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MEASUREMENT OF THE SOUND ABSORPTION COEFFICIENT OF MATERIALS IN A REVERBERANT CHAMBER USING AN OMNIDIRECTIONAL PARAMETRIC LOUDSPEAKER

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ABSTRACT

The omnidirectional parametric loudspeaker (OPL) is a sound source that exploits the phenomenon of the parametric acoustic array (PAA) to produce an omnidirectional sound field. It consists of hundreds of ultrasound transducers distributed on the surface of a sphere. Each transducer emits an ultrasonic signal modulated in amplitude by an audible exponential sweep sine (ESS). The signal is demodulated back to the audible range by nonlinear propagation in air. This work investigates the suitability of the OPL for some room acoustics measurements. We focus on measuring the sound absorption coefficient of materials in a reverberant chamber. In fact, the study proposes the first steps towards a methodology to measure the absorption coefficient of materials, similar to ISO 354 standard, but for an OPL. The ESS is used as excitation signal because it allows the OPL to concentrate the emitted sound power on a single frequency, leading to higher ultrasonic power levels and increasing the signal-to-noise ratio of the audible sound pressure levels. The procedure for obtaining the frequency dependent reverberation times is also described. The absorption coefficient and reverberation times measured with the OPL are compared with those of conventional dodecahedral loudspeaker.

Keywords: *room acoustics, reverberation time, parametric acoustic array, omnidirectional parametric loudspeaker, exponential sine sweep.*

1. INTRODUCTION

The concept of parametric acoustic arrays (PAA) in air, first proposed by Westervelt [1], has been widely used to generate highly focused audible sound beams. However, it took several years for PAA technology to be developed for practical applications after Westervelt's early work. Over the years, parametric array technology has been used in several applications (see [2–5]).

In [6], the OPL (omnidirectional parametric loudspeaker) was first proposed as a potential alternative to conventional polyhedron loudspeakers [7], which lose omnidirectionality at high frequencies. That initial prototype was constructed by setting hundreds of ultrasonic transducers on a sphere, resulting in the emission of sound beams in all directions. Although operational, it was not functional for room acoustics measurements. Following the theoretical research in [8], a new prototype with improved behavior was built [9]. Subsequent research improved its efficacy. It was found that employing exponential sine sweeps (ESS) led to a better signal-to-noise ratio [10]. In addition, the selection of the appropriate carrier frequency to modulate the signal emitted by the OPL resulted in an improvement of the acoustic power level over the entire frequency range [11].

The above improvements facilitated the start of preliminary room acoustics measurements with the OPL [12]). This work is a continuation of those initial investigations. Specifically, we present the methodology for measuring the absorption coefficient of a material in a reverberation chamber using the OPL, according to the ISO 354 [13] standard. The absorption coefficient of materials provides essential information for the selection of suitable materials for construction and the achievement of the desired sound quality and comfort in various applications, such as

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architectural acoustics, room design and noise control.

The remaining of this paper is organized as follows. In section 2, we describe the methodology and the experimental setup, while results are presented and discussed in section 3. Conclusions close the paper in section 4.

2. METHODOLOGY

All measurements were performed in the reverberation chamber of La Salle, Universitat Ramon Llull (see Fig.1). The reverberation time of both the empty chamber and the chamber with the sample was measured to obtain the absorption coefficient of the sample. The acoustic material tested is made of a panel constructed from recycled wood, measuring 3.5 cm in thickness, and glued onto a cardboard base of 1.2 cm.

