Accessible Acoustics: Cost-Efficient Methods for Sound-Driven Architectural Design

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Abstract

In recent years, architectural design has increasingly emphasized performance-based approaches alongside formal and spatial considerations, yet acoustics, despite their central role in spatial experience, remain under integrated due to limited access to iterative, accessible evaluation tools. Conventional acoustic testing depends on costly physical apparatuses or computational simulations limited by standardized material datasets, underscoring the need to rethink accessible methods and prompting the question: how can iterative, resource-efficient processes enable more precise, adaptable control of aural qualities in architectural-design?

Addressing this gap, Accessible Acoustics introduces an impedance tube system using off-the-shelf components, enabling rapid material-based prototyping and embedding acoustic evaluation within early-stage design workflows and education. Built for under $600, it consists of PVC piping, a full-range speaker, precision microphones, and a two-channel audio interface, coupled with a custom MATLAB script. The system automates logarithmic sine sweep generation (80–6300 Hz), dual-channel signal acquisition, and absorption coefficient calculation using frequency-domain transfer function methods. To validate accuracy, the setup is calibrated against ASTM E1050-12 through comparative testing with a Brüel & Kjær Type 4206 impedance tube. Statistical analysis and correction curves align the custom system's output with industry standard results, demonstrating reliable performance.

Beyond technical validation, the project positions acoustic measurement as both a design and pedagogical tool, establishing a foundation for data-driven, performance-based workflows. By enabling rapid iteration and direct testing of non-standard material assemblies, Accessible Acoustics functions as both evaluation and representation, informing comparisons, refinements, and sound-driven design strategies.

Keywords: *data-driven, material, computation, pedagogy.*

1. Introduction

As architects gain greater computational proficiency, they increasingly integrate performance feedback into the design process (Hensel and Menges, 2008), either by adopting existing analysis software or by developing custom analytical tools tailored to specific design needs (Peters, 2010). Considering the history of architectural design of sound, for much of the past 2,500 years, architects have relied on empirical knowledge to guide the design of a building's acoustic qualities (Addis, 2009). Between the 1930s and 1970s, advancements centered on refining techniques that enabled the creation of smaller and, consequently, more cost-effective models (Rindel, 2002). The primary function of a physical scale model is to investigate acoustic phenomena such as reflection sequences, as well as to analyze diffusion and diffraction (Gade, 2006).

Currently, the assessment of acoustic performance in architectural design is predominantly conducted through two primary methodologies: computational simulation and physical scale modeling. Computational simulation methods rely on wave-based methods such as finite element method (FEM), the boundary element method (BEM), and the finite-difference time-domain method (FDTD) or ray-based methods (Cox and D'Antonio, 2009; Badino et al., 2020). Wave-based methods numerically solve the wave equation, requiring the discretization of the room's volume or its boundary

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surfaces to capture interactions among all resulting elements. While highly accurate, these approaches are computationally demanding. In contrast, ray-based methods assume sound propagates along straight-line paths, with reflections calculated through geometrical principles. Each technique offers distinct strengths, and together they enable the study of different facets of acoustic performance in architectural spaces. Although these tools support the design process by allowing formal exploration, they offer only limited capacity to investigate how material properties shape acoustic behavior. Most commercially available simulation software is restricted to libraries of conventional building materials (such as glass, plywood, plaster, etc.), with pre-defined acoustic coefficients.

In physical scale modeling, two standardized methods are commonly used to evaluate the sound absorption of materials: the diffuse-field reverberation room method (ASTM C423) and the impedance tube method (ASTM E1050). ASTM C423 utilizes a diffuse-field reverberation room to measure absorption, providing the basis for calculating the Noise Reduction Coefficient (NRC). Reflecting real-world, random-incidence fields, this method is considered the industry standard for product testing and marketing purposes. However, it requires large material samples and is costly to perform. In contrast, ASTM E1050 uses an impedance tube to measure absorption at normal incidence (Beranek, 1942). While the results cannot be directly compared with those of ASTM C423, this method is significantly more cost-effective and requires only small material samples. For this reason, ASTM E1050 is widely used for engineering and research comparisons.

