Effects of Different Diffuser Types on the Diffusivity in Reverberation Chambers

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Summary
Knowledge of sound absorption properties of typical building materials is essential for all tasks related to room acoustic design. The Sabine absorption coefficient is measured in a reverberation chamber according to the international standard ISO 354. It is known that inter-laboratory reproducibility of these results is poor, which leads to uncertainties in prediction and nonconformity with building contracts. It is assumed that differences in the diffuse field conditions between laboratories are the main cause of the poor reproducibility. Achieving a diffuse sound field is the most important requirement for the reverberation chamber. Diffusing elements are therefore typically installed in reverberation chambers. In this study, the effects of hanging panel diffusers and hanging spherical volume diffusers on the diffusivity of the sound field in a reverberation chamber are investigated. The sound field diffusivity is characterized based on the equivalent sound absorption area of a highly sound absorptive sample and the diffuse field factor, which is the ratio of the measured spatial standard variation of the reverberation time to the theoretical spatial standard variation under diffuse field conditions. The results indicate that the diffuse field factor, as a potential diffuse field indicator, is suitable for rough estimation of the diffuse sound field conditions but does not constitute a reliable measure of the diffusivity in a reverberation chamber.

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1. Introduction

Knowledge of sound absorption properties of typical building materials is essential for all tasks related to room acoustic design and especially for the prediction of reverberation times in the planning phase of building constructions. The statistical absorption coefficient is measured in a reverberation chamber according to the international standard ISO 354 [1]. This absorption coefficient is referred to as *Sabine absorption coefficient*, which assumes the chamber to be completely diffuse [2]. It is known that the inter-laboratory reproducibility of these results is poor, meaning that differences of results between laboratories are much larger than can be accepted from a jurisdictional point of view. This leads to huge challenges for acousticians and manufacturers of acoustic elements [3,4]. Moreover, the measured absorption coefficients are often larger than unity and cannot be directly used in computer simulations, which are common tools for acoustic design and renovation projects.

It is assumed that differences in the diffuse field conditions between laboratories are the main cause of the poor reproducibility. A diffuse field is the most important requirement for ISO 354. Diffusing elements such as hanging panels or boundary diffusers are typically installed in reverberation chambers. Although efforts are made to increase diffusivity, whether or not the sound field in a reverberation chamber is sufficiently diffuse is questionable. The sound field in a reverberation chamber with a highly absorptive sample is clearly non-diffuse, so that the conditions for application

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of Sabine's equation are not met. Despite its shortcomings, Sabine's equation has been widely used and continues to be used for determination of the absorption properties of building materials. Several attempts have been made to improve Sabine's formula. The formula given by Eyring constitutes one of these refinements. However, all the proposed formulas assume a diffuse sound field. Accordingly, increased attention has to be paid to methods of enforcing the diffusion. Moreover, descriptors for the diffuse field conditions are needed to possibly define new requirements for laboratories within the standard.

Placing diffusers in the propagation path of sound waves results in a more uniformly distributed sound field throughout the reverberation chamber. The depth of boundary diffusers needs to be of the order of a quarter of a wavelength or larger to have a significant effect on the sound field [5] and, in the simple case of a plane-parallel space, they must also be applied to at least three of the boundaries, so that opposite surface pairs have at least one surface treated. Consequently, the size of boundary diffusers needed is often prohibitively large and expensive. Moreover, they can only influence a 180° solid angle of incident sound energy. A more economic solution is to hang panel diffusers in the volume of the room, which can influence a 360° solid angle of incident sound energy. On the other hand, panel diffusers cause the actual mean free path to differ from the theoretical ideal and might lead the reverberation chamber to act as a coupled-space, resulting in increased uncertainty when calculating the absorption coefficient [6]. One should also be aware that the possibility of hanging diffusers in the room is limited by the source and microphone positions and relative position to the walls. Therefore, the surface area potentially covered by hanging diffusers is smaller than for boundary diffusers.

