Diffuseness quantification of a reverberation chamber and its uncertainty with fine-resolution measurements

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A Thesis
In the Department
Of
Building, Civil and Environmental Engineering (BCEE)

Presented in Partial Fulfillment of the Requirements
For the Degree of Master of Applied Science (Building Engineering) at
Concordia University
Montreal, Quebec, Canada

July 2021

CONCORDIA UNIVERSITY

School of Graduate Studies

This is to certify that the thesis prepared

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Entitled: Diffuseness quantification of a reverberation chamber and its uncertainty with fine-resolution measurements

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Science (Building Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

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Insufficient diffuseness is the major cause of poor inter-laboratory reproducibility of acoustic measurements conducted in a reverberation chamber. Many previous studies 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 quantify the diffuseness of a reverberation chamber by using the three widely used diffuseness metrics of spatial variation of sound pressure levels, the relative standard deviation of decay rates, and the degree of time-series fluctuations. The measurements were also carried out with fine resolution microphone positions and varied configurations of acoustic diffusers. With the measurement data, the minimum number of measurement samples to obtain an accurate diffuseness quantification was determined. It is shown that nine independent microphone positions are sufficient to provide the acceptable confidence interval for frequencies above 315 Hz for all three metrics. However, twenty or more microphone positions are needed for the same accuracy if lower frequencies are considered for the reverberation chamber under investigation.

Keywords: reverberation chamber; diffuseness quantification; microphone positions

Acknowledgment

Upon the completion of this thesis, I am grateful to all those who have offered me encouragement and support during my graduate study.

Firstly, I’m extremely grateful to Dr. Joonhee Lee, my supervisor, who has provided me great instructions, valuable suggestions, and continuous support with incomparable patience and encouraged me profoundly throughout my graduate study. Without his dedicated assistance and insightful advice, the completion of this thesis would have been impossible.

Also, I would like to express my sincere gratitude to all the professors who have taught me in this university and who have greatly enriched my knowledge during my studies. Their inspirational and conscientious teaching has provided me with a firm basis for the composing of this paper and will always be of great value for my future.

My thanks also go to the scholars whose academic papers have enlightened me in the writing of this paper.

Finally, I would like to extend my deep gratefulness to my family and friends, whose encouragement and support have made my accomplishments possible.

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List of Abbreviations

Abbreviation	Description
s_{rel}	The Relative Standard Deviation of Decay Rate
SPL	Sound Pressure Level
σ_{SPL}	The Standard Deviation of Sound Pressure Level
DTF	The Degree of Time-Series Fluctuations.
CV	Coefficient of Variation
SMA	Spherical Microphone Array
N_m	The number of microphone positions.

Chapter 1. Introduction

1.1. Background

Accurate measurement of acoustical materials, such as absorption coefficient and transmission loss, is crucial for all projects related to the acoustical design of architectural spaces. According to the relevant standards (ASTM C423-17 (ASTM International, 2017); ISO 354:2003 (ISO, 2003)), the random incident sound absorption coefficient needs to be measured in a reverberation room that closely approximates a diffuse sound field. The diffuse sound field requires acoustic energy distributed uniformly throughout the space (homogeneity) and the sound incidences flow in a random direction (isotropy). However, it is impossible to obtain these ideal conditions in the actual reverberation chamber. Thus, the acoustic properties measured by those standardized procedures still encounter poor repeatability and reproducibility due to the difference between the diffuse condition of the sound field (Basheer *et al.*, 2017; Scrosati *et al.*, 2020). This under- or over-estimated acoustic properties pose a huge challenge for acoustic engineers and manufacturers to compare the acoustical performance of building elements measured across laboratories.

Previous studies have proposed assorted methods for evaluating and improving diffuseness in the reverberation chamber since the 1950s (Cook *et al.*, 1955; Lubman, 1966; Schultz, 1971). These methods led to several recommendations when measuring the reverberation time. For example, fixed and rotating diffusers are strongly recommended to be installed in the reverberation chamber to obtain an acceptable diffusion (ASTM C423-17 (ASTM International, 2017); ASTM E90-09(2016) (ASTM International, 2016)). Objective quantifiers, such as the departure of the attenuation curve from exponential attenuation (Davy *et al*., 1989), the dispersion of reverberation time across microphone positions (Bartel & Magrab, 1978), the spatial uniformity of sound pressure levels (ASTM E90-09(2016) (ASTM International, 2016)), and the cross-correlation between pressures at neighboring positions (Morrow, 1971; Nélisse & Nicolas, 1997), were used to investigate the effect of different types of diffusers on the diffuseness in a reverberation chamber. Isotropy indicators such as the diffuse profile (Epain & Jin, 2016), the acoustic intensity over time and across space (Lokki, 2008), and the wavenumber spectrum (Nolan *et al*., 2018) are also proposed to quantify the diffuseness of the sound field. The major limitation of those isotropy indicators is that the equipment is still expensive and a sufficiently fine resolution of the incidence angle is required to guarantee the accuracy of measurements (Jeong, 2016).

Indirect quantifiers were also proposed to examine the diffuseness of a sound field by using the room impulse response, which has become the dominant way to measure the acoustical parameters in enclosures. These indirect quantifiers include the degree of time-series fluctuation (Hanyu, 2014), kurtosis (Jeong, 2016), and the number of peaks (Jeon & Kim, 2010). Although many metrics were investigated, no consensus has been reached on which metric can be used to characterize the diffuseness of a sound field more accurately.

Another issue of diffuseness quantification is that the sound field uniformity and incidence isotropy are often affected by several factors, such as the volume and shape of the reverberation chamber, the temperature and humidity, the configurations of diffusers and absorbers, and the number of speakers and microphones. The uncertainty analysis of sound absorption and scattering coefficient conducted by Müller-Trapet & Vorländer (2015) showed that the number of measurements and the band center frequency are the main causes of measurement uncertainties in a given reverberation chamber. Basheer *et al.*, (2017) also found that the major component of uncertainty is the standard deviation of sound pressure levels in both the source room and the receiver room across the microphone positions. Even though ISO 354:2003 (ISO, 2003) specify the minimum number of microphone positions and their spacing, Müller-Trapet & Vorländer (2015) showed that more microphone positions are needed to provide adequate precision for the absorption coefficient measurements, especially at lower frequencies.

1.2. Thesis Objectives

To address the problems stated in section 1.1, the main objective of this study is to quantify the diffuseness of the reverberation chamber using standard measurement procedures and the newly proposed metrics. The efficacy of those metrics will then be discussed by comparing the results obtained with each metric in each diffuser configuration. The results could help to revise the specifications in the corresponding standards. The second objective of this study is to investigate the effects of the number of microphone positions on diffuseness quantification and find the optimal number of measurement samples to reduce the uncertainty of diffuseness quantification.

1.3. Study outline

This paper is divided into six chapters. Chapter 1 presents the introduction to this research. Chapter 2 includes a literature review of all prior research regarding the analysis of diffuseness quantification and the minimum number of measurements required for accurate diffuseness quantification. Chapter 3 provides the details of the diffuseness metrics analyzed in this study, the experimental setup and measurement procedures for data collection, and the methodology used to determine the uncertainty of diffuseness quantification with the number of measurements. Chapter 4 covers the diffuseness quantification results and the comparative analysis between the tested metrics. The uncertainty of diffuseness quantification with an increased number of microphone positions and the minimum number of microphone positions for a given accuracy is also determined. Chapter 5 summarizes the information presented in the preceding chapters and provides conclusions, future experimental considerations, and general thoughts concerning the research.

Chapter 2. Literature review

2.1. Diffuseness quantification

A reverberation chamber is designed to approximate a diffuse sound field with a uniform distribution of acoustic energy and random direction of sound incidence. It is mainly used for standardized acoustic measurements, such as sound absorption, transmission loss, and sound power levels. However, previous studies (Basheer *et al.*, 2017; Shtrepi & Prato, 2020; Weise, 2003) have shown that inconsistency of measurement results exists not only for different chambers but also for the same chamber at different positions. This poor measurement reproducibility and repeatability might be due to the actual diffuse field conditions of laboratories (Basheer *et al.*, 2017; Whitfield, 2019).

The general practice of increasing the diffuseness of reverberation chamber includes having an irregular room shape with no parallel walls (Hanyu & Hoshi, 2012; Toyoda *et al.*, 2004), adding suspended diffusers to increase the reflection and irregularities of the room surface, and using carefully designed rotating vane to continuously shift the eigenfrequencies and incidence angles of the chamber (Bartel & Magrab, 1978; Davy & Dunn, 1988; Wang *et al.*, 2020). The sound field is assumed to be more diffused while adding diffusers (Hanyu, 2018; Jeong, 2016; Nolan *et al.*, 2018; Vercammen & Lautenbach, 2013).