The OPL and a 1/2-inch diffuse field microphone (G.R.A.S 40AQ), were positioned inside the reverberation chamber, using a narrow stand. The microphone was linked to a conditioning amplifier (B&K Nexus) and the resulting output signal was directed to a Data Translation 9832 card (see the experimental setup of Fig.1), which was also employed to generate the ESS excitation signal. This signal was amplified with an Ecler XPA3000 adjusting the output voltage to 17 Vpeak, which was carefully chosen to ensure that the ultrasound transducers of the OPL would not be damaged [9]. The Ecler amplifier gain was fine-tuned by measuring the output voltage with an oscilloscope. The output amplified ESS was input to the OPL. In particular, we used the following ESS

$$x(t) = \sin\left[K\left(e^{t/L} - 1\right)\right] K, \tag{1}$$

with

$$K = \frac{2\pi f_1 T}{\ln f_2/f_1}, \quad L = \frac{T}{\ln f_2/f_1}. \tag{2}$$

The frequencies $f_1 = 20$ Hz and $f_2 = 14$ kHz represent the lower and higher measured frequencies, respectively. A linear fade-in from 20 Hz to 80 Hz and a linear fade-out from 12 kHz to 14 kHz were applied to reduce pre-ringing artifacts [14]. A signal duration of $T = 25$ s was chosen, followed by 10 seconds of silence to ensure that the decay curve reached the background noise level. The ESS was modulated using Upper Side Band Modulation (USBAM), with a carrier frequency of $f_c = 41.4$ kHz to ensure optimal performance of the OPL, see [10, 11]. Finally, the modulated ESS was emitted through the OPL and then captured with the microphone.

The captured signal was convoluted with the inverse filter of the ESS to obtain the impulse response of the room in each point [12]. The resulting impulse response was then filtered into 1/3 octave bands, and the reverberation time for each band was calculated using the integrated impulse response method. This involves backward integration of the squared filtered impulse response to obtain the decay curve [15].

A custom Matlab software was developed to control the various devices and perform signal processing during the measurements.

The measurements of reverberation time and the expression of the results for the absorption coefficient were carried out in compliance with ISO 354 [13]. This regulation states that reverberation time must be measured in the reverberation chamber with and without the sample of absorbing material. Based on the difference, the equivalent absorption area is calculated as,

$$\alpha_s = \frac{A_T}{S}, \tag{3}$$

with

$$\begin{aligned} A_T &= A_1 - A_2 \\ &= 55.3V\left(\frac{1}{c_2 T_2} - \frac{1}{c_1 T_1}\right) - 4V\left(m_2 - m_1\right). \end{aligned} \tag{4}$$

The value of S represents the area in square meters of the test sample, which was set to $S = 12\mathrm{m}^2$. The variables c_1 and c_2 are the speed of sound in the empty chamber and in the chamber with the absorbing sample, respectively. The speed of sound has been computed taking into account a temperature of 20°C in both cases. Moreover, T_1 and T_2 refer to the reverberation times, in seconds, of the reverberation chamber without and with the absorption material, respectively. Finally, the variable V represents the volume, in cubic meters, of the empty reverberant chamber. That of La Salle, Universitat Ramin Llull has a volume of 212 m^3.

The ISO 354 [13] standard describes the minimum number of decay curves to be measured in different positions. This number should be at least 12, which results from multiplying the number of microphone positions by the number of source positions. Moreover, a minimum of 3 different microphone positions and 2 different source positions should be measured. In this work, a total of 6 microphone positions and 3 sound source positions

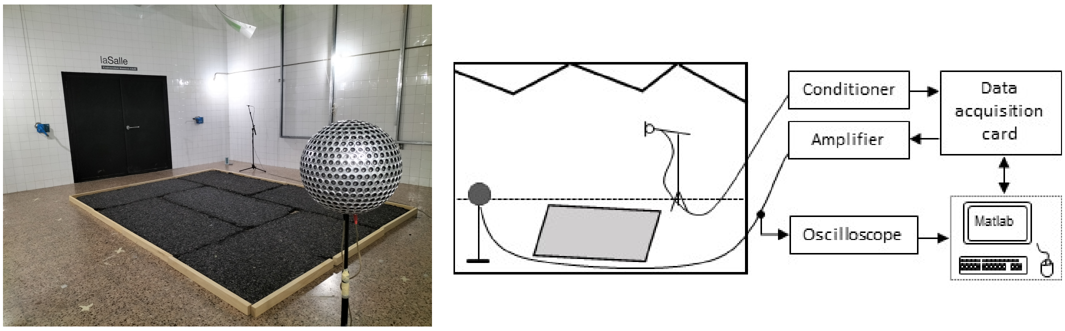

Figure 1. Reverberation chamber and experimental setup.

