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Diffuseness Quantification in a Reverberation Chamber and Its Variation with Fine-Resolution Measurements

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Abstract: Insufficient diffuseness is the major cause of the poor repeatability and reproducibility of building acoustical measurements in a reverberation chamber. Inaccurate results were reported for the prevailing methods in ISO and ASTM standards. Many previous studies, thus, have proposed new methods to quantify the diffuseness of a reverberation chamber more accurately, but there is no general agreement among researchers on the most reliable method. The number of measurement samples required for these diffuseness metrics is also unclear, even though it significantly impacts the robustness of the methods. This study, therefore, aims to compare the performance of the two widely used diffuseness metrics (spatial variation of sound pressure levels and the relative standard deviation of decay rates) in the standards and the recently introduced metric (degree of time series fluctuation). The measurements were carried out with fine resolution microphone positions and varied configurations of acoustic diffusers. The degree of time series fluctuation showed the best correlation with varying diffuser configurations in the low-frequency range. Confidence intervals and coefficients of variation of the three metrics by random sampling also indicated that DTF is more reliable for evaluating the diffuseness in a sound field as it is less influenced by the number of sampling.

Keywords: reverberation chamber; diffuseness quantification; measurement sampling

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1. Introduction

Accurate measurement of acoustical materials, such as absorption and transmission loss, is crucial for the acoustical design of architectural spaces. According to the relevant standards ASTM C423-17 [1]; ISO 354:2003 [2], sound absorption coefficients need to be measured in a reverberation chamber that closely approximates a diffuse sound field. In theory, the diffuse sound field requires acoustic energy distributed uniformly throughout the space (homogeneity) and equal sound intensity over all directions (isotropy), which are impossible to obtain in actual reverberation chambers. In a practical condition, a mixing room with small absorption and the greatest scattering room surfaces are desired [3,4]. Although specific guidelines for qualification of reverberation chambers are provided by the standards, previous studies pointed out poor repeatability and reproducibility of measured acoustic quantities in different laboratories even though they meet the criteria in the standards [5,6]. The inaccurate measurement of the acoustic properties poses a huge challenge for acoustic engineers and manufacturers to compare the acoustical performance of building elements measured across acoustic laboratories. In a room with unequal absorption and low scattering, especially in rectangular rooms, the measured reverberation time can deviate up to 50% and more from the value by the Sabine equation [3]. Accurate measurements of absorption or transmission loss of the specimen require averaging values measured over multiple locations in the reverberation chamber. Thus, the minimum variation across the chamber (homogeneity) is crucial for the accuracy of acoustic quantities.

There are several reasons for the non-diffusivity in reverberation chambers. First, in a room with a small volume, it can be challenging to achieve the diffuse sound field in the low frequency due to low modal density [7]. Second, paralleled walls or a lack of scattering elements make it difficult for an ideal diffuse condition [8]. Finally, the 'suction' effect of the absorbing sample causes an anisotropic energy distribution in the chamber [6].

The general practice of increasing the diffuseness of a reverberation chamber includes having an irregular room shape with no parallel walls [9,10], adding suspended diffusers to increase the reflection and irregularities of the room surface, and using a rotating vane to continuously shift the eigenfrequencies and sound incidence angles in the chamber [11–13]. The sound field is assumed to be more diffuse with more diffusers [14–17]. Despite these efforts to achieve a sufficient diffuse sound field in a reverberation chamber, the effectiveness of those treatments and the criteria to determine whether adequate diffuseness has been achieved remain unclear. For example, both ISO 354:2003 [2] and ASTM C423-17 [1] state that an acceptable diffuseness in the reverberation chamber can be achieved by adding diffuser panels or rotating vanes until a quantity of interest converges. However, this method proved inappropriate as there is no scientific proof that the converged value is true [18]. Other quantifiers, such as the relative standard deviation of decay rate over microphone positions from ASTM C423-17 [1], or the total confidence interval of sound pressure levels and sound absorption from ASTM E90-09 [19], were also widely used to quantify the homogeneity of the sound field, as shown in Table 1. Bradley et al. [20] utilized these standardized quantifiers to compare the efficacy of boundary and hanging diffusers on the diffuseness of the sound field; contractionary results drawn from these metrics suggested that more accurate quantifiers are needed to determine the room diffuseness.

In addition to those standardized quantifiers, Hanyu [14,21] proposed the degree of time series fluctuation (DTF) by using a decay-canceled room impulse response to quantify how a normalized reflected sound energy fluctuation deviates from the Schroeder integrated decay curve. Less diffuseness is expected in the sound field where the large time variation is observed in the reflected sound energy. The author compared the averaged DTF from six microphone positions in three conditions: (1) without diffusers, (2) with small diffusers, and (3) with large diffusers, and showed that this metric could be used for evaluating the effect of diffusers on the diffuseness of the sound field. This metric was later investigated by Vallis et al. [22], whose results suggested that no distinguishable difference was observed between the different orientations of the diffuser panel. The author also emphasized that it is critical to find a standardized measurement to quantify the diffuseness for future work.

Jeong [15] also proposed the kurtosis of the early part of an impulse response as a diffuseness indicator. By comparing the kurtosis analyzed in two reverberation rooms, with a different number of panel diffusers, with and without an absorbing sample, the study found that this metric is sensitive to the changes of room diffuseness. More recently, Wang et al. [13] suggested that the standard deviation of squared sound pressures is a better indicator of sound field diffuseness than the standard deviation of sound pressure levels because the diffuseness of the space is more related to the energy density in the sound field. In their study, the sound pressure levels were measured at 2461 points with a spacing of 5 cm to investigate the effects of panel diffusers on the sound field diffusivity. The authors found that panel diffusers are effective for the sound field diffuseness at higher frequencies while not for frequencies below 100 Hz. Other indirect methods, such as the number of peaks [23] and the mixing time [24], were also proposed to quantify the diffuseness of the sound field by analyzing the details of the impulse response. Scrosati et al. [6] quantified the diffuseness of multiple reverberation chambers by using a reference absorber method, and the authors found that the use of a reference absorber might be valid but challenging because the true value of the reference absorber is still in doubt.

