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The diffuse sound field according to literature: similarities and differences

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Abstract

Several acoustic measurement procedures are elaborated under the assumption that they happen inside an ideally diffuse sound field. However, the definition of diffuseness may vary between standards for different applications. Also, there has been discussion on the means to verify the degree of diffusion, on the hindrances to generate such field and how to overcome them. Therefore, this paper's goal is to revise the different definitions of "diffuse sound field" and define the conditions that in which it is reasonable to declare that the field is sufficiently diffuse for practical purposes. For that, there is also a review of diffuseness indicators. The analysis of several studies on the subject reveals that diffuseness is intrinsically related to an uniform sound intensity in all directions and phase directional incoherence. If this characteristic is present in a sufficient large number of points and applied in conjunction with a model that considers the propagation of plane waves, it means that the sound field can be considered as diffuse.

Keywords: acoustic field, statistical room acoustics, diffuseness, crossover time, crossover frequency.

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1. INTRODUCTION

A perfectly diffuse sound field is, in it's own essence, an idealized concept, not a practical one [1]. However, it is a common desired condition for materials and surfaces properties measurements [2–5], be it because of the expected random-incidence on the surface of interest [6–8] or simply by the use of statistical acoustics [1]. Henceforth, one expects more accurate geometrical acoustic simulations when a diffuse sound field is expected in the real scenario. Conversely, as Vorländer [9] points out, "the concept of a diffuse field is a good approximation for ordinary room dimensions and well-distributed absorption on the room boundaries". Indeed, for fairly general scenarios, a diffuse sound field is a more satisfactory approximation than, for example, a couple specific sound incidences. As such, in projects, a diffuse sound field may be approached as a desirable characteristic, as a strict project requirement or simply taken as a model by approximation.

A diffuse sound field or random-incidence at the specimen is expected for measurements [6–8] and many papers have been published with the aim to evaluate the diffuseness of the sound field, from several decades [10] to recent years [11–15]. However, as noted by Jeong [8], there's still no consensus on reverberant chamber designs and on how to quantify diffuseness. That being said, the concept of diffuseness in a sound field is still quite elusive. The effects of such divergences and misconceptions can be seen in the excessive variation of experimental results, such as the ones described by Scrosati et al. [16] when measuring acoustic absorption on reverberation rooms following the ISO 354 [2] standard.

In many cases, however, the complete definition of diffuse sound field is divided in parts, such as isotropy and homogeneity. Noticing that one could never reach the platonic idea of total diffuseness, one may define conditions for a sufficiently diffuse sound field [6]. Thus, this paper aims at revising the canonical definitions of an ideally or perfectly diffuse sound field, such as described by Jacobsen and Juhl [1], Blauert and Xiang [17], Kuttruff [18, 19], amidst other authors. Once that's realised, these definitions are discussed and brought to more realistic scenarios. Finally, the identification of existing diffuseness indicators is also foreseen in the scope of this paper, which includes the verification of how and which physical properties that might be related to diffuse field could be enough to indicate that such phenomenon is happening.

2. METHODS

Initially, the idea for this paper started was a simple open subject academic research, and a list of 10 articles and 2 books was prepared, read and analysed. Most articles were chosen by searching keywords such as "Diffuse acoustic field", "Diffuse sound field", "Acoustic field" and "Acoustic systems" in available academic databases. Only papers from 2018 onwards were selected at this stage, aside from some papers of interest to the author. As progress went on, the co-authors expanded the source material to include not only more definitions of the studied subject, but also classic authors such as Kuttruff [18, 19], Waterhouse [20] and Schroeder [7]. The bibliography was also stretched to include other concepts such as mixing, isotropy, diffuseness indicators and more.

3. DEFINITION OF (PERFECTLY) DIFFUSE SOUND

Schultz [6] brings some common definitions of diffuse field used at the time of writing:

1. in the diffuse sound field, there must be a total energy density that's uniform to all points in the room, and its radiation should occur at all points in all directions equally;
2. in the diffuse sound field, there must be equal probability of energy flow in all directions and random incidence angles on the room's surfaces;
3. the diffuse sound field occurs from the overlap of an infinite number of plane progressive sound waves, in such that all directions of radiation are equally probable

and the phase relations between these waves are random for any point inside the room.