While physical models offer a tangible and reliable means of evaluating acoustic behavior, they are often prohibitively time-consuming and costly, for research purposes, with the fabrication and measurement of a single design iteration frequently requiring several months. As a result, their application is typically reserved for projects in which acoustics are a central concern, such as concert halls and auditoria (Siltanen, 2010). As a result, acoustics is frequently considered late in the design process, diminishing its potential to shape form and material choices.

In this context, *Accessible Acoustics* aims to introduce a low-cost impedance tube system designed to democratize acoustic testing for experimental and pedagogical use. Constructed from readily available, low-cost components, the system incorporates a custom MATLAB workflow for automated data acquisition and analysis. The setup is calibrated following ASTM E1050 procedures, and its measurement accuracy is verified using correction curves and statistical validation, providing reliable performance for iterative design and material evaluation. The following sections outline two key components of the experiment: Materials and Methods (including Design and Fabrication, Data Acquisition, and Data Analysis and Calibration) and Acoustic Recalibration.

2. Materials and Methods

Several commercial systems are available for measuring the acoustic properties of materials, including both sound absorption and transmission loss, in accordance with established testing standards. Among these, the Brüel & Kjær Impedance Tube Type 4206 is widely regarded as the industry benchmark due to its high accuracy, reliability, and widespread adoption in acoustic research and testing. In this study, the sound absorption coefficient of the fabricated materials is determined following the ASTM E1050 standard. Fig 1 presents the schematic configuration of the impedance tube used for these measurements.

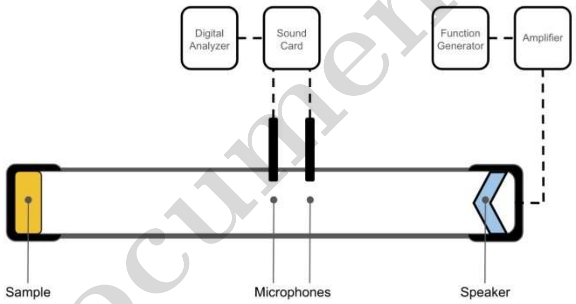

Figure 1. Schematic diagram of an industry-standard impedance tube with rigid termination to measure the absorption coefficient.

2.1 Design and Fabrication

Based on the conventional impedance tube configuration, the prototypical system consists of standard PVC tubing, a full-range loudspeaker, precision microphones, and a two-channel audio interface, built for under $600. A laptop running a custom MATLAB script is utilized to perform automated data acquisition and analysis. Fig 2 and Table 1 summarize the system components and the overall impedance tube configuration.

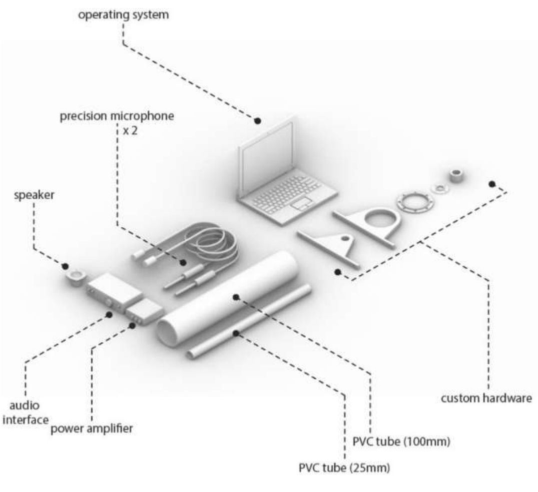

Figure 2. Components of the designed impedance tube setup.

Table 1. List of components for the designed impedance tube.