Despite these efforts to achieve a sufficient diffuseness 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 (ISO, 2003) and ASTM C423-17 (ASTM International, 2017) claimed that an acceptable diffuseness in the reverberation chamber can be achieved by adding diffuser panels or rotating vanes. The standards proposed to increase the number of diffusers until a maximum absorption coefficient is obtained. However, this method was inappropriate as there is no scientific proof that the converged value is the true absorption coefficient (Jeong, 2016). Other quantifiers such as the relative standard deviation of decay rate over microphone positions from ASTM C423-17 (ASTM International, 2017), or the total confidence interval of sound pressure levels and sound absorption from ASTM E90-09(2016) (ASTM International, 2016), were also proposed to quantify the uniformity of the sound field. Bradley *et al.* (2014) 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, Jeong (2016) 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. Another metric, the degree of time-series fluctuation (DTF) was based on the time and frequency characteristics of decay canceled response in the diffuse sound field (Hanyu, 2014). 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 can be used for evaluating the effect of diffusers on the diffuseness of the sound field. This metric was later investigated by Vallis *et al.* (2015), 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. More recently, Wang *et al*. (2020) suggested that the standard deviation of squared sound pressures is a better indicator of sound field diffuseness compared with 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.

Instead of using a single-channel microphone, sophisticated spherical microphone arrays (SMA) can be used to characterize the diffuseness. Lokki (2008) 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. Epain and Jin (2016) 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.* (2018) 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 major drawback of those isotropy indicators is that the measurement equipment is expensive and often requires complicated data processing (Jeong, 2016). Moreover, The SMA cannot provide accurate estimation at lower frequencies due to the limitation of spatial resolution, nor at high frequencies because of aliasing effects (Rafaely *et al.*, 2007). Although many new diffuseness indicators were proposed, as shown in Table 1, a systematic comparison between those metrics has not been provided yet.

Table 1. Proposed methods for quantifying the diffuseness of a reverberation room

Category	Metrics	Citation	Measurement	Description
Homogeneity	The relative standard deviation of the decay curve (s_{rel})	ASTM C423-17(ASTM International, 2017)	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(2016) (ASTM International, 2016)		
	The spatial standard deviation of the reverberation time	Bartel & Magrab, (1978); J. Davy, (1979)		
	Spatial Uniformity (s_P)	Wang *et al.*, (2020)		
Isotropy	Directional Diffusivity	Gover *et al.*, (2004)	Using Spherical Microphone arrays to analyze the direction of energy flow.	The Isotropy energy from all directions means high diffuseness.
	The spherical harmonic covariance matrix	Epain & Jin, (2016)		
	Wavenumber spectrum	Nolan *et al.*, (2018)		
Indirect method	Number of peaks	Jeon *et al.*, (2015)	Analyzing the details of the impulse response.	The less fluctuation of impulse response in the early decay means higher diffuseness.
	Kurtosis	Jeong, (2016)		
	Mixing time	Prislan *et al.*, (2014)		
	Degree of time fluctuation	Hanyu, (2014)		
	maximum absorption coefficient	ISO 354:2003 (ISO 2003)	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.*, (2020)	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.

2.2. The required number of microphone positions for spatial averaging

To get an accurate estimation of the true 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 (1976) 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/(independent frequency components) to obtain a confidence interval less than ± 1.0 dB. Lubman (1971) suggested that the required sample size is 12 for ± 1 dB, and 50 for ± 0.5 dB with 95% confidence. Tichy & Baade (1974) 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 this number of samples needed for a given accuracy can be reduced by adding a rotating diffuser. However, Schroeder (1969) claimed that the equivalent number of independent measurements depends on how the variability is measured. 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 (1978) found that the total variance of reverberation time obtained with 24 positions and 98 decay each, closely equals with the one obtained with six positions and 20 decays each. Thus, they proposed that six microphone locations are enough when results under 200Hz are not needed. Warnock (1983) 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 (2015) found that the 12 measurements (as ISO354:2003 (ISO, 2003) recommends) provide poor precision 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.

Moreover, spatial correlation functions between linear quantities measured at two points in a diffuse reverberation sound field showed that the two microphones could provide independent estimates of narrow-band sound pressure levels only if they are separated by a half-wavelength of the frequency of interest (Jacobsen & Roisin, 2000; Morrow, 1971). Thus, standard ISO 354: 2003 (ISO, 2003), ASTM C423-17 (ASTM International, 2017), and ASTM E90-09(2016) (ASTM International, 2016) require that microphone positions should be at least 1.5 m apart to provide accurate systematic variations with the sample positions in the room. This is true when one is only interested in estimating a spatial average of the sound pressure level or reverberation time with a limited number of samples. However, to obtain an accurate diffuseness quantification in a reverberation room, a large number of measurements are required.

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.

Chapter 3. Methodology

3.1. Diffuseness metrics

The diffuseness metrics investigated in this study 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 (2014).

3.1.1. The relative standard deviation of decay rate

ASTM C423-17 (ASTM International, 2017), 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, are shown in Table 2. The least-square fit of the energy decay curves is used to determine the decay rate by using the formula:

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

where L_i is the average of the sound pressure levels measured at the ith decay point, M is the number of decay steps started from 100 ms to 25 dB decay, Δt is the time interval (0.1 sec in this study), d_{air} is the decay rate due to air absorption. The relative standard deviation of decay rate is then calculated using equation (2):

$$s_{rel} = s_M / d_M \tag{2}$$

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

Table 2. Maximum relative values for variation of decay rate with microphone position in the room without absorption specimen.

One-third Octave Band Center Frequency, Hz	s_{rel}
100	0.11
125	0.07
160	0.04
200, 250, 315, 400	0.03
500 to 5000	0.02

3.1.2. The standard deviation of sound pressure levels

ASTM E90-09(2016) (ASTM International, 2016) 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 and the appropriate sampling rate. 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.* (2014) showed that the sound pressure level is the dominant factor that determines whether the reverberation chamber meets the criteria. Thus, in the present 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:

$$L_R = 10log\,(\frac{1}{n}\sum_{i=1}^{n} 10^{L_{Ri}/10}) \quad (3)$$

where L_{Ri} is the sound pressure level measured at the ith microphone location, and n is the total number of measurement positions. The standard deviation of the sound pressure levels can be computed using equation (4):

$$\sigma_{SPL} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}[L_{Ri} - L_R]^2} \tag{4}$$

3.1.3. The degree of time-series fluctuations

The last diffuseness metric utilized in this research work is the degree of time-series fluctuations proposed by Hanyu (2014). This metric is based on how the normalized reflected sound energy fluctuation deviates from the Schroeder integrated decay curve, with higher values indicating more diffuse room conditions. For this metric, the decay-canceled impulse responses are firstly calculated using the following equation:

$$g(t) = \frac{p(t)}{\sqrt{E_S(t)}} \tag{5}$$

where, $p(t)$ is the impulse response, and $E_S(t)$ is the Schroeder decay curve. Then the normalized decay-canceled impulse response $h(t)$ can be obtained using the equations (6) and (7):

$$h(t) = \frac{g(t)}{\sqrt{\overline{g^2(t)}}} \tag{6}$$

$$\overline{g^2(t)} \cong \frac{1}{t_2 - t_1}\int_{t_1}^{t_2} g^2(t)dt \tag{7}$$

where $\overline{g^2(t)}$ is the average decay ratio, with the integration time $t_1$and t_2 corresponding to -5 dB and -35 dB, respectively, on the decay curve. The fluctuation decay curve is defined as a ratio of $h^2(t)$ exceeds threshold k divided by the total of $h^2(t)$ as the following equation (8):

$$Z_k = \frac{\int_{t_1}^{t_2}\{h^2(t) > k\}dt}{\int_{t_1}^{t_2} h^2(t)dt} \tag{8}$$

Lastly, the degree of time-series fluctuation of reflected sound energy can be derived by finding a threshold value where the fluctuation decay curve Z_k is equal to 0.01.

3.2. Measurement

3.2.1. Reverberation chamber and diffuseness of sound field

Measurements were conducted in the reverberation chamber of Concordia University, Montreal, Canada. The room has a rectangular shape with a volume of 152.32 m^3 (6.98 m×6.13 m×3.56 m). 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. 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 rotating diffuser and hanging diffusers are shown in Figure 1.

Figure 1. Steel rotating diffuser (left) and corrugated plastic hanging diffusers (right).

According to standard ISO 354:2003 (ISO, 2003) and ASTM C423-17 (ASTM International, 2017), to achieve acceptable diffuseness, stationary diffusers or rotating vanes are strongly recommended. The ideal stationary diffusers should have a corrugated or curved structure with low sound absorption. Additionally, they should have a mass per unit area of at least 5 kg/m^2 and the surface area of diffusers should be between 0.8 and 3.0 m^2 (one side). These standards also recommend the panels to 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 rotating diffuser was also added to investigate if the rotating diffuser can produce a better diffuse sound field than stationary diffusers. 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 3.

Table 3. 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

3.2.2. Impulse response measurement

The impulse responses of the reverberation chamber were measured using Brüel & Kjær DIRAC room acoustics software Type 7841. The measurement setup is shown in Figure 2. The sound signal produced by the Dirac system went through the amplifier Type 2734A and then radiated into the reverberation chamber evenly in all directions using Omni-Power Sound Source Type 4292-L. 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 100Hz to 5000Hz. The measurement procedure starts with a standard level calibration of the microphone and a calibration of the diffuse sound field. A Brüel & Kjær Type 4189 microphone was used for the recordings, with a sampling frequency of 48000Hz.