These definitions, although theoretically accepted, are hard to apply in a literal or practical manner, serving as a platonic reference point that's quite far from practical considerations. It's worth mentioning that these are not conditions *per se*, but rather different ways to approach this idea.

According to Jacobsen [21], diffuseness can be described in two ways:

1. in a diffuse sound field, there's equal probability of energy flow in all directions;
2. a diffuse sound field comprehends an infinite amount of plane waves propagating with randomly related phases arriving from uniformly distributed directions.

It's worth underlining the conditions proposed in item 2. Jacobsen [21] considers plane waves with random phases. From that, is quite easy to imagine a sound field that's formed by sound sources statistically non-correlated (meaning that the processes are not related) and distant enough that one can approximate the punctual spherical sound emission to a plane wave. In his report, Jacobsen [21] also highlights that the model there defined is valid only for frequencies above the *Schroeder's frequency*.

Also, Jacobsen [21] states that the fulfilment of the second definition leads to the achievement of the first. A stronger definition is that "the statistical parameters [e.g. variance] characterising a diffuse sound field are spatially homogeneous and isotropic". More on what these terminologies mean is discussed on Sections 3.1 and 3.2.

However, according to Blauert and Xiang [17], the diffuse sound field is composed by many rays that have, statistically:

1. the same intensity, due to the discard of interactions (be it constructive or destructive) between waves (to which the term *isotropy* is associated);
2. same spatial distribution (to which the term *homogeneity* is attached).

Therefore, the ideally diffuse sound field is completely *homogeneous* and *isotropic*. It's worth emphasising that the definition presented by Blauert and Xiang [17] assumes that the "rays" (wave fronts might be more appropriate at this stage) are reflected in such a manner that all will have the same mean free path length between two reflections.

Kuttruff [18, 19], however, offers a similar yet different approach from the ones presented by Schultz [6], Jacobsen and Juhl [1], and Blauert and Xiang [17]. In his analysis, Kuttruff [18] presents the idea that an isotropic sound field happens when the differential sound intensity (I') is independent from the angular direction departing from a point. Thus, the energy density (w), calculated on Equation 1, and the irradiation density (B), calculated by Equation 2, are also independent from this angular direction. In the Equations, Ω is the solid angle, dependent on the azimuthal and polar angles ϕ and θ, and c is the speed of sound in air. Due to the angle independence, the differential intensity is a constant and then so are the energy density (w) and the irradiation density (B).

$$w = \frac{1}{c} \int\int_{4\pi} I'(\phi, \theta)\, \mathrm{d}\Omega \tag{1}$$

$$B = \int\int_{2\pi} I'(\phi, \theta) \cos(\theta)\, \mathrm{d}\Omega \tag{2}$$

Kuttruff calls this *isotropy*. It's noticeable that, on this case, we say that the sound field is isotropic on the analysed point. Kuttruff then argues that if the energy density (w) is independent of the direction, and there's no loss nor gain of energy that's proportional to the distance travelled, therefore all points in the space will have the same energy distribution [18]. Kuttruff affirms that this condition is not realizable because it would incur in the nonexistence of net energy flow. That this happens in such manner is impossible due to energy losses from the boundaries, which make the energy flow an inevitable phenomenon [18, 19]. It's worth remarking that Kuttruff treats isotropy and diffuseness as the same, which makes sense seen that both spatial and directional conditions are satisfied, such as in the model proposed by Blauert and Xiang [17].

Finally, Kuttruff presents concepts that are averages in time, like the mean free path length, which is the average distance a "sound particle" would travel between two successive reflections (through time). By adding the concept of averages and time domain analysis, the concepts may be brought to a more realistic field: in a diffuse sound field, one simply expects a low variance of energy density and energy density propagation throughout the room, both spatially and temporally. Of course, in a decaying sound field the low time variance would occur, at best, only for short time intervals.

Cox and D'Antonio [22] have a definition that simultaneously agrees to Blauert and Xiang [17] and Kuttruff [19], defining the conditions for a diffuse field as:

1. the reflected sound energy density should be the same for different positions in the room;
2. all directions of propagation are equally probable.

Cox and D'Antonio [22] also call the uniform propagation as isotropy.

Another topic that should not be neglected is the local or global character of sound diffusion. According to Schroeder [7], the sound field is completely diffuse when there is as uniform angular distribution over the solid angles (i.e. spatial) of the sound energy flow of the plane wave expansion at an evaluated point.

