Difficulties in comparing diffuse sound field measures and data/code sharing for future collaboration

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Summary
Although there have been a number of measures for quantifying the required diffuseness condition in reverberation chambers, each indicator has been limitedly validated in the authors' laboratory setup or a couple of chambers more. Moreover, it is less common to compare the acoustics of reverberation chambers. In this paper, diffuseness measures and required raw data to calculate the measures are summarized. Furthermore, some considerations for data/code sharing methods for inter-chamber comparisons are discussed. The collected reverberation chamber datasets and software will facilitate to compare the effectiveness of traditional diffuseness measures and to test newly proposed measures for diffuse sound field.

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1. Introduction

Acoustics in reverberation chambers is of utmost importance for standardized measurements of important acoustical quantities, namely, sound absorption [1], transmission [2], scattering [3], and power [4]. However, the reverberation chamber acoustics indeed differs tremendously from one chamber to another and we still do not know if we can make "sufficiently diffuse" sound fields in reverberation chambers. Many researchers derived theoretical frameworks and developed objective measures, each of which has been validated in a limited number of settings/chambers. A thorough validation of different diffuseness metrics in a number of reverberation chambers has not been reported yet. This is mainly due to limited access to the experimental data in the reverberation chambers and difficulties implementing others' metrics. The major consequence of lack of such thorough validations is that people have difficulties figuring out which measures/theories work well or not well in which conditions. The researchers in this field need to be more cooperative to move forward, so we present some ideas that could facilitate the collaborations and a large scale validation.

The main problem related to the reverberation chamber is a poor reproducibility of the measured quantities [5,6], and the ultimate end goal is to achieve reasonably similar values of the measured acoustic quantities in all "qualified" reverberation chambers. Developing diffuseness metrics are basically extracting important features for ensuring sufficiently diffuse sound fields in existing and future reverberation chambers. We can use the metrics to qualify/disqualify reverberation chambers and also use them to get insight on how to further improve diffuseness.

The ideal combination is that diffuseness measures should be *physics*-based and validated through *big datasets* of experiments in full scale reverberation chambers. Many ideas have been suggested over the last 50 years, but there is yet no consensus on reverberation chamber designs and how to quantify diffuseness. We are living in the era of big data, and we could easily share a large collection of reverberation chamber data in different formats, most likely in the form of impulse responses or something advanced to identify the important trends and hidden patterns, and valuable information. This paper revisits previous measures to figure out which raw data to share for traditional

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and newly suggested measures for a large scale validation. This paper focuses on diffuseness quantification in reverberation chambers (leaving out performance halls, which also need sufficient diffusion) mainly for sound absorption coefficient measurements according to ISO 354. The perceptual aspect of how a diffuse field should sound, e.g., Ref. [7], is not discussed in this paper.

2. What to be investigated in chambers

When a reverberation chamber is built, many people simply look at the statistics of the sound pressure variations in the room, which probably is not the best way to quantify the room. The sound pressure distribution depends not only on the room, but also the source position. Typically only a few source positions are tested. This assumption of a spatial uniformity is not rigorously needed for the main use of the chambers, i.e., measurements of sound absorption, transmission, and sound scattering. A more fundamentally important property of diffuse sound field is isotropy, uniform distribution of sound incidence. Some have suggested isotropic metrics, particularly estimating the net intensity over time in a steady state condition [8,9]. Note that the net intensity is the net flow of sound including the incident and reflected components, which is also highly affected by the specimen to be measured in the chamber.

Assuming that what we wish to measure in reverberation chambers is the *random incidence* acoustic quantities, what we strictly need is a *uniform* distribution of the *incident* intensity. However, the *incident* intensity is normally not easy to directly measure, as it is difficult to separate the incident from reflected components off the surface of interest. One possible way to separate the incident from reflected wave has been done using acoustic holography techniques, e.g., [10]. Readers also bear in mind that there are two types of isotropy to be quantified, full spherical isotropy in the sound field [11,12] and hemi-spherical isotropy on the surface [13-15]. For the standardized acoustic measurements such as ISO 354 [1], the latter condition should be fulfilled.