Both Lautenbach et al. [7] and Bradley et al. [8] studied a scale model reverberation chamber using different diffusion conditions: no diffusers, hanging panel diffusers and boundary diffusers. Lautenbach et al. suggest that the boundary diffusers produce a more diffuse sound field. Bradley et al. carried out a systematic analysis in order to fully understand the effect of each diffuser type on the sound field diffusivity. The study revealed that boundary diffusers and hanging panel diffusers, per unit surface area, produce roughly equivalent diffusion in the sound field. Moreover, there is no consensus on potential descriptors for the diffuse field conditions, and Bradley et al. highlighted inconsistencies in the results from the quantifiers suggested in ASTM E90, ASTM C423, and ISO 354.

The current study is part of an ongoing work, which aims to systematically compare the effectiveness of boundary diffusers, hanging panel diffusers and hanging spherical diffusers in producing a diffuse sound field in a full-scale reverberation chamber. The authors plan to characterize the sound field diffusivity based on a collection of objective measures, including the diffuse field factor, which will be introduced later on. The effects of each diffuser type will be assessed with the prospect of improving reverberation chambers design. Omnidirectional spherical diffusers may significantly improve the diffuse field conditions within the chambers and elude uncertainties due to the variation in the mean free path when using hanging panel diffusers. Each potential diffuse field indicator will be assessed with the prospect of defining a proper and reliable measure of the diffuse field conditions in the reverberation chamber.

The present paper focuses on the diffuse field factor, which compares the measured standard variation of the reverberation time with the theoretical standard variation under diffuse field conditions. The main aim of this paper is to show the possibilities and limitations of the use of the diffuse field factor as a potential measure of the diffuse field conditions, and it will not provide a systematic analysis of the effectiveness of the different diffuser types on the diffusivity of the sound field. Moreover, the data presented here is limited to a few selected sets and restricted to hanging panel and spherical diffusers only. The diffuse sound field conditions will be determined based on the diffuse field factor in the presence of a highly sound absorptive sample in the test chamber. The equivalent sound absorption area of the absorptive sample will also be considered, under the assumption that an adequately diffuse sound field distributes the incident sound energy more uniformly onto the sample. In this study, the term "volume diffusers" stands for hanging solid entities presenting a "volume", while "boundary diffusers" are defined as solid forms attached directly to the interior surfaces of the reverberation chamber.

2. Method

2.1. Reverberation chamber

A reverberation chamber of volume 243 m^3 (6.26 m x 7.86 m x 4.90 m) is considered. Opposite pairs of walls are parallel and made of concrete to ensure low absorption in the empty conditions.

2.2. Absorber

All measurements are conducted using a "known" absorptive specimen, which has been suggested as a calibrator for reverberation chambers in previous studies [9]. This specimen will be referred to as the "reference absorber".

The reference absorber is made of fifteen panels (100 x 600 x 1200 mm) of glass wool [10] assembled to form an absorbing plane. For stability of the mounting, each element is framed in a wooden frame of 18 mm plywood. The absorbing plane corresponds to a surface area of 11.8 m^2 and is backed by a 100 mm air cavity. The total height of the reference absorber is 200 mm. A frame is supporting the elements (Type E mounting [1]) and a fixture is made to close the air gap around the absorbing plane.

A round robin test is being conducted on this reference absorber and 7 European laboratories have participated so far. Part of the round robin results has been presented in [9]. Measurements of the equivalent sound absorption area have been made according to ISO 354 and using the same experimental setup. The decay curves have been recorded in third-octave bands according to the interrupted noise method.

2.3. Diffusers

As previously stated, the data presented in this paper is restricted to hanging panel and spherical diffusers only.

2.3.1. Hanging panel diffusers

The hanging panel diffusers are thin rectangular pieces of Plexiglas (900 x 1200 mm), each having a surface area of 2.1 m^2 (both sides of the panel).