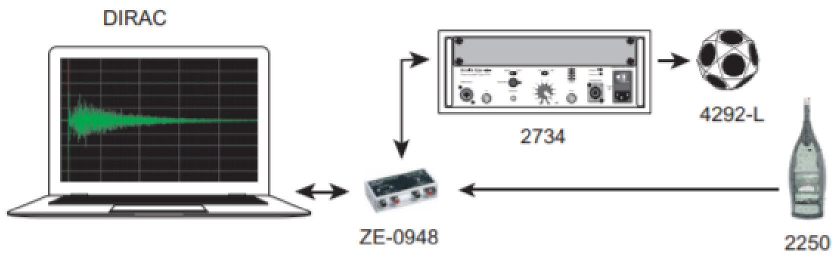

Figure 2. Impulse response measurement system

The measurement schematics are shown in Figure 3. The six diffusers hanging from the ceiling are indicated in light yellow. A rotating diffuser, with metal texture, is located in the top right corner. The acoustical source was positioned in one of the three reminding corners, at 1.67 m above the floor. Measurements were made at 120 microphone positions using a 12×11 grid and an interval of 0.4 m, as shown in Figure 4. The locations indicated in red were removed to avoid getting too close to the sound source or rotating diffuser. To include the vertical variations, for the 1st, 2nd, 3rd, 11th, and 12th columns of the measurement grid, microphones were placed at a 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 a height of two meters. The sampling coverage was selected based on the fact that 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 requirements. Corresponding decay curves were calculated using the integrated impulse response method. At each microphone position, the measurement was repeated ten times and averaged to eliminate any noise. The same measurement procedure was repeated for all the diffuser configurations described in Table 3.

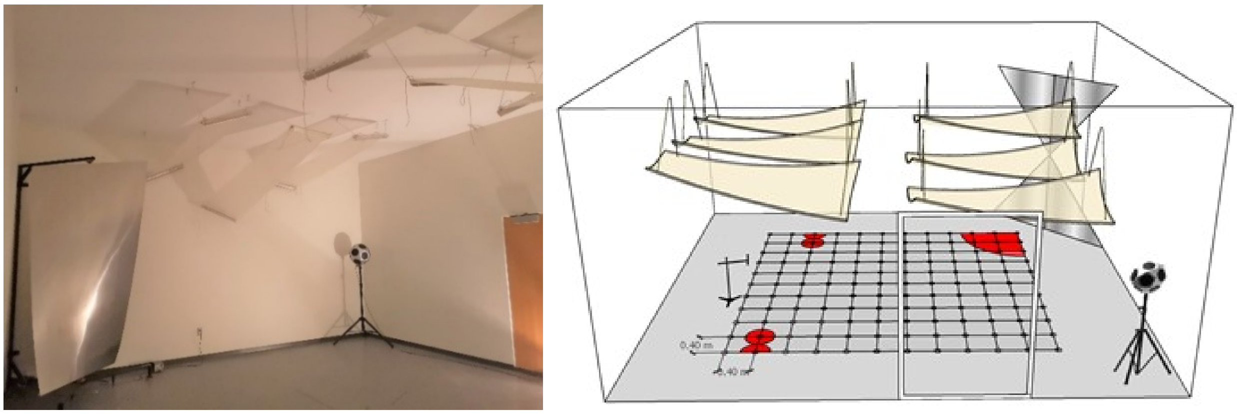

Figure 3. Schematic measurement setup at a reverberation chamber in Concordia Acoustics Lab. The diffusers hanging from the ceiling are indicated in light yellow. A steel rotating diffuser is located near the top right corner. The acoustical source was positioned in one of the three other corners, at 1.67 m above the floor.

3.2.3. Sound pressure level measurement

Pink noise was generated using the same equipment. The sound pressure level (SPL) was measured using a Type 2250 sound level meter. The measurement duration was set to 60 seconds. 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 $\pm$ 0.4 °C and the relative humidity was 40% with $\pm$ 2%.

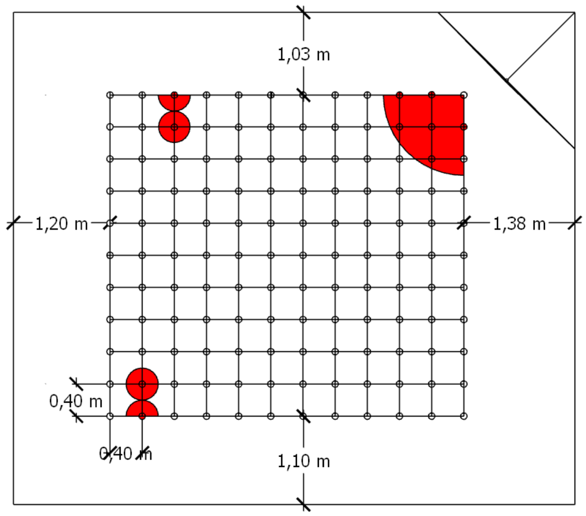

Figure 4. The measurement grid (11×12) used for the recordings. The distance between each microphone position was 0.4 m. 120 points were measured in total. Locations marked in red were removed to avoid getting too close to the sound source or rotating diffuser.

3.3. Uncertainty of diffuseness quantification

3.3.1. The confidence interval of diffuseness metrics

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 measurement is for diffuseness quantification. ASTM C423-17 (ASTM International, 2017) 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 (ISO, 2003). For the sound transmission loss measurement, ASTM E90-09(2016) (ASTM International, 2016) 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, it was not possible to use more than nine measurement positions with an inter-microphone distance of 1.5m.

To investigate whether more microphone 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 1.5m, 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 (9):

$$CI_{X,95\%} = 2 \times \left(1.96 \times \frac{\sigma_X}{\sqrt{N}}\right) = 3.92\frac{\sigma_X}{\sqrt{N}} \tag{9}$$

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

3.3.2. The coefficient of variation of diffuseness metrics

To compare the sensitivity of the three metrics with the number of microphone positions, the unitless coefficient of variations were calculated using the following equation:

$$CV_X = \frac{\sigma_X}{\mu_X} \tag{10}$$

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, which is presented in the next section, was determined using the confidence intervals and the coefficient of variations computed in each scenario.

Chapter 4. Results and discussion

4.1. Diffuseness quantification results

Figure 5 shows the relative standard deviation of decay rate (s_{rel}) measured in six diffuser configurations of the reverberation chamber using 120 measurement positions. Lower values indicate higher diffuseness for the given diffuser configuration. The red solid line in the figure shows the maximum allowable values required by ASTM C423-17. The configurations that meet the standard's requirement are the chamber with four hanging diffusers at 315 Hz and six hanging diffusers at 315 Hz and 2000 Hz. The measured values are approximately equal to the maximum allowable values specified by the standards, which are 0.03 and 0.02. In addition, adding hanging diffusers decreases the s_{rel} for frequencies lower than 200 Hz and frequencies above 800 Hz, while an unexpected increase is observed after the installation of the rotating diffuser, especially for the one-third octave bands centered at 315 Hz through 1000 Hz. The most significant discrepancies between the measured s_{rel} and the required are observed at frequencies lower than 200 Hz and frequencies higher than 4000 Hz, which suggests the sound field is less diffuse in lower frequency bands and higher frequency bands.

Figure 6 presents the standard deviation of sound pressure level (σ_{SPL}) as a function of frequency in the reverberation chamber with each diffuser configuration. Like s_{rel}, lower values indicate higher diffuseness conditions. Adding hanging diffusers decreases the σ_{SPL} for frequencies from 125Hz to 1250Hz, and the configurations with a rotating diffuser produce lower σ_{SPL} compared to those with hanging diffusers, except for frequency bands centered at 160 Hz. In general, the σ_{SPL} values are higher in lower frequencies, and decrease as the frequency increases and become flattered after 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.

Figure 7 provides the degree of time-series fluctuations (DTF) as a function of frequency measured using each diffuser configuration. The DTF quantifies the fluctuation of reflected sound energy and, thus, a lower DTF indicates higher diffuseness in the sound field. The curves measured in the empty room and the room with two, four, and six hanging diffusers have similar data shapes. Below 500 Hz, DTF decreases when the number of hanging diffusers increases, the lowest DTF values are obtained in the scenario where a rotating diffuser and six hanging diffusers were installed. At frequencies higher than 500 Hz, the number of hanging diffusers has less impact on the DTF, the diffuser configurations with a rotating diffuser produce higher DTF values compared to the scenario where only hanging diffusers were used. Furthermore, lower DTF is obtained when a rotating diffuser and six hanging diffusers were installed compared to the scenario with only a rotating diffuser.