The metrics suggested do not always make a clear distinction between diffusion in a stationary sound field and sound field diffusion in the decay process. Therefore, the term diffuse field implies too many different aspects [13], so great care should be taken when using this term, and better to choose the more precise wordings and explanations.

3. Problems of suggested metrics

We do not yet have a consensus on which metric(s) will be most useful to quantify the reverberation chambers. In addition, most metrics do not have a limit value as a criterion of being diffuse enough for standardized measurements in reverberation chambers. The popular properties of diffuse sound field investigated are (1) spatial uniformity of sound pressure, e.g., see [16], (2) spatial uniformity of reverberation time [17-19], (3) linear (or exponential) decay curves [20-21], (4) spatial correlation function [16, 22-24], (5) zero net intensity caused by a uniform distribution of net intensity components [8,9], (6) higher order statistics, [25-29], (7) amount of fluctuations along the decay trend [30-33].

The first and foremost problem is that most of the listed metrics have been validated only in limited laboratories or limited diffuser settings in a single chamber (or even with simulated impulse responses and measurements in a scale model) with limited variations of diffusers and absorbers. Therefore, with such limited experimental evidence, one cannot confidently set a limit for the suggested measures. As far as the authors understand, Schroeder was probably the only one who confidently set his own criterion for such metrics (we know that he changed his criterion from 10-fold overlap [34] to 3-fold overlap [35]), which probably add extra value to the Schroeder frequency and therefore most popular to use.

Secondly, different conclusions are drawn from different diffuseness measures. One interesting example is Bradley and co-authors' study, which tested three existing measures specified in the standards with various boundary diffusers in one scale model, concluding that maximum absorption coefficient, the relative standard deviation of decay rate, and the total confidence interval show contradictions in the conclusions from each quantifier [36]. This means one chamber could be qualified by one indicator, but not by another indicator, and vice versa, see Fig. 1. Another interesting example was reported, where using three different measures, namely, the spatial uniformity of sound pressure, the zero resulting intensity, and the coherence between measurement positions, only slight changes could be observed in the low frequency range. They concluded that the only diffuseness measure was the absorption coefficient according to ISO 354 [37].

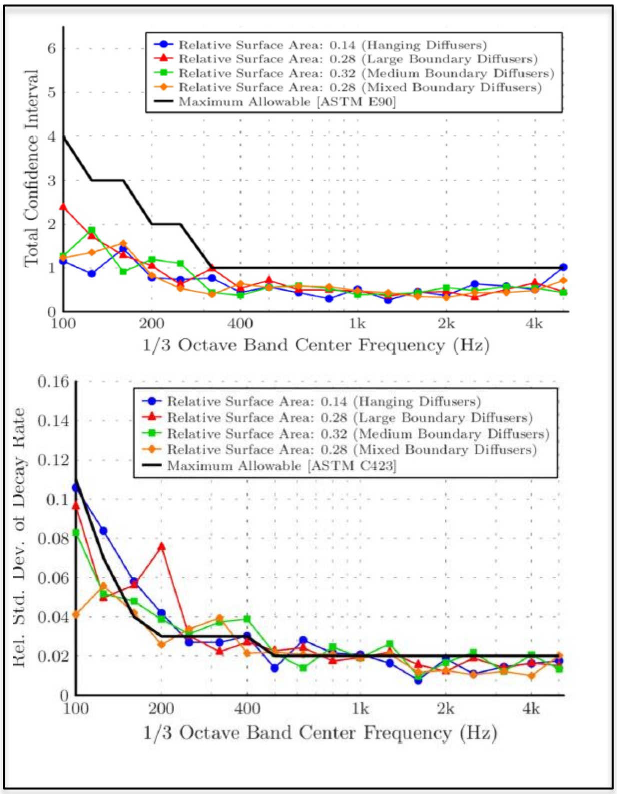

Fig. 1 All chambers are satisfactorily diffuse by the total confidence interval (upper) but all chambers are disqualified by the relevative standard deviation of decay rate (lower). From [36]

To thoroughly check the usefulness of the diffuseness measures, we should share our knowledge, software, and the experimental data.

