Diffuse sound field: challenges and misconceptions

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ABSTRACT

Diffuse sound field is a popular, yet widely misused concept. Although its definition is relatively well established, acousticians use this term for different meanings. The diffuse sound field is defined by a uniform sound pressure distribution (spatial diffusion or homogeneity) and uniform incident intensity distribution (directional diffusion or isotropy). In practice, reverberation chambers are assumed to be acoustically diffuse, and important acoustic quantities measured in there, i.e., sound absorption, scattering, transmission, and power, etc. However, the measured quantities vary tremendously in different chambers because the chambers are non-diffuse in variously different ways. Therefore, good objective measures that can quantify the degree of diffusion and potentially indicate how to fix such problems in reverberation chambers are needed. Acousticians often blend the concept of mixing and diffuse sound field. Acousticians often refer diffuse reflections from surfaces to diffuseness in rooms, and vice versa. Subjective aspects of diffuseness have not been much investigated. Finally, ways to realize a diffuse sound field in a finite space are discussed.

Keywords: Diffuse sound field, I-INCE Classification of Subjects Number(s): 73.3

1. INTRODUCTION

Diffuse sound field is a central assumption behind important standard acoustic measurements, simple predictions, and theoretical derivations. However, this term has been used for different meanings in different contexts, yielding quite some confusions and misconceptions. Therefore, this paper will address frequently held misconceptions. Furthermore, the major challenges related to the diffuse sound field are discussed.

2. DIFFUSE SOUND FIELD

2.1 Definition of diffuse sound field

The widely accepted definition of a perfect diffuse sound field is that the sound pressure should be uniform at any points (spatial diffusion or homogeneity), and that the incoming energy flow should be isotropic from all possible directions (directional diffusion or isotropy) (1). Ideally both requirements should be fulfilled, but in many cases, only either of the definitions is needed.

2.1.1 Homogeneity

There are certain cases that strictly require a homogeneous sound field in terms of the pressure level. For sound power measurements in reverberation chambers, e.g., ISO 3741 (2), a small variation in the sound pressure outside the reverberation radius should be guaranteed. For statistical energy analysis (SEA) (3), the homogeneity is strictly assumed, as the outcomes of SEA simulations are spatially-averaged field variables, e.g., a single sound pressure level from a 3D enclosure subsystem.

2.1.2 Isotropy

The isotropic condition is more fundamental than the homogeneity in a sense that an infinite number of uncorrelated plane waves distributed uniformly, i.e., a full isotropic sound incidence, can lead to a homogeneous sound field (4). However, this is only valid under the plane wave assumption, of which the pressure amplitude does not attenuate with the distance. However, isotropic incidence cannot ensure a uniform pressure at all field points with spherical waves from point sources, due to spherical spreading.

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Isotropy could mean two conditions. The first is isotropic incidence over the entire sphere of incidence angles, namely the spherical isotropy. The second is isotropy onto a test specimen over the hemisphere, referred to as the hemispherical isotropy, see Fig. 1. The random incidence absorption coefficient is based on the hemispherical isotropy, which is defined as the directionally averaged value defined by averaging the plane-wave sound power absorption coefficient over the entire hemisphere of incidence directions, with equal weighting for all directions (4). In a mathematical form, under the assumption that α depends on the angle of incidence, θ, but not on azimuthal direction ψ, the random incidence absorption coefficient is expressed as (5, 6)

$$\alpha_{rand} = \int_0^{\pi/2} \alpha(\theta)\sin(2\theta)\,d\theta\,. \tag{1}$$

For the ISO 354 measurement (7), the direction of incidence should be equally probable over the hemisphere, as the original goal is to estimate the random incidence absorption coefficient. The same applies for the random incidence transmission loss (8) and the random incidence scattering coefficient (9). Therefore, the hemispherical isotropy over the test specimen is crucial for most standard measurements in reverberation chambers.

