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SOUND FIELD RECONSTRUCTION IN ROOMS
AND ITS POTENTIAL APPLICATION IN IMPROVING
LOW FREQUENCY ROOM MODES DAMPING

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ABSTRACT
The Electroacoustic Absorber concept developed at EPFL consists of an actuated membrane system functioning as a multi-degree-of-freedom resonator capable of damping multiple room modes in the low frequency range. Originally, the performance of the Electroacoustic Absorbers to damp room modes was assessed through a few local frequency response measurements in the room at different locations. Recently, we have shown that the spatial sound pressure distribution in a complex-shaped room can be accurately reconstructed using a limited number of microphones, allowing a thorough understanding of the acoustics in a room space-wise and frequency-wise. This reconstruction framework opens door to potential application in the field of sound field control and active absorbers in a room. In this communication, we address the structure of the reconstruction framework and analyze its practical performance first in an empty room and then specifically with the presence of the Electroacoustic Absorbers. Afterwards, we can assess the accuracy of the results and suggest potential applications of the reconstruction framework in the future.

1. INTRODUCTION
The understanding of room modes has always been an integral part of room acoustics studies at low frequencies. Due to the coupling with the walls of the room, an uneven distribution of sound pressure both in space and frequency domain is established. Traditionally, one of the most common methods to analyze room acoustics at low frequencies is through the measurement of the Room Frequency Response (RFR). However, RFR measurements at a few scattered location in a room usually cannot provide the whole story, lacking spatial information of the sound field, especially in case of a non-rectangular room. Alternatively, one can study the acoustic of the room numerically through an FEM simulation of the sound field of the room but the accuracy of this method is highly dependent on how precisely designed the FEM model is. Recently, an active control concept of a multi-degree-of-freedom (n-DOF) Electroacoustic Absorber (EA) from EPFL [1] (which consists of a closed-box loudspeakers system with a current-driven feedback control to achieve a target impedance) was proven to effectively treat room modes at low frequencies and overcome several physical difficulties of other passive methods. However, it is also suggested there that the EA's performance could be improved if its control design can be based on an actual reconstructed sound field of the room instead of the simulated one from an FEM model.

In this communication, we provide a solution to overcome these drawbacks by designing a sound field reconstruction framework, which, from a limited number of measurement locations, can recover the enclosed sound field with high resolution and accuracy. The method is focused on exploiting the sparsity that exists in the room acoustics wave solution at low frequencies. The framework is first tested with an empty non-rectangular room to validate its robustness. Afterwards, the reconstruction process is challenged with the presence of 4 EAs at the corners of the room to show that it can be used to analyze the performance of active room treatment methods.

2. RECONSTRUCTION FRAMEWORK
An inherent sparsity of the wave solution of room acoustics at low frequencies lies in its modal decomposition form, where the spatio-temporal solution can be decomposed as a discrete sum of eigenmodes.

\[ p(t, \vec{X}) = \sum_n A_n \Phi_n(\vec{X})e^{j\kappa_n c t} \quad (1) \]

where \( A_n \) is the expansion coefficient, \( \Phi_n \) is the mode shape function and \( k_n = (\omega_n + j\delta_n) / c_0 \) is the complex wavenumber with \( \omega_n \) and \( \delta_n \) respectively as the modal angular frequency and the modal damping factor with \( c_0 \) as sound celerity. Furthermore, from [2], each mode shape function \( \Phi_n \) can be estimated by a finite sum of \( R \) plane waves sharing the same wavenumber \( |k_n| \).

\[ \Phi_n(\vec{X}) \approx \sum_{r=1}^{R} B_{n,r} e^{j\vec{k}_{n,r} \cdot \vec{X}} \quad (2) \]

where the plane wave vectors, representing by \( \vec{k}_{n,r} \) can be produced as a result of the spherical sampling of a sphere with radius \( |k_n| \). Combining Eq. (1) and (2), with \( C_{n,r} = A_n B_{n,r} \) we can now address the spatio-temporal response...
as a finite weighted sum of damped harmonic plane waves:

\[ p(t, \vec{X}) = \sum_{n,r} C_{n,r} e^{i\omega_n t - \delta_n t} e^{j\vec{k}_{n,r} \cdot \vec{X}} \]  (3)

One way to look at this equation is that if the modal parameters (\(\omega_n\) and \(\delta_n\)) and the expansion coefficients of the predefined plane waves can be determined from a series of microphone measurements in the room, then \(p(t, \vec{X})\) can be found by plugging any interested coordinates \(\vec{X}\) into Eq. (3). Transforming this result to the frequency domain, it is possible to reconstruct the sound field in the room at any desired frequency. The reconstruction procedure consists of modal identification and spherical sampling of plane waves is detailed in [3].

Figure 1. Geometry of the FEM model with a fixed source at one corner and a random microphones placement.

3. RESULTS

The reconstruction framework is tested both numerically using an FEM model (Figure 1) of a non-rectangular reverberation chamber and experimentally inside the chamber of the same geometry. Around 20-30 microphones are spread randomly inside the room to take advantage of the sparsity of the wave solution. The sound field is reconstructed for a rectangular volume that is at least 1m from the walls of the room in all directions. Both numerical and experimental results [3] show highly accurate reconstruction of the sound field in an empty room. Not only that the point to point comparison achieves high accuracy but the visual presence of the modal shapes are also correctly depicted. Furthermore, a video describing the frequency sweeping of 15Hz - 70Hz also shows that the reconstruction framework display precisely the transition between the modes of the room as the frequency increases.

Following a successful reconstruction of the sound field of an empty room, four 3-DOF EAs are put in the corner of the room. The reconstruction framework is again performed to see if it is able to record the changes in the resulting sound field. Figure 2 shows the comparison between the reference sound field and the reconstructed one for both an empty room and the room with the EAs. It can be observed that the reconstruction results precisely depict the changes in the room’s sound field. With the presence of the EAs, the overall sound pressure level is reduced and the spatial distribution of sound pressure becomes more equalized. These results show that our reconstruction framework can be used to analyze the sound field of a room through a limited number of scattered measurements. Furthermore, it is proven to be useful in evaluating active room treatment methods through the example with the EAs. From these promising results, one of the future work involves using the information from the sound field reconstruction to actively alter the control of the Electroacoustic Absorbers to enhance its absorption performance.

Figure 2. The spatial sound field for the sixth mode (around 45 Hz) of the reverberation chamber without (left) and with (right) the presence of the Electroacoustic Absorbers are depicted with high accuracy using the reconstruction framework (b) comparing to the reference sound field (a).

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5. REFERENCES