3.1 Homogeneous Sound Field

A homogeneous sound field, in the words of Jeong, is one in which "the sound pressure should be uniform at any points" [8]. This, in practical terms, means a sound field in which the variation of the measured sound pressures is as near zero as possible in relation to the positions of measurement (which is even a form of characterising the sound field as seen in Section 4). Furthermore, this property should persist over time.

The quality of a *homogeneous* sound field is called *homogeneity* or *spatial diffusion* [8]. Jacobsen, in a more mathematical language in his 1979 report, presents that the variance (second order moment of the probability density) in a homogeneous field depends only on the separation vector between two positions (i.e. $\mathbf{r}-\mathbf{r_0}$) [21]. Thus, variance of a certain quantity in a homogeneous sound field does not depend on the positions where they are being sensed, but on the relation between these positions.

3.2 Isotropic Sound Field

An isotropic sound field, as Jeong puts it [8], is one where "the incoming energy flow is isotropic in all directions". In a more practical approach, each point has small variance of energy flow over time.

The Merriam-Webster Dictionary defines isotropic as "exhibiting properties (such as velocity of light transmission) with the same values when measured along axes in all directions"[1]. Is that sense, when Jeong [8] and other authors [1, 23–25] mention "isotropic" as a quality of the sound field, they mean that energy flow is the same on all directions. The physical relations and interpretations of what this means are further developed in Section 3.3. The quality of an *isotropic* sound field can be called *isotropy* or *directional diffusion*.

Jacobsen displays, in his 1979 report, that one could say the field is isotropic in case the second-order statistics of the probability density function (i.e. variance) depends only on the norm of the vector $\mathbf{r}-\mathbf{r_0}$ where $\mathbf{r}$ and $\mathbf{r_0}$ are two positions inside the sound field [21]. Therefore, the variance of (e.g.) the sound pressure is dependent on $||\mathbf{r}-\mathbf{r_0}||$ and so its value is independent on the solid angle (θ and ϕ) of this vector.

Isotropy by itself is one of the fundamental conditions for diffuseness, as elaborated soon in Section 3.3.

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[1] https://www.merriam-webster.com/dictionary/isotropic

3.3 Discussion

After the bibliographic revision, it is noted that either energy, or energy density, has to be spatially uniform for the sound field to be considered diffuse - which is closely related to homogeneity. However, it's evident that, for practical applications, reverberation rooms don't have "infinite *n*" sound sources. Considering the aforementioned scenarios, like the measurement of the absorption coefficient, there would be just a handful of source and receiver positions. This means that energy density variation over the evaluated points, at any instant, should be low - and this property would persist over time. Also, energy flow or sound propagation should be uniform in all directions - which is then related to isotropy. This means that the evaluated points should receive the same energy density over time. The way they receive energy would be equally distributed to all directions in an incoherent manner - which relates to directional phase incoherence. It's not hard to notice that conditions such as the samples of absorbing materials or even room geometry itself could break homogeneity and/or isotropy.

When turning attention to how the diffuseness is approached as a premise, many papers bring conditions similar to the ones presented previously (in Section 3) [8, 11–14, 24]. However, these articles cite isotropy as the governing condition over diffuseness, such as Kuttruff's considerations on the matter [18, 19].

Perhaps, then, a topic worthy of discussion is that the isotropy of the sound field might be a powerful indicator of sound field diffusivity, seen the recurrent mention of the intertwinement of both concepts. This idea reaches even deeper once it's realised that almost all the presented definitions explicitly remark the directional uniformity of sound in a point in a diffuse sound field. However, different authors approach this in distinct manners:

1. Schultz [6] and Jacobsen [21] talk about the uniformity of the probability of energy flow;
2. Kuttruff [18, 19] says that the differential sound intensity is *independent* in all directions;
3. Blauert and Xiang [17] say that the intensity is *the same* on all directions;
4. Cox and D'Antonio [22] cite sound propagation.