Instead of using a single-channel microphone, sophisticated spherical microphone arrays (SMA) can be used to characterize the diffuseness. Lokki [25] proposed an energy-based analysis of spatial impulse response to estimate the diffuseness of the sound field as the ratio of the active sound intensity to the acoustic energy density. Gover et al. [26] visualized the angular distribution of incident sound energy by analyzing the anisotropy index of obtained directional impulse responses. Epain and Jin [27] estimated the diffuseness based on the homogeneity of the spherical harmonic covariance matrix spectrum, a new concept of diffuseness profiles was also introduced to show the dependence of diffuseness estimates on the order of spherical harmonic signals. Nolan et al. [16] analyzed the wavenumber spectrum in the spherical harmonic domain. They compared the isotropy indicator in different diffuseness conditions: (1) in an anechoic chamber (with a single source/with 52 uncorrelated sources surrounding the SMAs), and (2) a reverberation chamber (with and without absorption). The results showed that this method is suitable for evaluating the isotropy property of diffuseness of the steady-state sound field in a reverberation chamber. The SMA helps to characterize the nature of sound field diffuseness as it can measure the sound pressure or sound intensity from all directions. However, a drawback of those isotropy indicators is that the measurement equipment is expensive and often requires complicated data processing [18]. Moreover, The SMA cannot provide accurate estimations in lower frequencies due to the limitations of spatial resolution, nor in high frequencies because of aliasing effects [28]. Although many new diffuseness indicators were proposed, as summarized in Table 1, none of those metrics are proved to be more accurate to the diffuseness conditions than the existing metrics in the standards.

Table 1. Proposed methods for quantifying diffuse conditions of a reverberation room.

Category	Metrics	Reference	Measurement	Description
Homogeneity	The relative standard deviation of decay rate	ASTM C423-17 [1]	Decay rates or SPLs in multiple locations using fixed microphones or moving microphones.	Lower values of deviations across the sound field indicate higher diffuseness.
	Total Confidence Interval	ASTM E90-09 [19]		
	The spatial standard deviation of the reverberation time	Bartel & Magrab [11], Davy [29]		
	Spatial Uniformity	Wang et al. [13]		
Isotropy	The diffuseness estimate	Lokki [25]	Using spherical microphone arrays to analyze the direction of energy flow.	The isotropic sound energy from all directions means high diffuseness.
	Directional Diffusivity	Gover et al. [26]		
	The spherical harmonic covariance matrix	Epain & Jin [27]		
	Wavenumber spectrum	Nolan et al. [16]		
Indirect method	Number of peaks	Jeon et al. [23]	Analyzing the details of the impulse response.	Less fluctuation of impulse response in the early decay means higher diffuseness.
	Kurtosis	Jeong [15]		
	Mixing time	Prislan [26]		
	Degree of time fluctuation	Hanyu et al. [14,21]		
	Maximum absorption coefficient	ISO 354:2003 [2]	Measuring the sound absorption coefficient with an increasing number of diffuser panels.	The optimum diffuse configuration is achieved when it produces the maximum absorption.
	Reference absorber	Scrosati et al. [6]	Comparing the equivalent absorption area of the reference absorber with a minimum value.	The absorption correction factor can be used to quantify the reverberation chamber.

The accurate measurement of spatial variability across the sound field and consequential diffuseness quantification requires a large number of measurement samples. However, data acquisition is time-consuming, and thus, a trade-off is typically made between the number of microphone positions and the acceptable uncertainty.

For the sound pressure level measurements, Bodlund [30] proposed that the mean square pressure and the reverberation time estimates can be described by a simple gamma distribution for a typical hard-walled reverberant chamber. Consequently, the minimum number of microphone positions should be 285 divided by independent frequency components to obtain a confidence interval less than ±1.0 dB. Lubman [31] suggested that the required sample size is 12 for ±1 dB and 50 for ±0.5 dB with a 95% confidence interval. Tichy & Baade [32] reported that 43 independent samples are needed for the spatial averaging to be 90% confident that the uncertainty does not exceed 1.0 dB. They also reported that adding a rotating diffuser can reduce the number of samples needed for a given accuracy. However, Schroeder claimed that the equivalent number of independent measurements depends on how the variability is measured [33]. For example, the independent sampling interval is a half wavelength for sound power measurements and 0.3 wavelengths for sound pressure measurements.

For the absorption coefficient measurements, Bartel & Magrab [11] found that the total variance of reverberation time obtained with 24 positions and 98 decay each closely equals to the one obtained with six positions and 20 decays each. Thus, they proposed that six microphone locations are enough when results under 200 Hz are not needed. Warnock [34] proposed that 12 independent microphone positions should be used to obtain the uncertainty given by ASTM C423 based on a Student's t-distribution. Additionally, they proposed that three microphone positions are sufficient while using a rotating diffuser. More recently, Müller-Trapet & Vorländer [35] found that the 12 measurements, as ISO 354:2003 [2] recommends, provide poor repeatability for the absorption coefficient measurements at lower frequencies. They also developed an equation to determine the minimum number of necessary source-receiver combinations for the given frequency band. Although many previous studies attempted to find the optimal number of source and microphone combinations in the reverberation chamber for accurate measurement of the acoustic properties, how the number of measurements impacts the uncertainty of calculating different diffuseness metrics has not been fully investigated yet.

This paper, thus, aims to quantify the sound field diffuseness of a reverberation chamber using standard measurement procedures and the newly proposed metric, DTF. The accuracy of those metrics will then be discussed by comparing the results obtained with each metric in varying diffuse configurations. The fine-resolution measurements are made to investigate the effects of the number of measurement samples on diffuseness quantification. The confidence interval and the coefficient of variation of each metric are also calculated to compare the robustness of the diffuseness metrics.

2. Methods

2.1. Diffuseness Metrics

The diffuseness quantification metrics investigated in this paper are the relative standard deviation of decay rate (s_{rel}), the standard deviation of sound pressure levels (σ_{SPL}), and the degree of time series fluctuation (DTF) proposed by Hanyu [21]. The DTF was selected as a possible alternative of s_{rel} and σ_{SPL} as the DTF can quantify the diffuseness of the sound field at a single point and do not require multiple point measurements essentially. Additionally, DTF only requires a relatively simple room impulse response measurement compared to other metrics in Table 1 using a microphone array or a sound intensity probe.