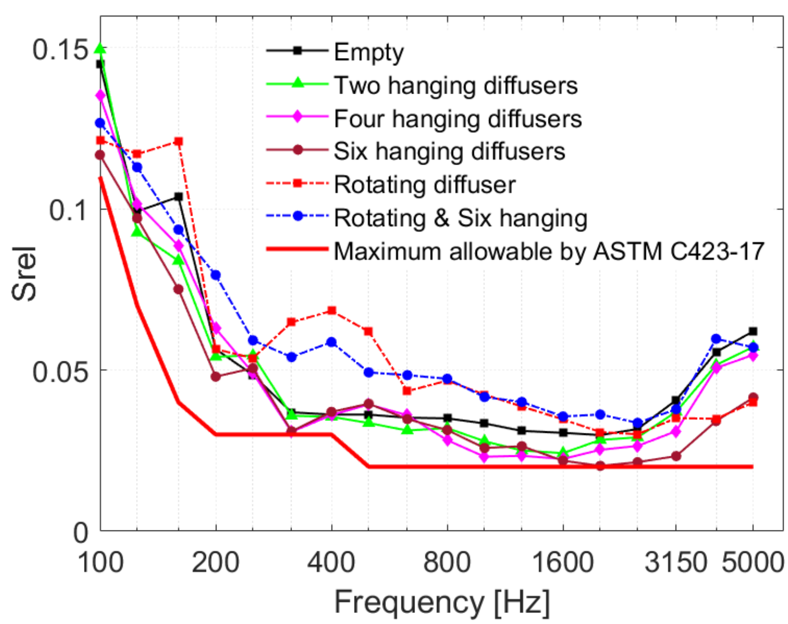

Figure 5. Comparison of the s_{rel} over 120 microphone positions measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six

hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

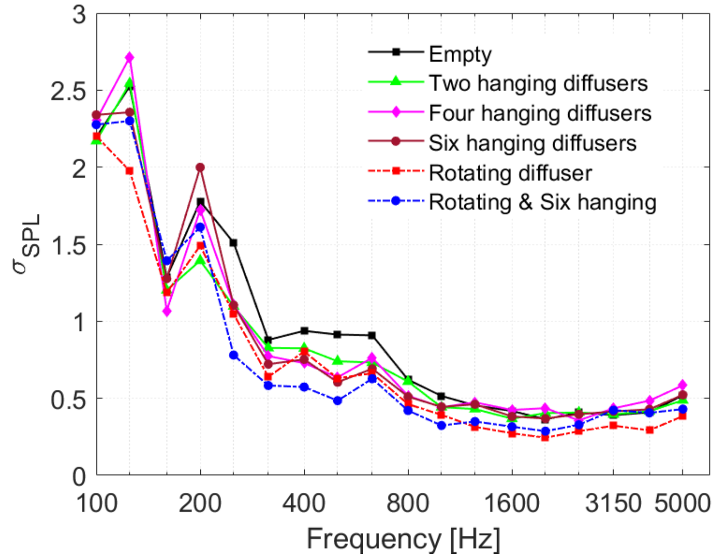

Figure 6. Comparison of the σ_{SPL} over 120 microphone positions measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

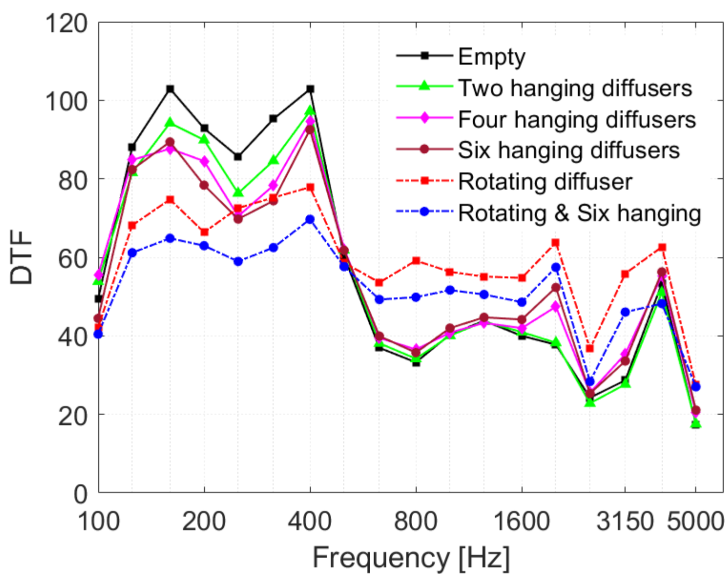

Figure 7. Comparison of the DTF over 120 microphone positions measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

The s_{rel} and σ_{SPL} exhibit similar data trends: the value of the metrics decreases with the increase of frequencies, as can be seen in Figure 5 and Figure Figure **6**. However, for the DTF, sharp peaks can be observed, especially at the lower frequency range, as can be seen in Figure 7. In addition, inconsistent results were obtained from these metrics regarding the optimal diffuser sound field. The s_{rel} shows that the optimal diffuse sound field is the room installed with six hanging diffusers, especially for frequencies below 500Hz and above 1250Hz. The σ_{SPL} suggests that for the frequency bands above 1250Hz, the room equipped with a rotating diffuser produces the most diffuse sound field. The DTF indicates that the optimal diffuser configurations for frequencies higher than 1250Hz are the chamber with two or four hanging diffusers. Based on recommendations found in ASTM C423-17 (ASTM International, 2017) and ISO 354:2003 (ISO, 2003), it was assumed that the diffuseness of the chamber would be improved by adding a rotating vane or by increasing the number of hanging diffusers. The new metric DTF was found to be in good agreement with this assumption, but only for frequency bands lower than 500Hz. For frequencies above 500Hz, however, the diffuseness of the sound field shows less improvement by increasing the number of hanging diffusers, as can be seen in Figure 7.

The comparison of s_{rel} between each diffuser configuration suggests that the sound field is more diffused with more hanging diffusers, as can be seen in Figure 5, which finding is in agreement with the standards, as well as with previous studies (Jeong, 2016; Kuttruff, 1981). However, in contradiction with earlier findings (Davy & Dunn, 1988; Tichy & Baade, 1974), the diffuseness of the reverberation chamber can be improved by adding a rotating diffuser since this study shows that adding rotating diffuser increases s_{rel} for frequencies from 315Hz to 1600Hz.

The σ_{SPL} indicates, on the contrary, that adding hanging diffusers or a rotating diffuser can improve the sound field diffuseness, as can be seen in Figure 6. The poor performance of the hanging diffusers on the reduction of uniformity of sound pressure levels for higher frequencies does not support the findings from previous research (Wang *et al.*, 2020). The discrepancy can be attributed to the limited number of diffusers installed in the room.

A noticeable disagreement was observed for the impact of the rotating diffuser on the sound field diffuseness. Although both standards ASTM C423-17 (ASTM International, 2017) and ISO 354:2003 (ISO, 2003) recommend using rotating vanes to improve the measurement accuracy of the sound absorption coefficient, this study founds that adding a rotating diffuser produces higher s_{rel} values, i.e., increases the uncertainty of absorption coefficient measurement (see Figure 5). These differences can be due to the fact that the vane might not have been placed or oriented properly to intercept all room modes. Another explanation could be that the vane is not fast enough to follow the microphone pressure variations introduced by the vane. These observations suggest using a rotating vane might be challenging when measuring the sound absorption or the sound transmission loss.

4.2. The accuracy of diffuseness quantification related to spatial sampling.

To investigate the effect of the number of microphone positions on diffuseness quantification, the three metrics, s_{rel}, σ_{SPL} and DTF, were calculated with an increased number of microphone positions over random repetitions. Figure 8 presents the diffuseness metrics calculated with an increased number of microphone positions for the one-third octave band centered at 125 Hz. The data reported in Figure 8 (a), Figure 8 (b), and Figure 8 (c) correspond to the s_{rel}, σ_{SPL} and DTF measured in the following configurations: (1) empty room with no diffusers (as a base comparison), and (2) the room with six hanging diffusers that produces the lowest relative standard deviation of decay rates. Similar results were observed in other frequencies but the fluctuations are less prominent (See Appendix A). The diffuseness metrics deviated significantly with an increased number of microphone positions and over random repetitions when using five to nine microphone positions, as suggested by the standards. The more microphone positions are selected, the lower deviations over repetitions are achieved. For example, the 95% confidence interval 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 shows similar trends but slightly smaller changes when different number of microphones were used compared with those measured in the empty room. The overlapping error bars observed for the metrics s_{rel} and σ_{SPL} , suggest the difficulties of diffuseness quantification 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 5 microphone positions were used.

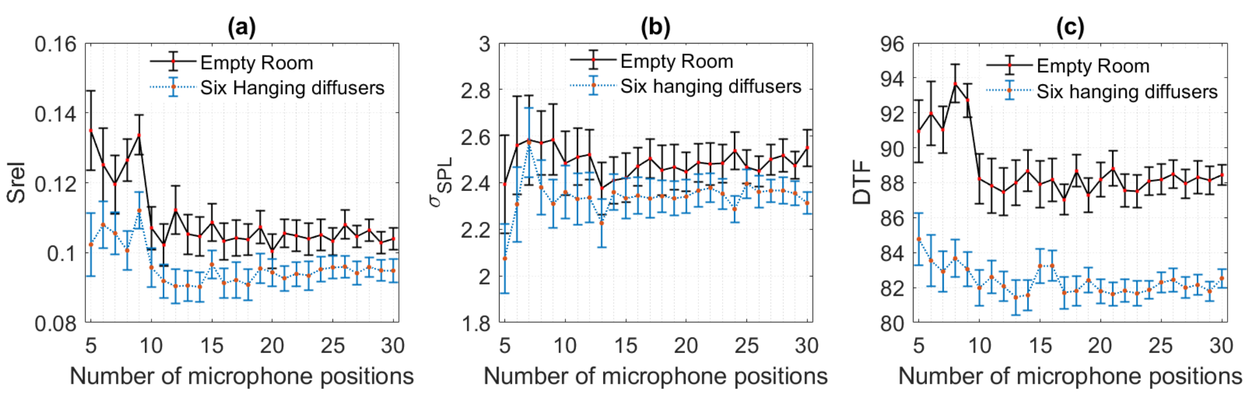

Figure 8. The s_{rel} measured in two diffuser configurations: (1) Empty room and (2) Room equipped with six hanging diffusers as a function of an increased number of microphone positions at 125 Hz. The error bar presents the 95% confidence interval of the metrics

computed using fifty repetitions of a subset of combinations randomly selected among the full data set of 120 microphone positions.