2.3.2. Hanging spherical volume diffusers

The hanging volume diffusers are spherical pieces of hard plastic with radius 180 mm. Each sphere occupies a volume of 0.02 m^3 and has a surface area of 0.41 m^2. The volume occupied by the sphere will be subtracted from the volume of the room when estimating the equivalent sound absorption area of the absorber under consideration.

2.4. Measurements

The measurement process starts by recording sound decays in the empty reverberation chamber with and without the reference absorber. The subsequent measurements consist of adding diffusers to the room in intervals of approximately 4 m^2 and recording the sound decays with and without the test specimen. The process is repeated for each diffuser type and for mixed diffuser configurations. It should be noted that the surface area covered by ten spherical diffusers is equivalent to that covered by two panel diffusers. This paper only presents the first sets of data, which already indicate the possibilities and limitations of the diffuse field factor. Measurements in the chamber standard configuration (19 hanging panel diffusers) are also performed. A summary of the configurations tested so far is provided in **Table 1**. **Figure 1** shows the measurement configuration featuring 20 spherical diffusers. The interrupted noise method is used. Three sound source positions are considered along with four receiver positions, resulting in 12 independent source-receiver combinations. Six sound decays are measured in the empty conditions, whereas eighteen sound decays are recorded in presence of the sample. Brüel & Kjær BK 2250 with Reverberation Time Software is used for sampling of the signal. The receivers are placed

Table 1 – Tested diffuser configurations – the surface area covered by ten spherical diffusers is equivalent to that covered by two panel diffusers

Surface Area [m^2]	Description
0	No diffuser
4.1	2 panel diffusers (average over 3 configurations)
	10 spherical diffusers
8.2	4 panel diffusers
	20 spherical diffusers
	2 panel diffusers + 10 spherical diffusers
41.0	19 panel diffusers

at a height of 1.25 m above the chamber floor and the sources consist of three built-in loudspeakers, placed in the corners of the chamber. The recorded data are analysed to calculate the equivalent sound absorption area of the absorber and the diffuse field factor.

Figure 1 – Measurement configuration featuring 20 spherical diffusers

2.4.1. Equivalent sound absorption area

It is here assumed that the equivalent sound absorption area of the reference absorber increases with the diffusion. Indeed, if one decomposes the sound field in a reverberation chamber into a horizontal component and a vertical one, the later will greatly be damped in the presence of a highly absorptive sample, while the horizontal sound field is much less affected by the presence of the absorber. Since in this case the horizontal field dominates, the absorption is likely to be underestimated. Using diffusers, one can redirect the incident waves onto the absorbing specimen more uniformly, and thus increase the absorption. As a consequence, an adequately diffuse sound field is likely to allow enough sound energy to be incident on the absorber. The mean value of the equivalent sound absorption area, averaged over source-receiver combination and decay per source-receiver combination is calculated for each measurement configuration according to ISO 354 [1].

2.4.2. Diffuse field factor

The diffuse field factor is suggested here as a potential measure of the diffuse field conditions in a reverberation room. The diffuse field factor compares the measured spatial standard variation of the reverberation time with the theoretical spatial standard variation under diffuse field conditions. The theory on the variation of the reverberation time is described in [11]. Using third-octave bands and a dynamic range of 30 dB, the theoretical spatial standard deviation of the reverberation time is given by [11]

$$\sigma_{s,t}(T_{30}) = \sqrt{1.09\frac{T_{30}}{f_c}}, \qquad (1)$$

where f_c is the center frequency. The hypothesis is that if the sound field is less diffuse, the actual spatial standard deviation will be higher than the theoretical values, and vice versa. A diffuse field factor is thus introduced, being the ratio of the measured spatial standard deviation to the theoretical one [7]

$$f_d = \frac{\sigma_{s,m}(T_{30})}{\sigma_{s,t}(T_{30})}. \qquad (2)$$

Although this is not to be expected, values slightly lower than unity are measured for sufficiently diffuse field situations (meaning that the measured standard deviation is slightly lower than theoretically estimated) [7]. The diffuse field factor is here calculated from 216 decays for each measurement configuration.

