MULTIFUNCTIONAL COMPACT ACOUSTIC ARRAY AND MACHINE LEARNING ALGORITHM FOR MEASURING THE SURFACE IMPEDANCE IN-SITU

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Estimating the in-situ acoustic properties of sound elements, such as sound absorbers, is absolutely crucial for practical acoustic diagnosis and as input for acoustic simulations. We propose a compact microphone array that can sample local sound field in the vicinity of a surface of interest. The measured pressure data are used to infer the broadband surface impedance through a physics-informed neural field framework. A parallel frequency-stacking architecture is used to reconstruct a broadband surface impedance within runtimes on the order of seconds to minutes. The system is calibrated and validated through both laboratory and real-world experiments, demonstrating reliable estimation of impedance and sound absorption under realistic conditions. The proposed approach provides a robust method for characterizing in-situ boundary conditions in architectural acoustics.

Keywords: acoustic array, room acoustics, surface impedance, absorption coefficient, physics informed machine learning

1. Introduction

The characterization of the acoustic properties of materials, specifically the surface impedance and absorption coefficient, is a fundamental challenge in architectural and environmental acoustics. While standardized laboratory methods, such as the reverberation room method, e.g., ISO 354 [1], and the impedance tube method, e.g., ISO 10534-2 [2], are common ways to quantify the acoustic properties, they often fail to capture the boundary conditions of "as-installed" performance of materials in real-world environments. The ISO 354 method employs Sabine's reverberation time equation to determine only the energy absorption properties of a specimen, rather than its surface impedance. ISO 354 measurements require reverberation chambers, where numerous diffusers are typically installed to promote a more uniformly distributed, though not perfectly diffuse sound field [3-6]. It is well known that such distributed sound incidence tends to increase the measured Sabine absorption coefficient compared to conditions without diffusers, e.g., see Ref. [7]. Consequently, the Sabine absorption and practical absorption coefficient measured in reverberation chambers can be interpreted as representing the upper-bound of achievable absorption performance of a specimen under idealized conditions. Therefore, the effectiveness of the absorber in real-world conditions is likely to differ from the lab test results. The impedance tube method is also based on rather unrealistic assumptions, such as plane wave incidence at normal direction to the surface of interest, which is a highly simplified and unrealistic scenario for sound fields in real three-dimensional environments.

Therefore, neither of them represents the absorption properties of installed absorber in practical cases, such as homes, offices, classrooms, performance spaces, and recreational spaces, etc. Furthermore, the poor inter-laboratory reproducibility shown in, e.g., Ref [8-9], inherent in ISO 354 measurements necessitate the development of robust and more reproduceable methodologies. This paper presents a development and validation of a combined hardware and software system: a multi-functional acoustic array designed for high-quality acoustic data acquisition and a software that can analyse the obtained pressure data near the surface of interest to extract the acoustical properties in forms of surface impedance and absorption coefficient of the surface. We will focus on the repeatability and robustness of the combined system in inferring the acoustic properties in various reverberation conditions.

2. Method

2.1 Measurement systems and software

The hardware consists of a calibrated micro-electro-mechanical system (MEMS) microphone array, configured as a 3×3 grid of high-quality sensors (AHS0604ST, AAC). In the current hardware used here, the data acquisition board supports a sampling rate of 32 kHz with 24 bits. A novel computational framework based on Physics-Informed Neural Networks (PINNs) was developed for inferring the surface properties [10]. Unlike purely data-driven models, PINNs incorporate the governing Helmholtz equation directly into the neural network's loss function, ensuring that the predicted sound fields remain physically consistent. This physics-informed approach allows for the reconstruction of the 3D sound field near the surface and subsequent extraction of surface impedance thanks to automatic differentiation that enables the estimations of the particle velocity as well as the pressure values [11,12]. Magnitude calibration of the array microphones was performed using a newly developed calibration method against a quarter-inch reference microphone (Type 4191, Bruel & Kjær), whose free-field sensitivity is traceable to the Danish Primary Laboratory of Acoustics (DPLA). Phase calibration was also performed, assuming ideal channel synchronization. A spherical sound source driven by a speaker (10F, Scan Speak) was employed for the calibration. The sound source was placed at about 2.5 m from the array and the reference calibration microphone [13].