So far, most measures are based on room acoustic parameters listed in ISO 3382 [38] and impulse responses at random positions. Thanks to the advances of array measurement techniques and signal processing, we could investigate/reconstruct the sound field more thoroughly with reasonably small reconstruction errors in certain frequency ranges [12]. These techniques require more spatial information of the sound field than randomly sampled impulse responses. Therefore, we need to discuss what to be measured in reverberation chambers for potential advanced diffuseness measures and share in future collaborations.

Spherical harmonics has been a useful tool to understand the directional uniformity of sound propagation in rooms and sound field reconstruction. Hence, several authors have investigated the use of a spherical harmonics basis for describing sound field diffusion. Ebeling [39] proposed a multiple expansion of the pressure correlation function expressed in the spatial frequency domain, leading to a measure for spatial

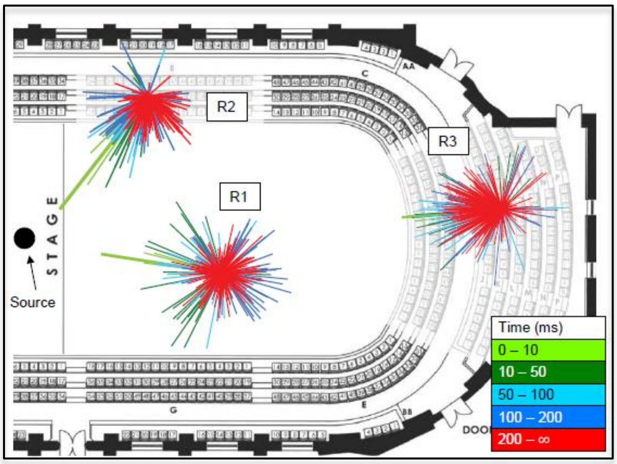

Fig. 2 IRIS measurement [42]

diffusivity. Pulkki [40-41] used spherical harmonics signals to estimate the directionality of the sound field as the ratio of the active sound intensity to the acoustic energy density. More recently, Nolan et al. [11] proposed to use a spherical harmonic expansion on the wavenumber spectrum, the underlying hypothesis being that in a perfectly isotropic sound field, the wavenumber spectrum is rotationally symmetric.

Recently, IRIS was released from Marshall Day Acoustics [42], which can measure B-Format impulse responses. Two promising ideas from B-format impulse responses are the directional energy ratios in the Cartesian coordinate and reverberation time ratios along the three orthogonal directions. Eventually more microphones will be needed to capture the higher order components, but currently the B-format data seem to be a good compromise between the performance and commercial availability.

4. Categorization of measures

Different raw experimental data are needed to calculate different diffuseness metrics. Recently suggested metrics require more complicated datasets with array microphones. It is agreeable that impulse responses are such good raw data, but not enough for extracting directional properties of sound propagation in rooms when they are randomly sampled in space. There are five categories in terms of the raw data needed.

4. 1. Parameter-based measures

There are diffuseness measures based on room acoustic parameters and noise levels. The most known measures are the standard deviation of the noise level sampled at multiple random positions

[16] and the diffuse field factor being the standard deviation of T_{20} or T_{30} [17-19].

4. 2. Impulse response-based measures

Many measures belong to this category, which require multiple impulse responses sampled in the central area of reverberation chambers. Bearing in mind that what we need a well distributed incidence of sound onto a specimen, it is reasonable to question if the impulse responses measured far from the specimen can contain meaningful changes in the incident intensity distribution on the sample. In other words, the impulse responses in the central space could be sensitive enough to capture the acoustic changes near the sample.