were considered. In addition, for each source-microphone combination, the reverberation time measurement was repeated three times. This resulted in a total of 54 measurements.

The experimental setup and procedure employed to perform measurements with the dodecahedron were similar to those used for the OPL.The main difference lies in the signal processing, as USBAM modulation is obviously not required to generate an audible signal.

3. RESULTS

Fig. 2 presents the reverberation times measured in the reverberant chamber according to the methodology described in the previous section. The upper subfigure shows the reverberation time of the empty chamber for the OPL and dodecahedron sources. The lower subfigure depicts the reverberation times with the absorbing material inside the chamber. The two subfigures present the RT (reverberation time) at the 1/3-octave frequency bands ranging from 125 Hz to 10 kHz, resulting from filtering the impulse response obtained with the ESS using the corresponding 1/3-octave band filters. A mean value is also displayed, calculated as the average of the RT for each 1/3-octave band. Additionally, the standard deviation of the reverberation time measurements has been calculated for each frequency band. This obtained standard deviation has been represented above each 1/3-octave band, as shown in Fig. 2.

As can be seen in Fig. 2, the reverberation times obtained with both sources are quite similar for the two configurations of the reverberant room (empty and with absorbing material). The most noticeable differences are found at low frequencies. As shown in [12], the signal-to-noise ratio of the decay curve increases with higher frequencies. Consequently, lower frequency bands have a lower signal-to-noise ratio, making it more difficult to achieve a good dynamic range necessary for accurate RT calculation. It should be noted that a dynamic range greater than 35 dB is necessary for all frequency bands in order to obtain reliable RT20 measurements.

In terms of standard deviation values, it can be seen that the values obtained with both the dodecahedron and the OPL are comparable. However, for frequencies below 315 Hz, the OPL exhibits slightly greater deviations compared to the dodecahedron. This divergence might be attributed to the lower signal-to-noise ratio achieved by the OPL for frequencies within this range, as compared to the dodecahedron. Furthermore, this consistent pattern is observed in both the empty chamber and the chamber incorporating absorption material.

Fig. 3 shows the sound absorption coefficient, α, of the acoustic material, which has been calculated based on the reverberation times shown in Fig. 2, for the OPL and for a standard commercial dodecahedron loudspeaker. As expected, the sound absorption of the material increases with frequency. From 125 Hz to 1 kHz, the absorption coefficient gradually rises from approximately α=0.16 to α=1. From 1 kHz to 8 kHz, the absorption coefficient remains close to α=1 for all frequency bands. Very similar results are obtained again with the OPL and the dodecahedron sources.

4. CONCLUSIONS

In this study, we developed a methodology to measure the absorption coefficient of a material using an omnidirectional parametric loudspeaker (OPL) as a sound source.