Following calibration, in-situ surface absorption measurements were conducted. Sound pressures were measured at two positions of the microphone array, located 20 mm and 50 mm from the surface, resulting in a total of 18 pressure points using the 3×3 array. At each array location, nine sound pressure values were recorded using a sufficiently loud exponential sine sweep signal with a duration of 5 s, covering the frequency range from 80 Hz to 4050 Hz. The corresponding spectra were obtained by applying a Fast Fourier Transform (FFT) to the measurements from all 18 microphone positions. The input data to the parallel frequency-staking neural network consisted of approximately 200 linearly spaced frequency bins selected from the averaged spectra between 130 Hz and 4000 Hz to estimate the acoustic properties up to the octave band from 125 Hz to 4 kHz. However, note that the 125 Hz and 4 kHz octave bands are not fully characterized, leading to a higher uncertainty then the rest of the frequency bands. This system is called ATLAS [14] and is shown in Figure 1.

2.2 Rooms and sound absorber tested

Unlike the laboratory measurements, two decisive factors determine the in-situ performance of an absorber in practical applications: the characteristics of the room in which it is installed and the mounting configuration. To investigate these effects, measurements were conducted in two rooms with distinct reverberation conditions, characterized by mid-frequency T30 values (500 Hz - 2000 Hz) of approximately 0.4 s and 5.5 s, respectively. The former corresponds to a typical room with dimensions of 9.4 m × 6.6 m × 3.0 m, representing a small- to medium-sized or residential acoustic environment, which is referred to as normal room. The latter is a reverberation chamber designed for ISO 354 measurements, with a volume of 215 m^3. Since excessive reverberation is known to pose challenges for in-situ measurements, the latter case serves as a stringent test of the proposed measurement system under extreme conditions. At the same time, it provides an opportunity to demonstrate the usability of ATLAS under diffuse sound incidence in reverberation chambers. Photos of the rooms are shown in Figure 2.

Two types of absorbers were evaluated: a porous absorber with high absorption performance for a broad frequency range (Industry Modus, Ecophon, size 1200 mm × 600 mm) and a perforated gypsum panel (Tile Quattro 20, Gyptone, size 600 mm × 600 mm) with an overall depth of system (ODS) of 200 mm with 100 mm glass wool inside the cavity. These absorber types are commonly employed to mitigate excessive reverberation and noise issues across a wide range of rooms and building applications. The speaker to generate the sine sweep signal is a 4-inch loudspeaker from Scan Speak, which is known to have a flat spectrum above 150 Hz. In all measurements, the loudspeaker is positioned approximately 400 mm from the microphone array mainly to achieve a high SNR, but the loudspeaker in real life condition can be anywhere as long as sufficient SNR is ensured. Due to this relatively short distance, the sound field is likely dominated by near-normal incidence at the array.