ASTM C423-17 [1], the standard for sound absorption measurement in a reverberation room by measuring decay rate, prescribes the maximum values for the variation of decay rate across microphone positions with no absorption specimen installed. The decay rate is defined as the negative of the slope of linear regression on the averaged decay curves [1,36]. The least-square estimate of the slope for the simple linear regression model can be calculated as:

$$\hat{\beta}_1 = \frac{n\sum_{i=1}^{n} y_i x_i - \sum_{i=1}^{n} y_i \sum_{i=1}^{n} x_i}{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2}, \quad (1)$$

where $\hat{\beta}_1$ is the slope of the model, x_i, y_i are a pair of data points, and n is the number of data points used for the least square fitting. The decay rate can be derived by substituting x_i and y_i in Equation (1) with $i\,\Delta t$ (integration time) and L_i (the average of sound pressure levels measured at the ith decay point). M is the total number of points used in the fitting procedure. Hence, the decay rate can be expressed as:

$$d = \frac{6}{M(M^2-1)\Delta t}\left[(M+1)\sum_{i=1}^{M} L_i - 2\sum_{i=1}^{M} iL_i\right] - d_{air}. \quad (2)$$

L_1 used for the fitting is 100 ms after the source is turned off and L_M is defined as 25 dB lower than L_1. d_{air} is the decay rate (dB/s) due to air absorption [37]. The relative standard deviation of decay rate (unitless) is then calculated using Equation (3):

$$s_{rel} = s_M / d_M, \quad (3)$$

where d_M and s_M are the mean and standard deviation of decay rates over all microphone positions, respectively.

ASTM E90-09 [19] describes measurement procedures for testing the sound transmission loss of building partitions in two adjacent reverberation rooms. The maximum total confidence intervals are introduced to specify the required diffuseness of the reverberation rooms. The maximum total confidence interval requires small variations in the sound pressure levels and sound absorption between measurement positions in the reverberation rooms. Bradley et al. [20] showed that the sound pressure level is the dominant factor that determines whether the reverberation chamber meets the criteria. Thus, in the current study, the standard deviation of sound pressure levels was used to quantify the diffuseness of the reverberation chamber. The average sound pressure level L_R in the reverberation chamber can be calculated by the following equation:

$$L_R = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{L_{Ri}/10}\right), \quad (4)$$

where L_{Ri} is the sound pressure level measured at the ith microphone location in dB, n is the total number of measurement positions. The standard deviation for sound pressure levels (dB) can be computed using Equation (5):

$$\sigma_{SPL} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (L_{Ri} - L_R)^2} \quad (5)$$

The last diffuseness metric utilized in this research work is the degree of time series fluctuation proposed by Hanyu [14,21]. The metric is based on how a normalized reflected sound energy fluctuation deviates from the Schroeder integrated decay curve. For this metric, the Schroeder decay curve $E_S(t)$ is firstly calculated as a backward integration of the squared impulse response [38]:

$$E_s(t) = \int_t^{\infty} p^2(\tau)d\tau, \quad (6)$$

where $p(t)$ is the impulse response. The squared decay-canceled impulse response, $g^2(t)$, can be calculated by using the following equation:

$$g^2(t) = \frac{p^2(t)}{E_s(t)} = \frac{p^2(t)}{\int_t^{\infty} p^2(\tau)d\tau}. \tag{7}$$

As the value of $g^2(t)$ depends on the decay rate or reverberation time of the sound field, a normalized decay-canceled impulse response, $h(t)$, is used to quantify the time fluctuation of reflected sound energy of an impulse response at a location of the sound field. Thus, $h(t)$ can be obtained by using $g^2(t)$ and an average value of a squared decay-canceled impulse response, $\overline{g^2(t)}$:

$$h(t) = \frac{g(t)}{\sqrt{\overline{g^2(t)}}}. \tag{8}$$

The fluctuation decay curve Z_k is defined as a ratio of the total of $h^2(t)$ when the value exceeds an energy ratio k divided by the total of $h^2(t)$ as the following Equation (9):

$$Z_k = \frac{\int_{t_1}^{t_2} \{h^2(t) > k\}dt}{\int_{t_1}^{t_2} h^2(t)dt}. \tag{9}$$

Lastly, the degree of time series fluctuation is defined as the threshold value k where the fluctuation decay curve Z_k is equal to 0.01. The degree of time series fluctuation indicates "how large the reflected sound energy is where the probability of occurrence is 1%" [21]. The metric is unitless, and a smaller DTF indicates higher diffuseness in the sound field. Figure 1 illustrates typical temporal structures of the functions ($p^2(t)$, $E_S(t)$, $h^2(t)$) for DTF calculation.

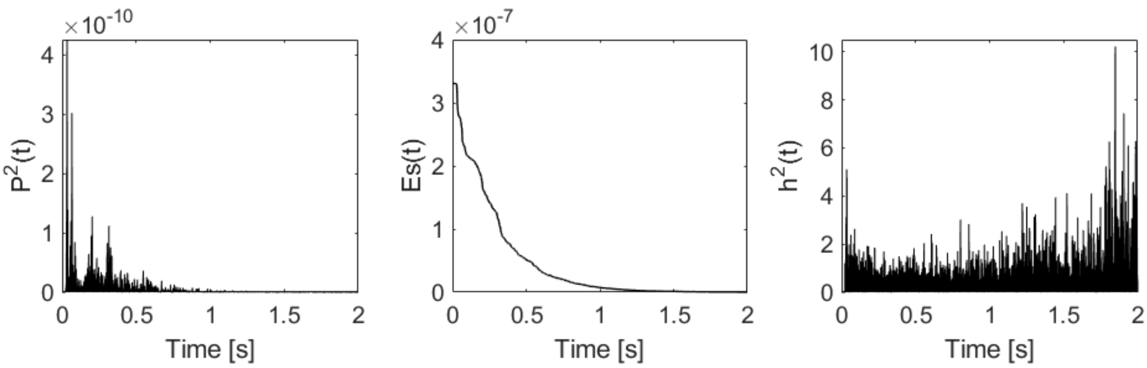


Figure 1. A squared impulse response (($p^2(t)$), a Schroeder decay curve ($E_S(t)$) and a squared decay-cancelled impulse response ($h^2(t)$) measured in an empty reverberation room at 1000 Hz for DTF calculation.

