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THE PERFORMANCE OF THE CABLE ROBOT SOUND FIELD CHARACTERIZATION MEASUREMENT SYSTEM

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ABSTRACT

The characterization of reverberant sound fields is of crucial importance for the further development of acoustic measurement methods, especially in scenarios that rely on diffuse sound field conditions. A prominent example of this is the inability to quantify the diffuseness of the sound field, which poses a challenge for several traditional measurement approaches carried out in reverberation chambers. To make progress in this area of research, we have developed a chamber with controllable room geometry (regular chamber) and a cable robot system capable of measuring room impulse responses with high spatial resolution. In this study, we evaluated the technical performance of this measurement system in a controlled laboratory environment. Preliminary measurements demonstrate the system is capable of accurately identify room mode shapes and evaluate alternative sound field quantifiers. These results underline the potential of the measurement system by providing a robust experimental framework for future investigations. This study is relevant for a better understanding of reverberant environments and for the development of experimental methods relying on the diffuse sound field.

Keywords: *sound field measurements, reverberant field, diffuse field, sound field characterization, cable robot*

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1. INTRODUCTION

Measurements in reverberant sound fields are of great importance in acoustics, since reverberation chambers are the essential infrastructure for a number of standardized measurements [1, 2] that require the presence of a diffuse sound field. Experimental and theoretical investigations of such sound fields began intensively in the 1970s, with notable contributions by Jacobsen [3], Ebeling [4] and Schultz [5]. In the course of technological progress, robotic [6] and motorized systems [7] have been increasingly developed in the last decade as a novel experimental approach that enables the measurement of spatial responses at finely distributed measurement points. Such measurements mainly allow the observation of sound field properties that can only be derived from spatial data, such as intensity and isotropy, which will hopefully lead to a better understanding of the diffuse sound field [8].

Building on our earlier efforts to establish the infrastructure for investigating reverberant sound fields in a regular chamber [9], we have further expanded our experimental capabilities by developing a cable robot microphone array (CRMA) [10]. The measurement system represents a significant improvement over manually moving the microphone [11] around the room under investigation by providing accurate, repeatable and automated spatial measurements. In this paper, we evaluate the performance of the newly developed CRMA from various technical aspects and highlight its effectiveness, accuracy and potential for the advancement of acoustic measurement methods. As a relevant example, we demonstrate the ability of the measurement system to identify mode shapes of a cuboid space for which analytical solutions exist.

2. CABLE ROBOT ARRAY DESIGN

The cable robot measurement system [12] consists of a planar, rectangular microphone array that can move to a given position in space. The array is constructed as a regular grid of 36 microphones arranged in a 6×6 square configuration. The array was 3D printed after a series of prototypes to ensure the required rigidity of the frame while minimizing the bulkiness of the array to limit its impact on the sound field. The array with the microphones can be seen in the photo in Figure 1. The array was specifically tailored to accommodate phase-matched Brüel & Kjær Type 4958 microphones, which are specifically intended for array applications. The distance between adjacent microphones in the array was set to $s = 4\,\text{cm}$ corresponding to a spatial Nyquist frequency of approximately $4287\,\text{Hz}$, which we understand to be the upper frequency limit of the setup.

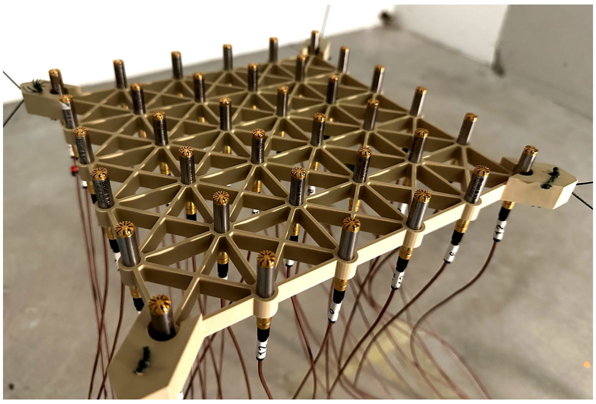

Figure 1. Photo of the microphone array composed of 36 microphones arranged in a rectangular grid of 6×6 microphones with the grid spacing of $s = 4\,\text{cm}$.