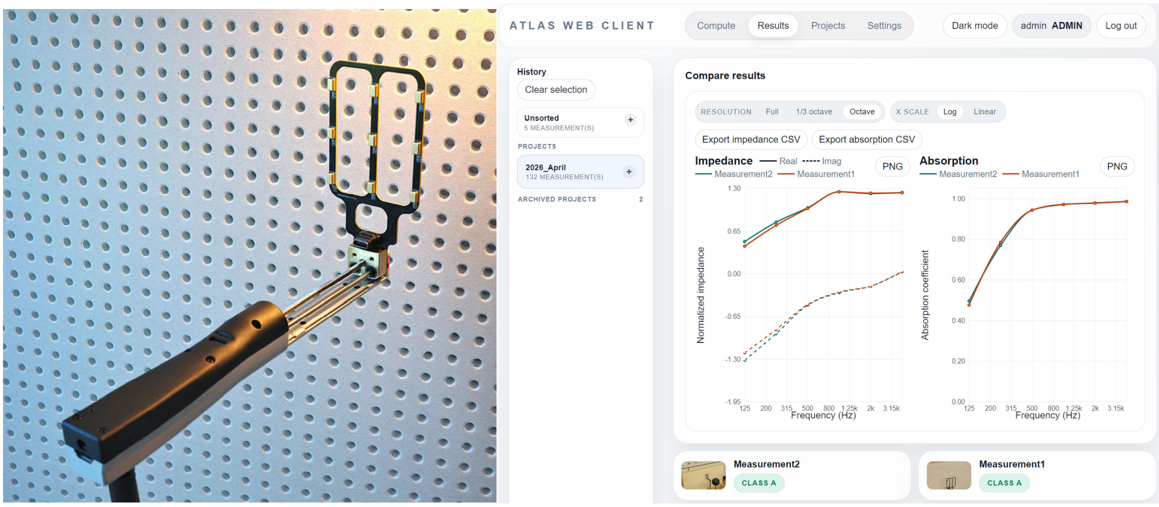

Figure 1: ATLAS microphone array 3×3 configuration (left) and Web client snapshot (right).

Figure 2: Reverberation chamber (left) and normal room (right).

2.3 Performance measures

The primary metrics quantified in this study are the surface impedance, Z_s, defined as the ratio p/v at the absorber surface, where p denotes the acoustic pressure (Pa) and v represents the particle velocity of air in the normal direction, and the corresponding absorption coefficient. As the measurements are conducted under in-situ conditions, no exact reference values are available. Nevertheless, ISO 354 reverberation room data (often provided by manufacturers in the form of the practical absorption coefficient, α_p) and empirical model predictions, such as Miki's model [15] for porous absorbers, are included for comparison.

Using the selected performance measures, the robustness of the system is evaluated. Specifically, the system is expected to produce consistent results under unchanged room and ambient conditions. To evaluate this, five repeated measurements were performed, and the variability among them was analyzed. It is hypothesized that larger deviations will occur at low frequencies, primarily due to reduced signal strength caused by the loudspeaker roll-off, higher noise levels associated with MEMS microphones, and increased background noise typically present in this frequency range.

