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Experimental characterization of the decaying sound field in a reverberation room

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ABSTRACT

Reverberation-chamber measurements of sound absorption coefficients are based on the assumption that the sound field is diffuse (i.e., homogeneous and isotropic). Such sound field should be established both before and during the sound decay. Yet, the test conditions for absorption measurements render the establishment of a completely diffuse sound field difficult, if not impossible. It is therefore of interest to discuss the concept of acoustic diffusion in a reverberation chamber. A recent investigation examined sound field isotropy in reverberation rooms in the steady state, based on an analysis of the wavenumber spectrum in the spherical harmonics domain. The purpose of the present study is to analyze the isotropy of the sound field in a reverberation chamber across time. The evolution of the sound decay is examined by estimating the wavenumber spectrum in successive time instances, leading to a time-dependent analysis of isotropy. Experimental results based on measurements in a reverberation room in four configurations (empty with and without diffusers, as well as with absorbing material on the floor, with and without diffusers) are presented.

Keywords: Sound absorption, Sound decay, Isotropy, Array processing

1. INTRODUCTION

Reverberation-room measurements of the statistical absorption coefficient of acoustic materials [1] depend critically on the diffusion of the sound field in the test chamber. The procedure is based on the simple reverberation formulas, provided that complete diffuseness of the sound field is achieved both before and during the sound decay. An ideal diffuse field can be defined as the superposition of an infinite set of plane waves with random phases and equal magnitudes, which directions of propagation are uniformly distributed over all angles of incidence. In such a sound field, the energy density is uniform in space and the energy flow is isotropic [2]. This definition can be extended to a set of exponentially decaying plane waves and thus, to the decaying sound field in a reverberation room. Yet, the test conditions for absorption measurements render the establishment of a completely diffuse sound field difficult.

The shortcomings of the measurement procedure have become increasingly evident as a result of numerous investigations [3,4], which show that the major cause of difficulties with the reverberation-room measurement of sound absorption can be ascribed to a lack

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of diffuseness of the sound field. A variety of methods for the measurement of sound field diffusion have been reported in the literature, mainly concerned with its evaluation in the steady-state. The measurement of diffuseness during the decay phase has not received similar attention, although a few papers have looked into the matter: Reverberation time and decay irregularities have been used as a criterion for diffusion [5,6]; Balachandran and Robinson [7] extended correlation measurements to the decaying state; Several studies have measured the acoustic intensity over time [8-10]. Besides, a promising line of approach describes diffusion on the basis of the angular distribution of sound energy: Venzke and Dämmig [11] extended the concept of *directional diffusion* introduced by Meyer and Thiele [12] to the decaying state, by measuring the angular variation of sound energy at various instants during the decay using highly directional transducers; More recently, Gover et al. [13] adapted the method to measurements with a spherical array of microphones; Extending this approach, Berzborn et al. [14,15] introduce the concept of Directional Energy Decay Curves (DEDC) derived from measurements of directional impulse responses using a spherical microphone array.

A recent investigation proposed an experimental method for evaluating isotropy in reverberant spaces in the steady-state, based on an analysis of the wavenumber spectrum in the spherical harmonics domain [16]. The aim of the present study is to extend the wavenumber spectrum analysis method to the decaying state. The evolution of the sound decay is examined by estimating the wavenumber spectrum over various time windows, leading to a time-dependent analysis of isotropy. The paper is organized as follows: the theoretical background is presented in **Sec. 2**. In **Sec. 3**, an experimental study is presented based on measurements in a reverberation chamber using a programmable robotic arm.