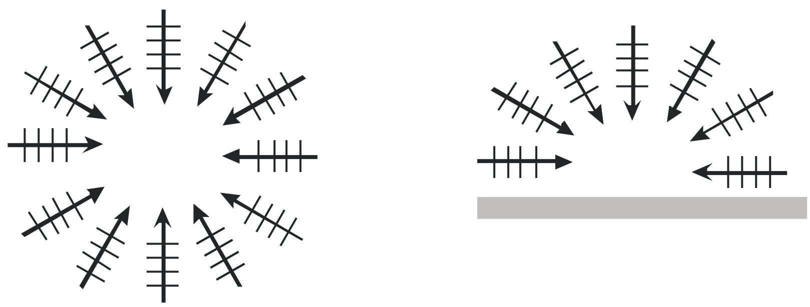

Figure 1 – 2D illustrations of full spherical isotropy (left) and hemispherical isotropy (right).

2.2 Consequences of diffuse sound field

We do use the consequences to indirectly access the diffuseness in enclosures. Important consequences include an exponential sound decay over time as assumed in Sabine's formula, spatial uniformity of the reverberation time (10), zero net intensity (11), no sudden increase or decrease in sound pressures in impulse responses (12-14), sensitivity of the room impulse response to the source location (15), number of peaks (16), and Gaussianity check (17-19). In the important standards, such as ISO 354 and 10140, reverberation times and sound pressure levels at multiple source-receiver combinations are measured instead of the sound power, respectively. Although the theoretical definitions of sound absorption and transmission coefficient are based on the incident power (Π_{in}), absorbed power (Π_{abs}), and transmitted power (Π_{trans}) as $\alpha=\Pi_{abs}/\ \Pi_{in}$ and $\tau=\ \Pi_{trans}/\ \Pi_{in}$, we can use easy-to-measure quantities to approximately estimating α and τ, such as reverberation time and sound pressure level, thanks to the diffuse sound field assumption.

3. FREQUENT MISCONCEPTION IN THE TERMINOLOGIES

What is quite well accepted is the definition of the diffuse sound field as an idealized sound field that consists of infinitely many uncorrelated plane progressive waves, with their intensity uniformly distributed with respect to direction (4). The resultant acoustic intensity is therefore zero. This definition implies that the single-point and two-point statistics of the pressure field are independent of both absolute position and orientation, so that the sound field is statistically homogeneous and isotropic (4). A pure-tone diffuse sound field consists of infinitely many uncorrelated single-frequency plane waves, all with the same infinitesimal amplitude but with randomly distributed phases (4). The waves arrive from all directions with equal probability. However, there are frequent confusions and misconceptions between related terms.

3.1 Diffuseness in rooms and diffuse reflection from surfaces

The word diffusion is derived from the Latin word, "diffundere", which means "to spread out". Diffusion is defined in Ref. (4) as the randomized sound-wave arrival directions at specified points in a room. Diffuse reflection is an idealized model of sound reflection from a rough surface, in which the scattering directivity is independent of the angle of incidence, thus losing all memory of their arrival directions. Note that the diffuse reflection does not mean that each surface element radiates omni-directionally (4). Lambert's cosine law describes the directional distribution of the acoustic power scattered from a diffusely reflecting surface, when the sound absorption coefficient of the surface is zero. Each surface element acts as an independent source of scattered sound power, with a cos(θ) polar angle distribution relative to the normal (4).

Some people argue that diffuseness in rooms and diffuse reflections are equivalent, i.e., diffuse reflections always lead to a more diffuse sound field. Diffuse reflection normally means the Lambert's cosine law, which from all the surfaces does not lead to a diffuse sound field within the room (4). The main reason is the room shape. Although all the surfaces are assumed to produce diffuse reflections, the sound field is tremendously influenced by the room's geometry, absorber and diffuser locations, and the source and microphone locations.

Practically, it is impossible to fulfil both homogeneity and isotropy at all points in a finite room. Perhaps, some combinations of room shapes and reflections patterns from the boundary surfaces, not necessarily the diffuse reflection, can lead to either the homogeneity or the isotropic condition in a limited region of the field points within the room. However, not a single good combination is widely accepted. This is why various room shapes and diffuser settings have been attempted in the existing reverberation chambers all over the world, which results in a poor inter-chamber reproducibility, see Sec. 4.1.