2.2. Measurement

Measurements were conducted in the reverberation chamber at Concordia University, Montreal, Canada. Figure 2 illustrates the measured reverberation chamber and measurement setups. The room is in a rectangular shape with a volume of 152.32 m^3 (6.98 m × 6.13 m × 3.56 m). The averaged reverberation time from 100 Hz to 5 kHz of the chamber without any acoustic diffuser is 4.64 s. The Schroeder frequency of the chamber is 349.1 Hz.

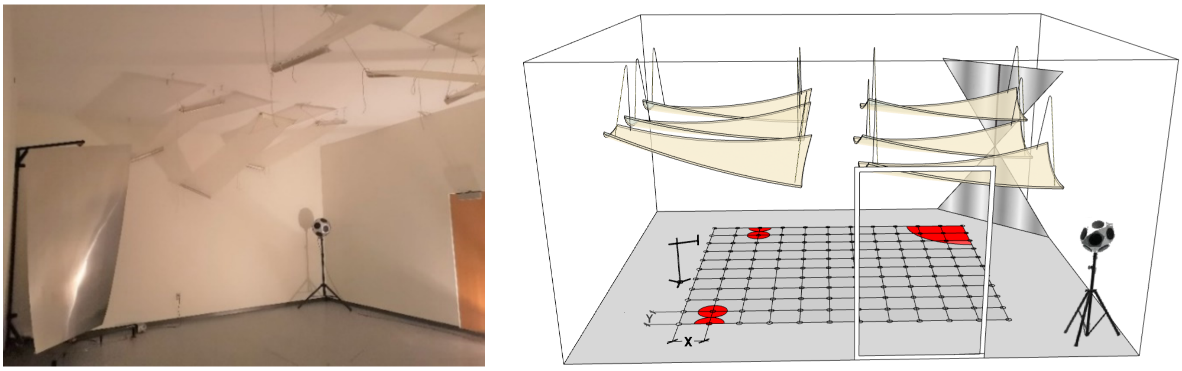


Figure 2. Left: A picture of the experimental setup in the reverberation room in Concordia Acoustics Lab. **Right**: A 3-D model of the reverberation chamber. The diffusers hanging from the ceiling are indicated in light yellow. A steel rotating diffuser is located near the upper-right corner. The measurement grid spacing (X, Y) is 40 cm.

According to standard ISO 354:2003 [2] and ASTM C423-17 [1], stationary diffusers or rotating vanes are strongly recommended to achieve acceptable diffuseness. These standards also recommend that the panels should be randomly oriented and positioned throughout the chamber. Thus, to meet those criteria, the diffuseness of the reverberation chamber was increased using an increased number of hanging diffusers, from 0 to 6, with a step of 2. The hanging diffusers used in this research work 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 approximately 2.08 m^2. The orientation of the hanging diffusers was designed with varying horizontal angles between the panels and the floor (from 3° to 24°) and vertical angles between the panel and a side wall (36° to 79°). The hanging heights range from 2.55 to 3.13 m.

The rotating diffuser was also added to investigate if the rotating diffuser can produce a better diffuse sound field than stationary diffusers. A steel rotating vane with a radius of 0.74 m and a height of 2.80 m was installed at the upper right corner of the room. For this research work, it rotates at the maximum speed of 3 rad/s. Six diffuser configurations were chosen using a mix of hanging diffusers and the rotating diffuser. The mixed diffuser type and the total surface area for each case are shown in Table 2. No absorber sample was placed during any measurements in this study.

Table 2. Diffuser configurations of the reverberation chamber, including the total surface area of the diffusers.

Diffuseness Condition	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Diffuser configuration	Empty room	Two hanging diffusers	Four hanging diffusers	Six hanging diffusers	Rotating diffuser	Rotating & Six hanging diffusers
Total diffuser surface area (m^2)	0	4.16	8.32	12.48	4.14	16.62

The impulse responses of the reverberation chamber were measured using Brüel & Kjær DIRAC room acoustic software (Type 7841), an audio interface (ZE-0948), a class-1 sound level meter (Type 2250), an omnidirectional Brüel & Kjær loudspeaker (Type 4292-L) with a maximum directivity deviation of ±4 dB, and a power amplifier (Type 2734A). An exponential sweep signal is selected due to its superior rejection of background noise and distortion. The length and gain of the e-sweep ware were adjusted to have signal-to-noise ratios higher than 50 dB for all one-third octave bands from 100 Hz to 5000 Hz.

Room impulse response measurements were made at 120 microphone positions using a 12 × 11 grid and an interval of 0.4 m, as shown in Figure 3. The locations indicated in red were removed to avoid getting too close to the sound source or rotating diffuser. Three different microphone heights were utilized to include the vertical variations. For the 1st, 2nd, 3rd, 11th, and 12th columns of the measurement grid, microphones were placed at the height of 1.1 m. The 4th, 5th, and 6th column microphones were placed at 1.5 m above the floor. All other microphone locations were placed using the height of two meters. The sampling coverage was selected since the microphone should be positioned at least two meters from any sound source and at least one meter from any room surface to comply with the ISO 354:2003 [2] requirements. Corresponding decay curves were calculated using the integrated impulse response method. At each microphone position, the measurement was repeated ten times and the obtained impulse responses were averaged to eliminate ambient noise. The same measurement procedure was repeated for all the diffuser configurations described in Table 2.

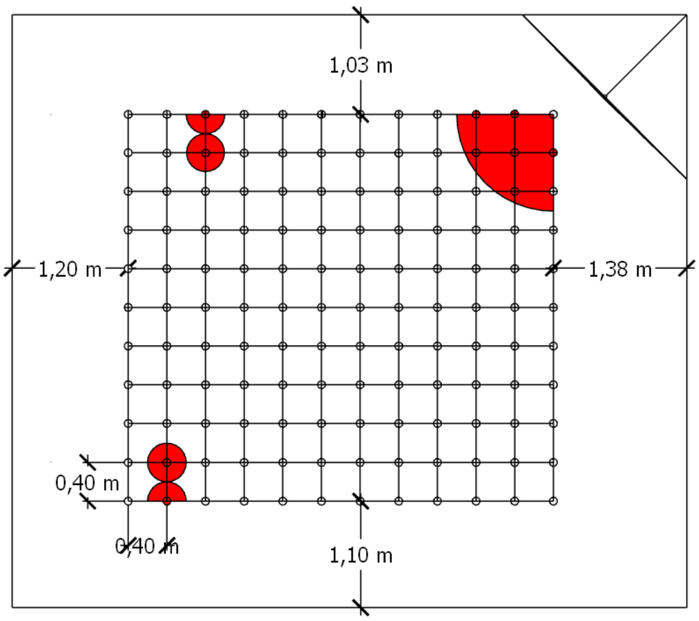


Figure 3. The measurement grid (11 × 12) used for the impulse response measurement. The distance between each microphone position was 0.4 m. 120 points were measured in total. Locations marked in red were removed to avoid getting too close to the sound source or rotating diffuser.