Hanyu suggested the idea of decay-cancelled impulse response to quantify the degree of fluctuation in impulse responses [30]. In general, the main difficulty of using impulse responses is that it decays over time, unlike the frequency-response functions. Hanyu assumed that the energy decay is always exponential, e.g., Sabine's formula. Interestingly, a similar idea was suggested by Jeong et al., but using the instantaneous slope in the decay curve because perfectly exponential decays will never occur in any reverberation chambers and could also artificially amplify the tail of the impulse response in non-diffuse conditions with multiple decay slops [31]. Sakuma and Eda compared the two methods using simulated impulse responses [33].

One thing to note is that the main problem behind the ISO 354 is the use of the diffuse field theory, namely Sabine's equation, in highly non-diffuse conditions when most absorption is concentrated on one large surface in the reverberation chamber. Such diffuse field simplifications/assumptions should be avoided as much as possible when quantifying the degree of diffusion in reverberation chambers.

Higher order room acoustic parameters have been suggested as they could capture diffuseness changes more (but not too overly) sensitively compared to low order statistics, e.g., mean and standard deviation. Kurtosis is one of the higher order statistics that has been investigated by several authors. Kurtosis becomes larger when the evaluation range for kurtosis contains extreme events, e.g., direct and strong early reflections [26,28,43,44], see Fig. 3. The sensitivity rating quantifies two different impulse responses with a slightly changed source position, which is based on the concept of acoustic mixing [25].

4. 3. Intensity-based measures

Del Galdo et al. suggested an energetic analysis of diffuseness based on STFT in a microphone array setting [8]. Nolan et al. also visualize the net energy flux in a reverberation chamber with and without an absorber sample based on experimental data suing a spherical array with 64 microphones [9], see an example in Fig. 4.

4. 4. Array-based measures

Several methods have been proposed for characterizing diffuseness based on a set of measured microphone signals. Gover et al. [45] estimated directional impulse responses using a spherical array beamformer to evaluate the distribution of acoustic energy arriving to the array from different directions.

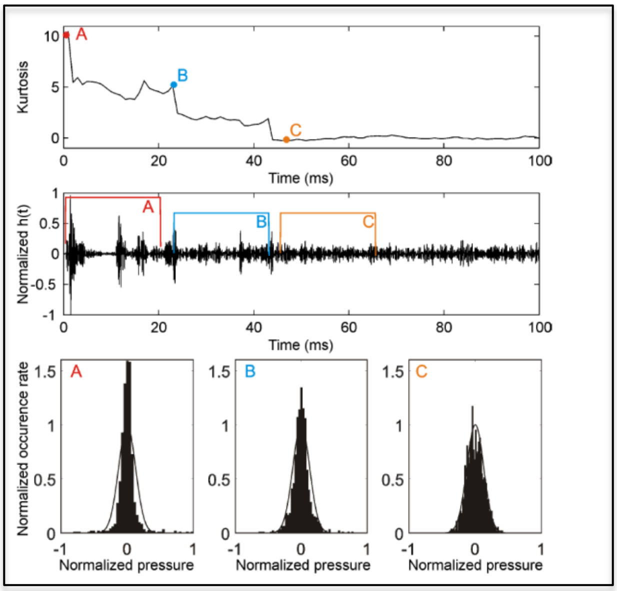

Fig. 3. Kurtosis exmaple from [26]

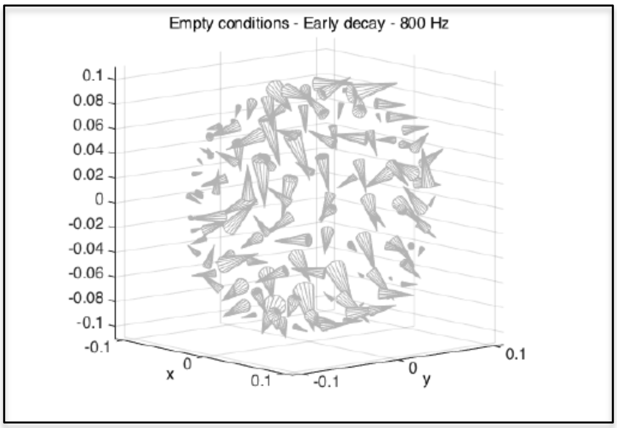

Fig. 4. Reconstructed intensity in an empty reverberation chabmer from [9]