For the selected cardinal coordinates, the orientation of the array is fixed parallel to the horizontal X-Y plane and with the sides of the array aligned to the axes of the coordinate system. In such a setting, the position of the array is completely defined by one positional vector **T**, composed of three cardinal coordinates. These also completely define the 36 individual coordinates of the microphones due to the fixed geometry of the array. The described movement constraints are implemented at the software control level, while additional degrees of freedom can easily be introduced if required. Similarly, the system allows easy adaptation to alternative microphone array geometries, depending on the requirements of the measurement in question.

The necessary suspension of the array is achieved by a set of eight cables that also maneuver the array in space by changing their length. Stepper motors wind and unwind the cables on a drum with high accuracy. Each of the four corners of the microphone array is connected to two cables that are routed past fixed attachment points on the walls, as shown in Figure 2. While the position of the array could theoretically be determined only by the length of the four upper cables, the presence of additional cables stabilizes unwanted oscillations of the pendulum-like response of the array.

Figure 2. Photo of the cable robot showing the array connected by 8 cables to the attachment points at the room boundaries. Six loudspeakers use for microphone localisation are as well visible on the walls.

The locations of the eight cable attachment points are software parameters required for processing the rotation instructions fed to the stepper motors. These coordinates can be adjusted when CRAM is deployed in other environments, such as larger reverberation chambers and concert halls, providing the necessary flexibility for future investigations. Currently, the CRMA is installed and operational in the regular chamber [9] of the InnoRenew CoE Acoustics laboratory.

3. ACOUSTIC LOCALISATION

One disadvantage of the cable robot is its relatively high positional uncertainty. The reasons for this include the load-dependent elastic elongation of the cables and the asymmetrical load on the microphone array, which is inevitably caused by the cable management. To overcome these uncertainties, the robotic cable system was combined with the previously presented acoustic localization system [13]. The core principle of the system is the use of acoustic triangulation to accurately determine the coordinates of each microphone in the array.

In order to obtain the information required for triangulation, six high-frequency loudspeakers were distributed on the walls. Impulse responses in the frequency range of 3000 Hz to 20000 Hz are measured between the microphones and the high-frequency loudspeakers. From the impulse responses the time of the first peak is extracted, $t_{n,m}$, which is related to the direct sound propagation distance

$$d_{l,m} = c \cdot t_{l,m} \tag{1}$$

from each loudspeaker ($l = 1, 2 \ldots, 6$) to each microphone ($m = 1, 2, \ldots 36$), with $c = 343\,m/s$ being the propagation speed of sound.

The basic version of the acoustic localization method includes an optimization procedure that iteratively determines the coordinate of an individual microphone. Specifically, the algorithm searches for the coordinate of a virtual microphone that best matches the measured distances. Geometrically, this procedure corresponds to the search for the intersection of spheres, each of which is cantered around a loudspeaker and has the radius $d_{l,m}$. To determine such an intersection point unambiguously, the number of spheres and thus the number of loudspeakers must be at least 4. However, the method becomes more robust and accurate if more loudspeakers are used.

The accuracy with which the microphone coordinates can be determined is significantly influenced by the accuracy of the determination of the distances to the individual microphones. One source of uncertainty in this respect is the quantization error in the determination of the peak time in the measured impulse response, which results from a finite sampling frequency. In our implementation, $f_s = 65\,536$ Hz is used, which leads to a theoretical spatial resolution of about $\frac{c}{fs} = 5.2$ mm for the determination of the distances. It follows that it would be beneficial to increase the sampling frequency which was not possible in our case. Another way to overcome this limitation is to introduce more loudspeaker for localization.

To even further improve the localization accuracy, we have implemented an advanced algorithm that determines the coordinates of the entire microphone array simultaneously – i.e. based on minimizing the error for the total of $6 \cdot 36 = 2166$ measured distances $d_{l,m}$. This approach significantly reduces the uncertainty below the already introduced peak detection quantification. In such a scenario, the coordinate of the entire array is defined by the coordinate of its center T and the possible rotations.

The acoustic localization approach is directly integrated into the motion protocol of the (CRMA) and autonomously adjusts the position of the array until the target position is reached within a predefined error threshold. Ongoing research will explore further benefits of this highly overdetermined localization system by challenging the exact positions of the loudspeakers and also variations in sound propagation speed.