The sound pressure level (SPL) was measured using a Type 2250 sound level meter while pink noise was played through the loudspeaker. The measurement duration was set to 60 s. Unweighted equivalent sound pressure levels for one-third octave band from 100 Hz to 5000 Hz were obtained at the same microphone positions as impulse response measurements, as shown in Figure 3. The SPL measurements were also repeated for every diffuser configuration to investigate how the performance of metrics varies according to the configurations. The temperature and relative humidity of the chamber were recorded using a Govee Thermo-Hygrometer. The temperature was 21.3 °C with ±0.4 °C, and the relative humidity was 40% with ±2%.

2.3. The Number of Measurement Samples Required for Diffuseness Quantification

Spatial variations are inherent in reverberation rooms. In the present work, we investigate the minimal number of measurements of randomly selected locations required for quantifying the diffuseness of the sound field. It is expected that the larger the sample size is, the more accurate the measurement is for diffuseness quantification. ASTM C423-17 [1] specifies measurements should be made using five or more positions that are at least 1.5 m apart. The required number of microphone positions for absorption coefficient measurement is reduced to three positions in ISO 354:2003 [2]. For the sound transmission loss measurement, ASTM E90-09(2016) [19] recommends a minimum number of four microphone positions. However, this standard also specifies that a larger number can be used if the confidence interval criteria are not met. Due to the dimensions of the reverberation chamber used for this study, a maximum of nine measurement positions can be used with an inter-microphone distance of 1.5 m.

To investigate whether more measurement positions are needed than the number recommended by the standards, the diffuseness metrics were first calculated using measurements collected using five or more positions, each separated using an inter-microphone distance of 1.5 m, as recommended by the standards. Then, more microphone positions (up to 100 positions) were randomly chosen to investigate the uncertainty of the diffuseness metrics. The diffuseness metrics which were calculated by random sampling are assumed to be normally distributed with a sample variance σ_X^2. Therefore, the estimated 95% confidence interval $CI_{X,95\%}$ can be calculated using Equation (10):

$$CI_{X,95\%} = 2 \times (1.96 \times \frac{\sigma_X}{\sqrt{N}}) = 3.92\frac{\sigma_X}{\sqrt{N}}, \tag{10}$$

where σ_X is the sample standard deviation, and N is the number of sampling repetitions.

To compare the sensitivity of the three metrics with the number of microphone positions, the unitless coefficients of variation (CV) were calculated using the following equation:

$$CV = \frac{\sigma_X}{\mu_X}, \tag{11}$$

where σ_X is the sample standard deviation, and μ_X is the estimated mean of the diffuseness metric X. The minimum number of microphone positions, presented in the next section, was determined using the confidence intervals and the coefficient of variations computed in each scenario.

3. Results and Discussion

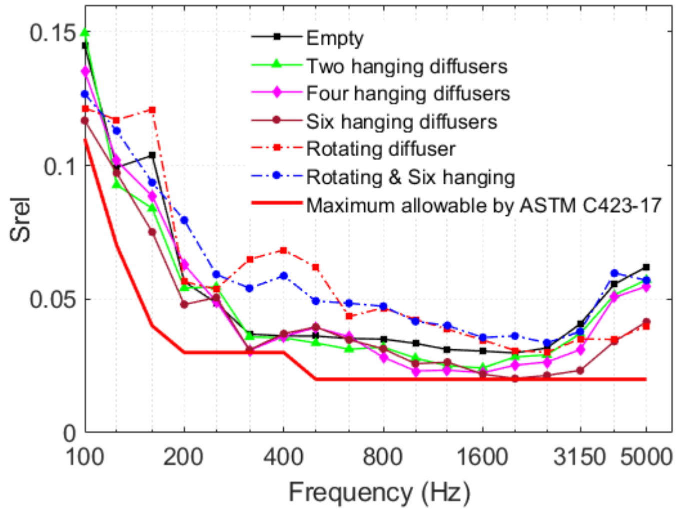
3.1. Diffuseness Quantification

Figure 4 shows the relative standard deviations of decay rates (s_{rel}), the standard deviation of sound pressure level (σ_{SPL}) and the degree of time-series fluctuations (DTF) with the six different diffuser configurations in the reverberation chamber by using 120 measurement positions. Lower values indicate higher diffuseness for the given diffuser configuration for all quantifiers.

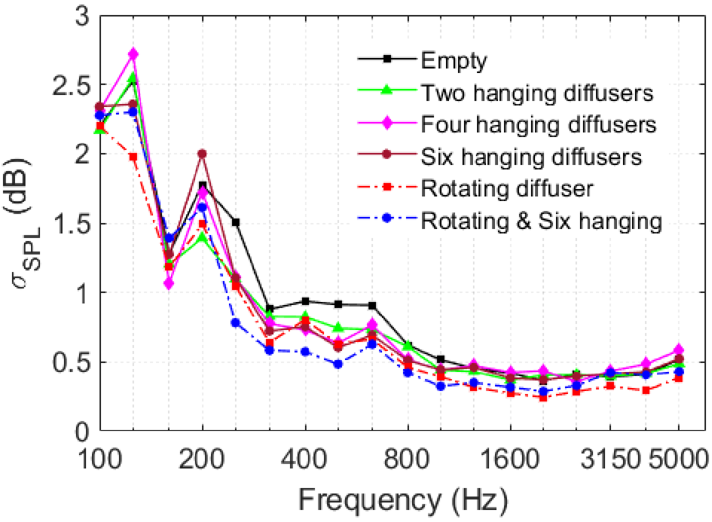
Adding hanging diffusers decreases s_{rel} in general over all frequencies, while an unexpected increase is observed after the installation of the rotating diffuser from 315 Hz to 1000 Hz one-third octave bands. The largest differences between the measured s_{rel} and the required values by ASTM C423-17 [1] are observed at frequencies lower than 200 Hz and frequencies higher than 4000 Hz, which suggests that the utilized diffusers are not effective for those frequency ranges.