2. THEORETICAL BACKGROUND

2.1 Wavenumber (or angular) spectrum and sound field isotropy

Let us consider the sound field produced by a pure-tone source with angular frequency $\omega = kc$ in a reverberation chamber. In steady-state, the resulting sound field can be represented as a superposition of plane waves [17], each traveling in a direction specified by the wavenumber vector $\mathbf{k} = (k_x, k_y, k_z)$

$$\mathrm{p}(\mathbf{r}, \omega) = \iiint_{-\infty}^{+\infty} \mathrm{P}(\mathbf{k}) e^{\mathrm{j}(\omega t - \mathbf{k}\cdot\mathbf{r}^T)} d\mathbf{k}, \tag{1}$$

where $\mathbf{r} = (x, y, z)$, and the time dependency $e^{\mathrm{j}\omega t}$ will be omitted throughout. In other words, the sound field is expressed as a superposition of plane waves. The quantity $\mathrm{P}(\mathbf{k}) = |\mathrm{P}(\mathbf{k})| e^{\mathrm{j}\phi(\mathbf{k})}$ is the *wavenumber* (or *angular*) *spectrum*, with $|\mathrm{P}(\mathbf{k})|$ and $\phi(\mathbf{k})$ its magnitude and phase, respectively. In the following, it is assumed that all plane waves satisfy the condition $\|\mathbf{k}\|^2 = k^2 = k_x^2 + k_y^2 + k_z^2$ with $k^2 \geq k_x^2 + k_y^2$ (indicating that they are propagating waves). Such plane wave decomposition is valid away from any source or diffracting element (where evanescent waves are *not* present).

In order to evaluate isotropy, the magnitude of the wavenumber spectrum is expanded into a series of spherical harmonics [16]

$$\left|\tilde{\mathrm{P}}(\theta, \phi)\right| = \sum_{n=0}^{\infty} \sum_{m=-n}^{n} A_{mn}(k) Y_n^m(\theta, \phi), \tag{2}$$

where $\tilde{\mathrm{P}}(\theta, \phi)$ denotes the two-dimensional wavenumber spectrum expressed in spherical coordinates, and the complex coefficients $A_{mn}(k)$ can be calculated from the orthonormality relation of the spherical harmonics functions. The relative monopole strength [16]

$$\iota = |A_{00}(k)| \Big/ \sum_{n=0}^{\infty} \sum_{m=-n}^{n} |A_{mn}(k)| \tag{3}$$

determines the degree of isotropy, the underlying hypothesis being that in a perfectly isotropic sound field, the wavenumber spectrum is rotationally symmetric. The measure ranges from 0 to 1: 1 in the case where the flow of energy is equal in all directions; 0 if the incident waves propagate in a single direction.

2.2 Implementation of the method

In practice, the wavenumber spectrum $\tilde{\mathrm{P}}(\theta, \phi)$ is obtained using a discrete plane wave expansion, based on a discrete approximation of Eq. (1)

$$\mathrm{p}(\mathbf{r}_r) = \sum_{l=1}^{L} \tilde{\mathrm{P}}(\mathbf{k}_l) e^{-\mathrm{j}\mathbf{k}_l \cdot \mathbf{r}_r}, \tag{4}$$

where the directions of propagation of the L plane waves are uniformly distributed over a spherical domain. The pressure field is sampled at a discrete number R of receiver positions, and can be expressed in matrix form as

$$\mathbf{p} = \mathbf{H}\mathbf{x}, \tag{5}$$

where $\mathbf{p} \in \mathbb{C}^R$ is the measured sound pressure vector, $\mathbf{x} \in \mathbb{C}^L$ is a complex coefficient vector containing the wavenumber spectrum $\tilde{\mathrm{P}}(\mathbf{k}_l)$ in Eq. (4), and $\mathbf{H} \in \mathbb{C}^{R \times L}$ is the transfer matrix containing the plane wave functions. The problem is typically underdetermined ($L > R$) and the estimation of $\mathbf{x}$ obtained via a regularized matrix pseudo-inverse [18]. Subsequently, a spherical harmonic expansion of the magnitude of each component of $\mathbf{x}$ can be obtained based on a discrete approximation of Eq. (2).

