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SOUND FIELD RECONSTRUCTION: TOWARDS LARGE-SCALE SPATIAL SENSING

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ABSTRACT

Over the last couple of decades, sound field analysis and reconstruction methods have enabled us to observe and better understand diverse acoustic phenomena, from jet-noise to the sound of historical violins. In a broad sense, sound field reconstruction methods consist of capturing the spatial properties of sound, in order to visualize, analyze, reproduce, or manipulate the sound field in various ways. Fueled by advances in instrumentation and signal processing, these methods have had a profound impact in the field of acoustics and have been widely adopted in areas like vibro-acoustics, spatial audio, room acoustics, materials and electroacoustics – among others. In this talk we discuss new approaches for capturing and reconstructing sound fields in space, motivated by some of the longstanding challenges in the field. Specifically, we consider: 1) novel sensing methods, with a focus on optical remote sensing and the acousto-optic interaction, to measure sound using light, 2) physical models for large-scale sound field visualization/reconstruction and 3) Deep Learning approaches for augmenting conventional acoustic measurements. Finally, we share an outlook of this multifaceted and increasingly relevant domain of acoustics.

Keywords: *Sound field analysis, Signal processing, measurement techniques, acoustic holography, room acoustics (3 to 5 keywords separated by a comma)*

1. INTRODUCTION

Sound field analysis and reconstruction methods have granted substantial advances in various areas of acoustics. Broadly, they have been instrumental in problems concerned with the study of sound and the spatio-temporal or spatio-spectral properties of sound fields. Such areas include sound radiation, underwater acoustics, architectural acoustics, audio capture, reproduction, and active control.

The interest in understanding sound through its visualization and experimental analysis goes hand-in-hand with the history of acoustics [1]. Some of the early techniques consisted of Schlieren visualizations, sequential measurements of sound coupled to photographic techniques, and stroboscopic illumination of sources. Despite the value of visualizing sound fields, these early techniques were qualitative in essence, and lacked quantitative information about the sound field. It is with the advent of microphone arrays and digital signal processing, that the analysis and characterization of sound fields became quantitatively accurate. It enabled to observe experimentally, analyze and understand complex sound fields and acoustic problems. Some areas that have driven advances in the field have been sound source localization and beamforming, holography and sound radiation, spatial audio and sound field control. Today, the high availability of sensors and sensing power, combined with increasing computational capacity and advanced signal processing, make of this field an exciting and rapidly evolving area of research.

This talk presents various recent techniques used for the measurement and characterization of sound fields. The research presented is concerned with sensing and reconstruction methods to capture full three-dimensional

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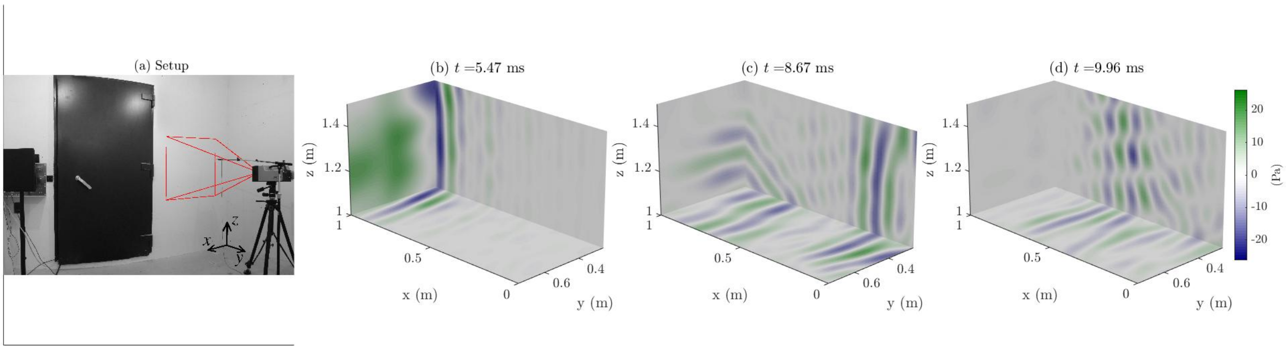

Figure 1. Volumetric measurement of the sound field in a room using remote acousto-optic measurements. Experimental setup showing the scanning laser head and the source (left), and the sound pressure on three of the faces of the reconstruvtion volume, showing the direct sound at 5.47 ms, floor and wall reflections at 8.67 and their interference at 9.96 ms.

acoustic fields over large volumes of space. The approaches discussed are organized into three different lines: 1) Acousto-optic sensing, which enables the non-invasive and remote measurement of sound, 2) Physical models for sound field reconstruction, which take into account specific physical properties of the sound fields to obtain predictions over large apertures, and 3) Deep-Learning techniques for enhancing the characterization of sound fields, via extending the range of validity of spatial and spectral predictions.

This short paper accompanies the corresponding keynote presentation in Forum Acusticum 2023. Parts of the work have previously been published in Refs. [2–4].

2. ACOUSTO-OPTIC SENSING

The acousto-optic interaction describes the phenomena resulting from the interaction between sound and light. When light traverses a sound field, it experiences refraction and retardation effects. The phase shifts induced by sound onto a beam of light, can be measured via optical interferometry, which enables the measurement of sound via a tomographic reconstruction [5–7]. However, conventional tomographic techniques (such as Filtered Back Projection - FBP, or Algebraic Reconstruction Technique - ART) are not well-suited for acousto-optic measurements. Existing tomography methods require that projections are uniformly spaced (as in FBP), which is very limiting in practice, or require very large number of measurements - of the order of millions or trillions (ART, SART, SIRT); totally unfeasible for acousto-optic measurements.