3. Results and analysis

3.1. Equivalent sound absorption area

The measured equivalent sound absorption area of the reference absorber is shown in **Figure 2** for all measured configurations as a function of frequency. The standard room configuration (19 hanging panel diffusers) achieves the highest absorption in the whole frequency range. The lower equivalent sound absorption area values obtained in the other diffuser arrangements suggest that these configurations do not sufficiently redirect the horizontal sound field into the vertical sound field, which prevents the energy from reaching the absorber. Compared to the case with no diffusers, no increase in the equivalent sound absorption area is found for the spherical diffusers below 200 Hz. The spherical diffusers, with a radius of 18 cm, are poor scatterers at frequencies below 1000 Hz. A combination of spherical diffusers with various sizes, including larger ones, would therefore be required to reach an increased diffusivity, resulting in a higher measured

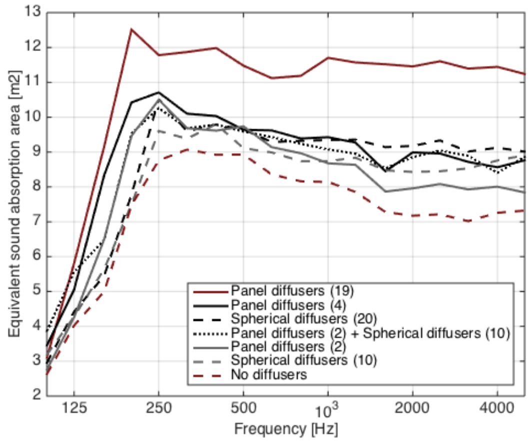

Figure 2 – Equivalent sound absorption area of the reference absorber for all measured configurations as a function of frequency

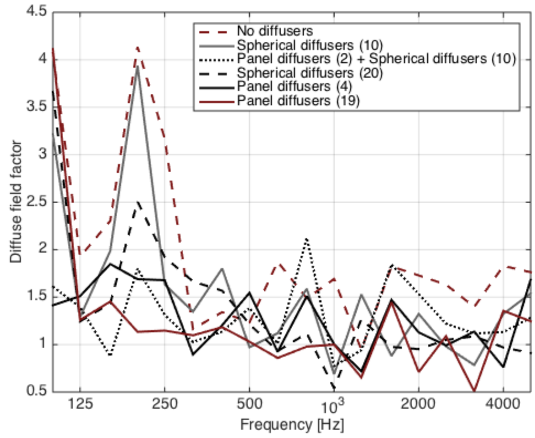

Figure 3 – Diffuse field factor in the presence of the reference absorber for all measured configurations as a function of frequency

absorption in the whole frequency range. For a fixed surface coverage, the hanging spherical diffusers seem to be more efficient above 1 kHz than the panel diffusers.

3.2. Diffuse field factor

The calculated diffuse field factor in the presence of the absorber is shown in **Figure 3** for each diffuser type as a function of frequency. Low values (around or below unity) of the diffuse field factor are meant to suggest a high degree of diffusion for the given diffuser configuration. The standard room configuration shows low diffuse field factor values in most of the frequency range, with values below 1 in some third-octave bands from 500 Hz and upwards. Within the measured configurations, this situation can be assumed to display the best diffuse field conditions. This result correlates with the highest measured equivalent sound absorption area as seen in **Figure 2**. The configuration without diffusers exhibits higher values than the standard configuration in the whole frequency range. As reflected in the measured equivalent sound absorption area, this situation can be seen as the poorest diffuse field conditions within the measured configurations. As suggested by the measured equivalent sound absorption area, the other configurations are expected to show intermediate values of the diffuse field factor. However, for individual third-octave bands, a large variation of the diffuse field factor values is found and the diffuse field factor is not always comprised between the two extreme diffuse field conditions. Similar results are found in **Figure 4**, which sets