2.3 Time analysis

In the present work, the isotropy of the sound field is analyzed as a function of time. Such analysis is particularly useful for examining its temporal evolution during the decay process and detecting asymmetries in energy distribution both in time and direction. It may be of interest, for instance, to exclude the early reflections and examine the later part of the decay only. In the present study we focus on an analysis of isotropy for time windows starting at a given time t_0 and extending until the end of the measured impulse response. Depending on the chosen value of t_0, it becomes possible to analyze the steady-state (t_0 = 0s), or to exclude the direct sound, early reflections, or late reflections. For an analysis window w_{t_0}, the corresponding frequency response H_{t_0} reads

$$H_{t_0}(\mathbf{r}, \omega) = \int_{-\infty}^{+\infty} w_{t_0}(t) h(\mathbf{r}, t) e^{-\mathrm{j}\omega t} dt, \tag{6}$$

where h is the measured impulse response at position $\mathbf{r}$. In the case of a rectangular window $w_{t_0}(t) = \begin{cases} 1 & \forall\, t \in [t_0, +\infty[\\ 0 & \forall\, t \in [0, t_0[\end{cases}$, Eq. (6) becomes

$$H_{t_0}(\mathbf{r}, \omega) = \int_{t_0}^{+\infty} h(\mathbf{r}, t) e^{-\mathrm{j}\omega t} dt. \tag{7}$$

The case t_0 = 0s includes the energy arriving over the full impulse response and thus corresponds to the *steady-state* response of the room. The subsequent analysis is performed on the frequency response H_{t_0} so that $\mathrm{p}(\mathbf{r}, \omega) = H_{t_0}(\mathbf{r}, \omega)$ [see Eq. (1)]. The evaluation of isotropy follows as explained in **section 2.1**, based on the windowed responses of the room. Alternatively, a short sliding time window can be used to isolate individual reflections (and, potentially, problematic reflections) in time and direction.

3. EXPERIMENTAL RESULTS

The proposed methodology is examined experimentally in a large (245 m^3) reverberation room at the Technical University of Denmark, using a programmable robotic arm to scan the sound field (see **Fig. 1**). The room is essentially box-shaped, although there are 19 removable panel diffusers. Four configurations of the room are considered: the empty (undamped) room with and without panel diffusers, and the room with extra absorption on the floor with and without panel diffusers. The absorption coefficient of the sample (10.8 m^2 glass wool of thickness 100 mm and flow resistivity 12.9 kPa.s/m^2) at 500 Hz is 1.04 (measured according to ISO 354 in the same reverberation chamber in the configuration with diffusers). A scanning robot UR5 (Universal Robot, Odense, Denmark) is programmed to move a free-field microphone (Brüel & Kjær, Nærum, Denmark) and forms an array of 310 sequential measurement positions. The array consists of two spherical layers with radii 0.25 m and 0.45 m respectively, each of them sampled at 144 positions chosen according to an equal-area grid on the sphere [19]. Additional sampling positions were used inside the spheres to achieve good stabilization of the eigenfrequencies [20]. It should be remarked that the current measurement system is not expected to provide valid results below 200 Hz, where the size of the array corresponds to about 10% of the wavelength in air (ka = 0.1), nor at high frequencies (above 3 kHz), where aliasing effects start to appear.