3. Results

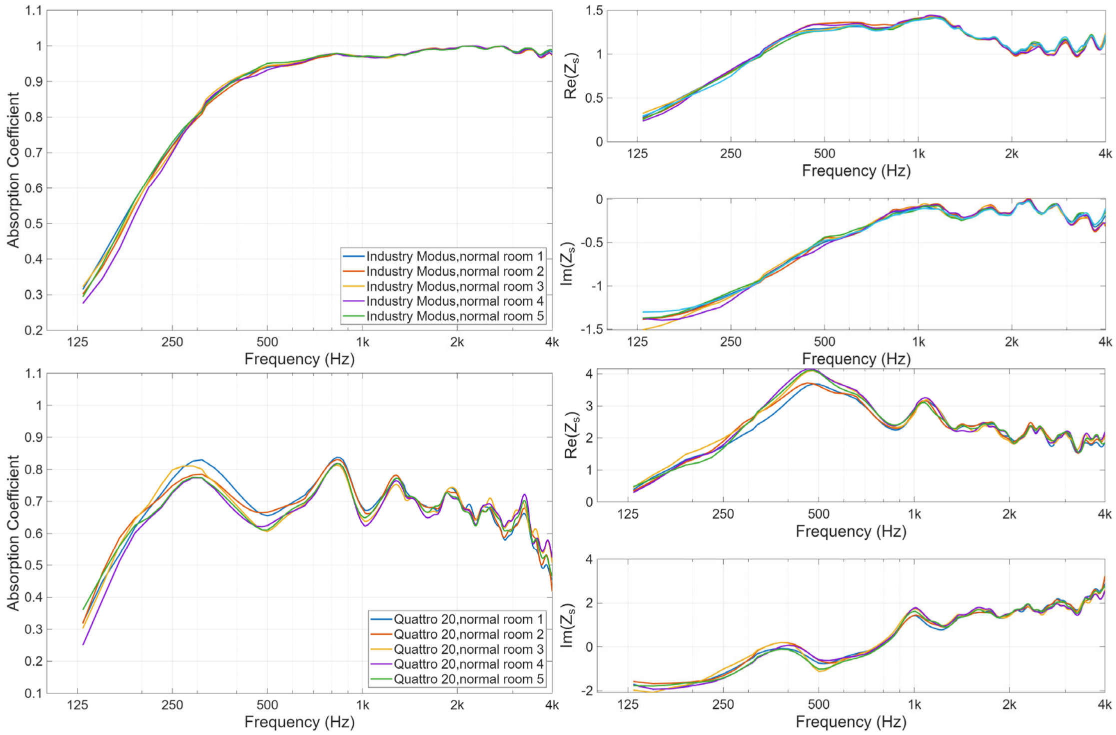

Figure 3: Repetition of five measurements under normal room condition, (Top) Porous, (bottom) Gypsum.

Figures 3 shows the surface impedance and absorption coefficients from five repeated measurements of two absorbers conducted under the normal room condition. Overall, the absorption coefficients and surface impedance values show generally excellent consistency across the repeated measurements. The spread for the porous absorber is much smaller than that for the perforated absorber. As expected, slightly larger deviations are observed at lower frequencies, but the maximum deviation in the absorption coefficient for the porous absorber is as small as 0.02 from the mean value even at 125 Hz.

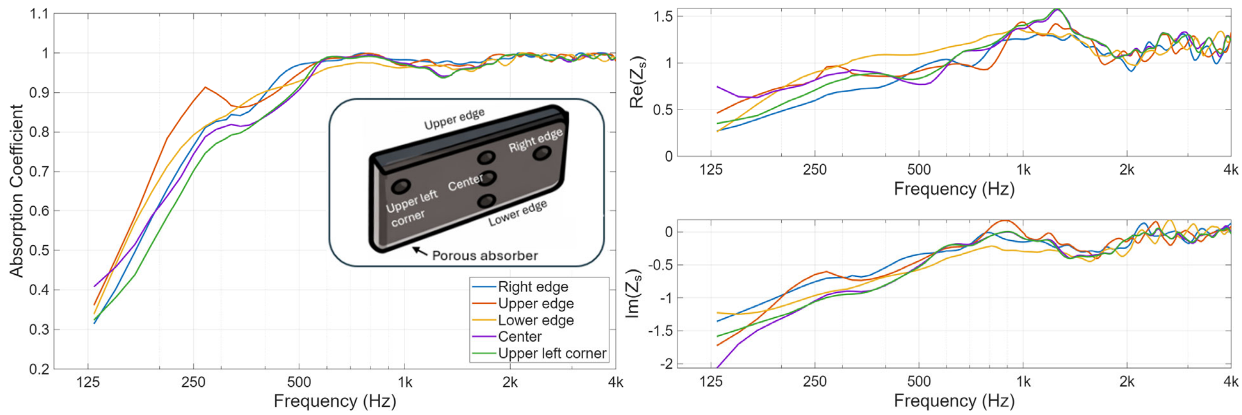

Figure 4: Five different location measurements for the porous absorber under normal room condition.

Figures 4 shows the surface impedance and absorption coefficients of the porous absorber sampled at different locations under the normal room condition. Naturally larger deviations for different measurement locations are shown than the same location measurements shown in Figure 3. The maximum deviation of absorption coefficient is found at 250 Hz, with absorption coefficient varying from 0.70 to 0.85. Particularly the upper edge position predicted the higher absorption than the other locations. Above 500 Hz, Similar absorption coefficients are estimated, converging to the expected value.

Figure 5 shows a comparison between the porous absorber measurements and available reference data, including the practical absorption coefficient, α_p, provided by the manufacturer, as well as the normal- and random-incidence absorption coefficients calculated via Paris's law [16] with the Miki model using the manufacturer's flow resistivity values for each octave band. The mean values of ATLAS data are presented as solid lines with data point markers, with the standard deviation indicated by shaded regions. Overall, the measured values agree well with the calculated absorption coefficients with larger deviation at low frequencies. A similar trend is observed for the surface impedance, where the measurement results follow the Miki model reasonably well above 250 Hz. The practical absorption coefficient is consistently overestimated across all frequencies, which can be associated to known limitations of the reverberation chamber measurements, including deviations from ideal isotropy conditions in reverberation chambers [6] and the effect of finite-sized specimens [17].