3.2 Diffuseness and diffusivity

It is still unclear which term describes the degree of diffusion more properly between diffuseness and diffusivity. The Oxford dictionary defines diffusivity as a measure of the capability of a substance or energy to be diffused or to allow something to pass by diffusion (20), while diffuseness is the noun form of diffuse. Therefore, both could be used as the term for a diffuse sound field measure.

From the previous literature, the term diffuseness emphases more on the spatial property of being spread out over a wide area or through a large volume, thus perhaps more suitable to represent the homogeneity condition (21). On the other hand, the term diffusivity could be misunderstood as a temporal rate of diffusion, because the term thermal diffusivity means the change in temperature in unit time, thus meaning how quickly a material reacts to a change in temperature (22).

3.3 Degree of diffuseness

Because diffusion is defined as the spreading of something more widely (23), it is a process of being diffuse. On the other hand, diffusivity or diffuseness is a measure of diffusion, and therefore it seems little awkward to say 'the degree of diffuseness', as no one says 'the degree of reverberation time', when it comes to reverberation. 'The degree of diffusion' could be used.

3.4 Mixing and diffuse sound field

Quite some people do not differentiate mixing from diffuse sound field. There is an important difference between mixing in a room and diffuse sound field. Mixing does not consider the absorption in the room, as its definition is how long it takes for there to be no memory of the initial state of the system. There is statistically equal energy in all regions of the space as a consequence of mixing (24). Mixing is even more idealized in such a way that it does not consider sound absorption in a space, and therefore many mixing time indicators are only functions of the room volume and dimensions. However, it is known that non-uniform surface absorption leads to non-diffuse sound fields, thus the diffuseness considers the absorption distribution in rooms (25). When a highly absorbing surface is added in a room, e.g., an absorber specimen in a reverberation room according to ISO 354, it will seriously degrade the diffuseness. As mixing is a necessary condition for the diffuse sound field, not a sufficient condition as shown in Fig. 2, a great care should be taken to discriminate these terms. See more discussions in Ref. (15).

3.5 Suggestions to avoid confusions

As the diffuse sound field could indicate quite different scenarios, e.g., homogeneity, spherical isotropy, hemispherical isotropy, or all of them, a care should be taken when referring to a sound field as being diffuse. In this sense, the general term 'diffuse' needs to be avoided unless strictly necessary and acousticians need to choose the right specific terms for the intended conditions depending on the context.

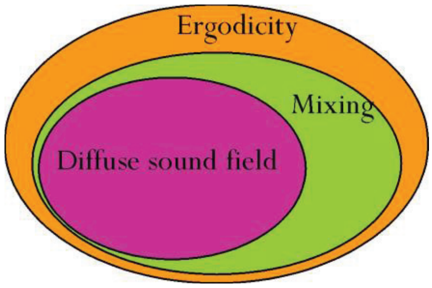

Figure 2 – Diffuse sound field and room mixing property.