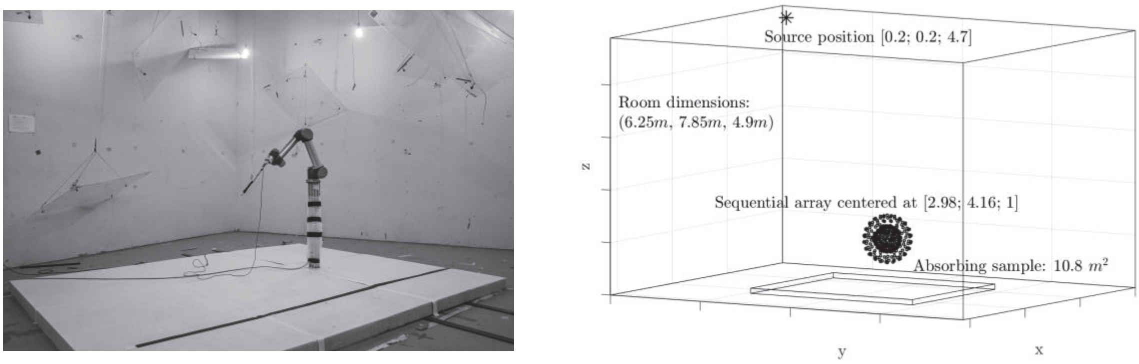

Figure 1 – Experimental setup

The room is excited by a built-in loudspeaker driven with exponential sweeps. An impulse response is measured at each of the 310 positions using the ITA-Toolbox [21]. The measured impulse responses are considered over various time ranges to investigate the temporal evolution of the sound decay and its isotropy. For each selected time range of the impulse response, the frequency response is calculated based on a DFT, and the complex coefficient vector **x** corresponding to the wavenumber spectrum is estimated using Eq. (5). A plane-wave basis of 2000 plane waves of unknown amplitudes is considered, whose directions of propagation are distributed uniformly based on a Thomson problem. Tikhonov regularization (i.e., a l_2 least-squares solution) is used for the regularized inversion, along with the L-curve criterion as a parameter-choice method. As for the spherical harmonic expansion in Eq. (2), only a limited number of spherical harmonic orders can be used in practice. The spherical harmonic expansion is here truncated at N = 7. Although possible, adding more spherical harmonics in the expansion of the wavenumber spectrum does not contain relevant information.

It can be remarked that one advantage of the method described in this work is that it does not require a prescribed array geometry. It can be used for any given array, provided that the basic sampling requirements are met [22,23]. In this paper, we use a spherical array as the method is meant to be compared in the future with another approach, based on the same set of data (see Ref. 15, presented in the same proceedings).

Figure 2 compares the resulting wavenumber spectrum at 500 Hz in the damped room without diffusers [left], and in the same room where 19 hanging panel diffusers have been installed [right]. The wavenumber results are averaged over the third-octave band centered at 500 Hz and include the arriving energy over the full impulse response (that is, these results correspond to the *steady-state* response of the room). It should be noted that, with the chosen time convention, the wavenumber spectrum represents the direction of propagation and not the direction of arrival (as apparent from **Fig. 2**). It can be seen that in both cases, no waves are propagating in the positive z-direction, because no sound is being reflected by the absorbing sample ($\alpha \approx 1.04$ at 500 Hz). In the room without diffusers, a few dominant incident directions are detected, seemingly corresponding to the direct radiation from the source and standing waves in the x-y plane (tangential plane to the absorber). When panel diffusers are added to the room, the distribution of incident energy is somewhat more uniform, as seen in **Fig. 2** (right).

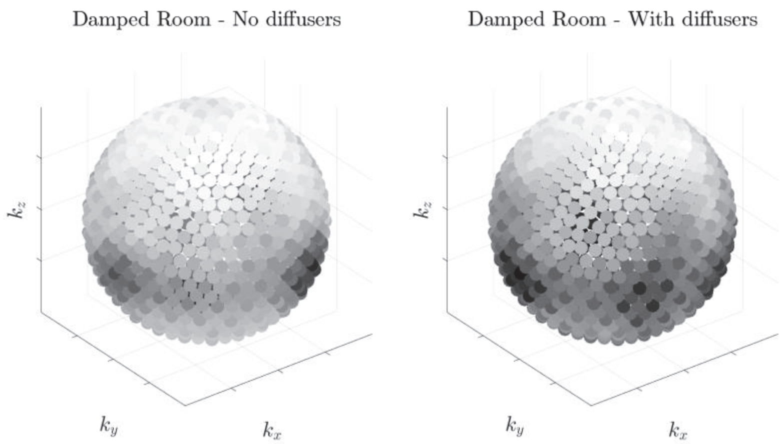

Figure 2 – Magnitude of the wavenumber spectrum in the damped room without diffusers (left) and with diffusers (right). Frequency: 500 Hz (1/3 oct.). t_0 = 0s.