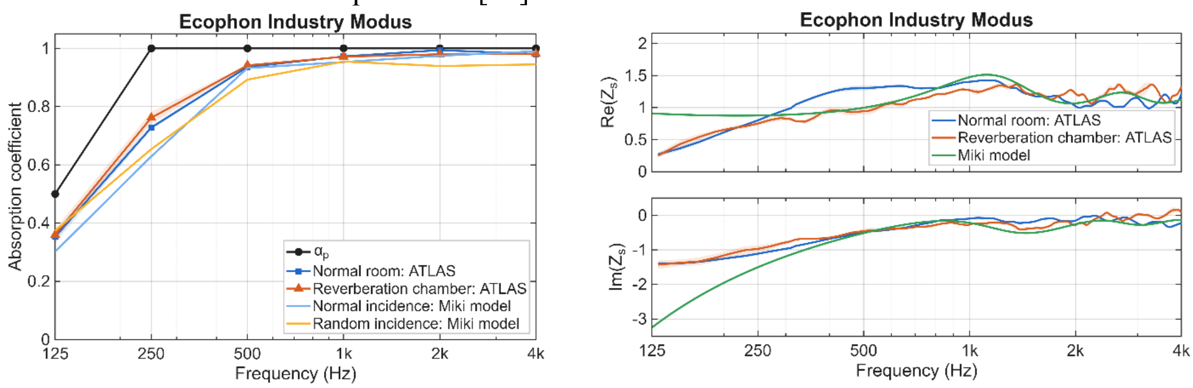

Figure 5: Comparison of absorption coefficient and surface impedance of the porous absorber among ATLAS measurements, practical absorption coefficient, and Miki-model predictions.

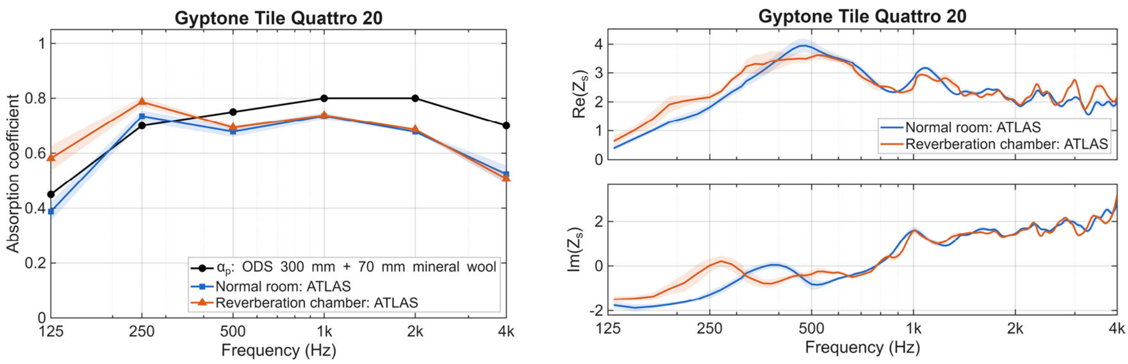

Figure 6: Comparison of absorption coefficient and surface impedance of the perforated absorber among ATLAS measurements and practical absorption coefficient.

Figure 6 compares the absorption characteristics of the measured perforated absorber. Note that the manufacturer does not provide the practical absorption coefficient for the exact configuration here (ODS of 200 mm and 100 mm thick glass wool). Therefore, the closest available dataset was used for comparison, corresponding to an ODS of 300 mm with 70 mm thick mineral wool. Overall, the ATLAS measurements are in reasonable agreement with the practical absorption coefficients. However, a noticeable overestimation is observed in the 125 Hz and 250 Hz band for the reverberation chamber measurements. This behaviour may be caused by either an insufficient SNR due to the limited output of the loudspeaker, or by elevated background noise during the measurement. This is further reflected in the increased standard deviation observed in the reverberation chamber results.