It's worth mentioning that in all these cases, the watched entity is a point in the space of the room inside which the sound is propagating. Thus, isotropy is a local feature of the sound field. Sampling many points in space is then a way to evaluate the sound field as a whole, such as in the metric proposed by Nolan [24]. Another remark that shouldn't be neglected is that, ultimately, these manners are all interrelated due to the conservation of sound energy [1]. Equations 3 and 4 explicit the relation between intensity, energy flow and propagation:

$$\nabla \cdot \mathbf{I}(t) = -\frac{\partial w_{\text{tot}}}{\partial t}, \tag{3}$$

$$\begin{aligned}\int_S (\mathbf{I}(t) \cdot \mathbf{n}) dS &= -\frac{\partial}{\partial t}\left(\int_V w_{\text{tot}}(t) dV\right) \\ &= -\frac{\partial E_a}{\partial t},\end{aligned} \tag{4}$$

where $\mathbf{I}(t)$ is the sound intensity, w_{tot} is the energy density, E_a is the total sound energy within the surface, and $\mathbf{n}$ is the normal vector pointing outwards from the evaluated point [1]. Evidently, one can say that energy flow and sound propagation come hand in hand. On the other hand, when homogeneity comes in discussion, it's implicitly a spatial characteristic of the sound field.

Continuing on the discussion of how isotropy is seen as more fundamental, Jeong [8] while referencing Morfey [26], says that, inside a plane wave model (PWM), "a full isotropic sound incidence can lead to a homogeneous sound field" [26] apud [8]. Kuttruff [19] displays this abstraction through a geometric analogy, given the premise that there's no variation on the wave front energy due to travelled distance, which fits nicely with the PWM. It's quite clear that, for this approximation to be applied in the least detrimental way possible, the observed points should be at a sufficient distance from the sound source so that the curvature of the wave front can be satisfactorily considered a plane. That includes a sufficient distance not only from the source, but also from walls, diffusers, and other reflective or scattering entities.

Moreover, many authors agree that isotropy is a more fundamental matter than homogeneity:

1. Berzborn et al. [14] imply that isotropy is the diffuseness fundamental characteristic;
2. Jeong [8], referencing Morfey [26], explicitly points out the idea of isotropy being more fundamental phenomenon that leads to homogeneity; and,
3. For Kuttruff [18], the isotropy of differential sound intensity leads to homogeneity in energy density throughout the room.

One important topic is that, depending on the context where one applies or considers diffuseness, one or other definition happens to display itself as more convenient. Jacobsen [21], for instance, writes two possible approaches, but affirms that the second one is more useful for defining and understanding the model of perfectly diffuse sound field, which is presented and thoroughly explained in his work.

4. CHARACTERISATION AND DIFFUSENESS MEASUREMENT

As mentioned in Section 1, high diffuseness is necessary for correctly estimating materials and surfaces sound related properties, such as absorption. Jeong, Nolan and Ballint [27] present that when diffuseness is considered to be enough, when in actuality it is not, the results of several characteristics of the sound field can be influenced. According to Lautenbach and Vercammen [28], this can lead to several biased choices on which reverberation chambers and experimental setups companies will use. Thus, the mere existence of diffuseness metrics is interesting to scientists and companies alike. However, Jeong, Nolan and Ballint [27] reiterate that the developed indicators usually are validated under the same circumstances under which they are developed. This represents a problem, as the lack of uniformity in analysis can lead to difficulties when comparing results from different chambers in different institutions, such as seen in the works by Vercammen [29] and Scrosati et al. [16].

As of this topic, a new problem arises, which is the vast gamma of manners to quantify diffuseness and the different types of data needed to calculate them. Jeong and Nolan [27] classify them in five different types, based on the nature of the used data:

1. parameter based measures;
2. impulse response based measures;
3. intensity based measures;
4. array based measures, and
5. frequency response statistics.

Parameter based measures are essentially based on the standard deviation or variance of some measurable characteristic of the sound field, such as sound pressure level (SPL) [30] or reverberation time [28]. It's worth remarking that these measurements are realised in random spots inside the room and thus, if the variance is small, one can verify the spatial uniformity of the parameters, agreeing with the concept of diffuse sound field.

Impulse response based measures are related to features extracted from the room impulse responses (RIR). Hanyu [31] proposes a method that analyses the time fluctuation in the reflected sound energy, extracted from a decay-cancelled impulse response. According to Hanyu, the "degree of time series fluctuation" is inversely related to the degree of diffusion of the room [31]. Jeong et al. presents a similar approach in quantifying how diffuse a room is, but by means of calculating the transition time based on a ratio between the instantaneous slope and the mean slope of the decay [32]. Jeong calls this the "slope ratio" of the decay curve. It is worth mentioning that higher order measures such as kurtosis, which can be extracted from the RIR measured in many points, can also be a way of quantifying the degree of diffusion in an enclosure, such as proposed by Jeong [33]. In this case, kurtosis will reduce as the sound field turns more diffuse.