In this talk, we discuss a reconstruction method (introduced in Ref. [2]), which is based on an algebraic reconstruction of the sound field, using elementary wave expansions as an interpolating basis. The approach enables to reconstruct a sound field from arbitrary projections, without explicit Fourier transformations, and it requires far less measurements than conventional tomography methods: it enables to reconstruct complex sound fields with just 10% of the measurements that would be required with conventional algebraic methods (Ref. [2] for details).

Figure 1 shows an example of a an in situ volumetric capture of the three-dimensional sound field in a room. The setup is shown (scanning Laser Doppler Vibrometer, and the measurement aperture outlined by the red pyramid), as well as three time-snapshots of the sound field in a volume. One can observe the direct field at 5.47 ms, two reflections from the ground and the opposing wall at 8.67 ms, and their interference at 9.96 ms. To the authors knowledge, it is the first time that an acoustic field has been measured volumetrically and remotely in such scale. This sensing technique has also been adapted to near-field acoustic holography [8] and sound field analysis in rooms [9].

3. PHYSICAL MODELS FOR SOUND FIELD RECONSTRUCTION

A significant approach for reconstructing sound fields is the use of tailored acoustic wave models. Traditional approaches use elementary wave functions such as plane waves, spherical and cylindrical waves, distributed point

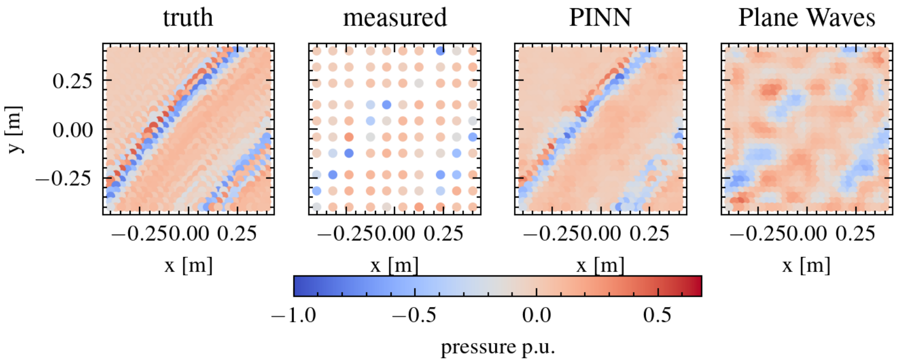

Figure 2. Sound field reconstruction using a Physics Informed Neural Network: Ground truth sound pressure (left); The 100 measurement grid measured over 80 × 80 cm^2 (center left); Prediction of the sound pressure by the PINN, over a continuous spatial aperture (center right); Prediction using a classical plane wave expansion.

sources or boundary element models [10, 11]. In recent years there has been a strong focus on signal processing and sparse reconstruction techniques and probabilistic models for modeling sound fields in space.

In this talk we discuss acoustic reconstruction models developed specifically for reconstructing reverberant sound fields in enclosures. The models aim at capturing the general physical structure of enclosed sound fields, to obtain valid reconstructions over large spatial domains. Some of the properties that generalize well across rooms are: a) the marked modal structure at low frequencies [12, 13], b) the increasing modal density with the square of frequency [14], c) the time domain structure consisting of direct sound, early reflections and late reverberation [3], d) the increasing reflection density with the time squared and e) the classical exponential decay of sound - either conformed by single or multiple decays. As an example, the model presented in [3] enabled to extrapolate the sound field from a measurement aperture of 0.50 m and 48 measurement points, into a reconstruction domain of 4.60 m, showing remarkable predictive capacity (specific results are omitted for brevity).

4. DEEP-LEARNING RECONSTRUCTION

In recent years, the use of data driven approaches and deep learning methods has become widespread for sound field analysis and reconstruction, showing great potential for spatial estimation / characterization of sound fields.

We discuss Deep Learning models for extending the valid frequency range of sound field reconstruction problems. Specifically, we examine generative models (Generative Adversarial Networks) which are trained to extend the bandwidth of the reconstructed signals. [4, 15] The goal is to overcome, or alleviate, the inherent band limitation of the reconstruction problem due to spatial discretization (typically band limited between a few hundred Hertz due to the finite aperture, and a few KiloHertz due to the inter-spacing between transducers). Deep generative models enable to enhace the frequency range of microphone array measurements, without requiring additional hardware or measurement effort [4].

We also examine Physics-informed Neural Networks (PINNs) to solve the inverse problem, i.e., reconstruct a sound field from a limited set of measured data. We present a PINN that predicts the sound pressure $p_\bullet(\mathbf{r}, t)$ at any position and time, based on a set of incomplete observations $\tilde{p}(\mathbf{r}_m, t_n)$. The PINN is a multi-layer perceptron network of 5 layers of 512 neurons with a sine function applied as the non-linearity and the last layer with a solitary neuron with linear activation. Figure 2 shows an example of the results obtained from experimental real data in a room. The true field and measured field are shown. It is apparent that the spatial sampling is insufficient to accurately represent the sound field. The PINN is able to train on these 100 measured data points, and obtain a good prediction (it is a grid-less predication that can be evaluated anywhere in the domain of interest). A classical plane wave reconstruction is also shown, where the wavefronts are not correctly reconstructed due to spatial undersampling.

5. CONCLUSIONS

This short paper outlines a few recent advances in sensing methods, physical models and deep learning for sound field reconstruction. These are mostly concerned with sound field reconstruction for reverberant fields in enclosures, with a specific focus on acousto-optic sensing methods, physical sound field models, and Machine learning with generative models and Physics-Informed Neural Networks.

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