4.3. Uncertainty results of diffuseness metrics

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 9 to illustrate 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 microphone positions and the one-third octave band center frequencies. For a given maximum acceptable measurement uncertainty and the frequencies that of interest, the minimum number of microphone positions required will thus be determined. For example, to be 95% confident that the measurement uncertainty of s_{rel} is less than 0.01 for frequencies from 100Hz to 5000Hz, twenty or more measurement positions are needed for the spatial averaging. However, the number required is increased to 50 if a lower confidence limit of 0.005 is required. Additionally, if a maximum number of nine microphone positions are used with an inter-microphone distance of at least 1.5 m, as recommended by the standards, the confidence intervals limit of s_{rel} will be 0.0125 if the frequency limit is 100Hz. Similar results were obtained for the σ_{SPL}, as shown in Figure 9 (b). 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 100Hz. The number of microphone positions required needs to be increased to 20 if a maximum allowable $CI_{\sigma_{SPL},95\%}$ of 0.02 is desired for all frequencies of interests. For the DTF measurements, as shown in **Figure 9** (c). 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, 15 or more microphone positions are needed for the same accuracy if lower frequencies are taken into consideration. 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 (See Appendix A).

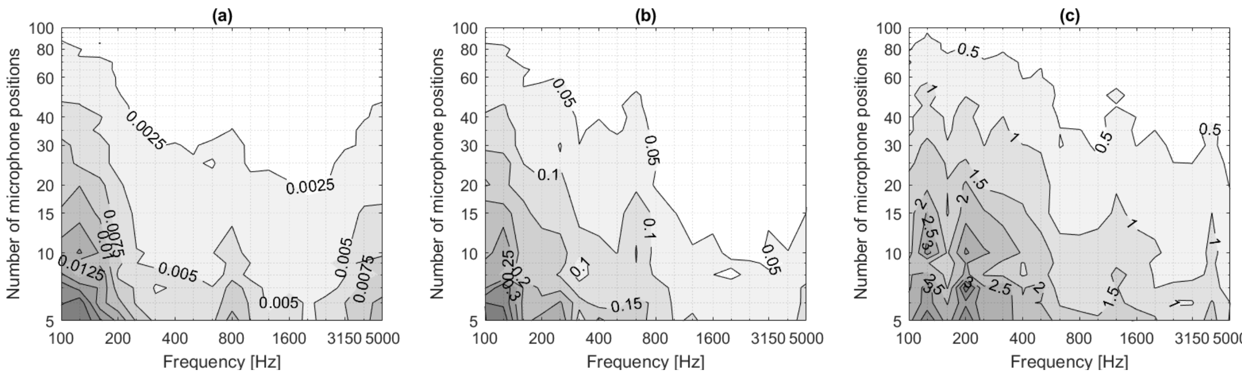

Figure 9. The 95% confidence interval of diffuseness metrics: (a) s_{rel}, (b) σ_{SPL} and (c) DTF measured in the empty room as a function of frequency with an increased number of microphone positions.

The contour plot of the coefficient of variation of three diffuseness metrics is shown in **Figure 10. The coefficient 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.**Figure 10. The DTF shows lesser variation compared with s_{rel} and σ_{SPL}, and the accuracy of diffuseness metrics increases with an increased number of microphone positions. 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. However, unlike the confidence intervals, the installation of hanging diffusers or rotating diffusers shows less impact on the variability of the diffuseness metrics compared to the mean (See Appendix B).

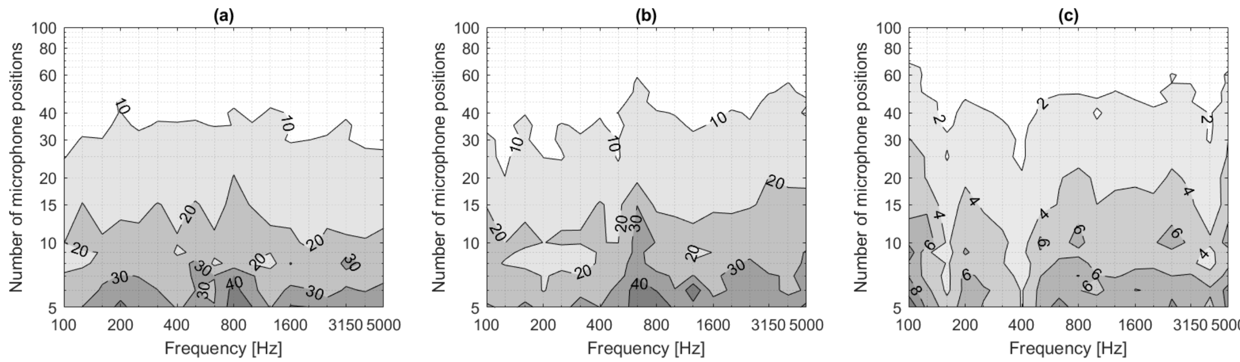

Figure 10. The coefficient of variation of diffuseness metrics: (a) s_{rel}, (b) σ_{SPL} and (c) DTF measured in the empty room as a function of frequency with an increased number of microphone positions.

The coefficient of variation of diffuseness metrics measured at 100Hz with the suggested number of microphone positions (as mentioned in Section 2.2) are presented in Table 4. It appears that the maximum coefficient of variations of s_{rel} and σ_{SPL} are almost three times the coefficient of variation 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 is utilized. These results may result from that s_{rel} and σ_{SPL} are to quantify spatial variation of measured acoustical quantities, and the DTF is developed to evaluate fluctuations of the reflected impulse responses in the sound field, and thus to be less dependent on the sound field sampling.

Table 4. The coefficient of variations of the diffuseness metrics at 100Hz with a different number of microphone positions

Coefficient of Variations at 100 Hz	the number of microphone positions					
	5	9	12	15	20	24
$\mathbf{CV}_{s_{rel}}$	26.06%	18.73%	15.01%	9.50%	8.98%	7.27%

$\mathbf{CV}_{\sigma_{SPL}}$	34.07%	21.14%	17.59%	14.68%	12.02%	7.64%
$\mathbf{CV}_{\mathbf{DTF}}$	10.54%	7.94%	7.31%	5.10%	4.45%	4.29%

Chapter 5. Conclusion

5.1. Summary

The purpose of this research work was to find an effective method to quantify the diffuseness of the reverberation rooms and to determine the optimal number of microphone positions 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 the reverberation chamber with six diffuser configurations. According to the standards (ASTM C423-17 (ASTM International, 2017), ASTM E90-09(2016) (ASTM International, 2016), ISO 354:2003 (ISO, 2003)), it was expected that the sound field would be more diffuse with more hanging diffusers or when using rotating vanes. However, inconsistent conclusions drawn from these metrics regarding the efficacy of diffusers indicate that more accurate metrics are required for diffuseness quantification.

In addition, the results showed that adding hanging diffusers will decrease the relative standard deviation of decay rates, and thus increase the accuracy of reverberation time measurements. The application of a rotating diffuser, on the contrary, will reduce the spatial variation of sound pressure levels, but increase s_{rel} especially for frequency bands from 315 Hz to 1000 Hz i.e., provides less accurate decay rate measurements for those frequencies. Therefore, unlike the recommendations from standards, the rotating vanes should be used cautiously, especially when measuring sound absorption.

It was also found that the calculated diffuseness metrics s_{rel} and σ_{SPL}, and DTF vary greatly with the number of microphone positions, especially when only a limited number of independent sampling points are available in lower frequencies in the room. The effect of the number of microphone positions on measurement accuracy suggests that 20 or more microphone positions are needed to ensure the confidence interval of s_{rel}, σ_{SPL} and DTF less than 0.01, 0.20 dB, and 2.50 for frequencies from 100Hz to 5000Hz.

5.2. Limitations

As with the majority of studies, the finding of this thesis is subject to several limitations. Firstly, random errors could happen especially when the room is equipped with a rotating diffuser because the measurements were made by using one microphone moved to multiple locations instead of measuring multiple locations simultaneously. Secondly, the results show that adding more hanging diffusers or the rotating diffuser as recommended by the standards does not improve the sound field diffuseness for specific frequencies. However, there may exist an appreciable difference between metrics when a larger number of hanging diffusers are used or if a more efficient rotating diffuser is used. Lastly, the vertical variations between measurements could also be a source of error for the optimal number of microphone positions and should be investigated in future work.