Intensity based measures, on the other hand, use sound intensity measurements to calculate an indicator, such as the equation presented by Del Galdo et al. [34]. It can also refer to techniques that use the reconstruction of the field's intensity, such as applied by Nolan et al. [15]. A weakness of the indicator proposed by Del Galdo et al. [34] is the overestimation of the diffuseness when it's low. A rectification, on the other hand, is impractical due to the nature of the microphones, as they can only measure a general intensity and are not able to discern between a well directed plane wave and diffuse field interactions.

Microphone array based measurements are usually attached to sound energy distribution analysis. A very prominent example is the isotropy indicator presented by Nolan et al. [23]. The method utilizes a microphone array to measure the sound pressure followed by an analysis of the wavenumber spectrum to calculate the isotropy and the phase distribution of the sound field. These are obtained from calculating the spherical harmonics series' coefficients of the wavenumber spectrum and analysing the ratio between monopole contribution in relation to the sum of all contribution from all the harmonics (isotropy) and the distribution of the phase in spherical harmonics. It's important to underline that Nolan's characterization has two steps: the evaluation of isotropy [24] and the evaluation of phase distribution [23].

The frequency response statistics come from the studies realised by Schroeder during the XX century, its most common parameter being the Schroeder's frequency (extensively examined along section 5.1) [27]. However, Schroeder's frequency is, in it's essence, a value related to modal overlap and not diffuseness. Moreover, it doesn't account for room geometry, mean free path or sound absorption distribution and scattering, which are all characteristics that have influence over the room diffuseness.

4.1 Other Approaches

Other means of characterising the sound field also exist. The ISO 354 standard has an interesting way to assess diffuseness of the chamber to be used on the measurements. It involves the performance of successive measurements of the absorption coefficient of a sample with the addition of diffusing elements at each iteration, starting with none. The value of the sound absorption will reach a maximum value and stabilize, which means that the diffuseness is maximum from that point on (i.e. the chamber is as diffuse as can be) [2]. However, some flaws in this approach can be pointed out. For starters, there is not a well validated procedure to evaluate the degree of diffusion. Therefore, one can not quantify the increase in diffusion generated by the addition of a diffusor - or even if the sound field is indeed more diffuse. Also, effects like double decay curves may be introduced depending on the used diffusers [35]. Moreover, Jeong criticises the method since [8]:

1. the increase of the measured absorption coefficient alongside an increase in diffusers in not necessarily monotonic;
2. "there is no scientific evidence that the converged value is correct"; and,
3. the process is cyclical, since the amount of diffusers to measure the absorption coefficient is determined by the measured absorption coefficient itself.

Still regarding diffusers, Vercammen even proposes a corrected version of this equation by considering the effect diffusers have over the mean free path. This approach showed less discrepant results between simulations [29].

Another tool that is vastly used to characterise diffuseness in a room are correlation functions. Jacobsen's 1979 report brings a thorough explanation on their use [21] and leads to a calculated quantity D, whose formula is in the following Equation 5:

$$D = \sqrt{{\rho_{pu_r}}^2(0) + \rho_{\check{p}u_r}^2(0)}, \tag{5}$$

in which D would be a “diffuseness index” (Jacobsen doesn’t name this quantity), and $\rho^2_{pu_r}(0)$ and $\rho^2_{\check{p}u_r}(0)$ are the temporal correlation coefficients between sound pressure p, particle velocity and the Hadamard transform of the sound pressure $\check{p}$. Mathematically speaking, D is the envelope of the correlation process $\rho^2_{pu_r}(0)$ [21]. Jacobsen, however, produces this index to illustrate a different problem, with regards to the incompatibility of the model proposed in his report and most quantitative methods previously proposed at the time [21].

The author also argues that a more appropriate approach would be to define a criterion for diffusion by means of a statistical hypothesis testing, in which the author provides the hypothesis that “[...] the mean-square particle velocity components have the same normalised spatial variance, unity, and the same mean [...]” [21]. This hypothesis is applied to a room driven with a pure tone and testing is to be realised with many discrete frequencies. Jacobsen also presents an alternative involving examination of frequency responses at different positions [21].