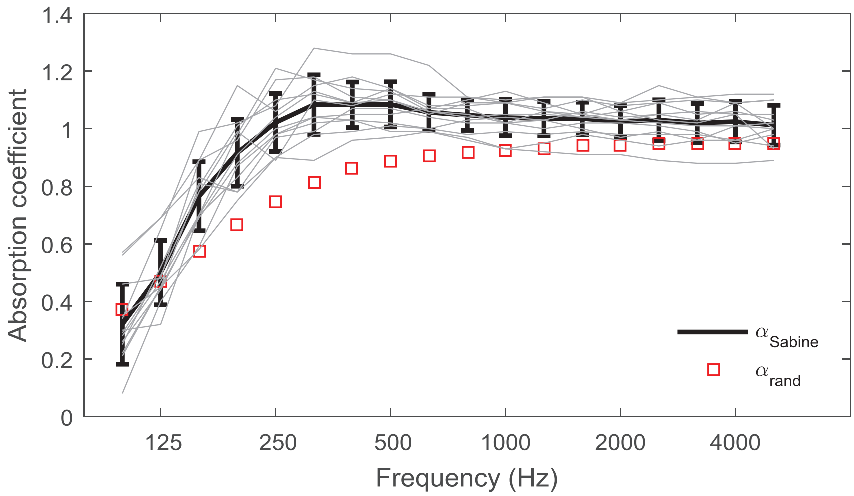

Figure 3 – α_{Sab} of a 10 cm mineral wool with rigid backing measured in 13 chambers. The error bar: standard deviation and grey lines: individual chamber data. α_{rand} based on Miki's model and local reaction (28).

An example could be the diffuse absorption coefficient. Some refer this to the absorption coefficient calculated by Paris' law in Eq. (1), which is more correctly named the random incidence absorption coefficient. Some uses this term to refer to the absorption coefficient measured in reverberation chambers according to ISO 354, which is more correctly called the Sabine absorption coefficient (4).

4. CHALLENGES

4.1 Poor inter-chamber reproducibility for quantities measured in reverberation rooms

The diffuse sound field assumption is central for all measurements in reverberation chambers. However, reverberation chambers are non-diffuse in fundamentally different ways (26), so the quantities measured in different reverberation chambers differ a lot. For example, the Sabine absorption coefficient depends largely on the test chamber even with an identical specimen and is far from the random incidence absorption coefficient calculated by Miki's model (27) and local reaction in Fig. 3 (28), which clearly means that we need to improve the diffuseness condition in the existing reverberation rooms. The first step would be objectively quantifying the diffuseness to understand which reasons lead to such a poor inter-chamber reproducibility.

The annex A of ISO 354 recommends to increase the number of diffusers until a maximum absorption is achieved (7), which is inappropriate for several reasons. First, the convergence is not monotonic with the number of diffusers. Second, there is no scientific evidence that the converged value is correct. Third, this procedure is circular to quantify the diffuseness in the reverberation chamber for measuring the Sabine absorption by the convergence of the Sabine absorption coefficient. What is most problematic is the background belief that the higher the absorption, the higher the diffuseness in the test chamber. The truth is that an anisotropic sound field can yield a higher absorption coefficient than the true diffuse absorption coefficient (29-32), and therefore the highest absorption does not mean the highest diffusion. Some reverberation chambers almost always give absorption coefficients higher than the average absorption coefficient across the chambers, which could possibly be more attractive to absorber manufacturers, while some chambers almost always underestimate. What makes investigations difficult is that the true absorption coefficient of a specimen is not easy to determine, and therefore we only rely on some models under certain approximations. For example, the well-known random incidence absorption coefficient in Eq. (1) is based on the plan waves incident onto an infinitely large absorber, and therefore a finite absorber would not behave this way with spherical waves. The effects of each approximation are not identified as well as the combined effect. Without knowing the true absorption coefficient, it is extremely difficult to evaluate which diffuser setting produces the most accurate absorption coefficient and maximizes the diffuseness.

4.2 No well-accepted quantifiers

Admittedly, there is no good measure for diffuse sound field. Some ideas have been suggested, also refer to Sec 2.2, but there are no quantifiers that are universally accepted and practically useful. Some standard indicators are listed in the current ISO and ASTM standard, the maximum absorption coefficient (α_{max}), relative standard deviation of sound decay (s_{rel}), and total confidence interval of sound decay and absorption area (CI_{tot}). Bradley et al. recently investigated these standard diffuseness quantifiers in a scaled model, summarizing that there are contradictions in the conclusions drawn from each standardized quantifier (33). Therefore, we cannot fully rely on the current standard quantifiers. The most promising way would be to directly quantify the spherical/hemispherical isotropy condition via array measurements with advanced signal processing, e.g., Ref (34). Once the incident intensity distribution onto a specimen in a reverberation chamber is measured, it can be used to quantify the hemispherical isotropy condition and later used as a weighting function to inversely estimate the true absorption coefficient, e.g., Refs. (31,32).