5.3. Future Research

Continuation of work described in this study could include a comparison of results obtained in different laboratories. Alternative diffuseness metrics like isotropy indicator, wavenumber spectrum (Nolan *et al.*, 2018) could also be applied to provide more detailed information on the sound field. Additionally, sampling the sound field by using an array of fixed microphones with fine resolution measuring simultaneously is also promising to determine the optimal number of microphone positions for more accurate reverberation room measurements.

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Appendix A: Diffuseness metrics with increased Nm

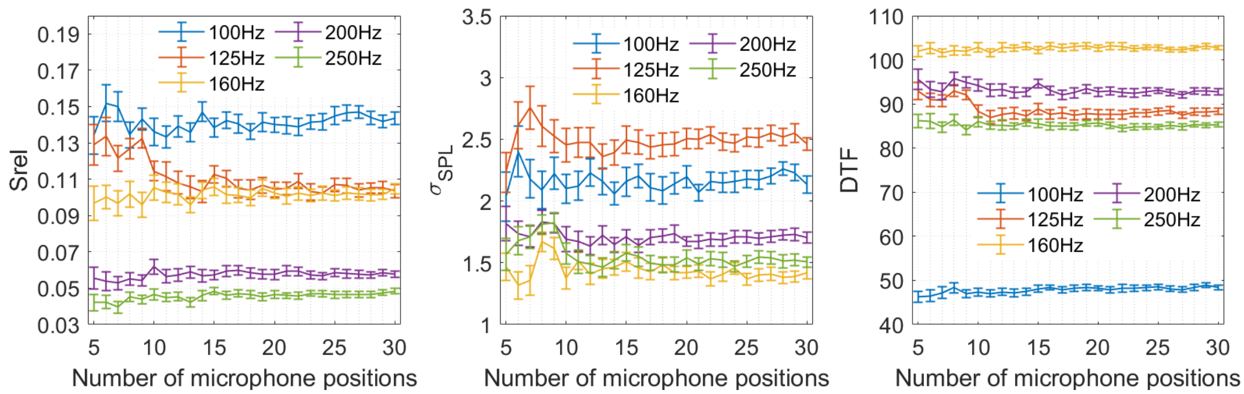

FIG. A. 1. The s_{rel}, σ_{SPL} and DTF calculated with an increased number of microphone positions in the empty room for lower frequency bands. The error bars present the 95% confidence interval of the metrics.

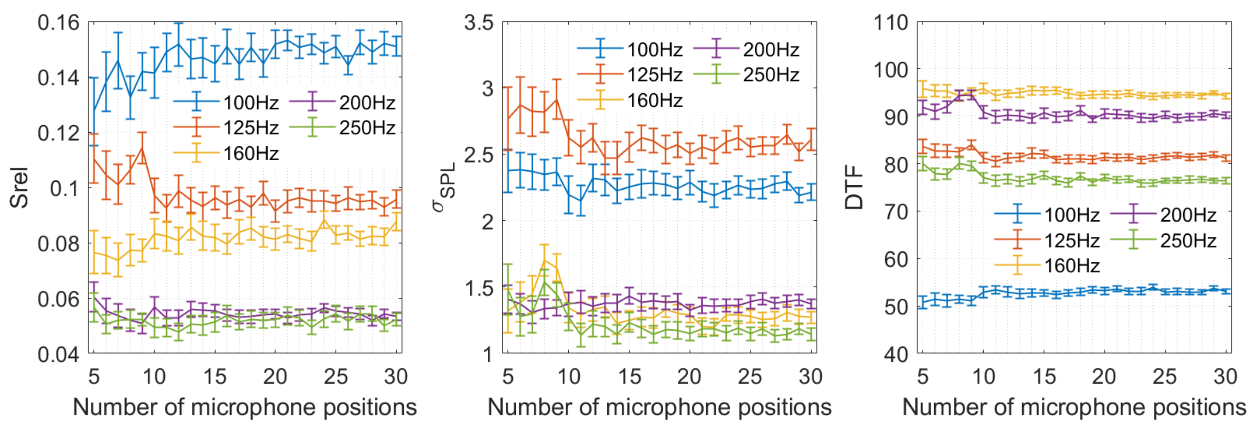

FIG. A. 2. The s_{rel}, σ_{SPL} and DTF calculated with an increased number of microphone positions in the room with two hanging diffusers for lower frequency bands. The error bars present the 95% confidence interval of the metrics.

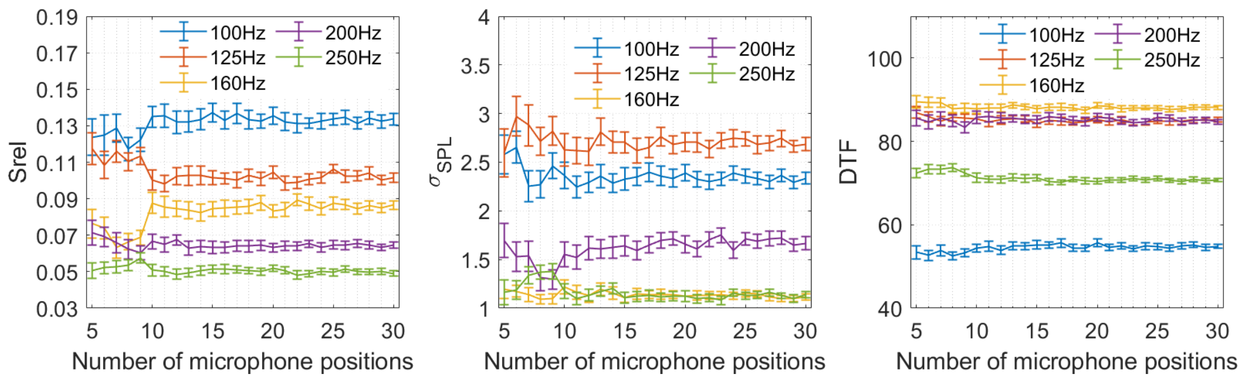

FIG. A. 3. The s_{rel}, σ_{SPL} and DTF calculated with an increased number of microphone positions in the room with four hanging diffusers for lower frequency bands. The error bars present the 95% confidence interval of the metrics.

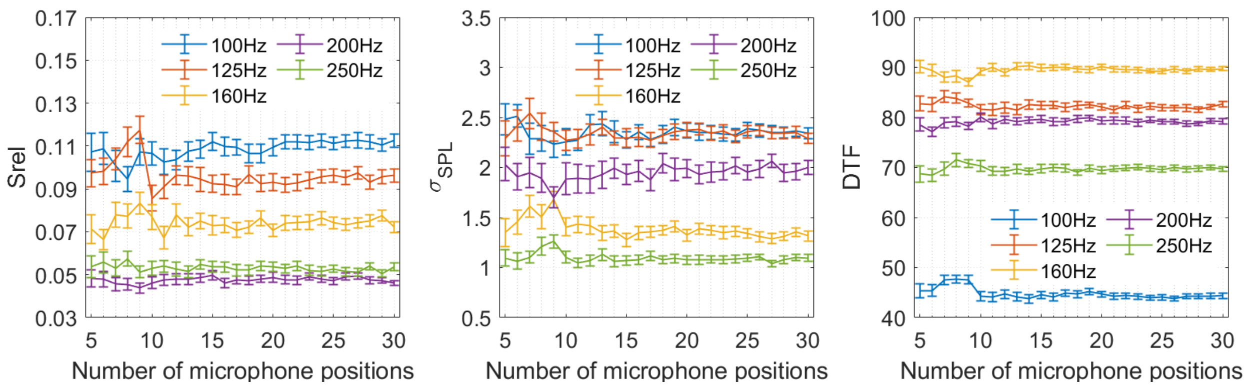

FIG. A. 4. The s_{rel}, σ_{SPL} and DTF calculated with an increased number of microphone positions in the room with six hanging diffusers for lower frequency bands. The error bars present the 95% confidence interval of the metrics.

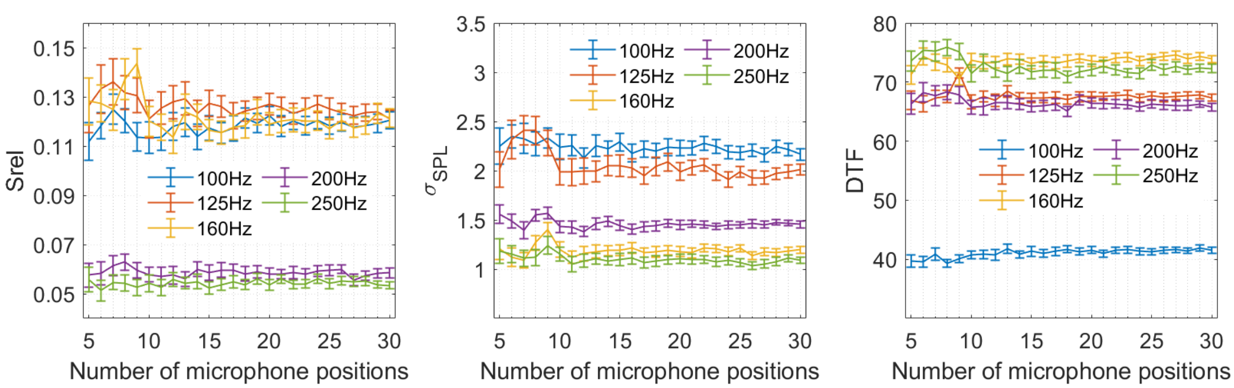

FIG. A. 5. The s_{rel}, σ_{SPL} and DTF calculated with an increased number of microphone positions in the room with a rotating diffuser for lower frequency bands. The error bars present the 95% confidence interval of the metrics.