4. MOTION PERFORMANCE

4.1 Scanning range

An important feature of the CRMA is its scanning range, i.e. its ability to reach different parts of space. With the current configuration it is a challenge to move the array close to the limits of space, as the unfavorable angle of the cables causes very high tensions that the cables have to withstand. An improvement in this regard would be the addition of extra cables, which increases the complexity of the system.

The tests of the system have shown that more than half of the distance in each of the three spatial dimensions of the chamber can be easily reached by the CRMA, as shown graphically in Figure 3. However, it should be noted that given the volume of the chamber, this scanning area represents only 27% of the volume, which is a significant limitation when using the system.

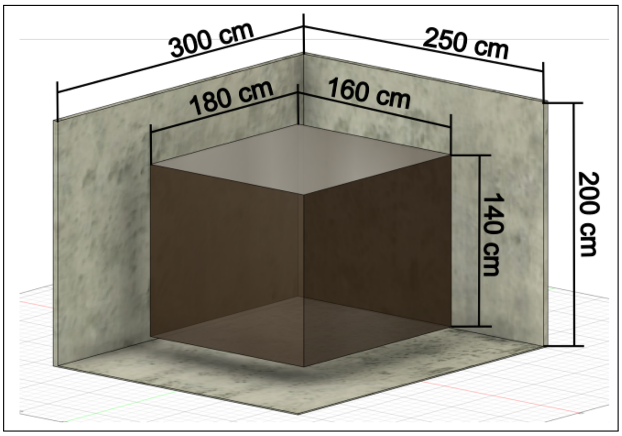

Figure 3. A graphic representation of the regular chamber - a cuboid room of the given dimensions. The inner cuboid represents the scanning range of the CRMA.

4.2 Position accuracy

The most important feature of the CRMA is the accuracy of the positioning. For this purpose, 6 positions within the identified scanning range were selected. At these positions, the coordinates of the array were also recorded with a laser scanner by applying color markers on the cable attachment points [14]. From these the center of the array can be easily calculated.

Performing this test resulted in a measurement deviation of 3.5 mm in the position of the array center point, while the alignment of the array deviated on average by the angle in radians of 0.004. To put these figures into perspective, we should bear in mind that ¼-inch microphones were used, where the positioning error was about half this diameter. Apart from some very position-sensitive measurements, this accuracy should be sufficient for most practical applications.

4.3 Scanning resolution and measurement time considerations

The regular grid spacing of the microphone array currently used is $s = 4$ cm. In order to scan a cubic meter of volume with such a microphone spacing, 384 measurements with the 36 microphones must be taken. As the positioning system is constantly evolving, the time it takes for the array to move between measurement positions can only be estimated. However, 2 minutes have been typically observed for the CRMA to reach a measurement point with an accuracy of less than 5 mm. Under these assumptions, the scanning time is 12 hours and 48 minutes per cubic meter.

It can be as well considered, that the number of measurement points in a volume and consequentially the measurement duration is inveresly proportional to the third power of the distance between the microphones $\propto (1/s)^3$. Therefore, the duration would be considerably shorter if a coarser array were used.

It is highly unlikely that such a high scanning resolution is practiced, which could easily take several days for a larger volume/room. The convenient aspect on the other hand is that the system is fully automated, which means that no operator assistance is required. However, such a measurement duration warns us against assuming the sound field in a room as a stationary acoustic system. Varying air temperature and humidity can significantly affect the air attenuation and also the speed of the sound. Therefore, the climatic conditions for such long measurements must be kept constant and monitored for the dura-