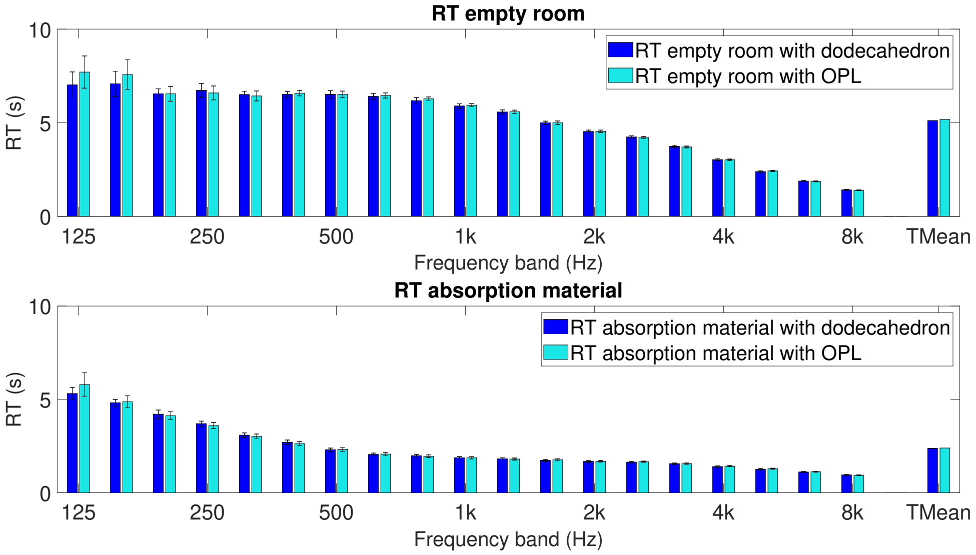

Figure 2. Reverberation time comparison for the OPL (blue) and the dodecahedron (turquoise) in the reverberation chamber, with and without the absorbing material.

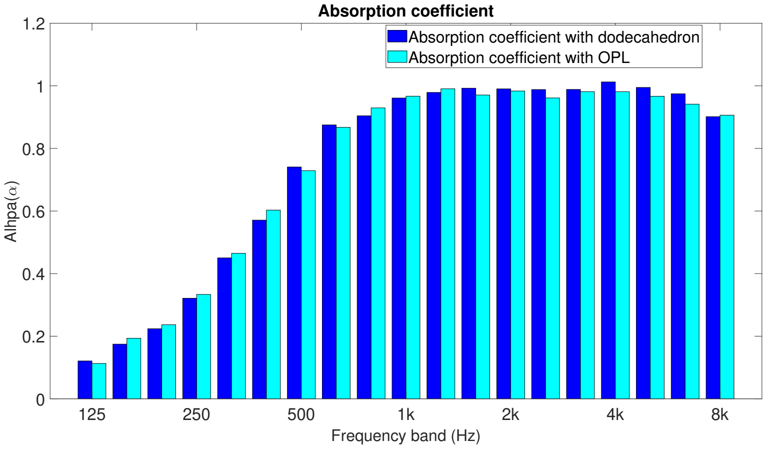

Figure 3. Comparison of the absorption coefficients, calculated from the measured reverberation times (TRs) obtained with the OPL (blue) and a standard commercial dodecahedron loudspeaker (cyan).

Exponential sine sweeps (ESS) were employed as the excitation signal for the OPL. The latter is based on the parametric acoustic array (PAA) phenomenon, which emits focused audible sound beams based on natural non-linear demodulation in air. The ESS signal has shown a sufficiently high signal-to-noise ratio inside the reverberation chamber, which facilitates accurate calculation of the reverberation time (RT20) in all frequency bands.

To determine the absorption coefficient of a material, we conducted reverberation time measurements in an empty chamber and in a chamber with absorbent material. By comparing the reverberation times of these two configurations, we derived the absorption coefficient of the material. To assess the performance of the OPL, we also compared its performance with that of a conventional dodecahedral loudspeaker in terms of measurement accuracy and reliability. Additionally, we conducted an analysis of the standard deviation for the measurements taken within each frequency band, considering both the OPL and the standard dodecahedron as sound sources. This examination revealed that, upon initial observation, the standard deviation appears to be quite similar for both sources.

Future work will involve measuring the absorption coefficient of a wider variety of samples in the reverberation chamber using the OPL. The objective is to verify the effectiveness of the methodology on materials with different characteristics. In addition, future work will involve obtaining other room acoustic parameters related to reverberation time.

5. ACKNOWLEDGMENTS

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