4. Discussions

The new in-situ measurement system is highly useful for day-to-day consulting work, enabling the identification of problematic absorbers, such as user-painted porous absorbers or insufficient mineral wool filling behind perforated panels, in a non-destructive manner. In fact, the real-world performance of absorbers is often unknown and compiling data from actual installations together with laboratory measurement data would provide valuable insight into how and where to install the absorbers.

The inferred surface properties can be exported to room acoustic simulations, particularly wave-based numerical models, such as COMSOL [18] and TREBLE [19], which require surface impedance as an input, a parameter that is currently often unavailable. Geometrical acoustics methods can also benefit from the proposed measurement system through improved boundary condition characterization.

Manufacturers of absorbers can use this system for quality assurance at the end of the production process or during the product development stage, enabling rapid iteration of design parameters. As sustainability becomes increasingly important, many manufacturers aim to reuse existing absorbers. This system can also support quality assurance by helping determine whether such absorbers remain suitable for reuse.

The current version of the device is relatively easy to set up, requiring a single USB-C connection to a laptop and supporting Bluetooth control and file transfer. Each characterization takes approximately one minute, including two sine sweep recordings of five seconds each and subsequent inference of the surface properties on a cloud server. This is a significant advantage over conventional laboratory methods, such as reverberation chamber and impedance tube measurements for which cutting or preparing a large sample is often time-consuming and challenging. The results are stored on a cloud server and can be accessed remotely via smartphones and other portable devices.

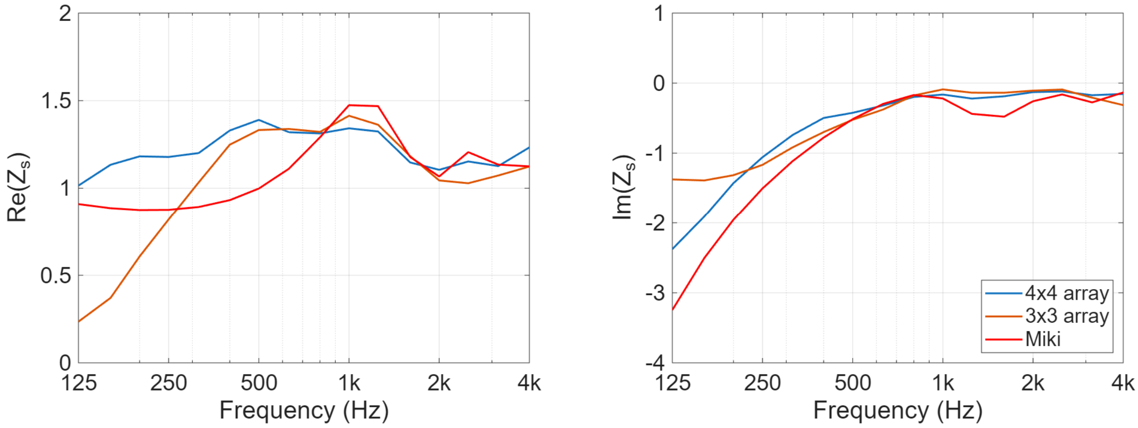

Figure 7: Comparison of surface impedance of the porous absorber among ATLAS measurements and Miki model.

Although it is not thoroughly reported here, a calibrated 4×4 array with MEMS microphones having higher inherent noise was tested. For the porous absorber, the surface impedance result is compared between the 3×3 and 4×4 configuration in Figure 7. It is quite remarkable that the 4×4 array captures the low frequency range quite accurately with a flatter curve in the real part of the surface impedance, and lower values in the imaginary part as well, compared to the 3×3 configuration.

5. Conclusions

A novel MEMS microphone-based array was developed, and its performance was evaluated for inferring in-situ absorption properties of absorbers using physics-informed neural networks. With a 3×3 array, pressures at only 18 points near the surface are sampled, which are used as training data, together with the governing equation, resulting in a successful estimation of the surface impedance at the surface of interest. The reliability of the system was assessed with repeated measurements under practical conditions. The in-situ absorption properties are compared with the practical absorption coefficients and empirical model predictions, demonstrating that noise-included real-life measurement data can be used to successfully infer the relevant acoustic properties via a novel PINNs-based method in the frequency range between 125 Hz to 4000 Hz.

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