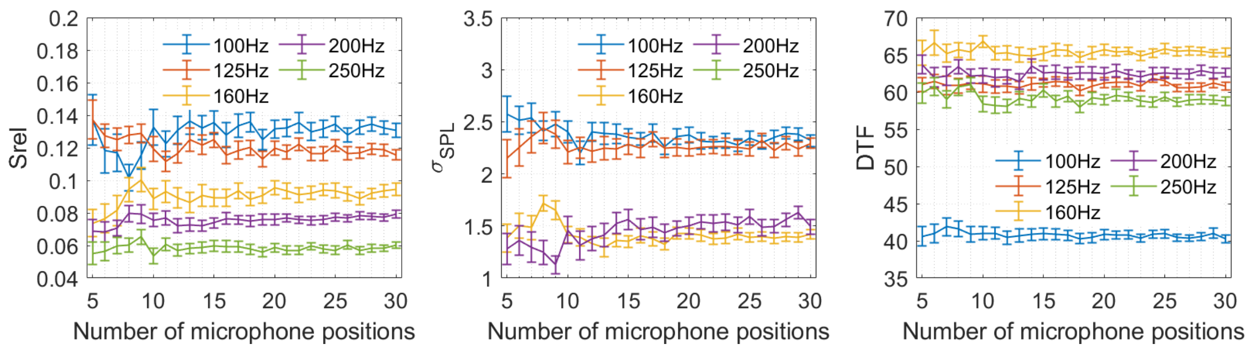

FIG. A. 6. The s_{rel}, σ_{SPL} and DTF calculated with an increased number of microphone positions in the room with a rotating and six hanging diffusers for lower frequency bands. The error bars present the 95% confidence interval of the metrics.

Appendix B: Confidence interval of diffuseness metrics with increased Nm

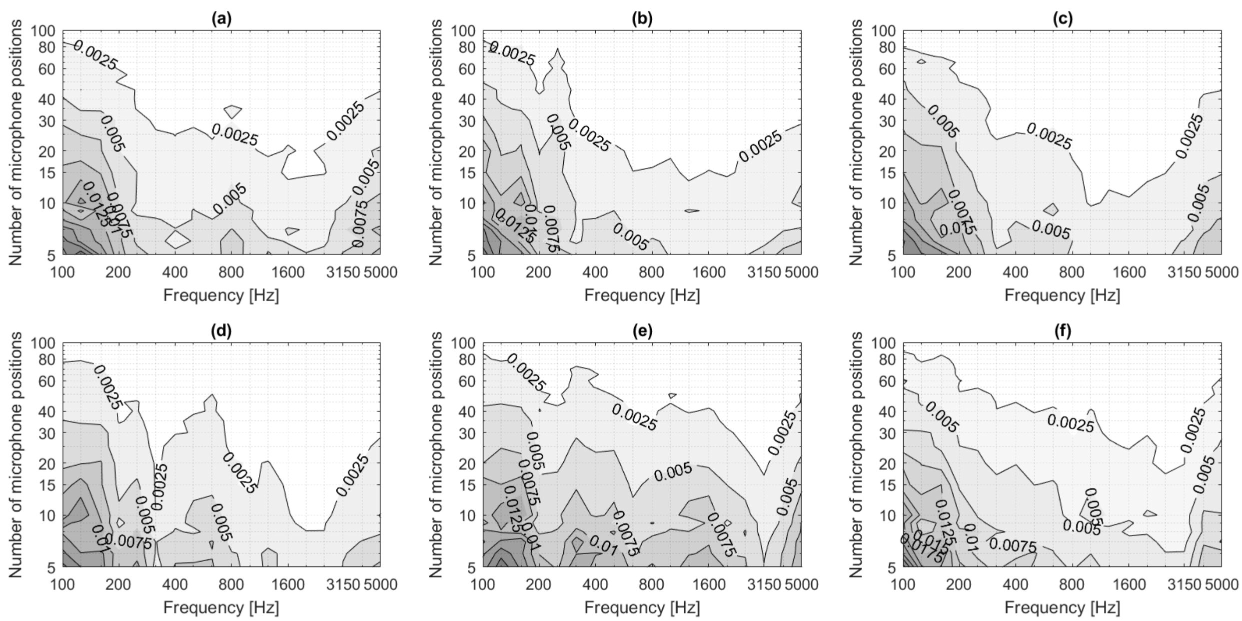

FIG. B. 1. The comparison of $CI_{s_{rel},95\%}$ measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

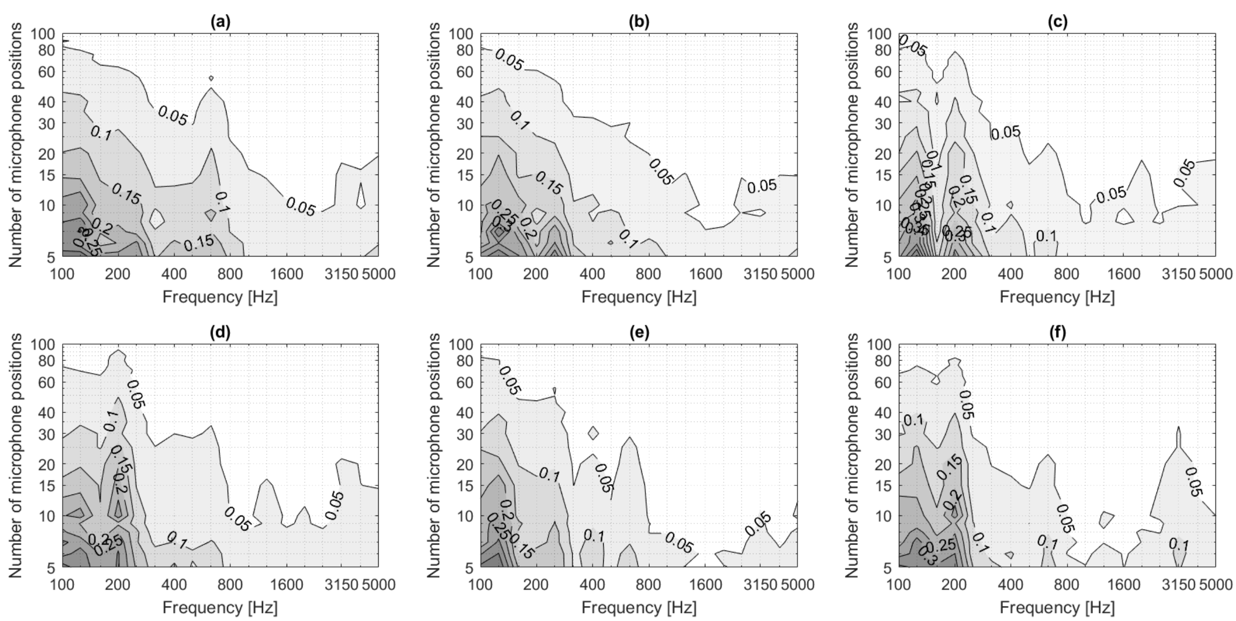

FIG. B. 2. The comparison of $CI_{\sigma_{SPL},95\%}$ measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

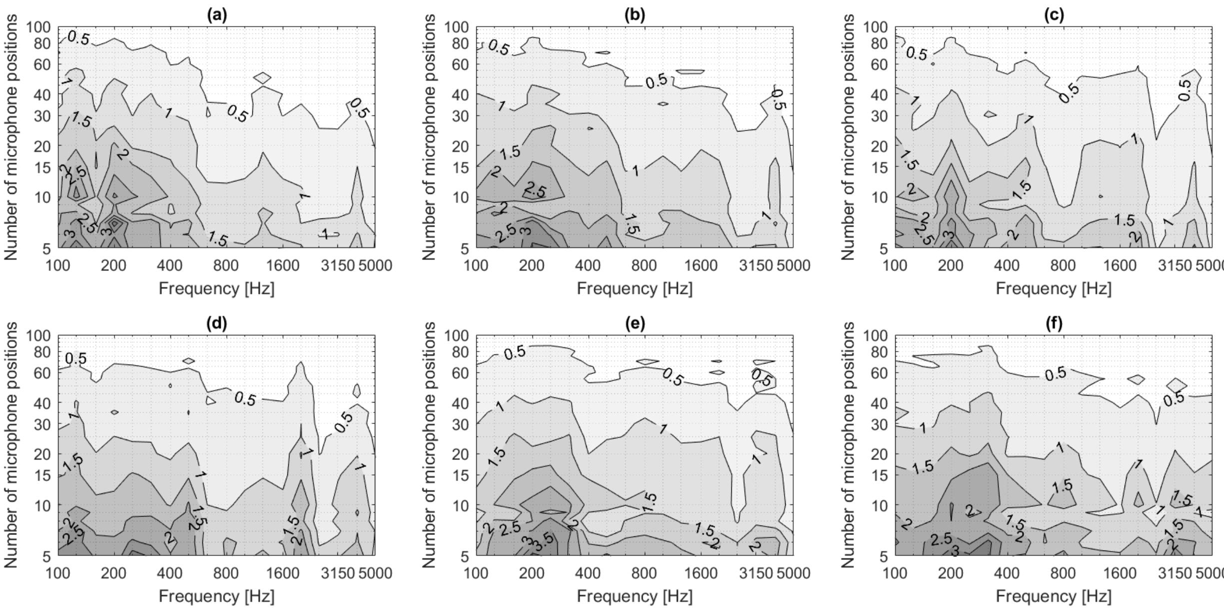

FIG. B. 3. The comparison of $CI_{DTF,95\%}$ measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