5. STATISTICAL ROOM ACOUSTICS

It’s worth mentioning that the perfectly diffuse sound field model is at the core of Statistical Room Acoustics. This area applies statistical considerations to make an easier yet powerful analysis of the acoustical characteristics inside a room, especially at higher frequencies. For these techniques to be applied, there are certain premises that should be respected. In any case, the analysis can be realized relatively independently in three different domains: space, frequency and time.

The spatial analysis is the diffuse-field distance, which is the distance r from a point source at which the direct and reverberant energy densities are equal [19]. It is calculated by:

$$r_c = \sqrt{\frac{A}{16\pi}} \quad (\mathrm{m}), \tag{6}$$

in which A is the equivalent absorption area.

The frequency and time domains analysis result in the crossover frequency and crossover time, respectively. They are more thoroughly explained in the following Sections. Also, Schroeder entangles the crossover frequency (or Schroeder frequency), diffuse-field distance (or reverberation distance, or critical distance) and crossover time (or diffuse-field time interval) in his 1996 paper [36].

5.1 Frequency Domain Analysis

On the frequency domain, the applied analysis are classically confined to frequencies above the *Schroeder’s frequency* [1, 21], which is a variable parameter from system to system, and that divides the spectrum in two parts. As such, to each half a different approach is used.

Below Schroeder’s frequency, Jacobsen recommends the use Modal Room Acoustics, which works the modes and natural frequencies independently, and whose sum should represent the sound wave with fidelity and using few terms [1]. This approach is very efficient for lower frequencies. However, in accordance with the rising of the frequency, the amount of terms that are summed and the association of errors of dimensional or geometric nature on these terms results in errors proportionally unacceptable [1].

From Schroeder’s frequency onwards, usually, the systems are handled using *Statistical Room Acoustics*, which assumes certain hypothesis (that are not included in this study), which mitigate the error problem and also allow to learn several of the room’s sound field characteristics without needing too many specific information about the system itself. On this context, one might be able to think of Jacobsen’s abstraction of a sound field with uncorrelated sound sources uniformly dispersed around the room [1, 21]. The non-correlation between these sources results on the effects of interference between their outputs being overlooked and their intensity is, on average, uniform.

A stochastic approach above Schroeder’s frequency is justified due to the high modal overlap that occurs consistently in this region of the spectrum. Modal overlap is calculated as in Equation 7:

$$M = n(f) \times \Delta f \quad (\cdot), \tag{7}$$

where M is the modal overlap, $n(f)$ is the modal density and Δf is the 3-dB bandwidth centered on the pure tone frequency [1, 21]. The equation for modal density is simplified when calculating the Schroeder's frequency:

$$n(f) = \frac{4\pi V}{c^3} f^2 \quad (\cdot) \tag{8}$$

and the modal bandwidth is related to damping and reverberation time:

$$\Delta f = \frac{\eta}{\pi} = \frac{3\ln(10)}{\pi T_{60}} \quad (\mathrm{Hz}). \tag{9}$$

Jacobsen and Juhl [1] state that when the modal overlap exceeds approximately 3, the statistical approach is appropriate. In reality, this means that, above a certain frequency, it is not possible to excite a single mode since they are also excited by different neighbouring modal frequencies.

Solving Equation 7 for the frequency, one obtains the Schroeder's frequency:

$$f_S = \sqrt{\frac{c^3}{12\ln(10)}} \times \sqrt{\frac{M T_{60}}{V}} \quad (\mathrm{Hz}), \tag{10}$$

in which c is the speed of sound in air, T_{60} is the reverberation time and V is the room's volume. One may then consider $c = 340\,\mathrm{m/s}$ and $M = 3$, which morphs Equation 10 into its most simple and usual form:

$$f_S = 2000 \left(\frac{\mathrm{m}}{\mathrm{s}}\right)^{3/2} \times \sqrt{\frac{T_{60}}{V}} \quad (\mathrm{Hz}). \tag{11}$$

In his 1996 paper [36], Schroeder showed that the constant with unusual dimension may be removed if thinking on terms of wavelength instead of frequency.