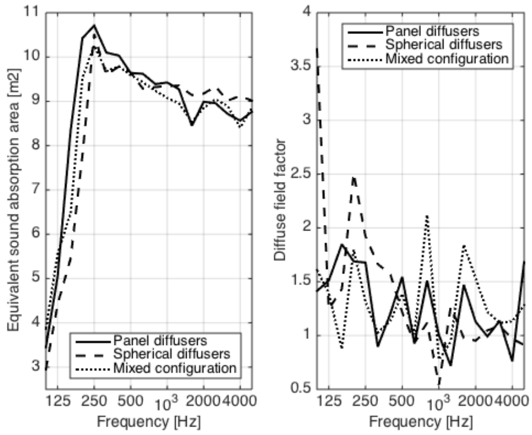

Figure 4 – Equivalent sound absorption area (left) and diffuse field factor (right) as a function of frequency for a fixed surface coverage of diffusers

the diffuse field factor and the equivalent sound absorption area as a function of frequency for a fixed surface coverage of diffusers. Correlated data trends are expected. The fluctuations in the diffuse field factor however indicate that the diffuse field factor, evaluated in third-octave bands, is a poor indicator of the diffuse field conditions and cannot be used as a tool to fully characterize the diffuse field conditions in a reverberation chamber. For further analysis, the correlation between the average equivalent sound absorption area and the average diffuse field factor is examined. The arithmetic mean in the third-octave bands centred from 315 Hz to 5000 Hz is used. At lower frequencies, i.e. for frequencies below and in the region of the Schroeder cut-off frequency, the procedure is not expected to yield accurate results.

The results are presented in **Figure 5**. A high degree of correlation is found (R^2 = 0.88). The

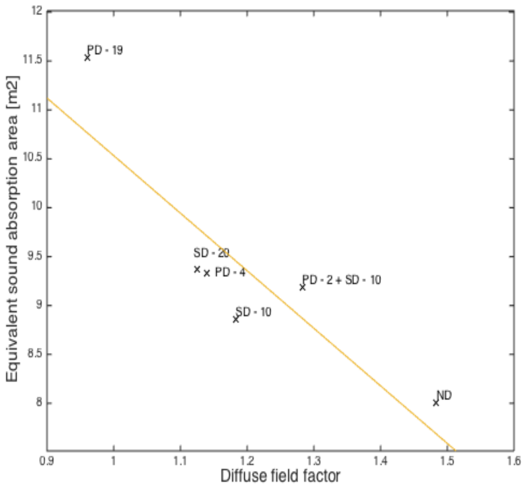

Figure 5 – Correlation between the average equivalent sound absorption area and the average diffuse field factor in the presence of the reference absorber (ND = no diffusers; PD = panel diffusers; SD = spherical diffusers). Both are averaged from 315 Hz to 5 kHz

averaged diffuse field factor allows for differentiation between poor and satisfactory diffuse field conditions, but remains an indicator for rough estimation of the diffuse sound field conditions. By excluding the two extreme data points, the correlation coefficient drops to 0.33, meaning that within the intermediate data points, the results do not seem to be consistent. Thus, the averaged diffuse field factor does not constitute an accurate indicator of the diffuse field conditions.

4. Conclusions

The effects of hanging panel diffusers and hanging spherical diffusers on the diffuse field conditions have been examined in a full-scale reverberation chamber. For this purpose, two acoustical parameters have been measured: the equivalent sound absorption area of a reference highly absorptive sample, and the diffuse field factor in the presence of the reference specimen.

As expected, the results indicate that the equivalent sound absorption area is rather sensitive to the change in diffuse field conditions in the reverberation chamber. The averaged diffuse field factor, as a potential diffuse field indicator, is suitable for rough estimation of the diffuse sound field conditions but does not give consistent results for small changes. It does not constitute a sufficiently reliable measure of the diffusivity in a reverberation chamber.

The current study has produced an interesting set of data and the authors plan to further evaluate the diffusivity in reverberation chambers by exploring alternative quantifiers. Advanced acoustical array systems and novel measurement methods will be used. In particular, the sound field isotropy will be examined using spherical microphone array systems.

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