Adding hanging diffusers decreases σ_{SPL} especially for frequencies above 125 Hz, as shown in Figure 4b. The configurations with a rotating diffuser also produce lower σ_{SPL} above 125 Hz, which was not found in the result with s_{rel}. The amount of improvement in the σ_{SPL} values are significant in lower frequencies below 800 Hz and become less substantial above 1000 Hz. The maximum value of σ_{SPL} is 2.70 dB at 125 Hz, with the four hanging diffusers configuration, and the minimum value is 0.30 dB at 2000 Hz with a rotating diffuser.

The DTF values in Figure 4c decrease when the number of hanging diffusers increases and a rotating diffuser is added for the frequencies below 500 Hz. The lowest DTF values were obtained when a rotating diffuser and six hanging diffusers were installed. In the frequency range, the change of the DTF values between the diffuser configurations was the most prominent among the three metrics. At frequencies higher than 500 Hz, the number of hanging diffusers has less impact on the DTF, and the diffuser configurations with a rotating diffuser produce higher DTF values compared to the scenario where only hanging diffusers were used, which was also found in the result with s_{rel}.



(**a**)



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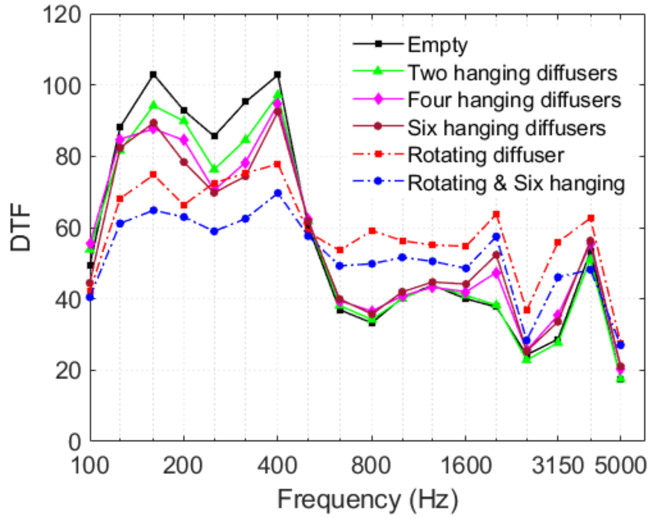


(**c**)

Figure 4. Diffuseness metrics of (**a**) s_{rel}, (**b**) σ_{SPL} and (**c**) DTF over 120 microphone positions measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

Inconsistent results were obtained from these metrics regarding the optimal diffuser sound field. The σ_{SPL} showed the most correlated trend with an increasing number of hanging and rotating diffusers in all frequencies. However, the differences between the diffuser conditions are not much discernable, which can be problematic, especially in terms of spatial sampling. The s_{rel} shows that the hanging diffusers effectively increase the diffuseness in the chamber over all frequencies, but the rotating diffuser does not. The DTF shows the best correlation with diffuser configurations including the rotating diffuser but only shows that trend for the frequencies of 500 Hz and below.

Using a sine sweep signal to measure impulses responses for DTF and s_{rel} calculations can be a possible source of error for the unexpected result with the rotating diffuser, especially in high frequencies. The trend with σ_{SPL} confirmed the enhanced diffuseness by installing the rotating diffuser. The sound field with the rotating diffuser became time-variant, and the measurements using a sine sweep were more prone to error with the time-variant sound field. Even though the possible fault in the measurement, the results with DTF and s_{rel} still showed good agreement with the diffuser installations in low frequencies (under 500 Hz), which are a critical region for diffuseness due to their modal behaviors.

There is a conceptual difference between DTF and the other two diffuseness metrics on how to quantify the diffuseness of the sound field. σ_{SPL} and s_{rel} both intend to measure the spatial uniformity of the sound field (homogeneity) and cannot be applied to describe the diffuseness of the sound field at a single location. On the other hand, DTF indirectly evaluates homogenous and isotropic characteristics of the sound field together by analyzing the time fluctuation of reflected sound energy. DTF assumes that homogeneity and isotropy of a sound field are negatively correlated with the time fluctuation of reflected sound energy in an impulse response. Thus, a large time fluctuation of reflected sound energy is expected in a sound field with low diffuseness. DTF can be applied to a single location of the sound field or an entire room by averaging the values over several locations. The DTF, thus, is likely less sensitive to spatial sampling (which will be presented in the next section), and this characteristic could lead to the results that the DTF showed the most sensitive result to the effect of diffusers on the diffuseness.

3.2. The Effects of the Number of Measurement Positions on Diffuseness Metrics

The three metrics were calculated with an increased number of microphone positions over fifty random repetitions to investigate the effect of the number of measurement positions on diffuseness quantification. Figure 5 presents the diffuseness metrics calculated with an increased number of microphone positions for the one-third octave band centered at 125 Hz in the following configurations: (1) empty room with no diffusers (as a base comparison), and (2) the room with six hanging diffusers. Similar results were observed in higher frequencies, and the differences become less prominent with higher frequencies.

The diffuseness metrics deviate significantly with increased measurement positions and over random repetitions when using five to nine microphone positions, as suggested by the standards. The more measurement positions are selected, the lower deviations over repetitions are achieved. For example, the 95% confidence interval ($CI_{95\%}$) of s_{rel} measured in the empty room was 0.02 with five microphone positions, and it decreased to 0.01 when 20 or more microphone positions were used. Additionally, the s_{rel} measured in the room with six hanging diffusers showed similar trends but slightly less change when a different number of positions were used. The overlapping error bars observed for the metrics s_{rel} and σ_{SPL}, indicate a high chance of quantifying the diffuseness inaccurately when only a limited number of microphone positions are used. The DTF, unlike the s_{rel} and σ_{SPL}, shows clearly lower values for six hanging diffusers configuration compared to empty rooms, even when only five microphone positions are used.