Figure 3(a) compares the magnitude $\sum_{m=-n}^{n}|A_{mn}|$ of the moments from the spherical harmonic expansions in the undamped and damped room without (black) and with (blue) diffusers, for the third-octave band centered at 500 Hz. In order to analyze the changes in isotropy at different times, and as described in section 2.3, the wavenumber spectra and corresponding spherical harmonic expansions are calculated using windows starting at t_0 = 0s, 50ms, 100ms, … 1.4s, although **Fig. 3(a)** displays results for t_0 = 0s, 0.5s, and 1s only. For t_0 = 0.5s and 1s, the analysis of isotropy is restricted to t > 0.5s and t > 1s, respectively.

In the undamped room, the monopole moment dominates the spherical harmonic expansion of the wavenumber spectrum (both in the empty room and in the room with added panel diffusers), indicating a fairly isotropic sound field. Addition of panel diffusers essentially reduces the contribution of the 2nd and 4th order spherical harmonic moments, which account for standing waves in the x-, y- and z-directions (this is seen in the corresponding wavenumber spectra, not shown for conciseness). These moments are less prominent in the late decay (see t > 1 s, without diffusers), suggesting that the sound field is composed of multiple waves of similar amplitude (stronger early reflections are, in fact, excluded).

In the damped room, due to the presence of the absorbing sample, the sound field is less omnidirectional and higher-order moments are required to describe the wavenumber spectra. This indicates that the wave field is less isotropic than in the undamped case, in agreement with previous findings [16]. In particular, in the room without diffusers at $t >$ 0.5 s and $t >$ 1 s, the wavenumber spectrum is best described by the 1st, 2nd and 4th order spherical harmonic moments. Inspection of the wavenumber spectra (not shown for conciseness) reveals persisting tangential components in the late decay, corresponding to standing waves in the *x-y* plane. This is in agreement with the general behavior of sound propagating in a rectangular room containing a highly absorptive surface and no scattering objects, as described in e.g. Ref. 24, where it is shown that the grazing part of the sound field is less affected by the absorption than the non-grazing field. The results show no evidence of such persisting waves when panel diffusers are installed (see **Fig. 3(a)**, damped room with diffusers), suggesting that the panels re-direct the sound waves successfully.

Figure 3(b) shows the isotropy indicator in the four configurations as a function of time, for the successive time windows corresponding to $t >$ 0 s, $t >$ 50 ms, $t >$ 100 ms, … $t >$ 1.4 s. The results confirm that the sound field is less isotropic in the damped room than in the undamped room ($0.27 < \iota < 0.47$ in the damped room without diffusers, against $0.70 < \iota < 0.78$ in the undamped room), and that addition of panel diffusers influences positively the isotropy of the wave field (in the steady-state, isotropy increases by 11.4 % in the undamped room, and by 12.1 % in the damped room). Yet, the sound field in the undamped room with diffusers is not perfectly isotropic (ι_{max} = 0.84), which is to be expected as perfect isotropy is difficult to achieve in a room.

In the damped room without diffusers, the sound field is highly anisotropic in the steady-state (ι = 0.27), due to the direct radiation from the source and a few interfering modes (see **Fig. 2**). As time progresses, the results indicate increasing *isotropy* initially (ι increases from 0.27 to 0.47 between $t >$ 0 s and $t >$ 0.55 s) as there is no influence of the source and early reflections, followed by increasing *anisotropy* (ι drops from 0.47 to 0.42 between $t >$ 0.55 s and $t >$ 1.4 s), seemingly caused by persisting sound waves propagating back and forth in the *x-y* plane, after sound waves in the other directions have been absorbed (i.e., sound in the non-grazing field is absorbed more quickly than in the grazing field [24]). In the damped room with diffusers, room reflections seem to build up faster, in a way that increases isotropy earlier (ι = 0.53 at $t >$ 0.2 s). It can further be noticed that in the undamped room without diffusers, a comparable buildup of room reflections is detected, where the isotropy indicator reaches a plateau at $t >$ 0.9 s, presumably due to mixing. In this case, a longer processing time would be required to examine the behavior of the sound field in the later decay.