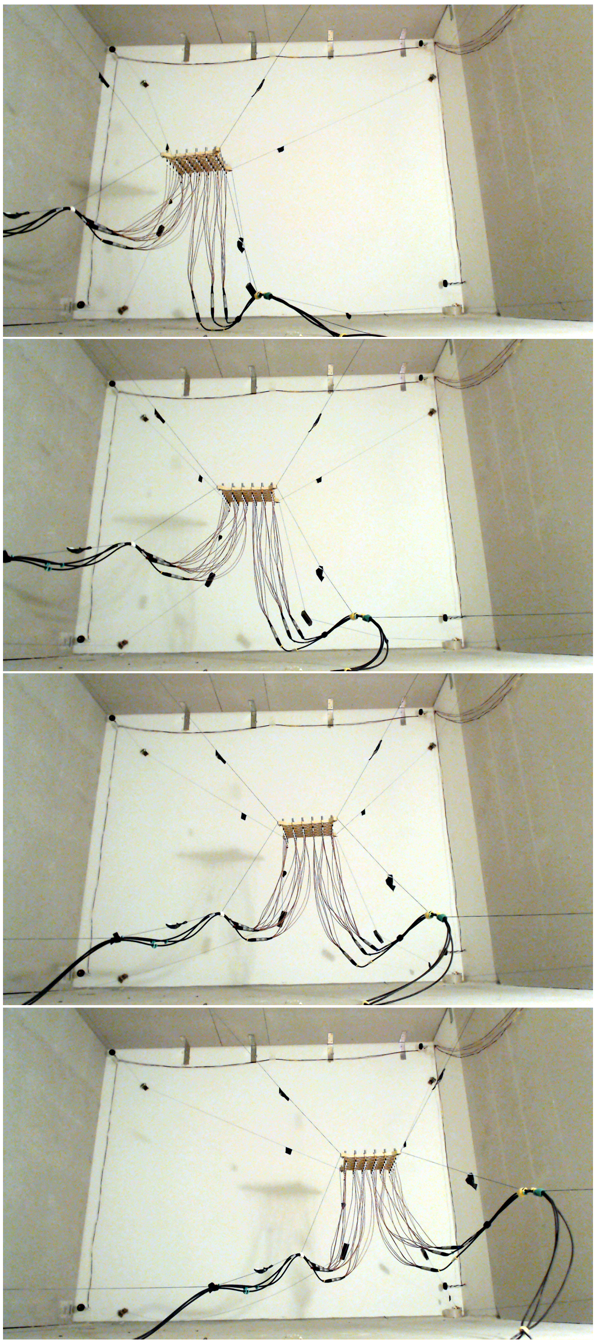

Figure 4. Photos of the position of the array at four consecutive measurement points (from top to bottom), with the array moving from left to right.

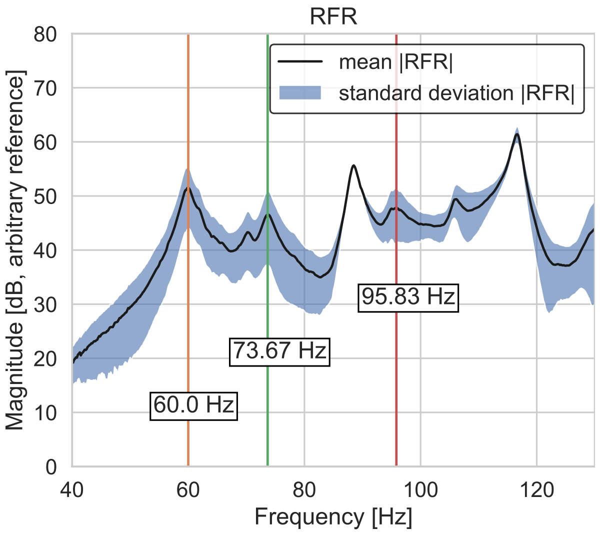

Figure 5. Mean absolute room frequency response measured in the horizontal plane of the room. The identified resonances are marked by vertical lines.

tion of the measurements. An important decision in this respect was to build the rectangular chamber as a facility within the acoustics laboratory that ensures stable climatic conditions throughout the measurements

5. DETERMINING RESONANCES AND MODE SHAPES

As an example, a CRMA measurement was performed to visualize the modes in the horizontal plane of the room. The loudspeaker was placed in the corner of the room to successfully excite a large number of modes while the array moved in a grid of 4×4 array measurement points. Overall, the room acoustic response (RFR) was measured in the horizontal plane in a 120 cm square with a distance of 4 cm between the microphones. Screenshots of the position of the array in 4 of 16 array measurement points can be found in Figure 4.

Frequency response was measured generating a 10 s exponential harmonic sweep of the duration of 10 s from 20 Hz to 20 kHz. In total 576 RFR were measured of which the mean and the standard deviation of the absolute value are shown in Figure 5. The identified frequencies $f_1 = 60.0$ Hz, $f_2 = 73.67$ Hz and $f_3 = 95.83$, which of high magnitude and deviation, are marked with vertical lines and correspond to the lowest modes in the x-y plane.