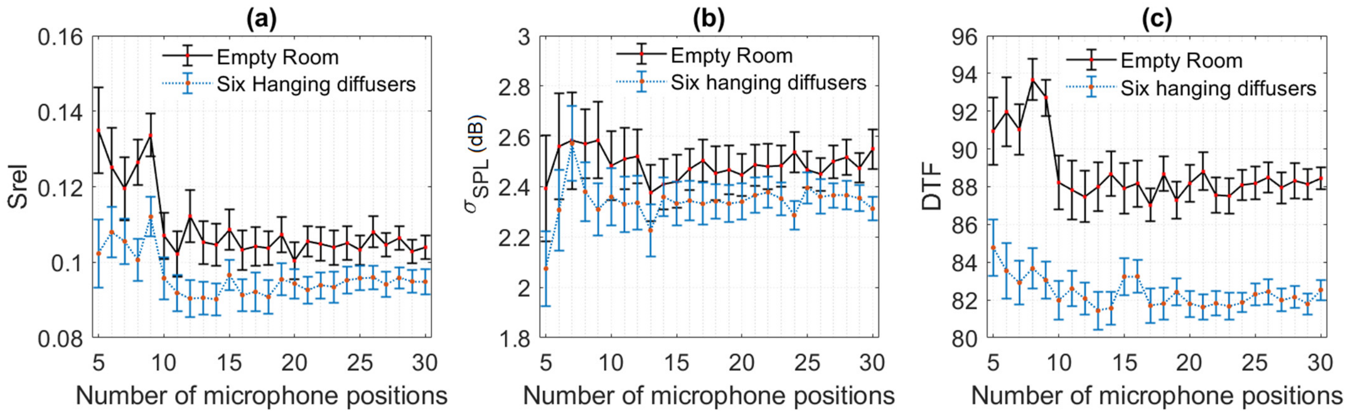
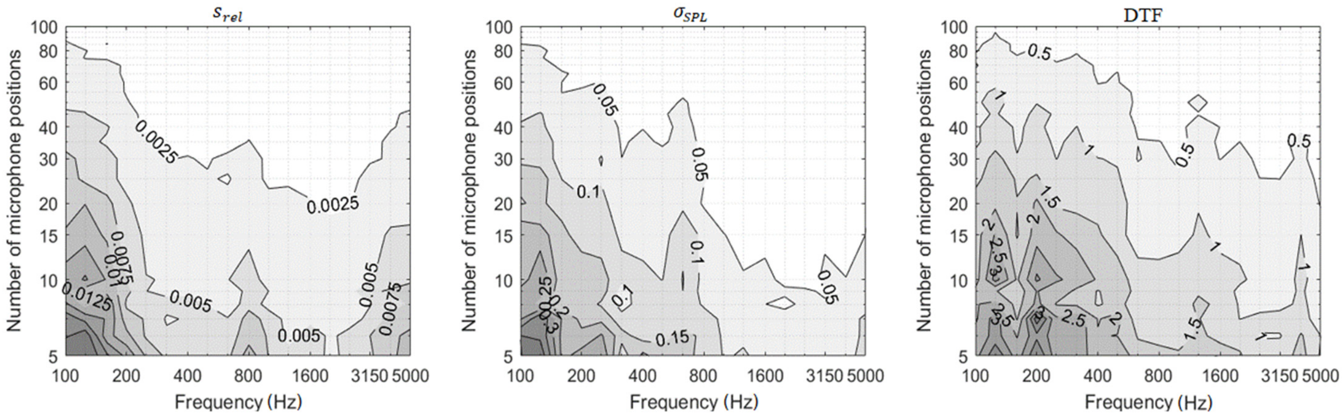


Figure 5. The diffuseness metrics of (**a**) s_{rel}, (**b**) σ_{SPL} and (**c**) DTF were measured in two diffuser configurations: (1) Empty room and (2) Room equipped with six hanging diffusers as a function of an increased number of microphone positions at 125 Hz. The error bar presents the 95% confidence interval of the metrics computed using 50 repetitions of a subset of combinations randomly selected among the full data set of 120 microphone positions.

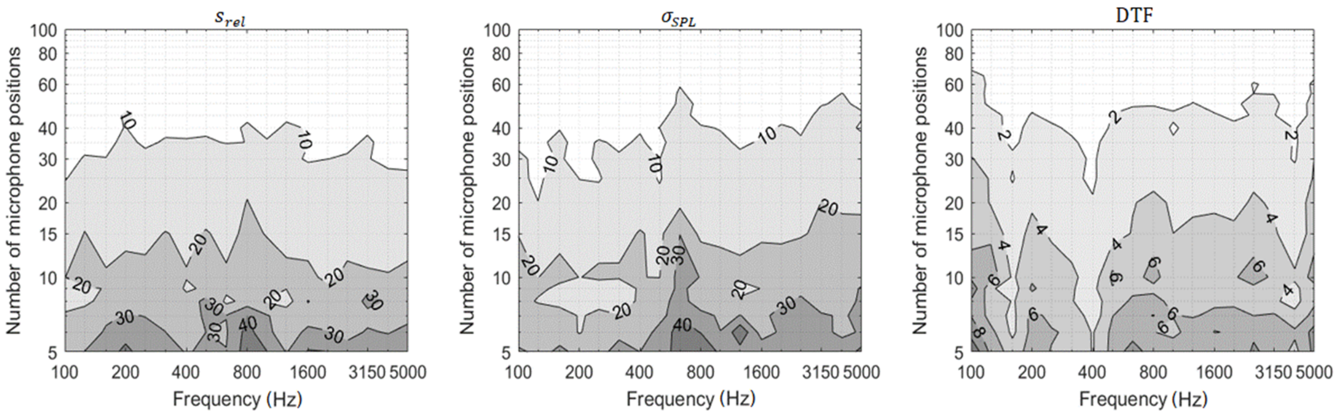
The 95% confidence interval of s_{rel}, σ_{SPL} and DTF measured in the empty room with an increased number of measurements is shown as a contour plot in Figure 6 to present the measurement accuracy of each metric. The contour line represents the 95% confidence intervals at each one-third octave band frequency. Broader confidence intervals are generally obtained at lower frequencies. The graphs show that the measurement accuracy of the diffuseness metric depends on the number of measurement positions and frequencies of interest. For a given maximum acceptable measurement uncertainty and the frequencies of interest, the minimum number of microphone positions required can thus be determined. For example, to be 95% confident that the measurement uncertainty of s_{rel} is less than 0.01 for frequencies from 100 Hz to 5000 Hz, twenty or more measurement positions are needed for spatial averaging. However, the number required is increased to 50 if a lower confidence limit of 0.005 is required. Similar results were obtained for the σ_{SPL}, as shown in Figure 6b. Nine independent microphone positions with a minimum distance of 1.5 m result in a maximum $CI_{\sigma_{SPL},95\%}$ of 0.30 for frequencies above 100 Hz. The number of microphone positions required needs to be increased to twenty if a maximum allowable $CI_{\sigma_{SPL},95\%}$ of 0.02 is desired for all frequencies of interest. The maximum values of $CI_{DTF,95\%}$ is observed at 125 Hz and 200 Hz with five and seven microphones, respectively. Five or nine microphone positions can ensure a confidence interval less than 2.5 for frequency above 315 Hz. However, fifteen or more microphone positions are needed for the same accuracy if lower frequencies are considered down to 100 Hz. The number of microphone positions required for a given accuracy is almost equal for all other diffuser configurations, except for the room with six hanging diffusers, in which fewer microphone positions are required.

