencies will be higher than predicted with (3) and formula (3) will 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: $d = 60/T_d$, directly resulting in:

$$\frac{s_M}{d_M} = \sqrt{\frac{\text{var}(T_{60})}{T_{60}}}$$  \hfill (7)

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.

<table>
<thead>
<tr>
<th>TABLE 1. Requirements for the relative standard deviation of decay rate according to table A3.1 of [2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>125</td>
</tr>
<tr>
<td>250</td>
</tr>
</tbody>
</table>

This requirement suggests that the relative standard deviation is a value independent from reverberation time. From formula (3) however can be seen that it is not the relative standard deviation but $\text{var}(d)/d$ (or $\text{std}(d)/\sqrt{d}$) 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:

$$\frac{s_M}{d_M} = \sqrt{\frac{\text{var}(T_{60})}{T_{60}}} = \frac{1}{\sqrt{T_{60}}} \left( \frac{10}{\ln 10} \right) \left( \frac{720}{BD^3} \right) \left( \frac{D \ln 10}{10} \right)$$  \hfill (8)

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 is independent of the value of the reverberation time. A value below 1 means that the spatial variance is smaller than the theoretical value, possibly implicating a sufficient diffuse reverberation room. A value over 1 may implicate a certain kind of spatial variance in the room, which can lead to a lesser reproducibility.

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.
Figure 1 shows the positions of the diffusers; figure 2 is a picture of the room.

FIGURE 1. Positions of the diffusers in the reverberation room of Peutz.

FIGURE 2. Reverberation room at Peutz, view from the top through the transparent diffusers.

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 analyzed. The measurements were performed for one-third octave band frequencies from 100 to 5000 Hz.

From the measurements the ensemble variance $\text{var}(T_{60})$ is calculated for each source-microphone position and the result is averaged for the 12 source-microphone positions and denoted as $\text{var}(T_{60})$. 
The total variance $\text{var}(T_{60})$ is calculated from the 12 ensemble averages of the reverberation time. The spatial variance is obtained by subtracting the variance of the ensemble average:

$$\text{var}_s(T_{60}) = \text{var}(T_{60}) - \overline{\text{var}}(T_{60})/18$$  \hspace{1cm} (9)

**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:

$$C_{\tau_2 \tau_1} = \frac{t_{\tau_1} - t_{\tau_2}}{1 + g_{\tau_2} / g_{\tau_1}}$$  \hspace{1cm} (10)

The correction factor $C$ is:

$$C = \int_{\tau_1}^{\tau_2} p^2(\tau) \delta(\tau)$$  \hspace{1cm} (11)

This correction factor however should not be optional at all, since large errors will occur when this correction factor is set to zero. However, for an ideal decay the $C$ can be estimated rather accurately. Assuming an exponential decay, from the definition of reverberation time the decay curve is described with:

$$E(t) = E(0)e^{-\tau / T_{60}} = E(0)e^{-t / 13.82 / T_{60}}$$  \hspace{1cm} (12)

Knowing the pressure at time $t_1$, from integration it follows that:

$$C = p^2(t_1) T_{60} \overline{T_{60}} / 13.82$$  \hspace{1cm} (13)

Unfortunately the correction factor depends on the reverberation time, and the $C$ was needed to calculate this reverberation time. This chicken and egg problem can be solved by a first linear regression of the non-integrated decay curve, using the resulting $T_{60}$ as a first approximation to calculate $C$. After calculating the more accurate $T_{60}$, using (10), this new value can again be used to calculate a second approximation of $C$, but generally this is not necessary and does not change the result significantly.

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 situations:
- the standard situation (with panel diffusers);
- without panel diffusers;
- with circular diffusers mounted to two walls and the ceiling (see figure 3).

The circular diffusers were made of polyester. The weight was increased at the inside with a mixture of sand and harsh. The diameter of the diffusers is 2,185 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$^3$.

FIGURE 3. Reverberation room at Peutz with circular diffusers.

In each room mode the room was measured:
- without sample;
- with a sample in the middle of the floor;
- with a sample in one of the corners;
- 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/m$^3$) in a wooden casing (1,2*0,6m), covered with a nonwoven fleece (Lantor type 3103HO) and an open wire mesh for protection. The back is made of a 3 mm hardboard.

MEASUREMENT RESULTS

At the moment of finishing this paper only a limited number of measurement results were available.

FIGURE 4. Diffuse field factor $f_d$ for the standard operating mode of the reverberation chamber, without sample and with sample in the middle of the floor.
Figure 4 shows the diffuse field factor $f_d$ in the standard situation, without sample and with the sample in the middle of the floor. The results illustrate that at middle and high frequencies $f_d$ is slightly below 1. For low frequencies, and also for the 5 kHz third octave band, $f_d$ is much higher. If the diffuse field factor $f_d$ is actually a parameter related to how diffuse the sound field is, it would be expected that $f_d$ is higher in the situation with sample. Although for most frequencies the $f_d$ is higher with sample, it is not the case for all frequencies. But at the lower frequencies where the $f_d$ is larger than 1 in the room without sample, the situation with sample gets much worse.

OUTLOOK

At the presentation the measurement results on variance of reverberation time for different situations will be shown.

Obtaining a more diffuse field is one of the possibilities to reduce the inter laboratory spread, but not the only one. It is the intention of the ISO working group that there will be a reference absorber to verify if the laboratory result is within the required range. It was found ([3],[4]) that this method can play an important role to reduce the spread, especially to rule out the outliers.

REFERENCES