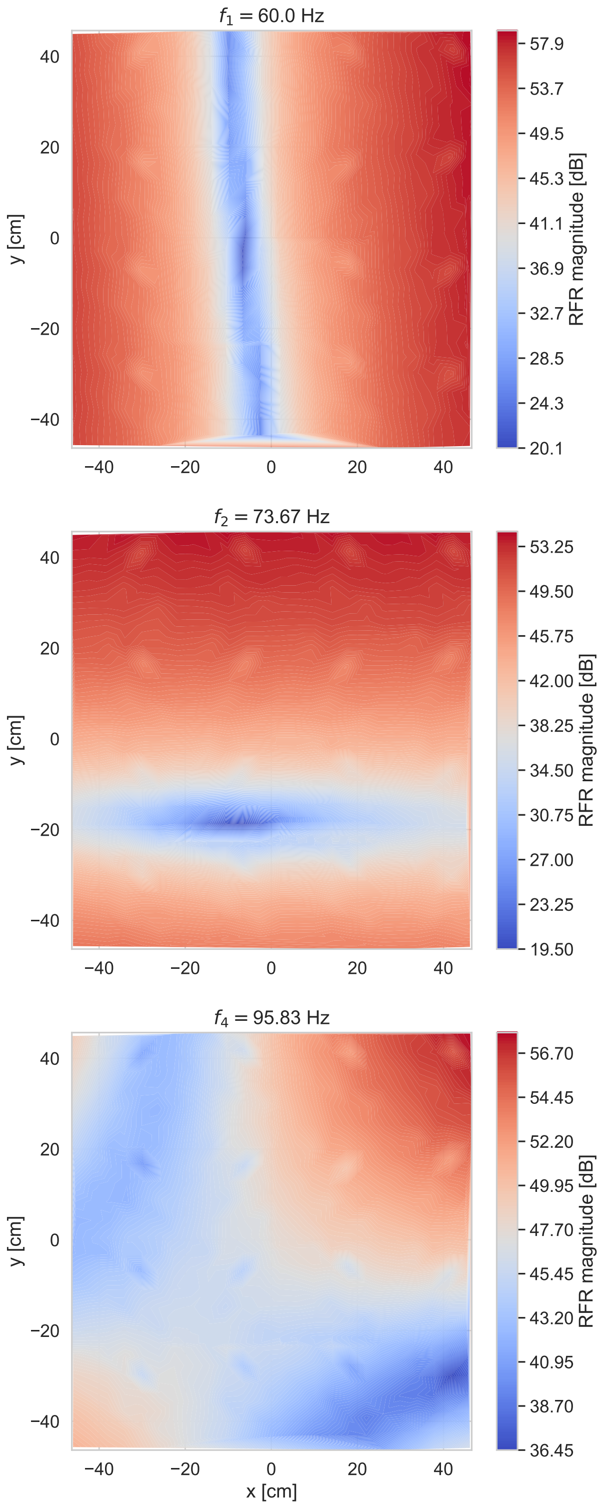

Figure 6. Mode shapes corresponding to the identified resonances shown as the RFR magnitude

The spatial distribution of the frequency response, i.e. the mode shapes, is shown in Figure 6. It can be seen that the modes coincide with two axial and one tangential mode with the corresponding modal numbers (1,0), (0,1) and (1,1). This brings a qualitative agreement with the expected modal shapes of a cuboid room [15].

Taking into account the known analytical solutions for such a room, the resonant frequency of the tangential mode can be calculated as

$$f_3' = \sqrt{f_1^2 + f_2^2} = 95.01\,\text{Hz} \tag{2}$$

from the resonant frequencies of the two axial modes. This value is in very good agreement with the measured $f_3 = 95.83\,\text{Hz}$.

The frequencies of the determined modes can also be compared with a FEM simulation that was previously carried out as part of the regular chamber design [14]. The FEM results of the corresponding modes were 57.2 Hz, 68.6 Hz and 89.6 Hz, which is up to 5 Hz below the measured values. There may be several reasons for this discrepancy, including deviations from the cuboid geometry of the room. This hypothesis is partially supported by the observed slight rotation of the axial modes, which ideally run parallel to the room boundaries. In addition, factors such as air conditions were not taken into account in this comparison. However, apart from some explainable deviations, a solid agreement between the measured values and the FEM model can be observed.