4. CONCLUSIONS

An experimental method to evaluate sound field isotropy in the decaying state has been proposed, based on measurements with an array of microphones. By considering measured impulse responses over various time windows, it is possible to examine the temporal evolution of the wavenumber spectrum, which determines the magnitude of the sound waves arriving from definite directions at the observation point. The extent of sound field isotropy as a function of time is subsequently assessed by expanding the wavenumber spectrum in the spherical harmonics domain for each time window.

Experimental results obtained in four reverberation chamber configurations indicate that the method is suitable for evaluating the isotropy of the reverberant field in the decaying state. The analysis not only confirms the anisotropy of the sound fields, but also reveals asymmetries in energy distribution both in time and direction. It is anticipated that the proposed framework will be of value in diagnosing biases in laboratory configurations, as well as in analyzing the deviations encountered across standardized laboratories.

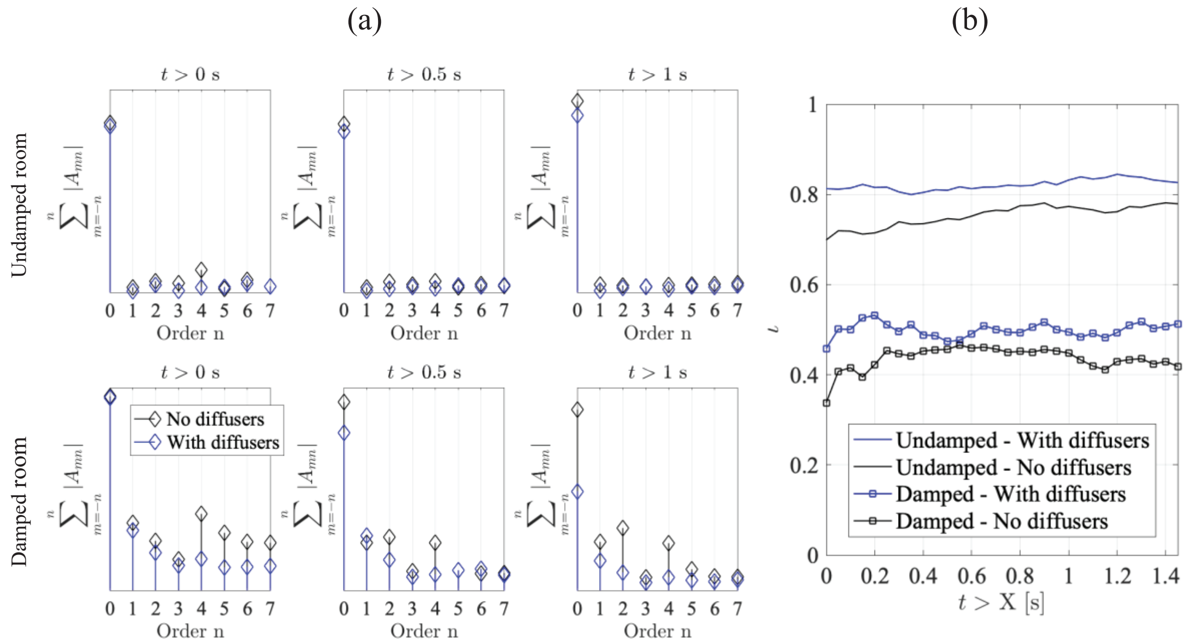

Figure 3 – (a) Spherical harmonic expansion at 500 Hz (1/3 oct.) in the undamped (top) and damped (bottom) room without and with diffusers. The results are presented for several time windows of the measured impulse response. (b) Isotropy indicator at 500 Hz (1/3 oct.) calculated in the undamped and damped room without and with diffusers for (t > 0 s; t > 50 ms; t > 100 ms; … t > 1.4 s). Truncation order: $N = 7$.

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