DIFFUSENESS QUANTIFICATION OF A REVERBERATION CHAMBER AND UNCERTAINTY WITH FINE-RESOLUTION MEASUREMENTS

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Insufficient diffuseness is the major cause of poor inter-laboratory reproducibility of building acoustical measurements in a reverberation chamber. Many previous studies proposed methods to quantify the diffuseness in the chamber objectively, but there is no general agreement for the accuracy across these methods. Additionally, a number of measurement sample required for these diffuseness metrics is still unclear even though it significantly impacts on results. This study, therefore, aims to quantify the diffuseness of a reverberation chamber by using assorted objective metrics like spatial variation of sound pressure levels, relative standard deviation of decay rates and diffuse field factor. The measurement is also carried out with fine-resolution microphone positions and varied configurations of acoustic diffusers. With the measurement data, the effect of a number of measurement samples on the diffuseness quantification is investigated. Then, effectiveness and robustness of those objective metrics are discussed.

Keywords: reverberation chamber, diffuseness, microphone positions

1. Introduction

A reverberation chamber is a room designed to create a diffuse sound field with a uniform distribution of acoustic energy and random direction of sound incidence. However, in reality, different reverberation chambers have different diffuseness conditions because of the room properties (geometry, surface materials) and diffuser configurations (types, number, and orientation). Thus, to obtain accurate acoustical measurement quantities such as sound absorption coefficients, sound power levels, and transmission loss, it is necessary to quantify the diffuseness of a sound field and the influence of the diffuseness measurements. There are mainly two ways to quantify the diffuseness of a sound field. The spatial homogeneity can be measured by variation of sound pressure levels [1, 2], relative standard deviation of exponential decay curves [3], diffuse field factor [4] and kurtosis [5]. The isotropy of a sound field can be quantified by energy isotropy [6] and wavenumber spectrum [7]. Homogeneity is relatively easier to analyze compared with isotropy because the most isotropy measures require a multi-channel microphone array system [8].
The primary objective of this study is to quantify the diffuseness in a reverberation chamber by using assorted objective metrics like spatial variations of sound pressure levels, relative standard deviation of decay rates, and diffuse field factors. The effect of a number of measurement positions utilized on diffuseness quantification is also studied.

2. Method

2.1 Reverberation Chamber

A reverberation chamber of a volume of 152.3 m$^3$ (6.98 m×6.13 m×3.56 m) at Concordia University in Montreal is investigated. The maximum of six randomly oriented hanging diffusers has been used. The used hanging diffusers are corrugated plastic panels with a length of 2.6 m and a width of 0.8 m. Each diffuser has a surface area of 2.08 m$^2$. Fig. 1 illustrates diffuser configurations in the reverberation chamber.

![Diffuser Configuration](image)

Figure 1: A reverberation chamber with six hanging diffuser panels at Concordia Acoustics Lab.

2.2 Diffuseness Quantification

There is no consensus yet which metrics would be the most accurate to quantify the diffuseness of reverberation rooms. Thus, the comparison of the effectiveness of different diffuseness metrics are presented in this paper. Based on previous research findings, the three following metrics are considered in our study.

1. Spatial uniformity of sound pressure levels, $\sigma_P$

   A small variation in the sound pressure is required in the reverberation room qualification by standard ISO 3741 [1] and AHRI 220 [2]. The criteria of achieving adequate diffuseness in those standards are given in terms of the maximum allowable standard deviation of sound pressure levels across different measurement locations for each one-third octave band. The equation to calculate the standard deviation is given by:

   $$\sigma_P = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (L_i - \bar{L})^2},$$

   (1)
where N is the number of receiver positions, $L_i$ is the sound pressure level measured at the $i^{th}$ receiver position, and $\bar{L}$ is the average sound pressure level over all receiver positions.

2. Relative standard deviation of decay rates, $s_{rsd}$

The relative variation of the decay rates over microphone positions with no test specimen must be measured to qualify a reverberation chamber according to ASTM C423-17 [3]. At each 1/3 octave band frequency between 100Hz and 5000Hz, one can calculate the standard deviation of decay rate by using the following equations:

$$s_M = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (d_{Mi} - d_M)^2}, \quad (2)$$

$$d_M = \frac{1}{N} \sum_{i=1}^{N} d_{Mi}, \quad (3)$$

$$s_{rsd} = \frac{s_M}{d_M} \quad (4)$$

where N is the number of receiver positions, $d_{Mi}$ is the decay rate at at the $i^{th}$ receiver position, $d_M$ is the average decay rate over all receiver positions, $s_M$ is the standard deviation of decay rate, and $s_{rsd}$ is the relative standard deviation of decay rate.

3. Diffuse field factor, $f_d$

The diffuse field factor, introduced by Lautenbach et al. [9], is defined as the ratio between a standard deviation of the measured reverberation times and the one obtained theoretically under diffuse sound field conditions. It can be calculated as follows:

$$f_d = \frac{\sigma_{s,m}(T_{30})}{\sigma_{s,t}(T_{30})} \quad (5)$$

$$\sigma_{s,t}(T_{30}) = \sqrt{1.09 \frac{T_{30}}{f_c}} \quad (6)$$

where $f_c$ is the center frequency, $\sigma_{s,m}(T_{30})$ and $\sigma_{s,t}(T_{30})$ are the measured and theoretical spatial standard deviation of reverberation time respectively.