It's worth mentioning that Schroeder's frequency by itself is an indicative of the occurrence of high modal overlap, which on its turn implies the possibility of analysing the system by means of stochastic methods. The indirect nature of the relation between Schroeder's frequency and the existence of a diffuse sound field might seem alien at first sight, but it's quite appropriate, as minutely explained and deducted by Jacobsen [21]. Therefore, usually the crossover frequency and Schroeder's frequency are seen as equivalent.

5.2 Time Domain Analysis

When approaching diffuseness of a sound field in the time domain, the feature that should be observed is not the density of modes excited in the room, but the density of arrivals of wave fronts in a certain point of the room [37]. There's a moment during reverberation in which there's a change in discrete behaviour to statistic behaviour. This moment is called *crossover time*. The mechanism through which this transition happens is related to the history of absorptions and scattering processes through which the wave fronts are submitted.

First and foremost, the idea that there's a crossover time comes from the fact that if the spectrum of the impulse response of a room displays a Gaussian behaviour after Schroeder's frequency, therefore the Inverse Fourier Transform of the spectrum should result in a Gaussian distribution beyond a certain time value. Usually, the crossover time analysis is done by applying *Matching Pursuit* algorithms and eXtensible Fourier Transforms (XFT) [37].

A phenomenon that's worth mentioning alongside diffuseness of the sound field is *mixing*. Mixing is understood as being a characteristic of the sound reflection on the room's walls, in the sense that more mixing means that the wave front reflects more times on more surfaces. Rooms with geometries that favour mixing, such as the ones with complex forms or non-parallel walls, tend to also favour the existence of a diffuse sound field. This can be observed because each reflection can be seen as secondary sound source and, if there's more secondary sound sources (for each reflection in a surface), the closer to reaching the ideal “infinite n” sound sources, without presenting the impracticalities that this idea implies. However, one can say that mixing is necessary for obtaining a diffuse field, but not sufficient [8]; usually, low and homogeneous absorption is cited alongside it as a premise [19].

Mixing is also associated to the concept of ergodicity. An ergodic system is said to be one in which all phase space states are occupied in a uniformly random manner. This implies that the energy is equally distributed. This ultimately means that a diffuse field is formed [37].

However, there are differences between *crossover time* and *mixing time*. While the former is related to the distance between the source and the receptor, the latter is not related with this measure [37]. There's also a more fundamental difference between these metrics. While crossover time would indicate the moment the sound field would become locally diffuse, mixing time would be the time beyond which the room enters an "energetic equilibrium" state due to the divergence on the initially adjacent wave fronts. Defrance and Polack [37] even highlight that thinking on mixing time is quite naive, give that this phenomenon happens in an assimptotic manner. The authors also remark that a mixing state would happen after the crossover time [37]. Thus, it's not strange that if a room displays a good mixing, it will most likely have a diffuse sound field, as it would be beyond the crossover time.

6. FINAL COMMENTS

The general objective in this research was to characterize what a diffuse field, or a sufficiently diffuse field, is. Diffuseness in acoustic fields continues to be quite the nebulous idea when approaching real sound fields in its many applications. However, many researchers currently look for ways to account for this quality of acoustic fields in a practical way. Some basic and easy to evaluate requirements are the crossover (Schroeder) frequency, crossover time and diffuse-field distance [36]. Unfavourable room geometries, like shoebox rooms, are easily detected, by knowing the project of the room and undesired standing waves may be mitigated by the use of diffusing elements, which also increases mixing [22].

It is worth remarking once again that diffuseness in an acoustic field is an idealised concept and that for now it cannot be directly measured. Notwithstanding, its properties can sometimes be quantified, such as Nolan's metric involving isotropy and directional phase distribution [23]. Since isotropy is more fundamental than homogeneity, it seems the analysis of these two properties in several points in the room is enough to conclude if the sound field is sufficiently diffuse or not.

Because this was intended to be a purely bibliographic review of the concept, experimental verifications are not being done in this article and should be further investigated. Similarly, theoretical considerations imported from the field of Physics could also be of great utility in cementing the relations proposed in this paper. It should be remarked that the matter relating to diffuseness is old, but still one of the frontiers of knowledge in Acoustics. Thus, with new techniques and improved processing power, the use of more sophisticated analysis and simulations can also be very useful in determining the intricacies of the sound fields.

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