6. CONCLUSIONS

PleasThis paper presented the development and evaluation of the Cable Robot Microphone Array (CRMA) for spatial sound field measurements. The technical design was described in detail, focusing on the integration of a precise acoustic positioning system to overcome the positioning uncertainties associated with cable-driven systems. The performance of the CRMA was demonstrated by its ability to identify room resonances and correctly represent mode shapes. Despite its promising capabilities, the spatial resolution should be well chosen to avoid overly time-consuming measurements. However, the measurements are fully automated, which is very convenient.

Overall, the CRMA represents a robust experimental framework for the investigation of reverberant sound fields. Based on the CRMA measurements, advanced acoustic quantities and parameters will be investigated in the future, such as acoustic intensity, isotropy and sensitivity [16]. These will be evaluated in the particular acoustic environment of the regular chamber - a room whose geometry can be varied. In addition, the influence of materials such as absorbers and diffusers on the sound field will be investigated.

7. ACKNOWLEDGMENTS

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8. REFERENCES

[1] International Organization for Standardization ISO 354:2003, "Acoustics – Measurement of sound absorption in a reverberation room.".

[2] International Organization for Standardization ISO 3741:2010, "Acoustics-Determination of sound power levels and sound energy levels of noise sources using sound pressure - Precision methods for reverberation test rooms." 2010.

[3] F. Jacobsen, *The Sound Field in a Reverberation Room - Note no. 31261*. Technical University of Denmark, 2010.

[4] Ebeling K. J., "Statistical properties of random wave fields," *Physical acoustics: Principles and methods.*, vol. 17, pp. 233–310, jan 1984.

[5] T. Schultz, "Diffusion in reverberation rooms," *Journal of Sound and Vibration*, vol. 16, pp. 17–28, may 1971.

[6] M. Nolan, E. Fernandez-Grande, J. Brunskog, and C.-H. Jeong, "A wavenumber approach to quantifying the isotropy of the sound field in reverberant spaces a)," *The Journal of the Acoustical Society of America*, vol. 143, no. 4, pp. 2514–2526, 2018.

[7] I. B. Witew, M. Vorländer, and N. Xiang, "Sampling the sound field in auditoria using large natural-scale array measurements," *The Journal of the Acoustical*

Society of America, vol. 141, pp. EL300–EL306, mar 2017.

[8] C.-H. Jeong, "Diffuse sound field: challenges and misconceptions," in *Proceedings of 45th International Congress and Exposition on Noise Control Engineering* (Wolfgang Kropp, ed.), pp. Pages 1015–1021, 2016.

[9] R. Prislan and J. Brunskog, "A Regular Chamber - Design of a Test Facility for The Investigation of the Reverberant Sound Field," in *Proceedings of the 29th International Congress on Sound and Vibration*, 2023.

[10] R. Prislan and A. Dufour, "Experimental sound field characterization with automated high-resolution impulse response measurements," in *Experimental sound field characterization with automated high-resolution impulse response measurements*, (10th Congress of the Alps Adria Acoustics Association : international scientific congress : 20.-21. September 2023, Izola, Slovenia : AAAA 2023), pp. 147–152, 2023.

[11] R. Prislan and D. Svenšek, "Room mode shape visualization using a multi-microphone measurement technique," in *Proceedings of the 7th AAAA Congress*, (Ljubljana), 2016.

[12] Z. Zhang, Z. Shao, Z. You, X. Tang, B. Zi, G. Yang, C. Gosselin, and S. Caro, "State-of-the-art on theories and applications of cable-driven parallel robots," *Frontiers of Mechanical Engineering*, vol. 17, p. 37, sep 2022.

[13] R. Prislan, "Microphone positioning using acoustic location," in *Forum Acousticum Lyon*, (Lyon), p. 5, European Acoustics Association - EAA, 2020.

[14] R. Prislan and U. Kavka, "The potential of using a laser scanner to facilitate in-situ room acoustic measurements," in *24th International Congress on Acoustics : proceedings : ICA 2022*, (Gyeongju, Korea), pp. 510–515, oct 2022.

[15] F. Jacobsen and P. Moller Juhl, *Fundamentals of General Linear Acoustics*. 2013.

[16] R. Prislan, J. Brunskog, F. Jacobsen, and C.-H. Jeong, "An objective measure for the sensitivity of room impulse response and its link to a diffuse sound field," *The Journal of the Acoustical Society of America*, vol. 136, no. 4, pp. 1654–1665, 2014.