2.3 Measurement

There were mainly two parts of measurements. Firstly, impulse response measurements were conducted. The reverberation chamber was excited by an exponential sweep signal at 3 different source locations (nearby three corners of the chamber) with a height of 1.65 m. Corresponding decay curves and reverberation times were obtained for 132 microphone position with 12 × 11 grids with an interval of 0.4 m, as shown in Fig. 2. The three microphone’s heights of 1.1 m, 1.5 m and 2 m were adopted to determine if there is any influence of vertical locations on the results. The impulse to noise ratio of all the obtained impulse responses across 1/3rd octave frequency bands from 50Hz to 8000Hz are higher than 50 dB and most of them are even higher than 60 dB. Secondly, sound pressure level distributions were measured. The same 132 microphone positions were used. The heights of the microphone were adjusted from 2 m to 1.25 m. These two measurements were repeated with a varying number of panel diffusers (0, 2, 4, 6). Fig. 2 illustrates the measurement scheme with measurement positions. The different numbers of positions are used to calculate the diffuseness metrics to investigate the effect of a number of measurement positions utilized. The numbers of microphone positions used in the current study are 132, 66, 9 and 5. Fig. 2 shows the locations of randomly chosen microphone positions and source locations. According to ASTM C423-17, the measurement shall be made at five or more positions which are
at least 1.5 m apart from each other, and 0.75 m apart from any surface, indicating that 9 is the maximum number of microphone positions for this reverberation chamber.

![Figure 2: A schematic diagram of measurements with loudspeaker and microphone locations.](image)

3. **Results and Discussion**

Fig. 3 shows the spatial standard deviation of sound pressure levels in the reverberation chamber calculated over 1/3 octave band from 50 Hz to 8000 Hz for the different diffuser configurations. Lower deviations indicate higher diffuseness of the sound field. As shown in Fig. 3(a), all sound pressure level deviations are lower than the maximum acceptable values prescribed by ISO 3741 and AHRI 220 for frequencies higher than 1000Hz, indicating the sound field is highly uniform. No discernible patterns observed between the results obtained by increasing a number of diffusers. The results imply that sound pressure level uniformity may not be an appropriate indicator of diffuseness in the sound field. By comparison with the results calculated with the 132, 66, 9 and 5 microphone positions, it can be found that the values of this metric change significantly. The disparity between the different diffuser configurations is also more prominent when reducing the number of measurement positions.

Fig. 4 presents the relative standard deviation of decay rates in the reverberation chamber with no diffusers, 2, 4 and 6 panels. It is evident that the relative standard deviation of decay rates decreases by adding the diffusers. However, the values are higher than the maximum allowable criterion in ASTM C423-17. Similar to the spatial uniformity of sound pressure levels, the relative standard deviation of decay rates results varies considerably when reducing the number of receivers. Contradictory results can be drawn from when choosing the different number of microphone positions. When 132 or 66 microphone positions are selected, all relative standard deviation values are above the maximum allowable values. However, if the number of receivers is reduced to 5 or 9, the values meet the requirement at
certain frequencies as shown in Fig. 4 (c) and (d). Thus, without determining the appropriate number of measurement positions, it is difficult to evaluate the diffuseness of the room with these metrics.

Figure 3: The standard deviation of SPL with (a) 132, (b) 66, (c) 9 and (d) 5 microphone positions.

Figure 4: Relative standard deviation of decay rates with (a) 132, (b) 66, (c) 9 and (d) 5 microphone positions.

The hypothesis of a diffuse field factor is that actual spatial standard deviations are greater than the theoretical value when the diffuse sound field is assumed. The diffuse field factor greater than unity presents how deficient the measured sound field is. As found in Fig. 5(a) and (b) with receiver numbers of 132 and 66, the diffuse field factor decreases by adding diffusers in the room, which indicates the
improved diffuseness. The results are in accordance with the results with the relative standard deviation of decay rates. However, this trend is not apparent for frequencies lower than 400 Hz and higher than 5 kHz as shown in Fig. 5(a). The results with 9 and 5 receiver positions are not consistent with results with the higher numbers of positions. The results show that the number of measurement positions affects the accuracy of diffuseness quantification.

Figure 5: Diffuse field factor obtained with (a) 132, (b) 66, (c) 9 and (d) 5 microphone positions.

4. Conclusions

In this study, three assorted diffuseness metrics of the spatial uniformity of sound pressure level, relative standard deviation of decay curves, diffuse field factor are calculated with measured impulse responses and sound pressure levels in the reverberation chamber. The relative standard deviation of decay rates and diffuse field factors, on the contrary to the results with the variation of SPL, show a clear tendency of decrease when more diffuser panels were added. In addition, the results showed that the three diffuseness metrics vary greatly with the number of microphone positions utilized. Lastly, contrary to the results with the spatial uniformity of SPL, the results with the relative standard deviation of decay rates and diffuse field factors show that the sound field is not diffuse enough according to the corresponding literature. Further work needs to be conducted on the effect of using a rotating diffuser and including more diffuseness metrics like kurtosis and sound field diffusion coefficient [10].
REFERENCES