Epain and Jin [46] analyzed the spherical harmonic covariance matrix to estimate diffuseness arising from the presence of multiple uncorrelated sources. More recently, Nolan et al. [11] proposed an array-based method for evaluating isotropy in enclosures, based on an analysis of the wavenumber spectrum in the spherical harmonics domain. Because the spherical harmonic expansion is performed on the wavenumber spectrum (rather than on the recorded pressure signals directly), this method, as opposed to Refs. [45,46], is not restricted to measurements with a spherical array or other geometry (valid for uniform or random spatial sampling). Yet, other measures using spherical microphone array processing have been proposed that consist of measuring the acoustic intensity over time [40,47].

4. 5. Frequency response statistics

It is important to remember that Schroeder summarized statistical parameters of the frequency response curves of large rooms in 1987 [48], which was translated from his early German paper. This is a great piece of work, and very inspiring. In the frequency domain, the Schroder frequency suggested in [48] is the most widely-used parameter to justify the use of statistical approaches for sound field based on the modal overlap. Note that these ideas in the frequency response statistics cannot be directly adopted in the impulse response statistics, as the impulse response decay over time unlike the frequency responses.

5. Data Sharing

Open science, data sharing, software sharing is the future of science [49]. Too few findings are successfully reproduced in science, e.g., 6 out of 53 studies in basic cancer biology have been reproduced [50] as investigators fooled themselves due to a poor understanding of statistical concepts [51]. However, scientists disagree about how much and when they should share data, and they debate whether sharing it is more likely to accelerate science and make it more robust, or to introduce vulnerabilities and problems. Despite complications and concerns, the upsides of sharing can be significant. For example, when information is uploaded to a repository, a digital object identifier (DOI) is assigned. Scientists can use a DOI to publish each step of the research life cycle, not just the final paper. In so doing, they can potentially get three citations — one each for the data and software, in addition to the paper itself [49].

Although there is a time cost associated with uploading and organizing raw data, it isn't hugely difficult to share data. Online repositories such as FigShare or Zenodo make it increasingly easy to deposit scientific content for widespread consumption. More than 400 virtual communities have formed to share data, software and documented workflows so that a user can deploy them straight away, says Tim Smith, who oversees collaboration and information services at Zenodo [49].

For data sharing, there is a good guide for public access to research data [52]. The advantages of data sharing are well listed in [53]. Our initial suggestions are to share the followings for studing the acoustics in reverberation chambers:

- Chamber size, diffusers, equipment used.
- Impulse response database (empty and with diffusers) – to see a relative change from the empty to the chambers' default setting.
- Impulse responses with a reference absorber being installed.

In relation to data sharing, there are unsolved problems. There is no clear answer to the following questions on what is the most appropriate mechanism to ensure credit is given to those individuals who have participated in the original data collection? Should one or all of the authors of the original investigation be offered authorship in the reanalysis, or at least acknowledgment, or would this taint the credibility of the reanalysis? Should the original authors have no role in authorship but be expected to assist the individuals in the reanalysis if questions arise during this process? Should there be a fixed time after study conclusion or primary publication during which period there would be a moratorium on publications by investigators other than the original researchers? Should there be an independent and neutral group that determines the appropriateness of requests for the data? These questions are too hard to answer in this paper but could be discussed during the conference.

6. Conclusions

With the current knowledge, we cannot assure which diffuseness measures can quantify which aspects of diffuse sound field. By sharing data and software, we can cross-check the suggested measures in various full-scale reverberation chambers, which helps set a limit value for the suggested measures. Many measures require impulse responses as raw data, so sharing impulse responses in reverberation chambers will be the first step, but other advanced simulations or experimental results with microphone arrays could be useful for future measures to quantify the isotropic condition.

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