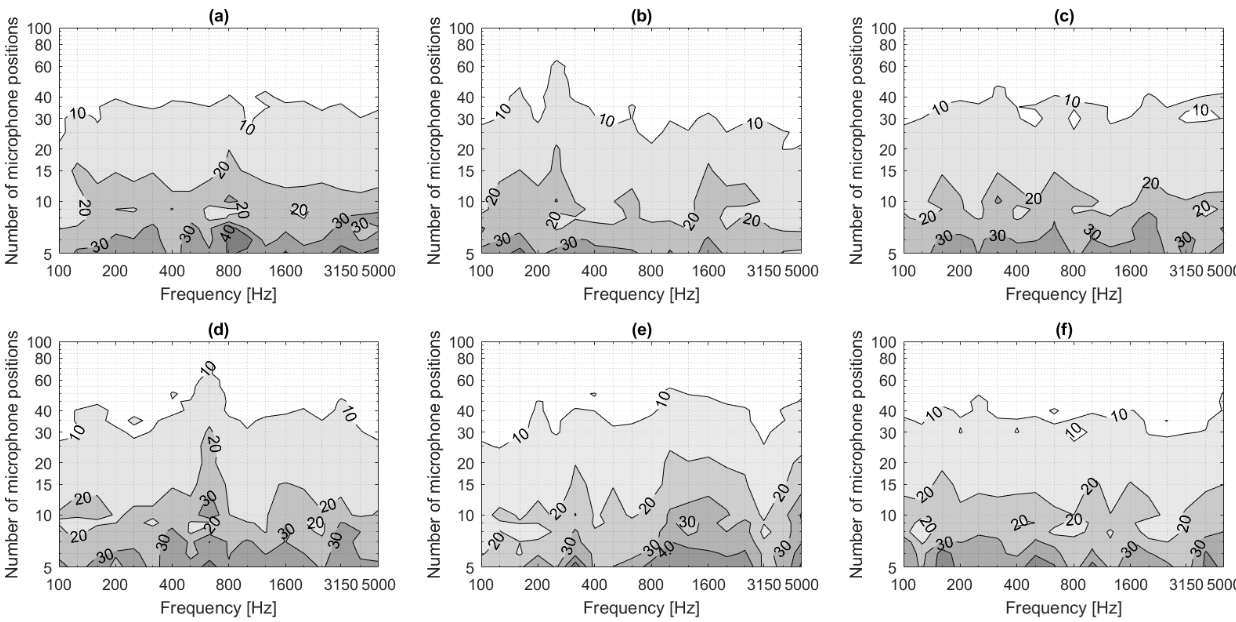

FIG. B. 4. The comparison of the CV of s_{rel} measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

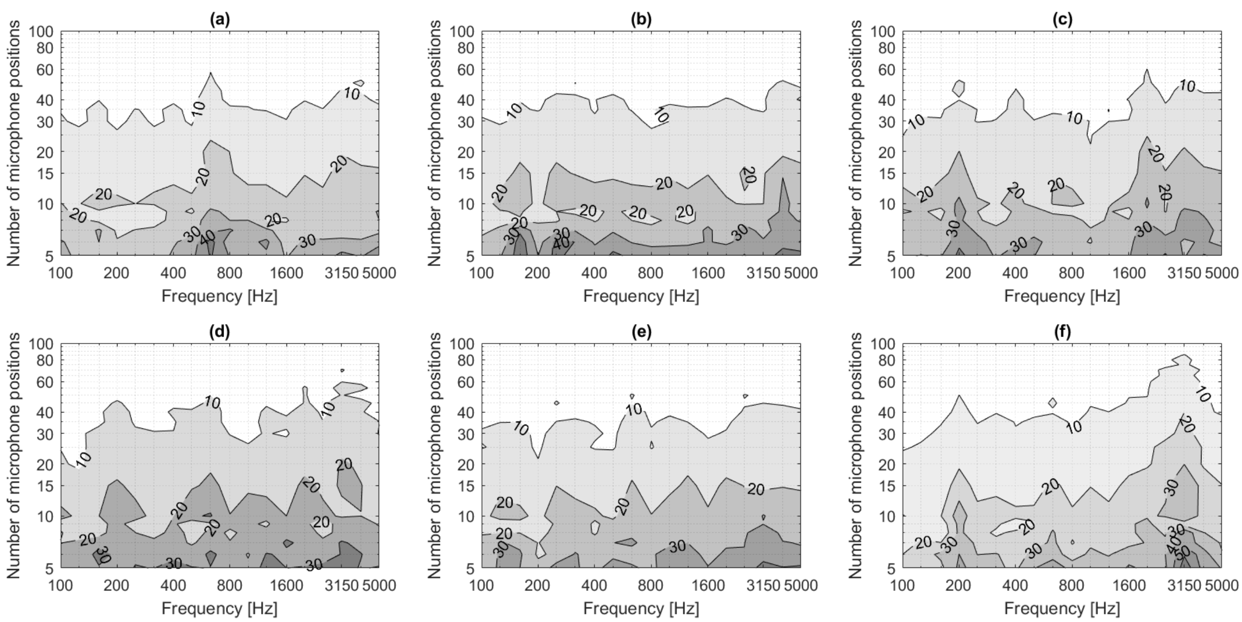

FIG. B. 5. The comparison of the CV of σ_{SPL} measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.

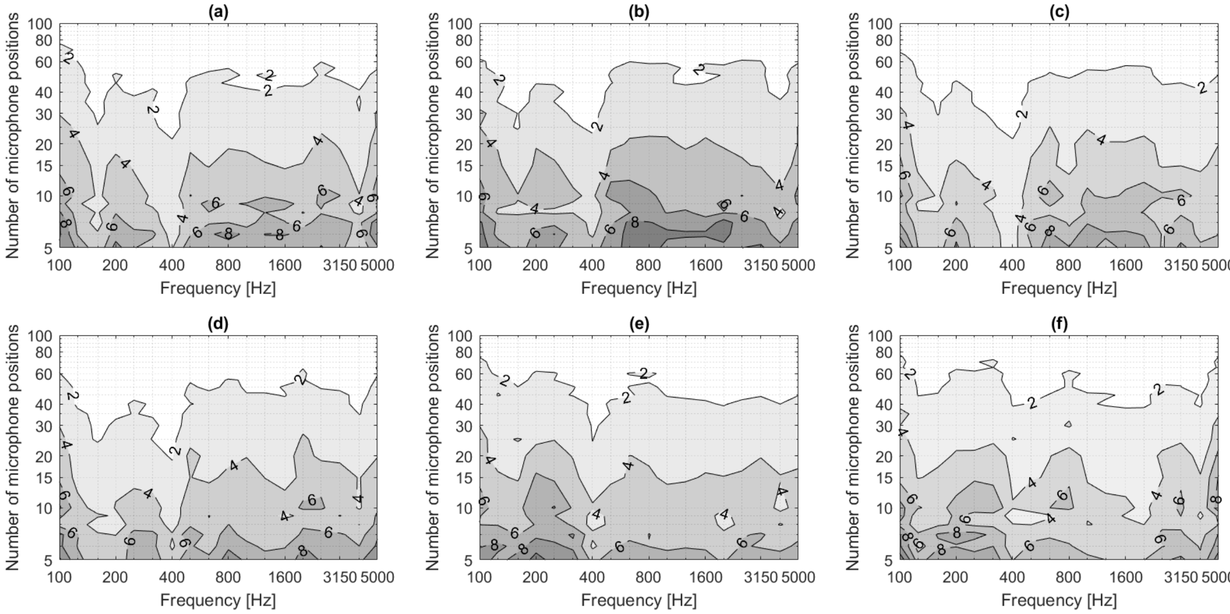

FIG. B. 6. The comparison of the CV of DTF measured in six diffuse conditions: (1) Empty, (2) Two hanging diffusers, (3) Four hanging diffusers, (4) Six hanging diffusers, (5) Rotating diffuser only, and (6) Rotating diffuser & six hanging diffusers.