The coefficients of variation (CV) have been calculated for the same data for comparing the results between the metrics as the CI values in Figure 6 depend on the units of the metrics. The contour plot of the CV of three diffuseness metrics is shown in Figure 7. The CV of diffuseness metrics: (a) s_{rel}, (b) σ_{SPL} and (c) DTF measured in the empty room as a function of frequency with an increased number of microphone positions. The CV values decreased with an increased number of microphone positions, which indicates the higher accuracy of diffuseness metrics by spatial sampling.



(**a**) (**b**) (**c**)

Figure 6. The 95% confidence interval of diffuseness metrics: (**a**) s_{rel}, (**b**) σ_{SPL} and (**c**) DTF measured in the empty room as a function of frequency with an increased number of microphone positions.



(**a**) (**b**) (**c**)

Figure 7. The coefficients of variation of diffuseness metrics: (**a**) s_{rel}, (**b**) σ_{SPL} and (**c**) DTF measured in the empty room as a function of frequency with an increased number of microphone positions.

The DTF shows lesser variation compared with s_{rel} and σ_{SPL}. The results show that the DTF values are less influenced by a number of samplings. For example, if a maximum number of nine microphone positions which are at least 1.5 m apart is used according to the standards, the maximum coefficient of variation of s_{rel}, σ_{SPL} and DTF are 28.23%, 32.61% and 6.40%. Consistent results are obtained for the other diffuser configurations.

The CVs of the three metrics measured at 100 Hz and 1 kHz with the suggested number of microphone positions are presented in Table 3. The maximum CVs of s_{rel} and σ_{SPL} are almost three times the CV of DTF when only five microphone positions are utilized, which indicates that the DTF is more robust than s_{rel} and σ_{SPL} when a small number of measurement locations are utilized. These results may result from that s_{rel} and σ_{SPL} are to quantify the spatial variation of measured acoustical quantities, and the DTF is developed to evaluate fluctuations of the reflected impulse responses in a single location in the sound field, thus being less dependent on the sound field sampling.

Table 3. The coefficient of variations (CV) of the diffuseness metrics at 100 Hz and 1000 Hz with a different number of measurement samples.

Metrics	Freq (Hz)	Number of Measurement Samples					
		5	9	12	15	20	24
s_{rel}	100	26.06%	18.73%	15.01%	9.50%	8.98%	7.27%
	1000	39.85%	24.55%	21.03%	18.79%	16.54%	12.47%
σ_{SPL}	100	34.07%	21.14%	17.59%	14.68%	12.02%	7.64%
	1000	42.76%	28.22%	17.91%	17.56%	17.31%	11.24%
DTF	100	10.54%	7.94%	7.31%	5.10%	4.45%	4.29%
	1000	6.11%	5.20%	4.11%	3.52%	3.09%	2.39%

4. Conclusions

This research work aimed to find an effective method to quantify the diffuseness of the reverberation rooms and determine the optimal number of measurement samples required for accurate spatial sampling. To quantify the diffuseness, two widely used diffuseness metrics, s_{rel}, σ_{SPL} and a recently proposed metric, DTF, was measured in a reverberation chamber with six diffuser configurations. According to the relevant standards, it was expected that the sound field would be more diffuse with more hanging diffusers or when using rotating vanes. Inconsistent results regarding the optimal diffuser configurations were provided by the three metrics, s_{rel}, σ_{SPL} and DTF. DTF showed the best correlation with varying diffuser configurations but only in the low frequency range.

It was also found that s_{rel}, σ_{SPL}, and DTF vary significantly with the number of measurement samples, especially when only a limited number of sampling points are available in lower frequencies. The maximum coefficient of variations (CV) of s_{rel} and σ_{SPL} are almost three times the CV of DTF, which indicates that the DTF is more robust than s_{rel} and σ_{SPL} as it is less influenced by the number of samplings.

As with the majority of studies, the finding of this study is subject to some limitations. Firstly, this study was carried out in one reverberation chamber. The study only investigated how to achieve acceptable repeatability of the diffuseness quantification in a reverberation chamber and did not examine the reproducibility of those diffuseness metrics over different reverberation chambers. How much the accuracy of the acoustic properties measured in a reverberation chamber is influenced by insufficient diffuseness was not investigated, either. It should also be noted that this study was carried out in a reverberation chamber without installing any acoustic sample, which prevent investigation of the "suction" effect. Additionally, the study utilized a sine sweep signal to measure impulse responses which can affect the accuracy of s_{rel} and DTF calculation in higher frequencies. Lastly, there were a limited number of diffuseness metrics used in this study.

The continuation of work described in this study could include comparing results obtained in different laboratories. More diffuseness metrics, including an isotropic-based metric, such as wavenumber spectrum [16] by using SMA, could also be applied to provide more detailed information on the sound field. Sampling the sound field using an array of fixed microphones with fine resolution measuring simultaneously looks also promising to determine the optimal number of measurement positions for more accurate diffuseness quantification with less time and labor.

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