4.3 Realization of diffuse sound field in reverberation chambers

Realization of a diffuse sound field is admittedly the ultimate goal. Most existing reverberation chambers have problems in several frequency bands seen from Peutz's round robin data (28), but it is still unclear what caused such problems. Once a proper objective quantifier is set up, the final goal is to suggest the ways to fix the lack of diffusion in the existing reverberation chambers.

One could suggest optimum designs of the reverberation chamber for future constructions. One idea is to use topology optimization to maximize the diffuseness in reverberation chambers, not aiming at a perfect diffuseness, for a given volume and shape of the chamber. Using the topology optimization, boundary diffuser designs can be optimized subject to the hemispherical isotropic condition for a broad frequency band, preferably covering from 125 Hz to 4 kHz. However, topology optimization results should rather be re-analyzed to gain insights of the interactions between the room boundary and the specimen installed and how to uniformize the incident intensity, as topology optimization often leads to unrealizable and difficult-to-interpret designs.

4.4 Plane wave assumption

The plane wave assumption is the most widely accepted for modeling the diffuse sound field, but in reality it is impossible to generate an infinitely many plane waves (35). One reason is a finite space with a finite number of source (normally only one source is used), while a sufficient distance is required for a wave to be assumed to be planar, particularly at low frequencies. In reverberation chambers, the actual sound fields consist of spherical waves from image sources that are more or less point sources.

4.5 Various models in different domains

There are several different models for the diffuse sound field, which is not a problem by itself. In the frequency domain, the Waterhouse model is commonly accepted (35). Ebeling developed an angular spectrum method using the Waterhouse model (37). Recently, a time domain model based on the Poisson process is implemented (38) and used to test audible reflection density in late reflections (38), echo detection (39), and subjective diffuseness (40). It is, however, unknown or not well established which aspects are similar among the different models and which model is most suitable and realistic to investigate which aspects of the diffuse sound field.

Note that the frequency domain model is built on the plane wave assumption, whereas the time domain model includes the geometrical divergence from point image sources, which is more realistic for many room acoustic applications. The Waterhouse model is useful to investigate the effects of a fixed number of plane waves only for pure-tone excitations. The time domain model can take into account the increasing reflection density over time by varying the number of reflection number according to the theoretical reflection density, $dN_{refl}/dt=4\pi c^3 t^2/V$, V being the volume of the room, and c the speed of sound (5). When the geometrical divergence characteristic is omitted from the time domain model, the frequency domain model and the time domain model are found to be equivalent with the same number of plane waves (40).

4.6 Missing link between objective and subjective indicator

It is admittedly true that the objective quantification is much more important for acoustic measurements in reverberation chambers. On the other hand, subjective diffuseness should not be overlooked in music performance halls, but very little has been investigated how the diffuseness is linked to the holistic impression of the performance hall, and how it is related to spaciousness parameters, such as the lateral fraction and late lateral strength. Some preliminary investigations are shown in Ref. (40).

4.7 Lack of investigation of random phase of incoming waves

Note that a random distribution of phase of the wave incident on the sample is a strict assumption for the random incidence absorption and transmission coefficient (5, 32). Unfortunately, the random phase condition has not been investigated yet probably because this information is hard to obtain.

5. CONCLUSIONS

Several confusions and challenges about the diffuse sound field are discussed. Misconceptions in the different terms are addressed, particularly between diffuseness in rooms and diffuse reflection from surfaces, and between mixing and diffuse sound field. Among many challenges, the poor inter-chamber reproducibility of the acoustic quantities measured in reverberation chambers can be improved by objectively quantifying the diffuseness in reverberation chambers. Optimized designs of test chambers with a maximized diffuseness, not fully diffuse though, should be investigated further. Some missing links between the different domain models, and correlations between subjective evaluations and objective quantifiers are further investigated. The difference between the plane wave and spherical wave assumption needs to be clarified.

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