Tube Part	Part Description	Count	Cost ($)
Sound Source	Dayton Audio ND65 Driver	1	35
Microphone	PreSonus Microphone	2	250
PVC Tube	4” & 1-½” Diameter, 4’ Length	4	35
PLA Flange & Endcap	3D Printed or Standard PVC fixtures	2	20
Sound Card	Focus Rite Scarlett 2i2 Audio Interface	1	230
Hardware	Nuts, bolts, and adhesive	n/a	25

The assembled setup integrates the described components into a two-tube configuration that accommodates distinct frequency ranges. The dimensions of the two impedance tubes mirror those of standard industrial impedance tubes. They replicate the distance between the sound source and microphones, ensuring comparable measurement conditions (Fig 3).

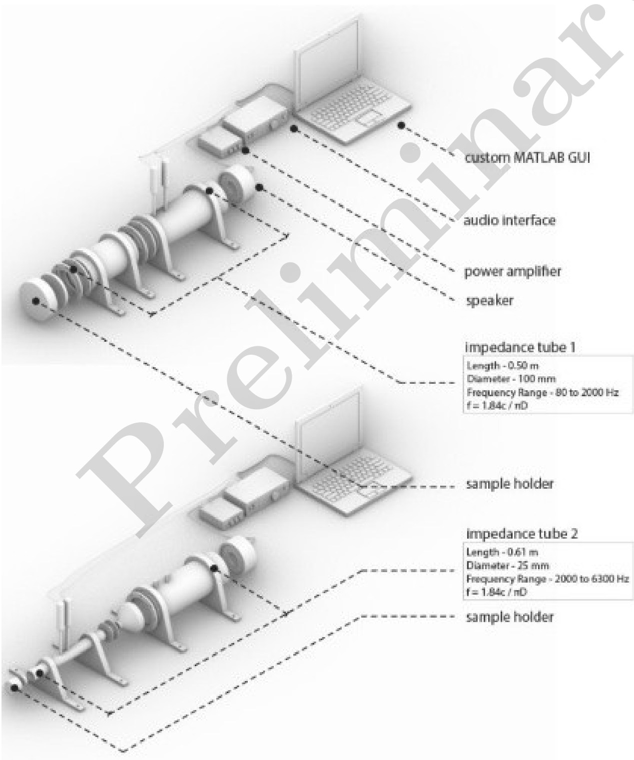

Figure 3. Proposed design of the impedance tube setup and variations for the frequency range.

Impedance Tube 1 uses a PVC pipe 0.5 m in length and 100 mm in diameter, suitable for testing within the 80–2000 Hz range. Impedance Tube 2 employs a smaller PVC pipe, 0.61 m long and 25 mm in diameter, optimized for higher frequencies between 2000 and 6300 Hz. To minimize external noise and signal loss, the tube is wrapped in glass fiber and sealed with 3D-printed fittings. Together, these two configurations allow the system to capture a range of audible frequencies with a workflow like a commercial testing apparatus.

2.2 Data Acquisition

The built impedance tube is integrated with a custom MATLAB GUI for automated data acquisition and analysis (Fig 4).

Figure 4. Excerpt of data acquisition workflow using the custom graphic user interface with the built impedance tube.

The data acquisition and analysis process follows a structured, automated sequence controlled through the custom MATLAB interface. The process integrates sound generation, signal acquisition, and real-time processing to compute the acoustic parameters. The following subsection outlines the automated workflow implemented for the impedance tube measurements. The individual steps of the methodology are described below.

2.2.1 Generate a Logarithmic Sine Sweep

The MATLAB workflow generates two identical sound tests. The first measures baseline conditions in the empty tube, and the second records responses with the material sample in place. A sweep between 80 and 6300 Hz played through a full-range speaker while two precision microphones simultaneously record the incident and reflected signals. The MATLAB script automates this process, controlling playback and synchronized dual-channel recording via a 44.1 kHz, 16-bit sampling rate.

2.2.2 Retrieve and Save Microphone Data

The recorded signal is separated into two channels—Microphone 1, capturing the incident wave before the sample and Microphone 2, capturing the reflected wave after it, and both are saved as .wav files for subsequent analysis. This process is carried out with the empty tube and once the material sample is placed. Fig 5 illustrates the system coordinating sound generation and recording.

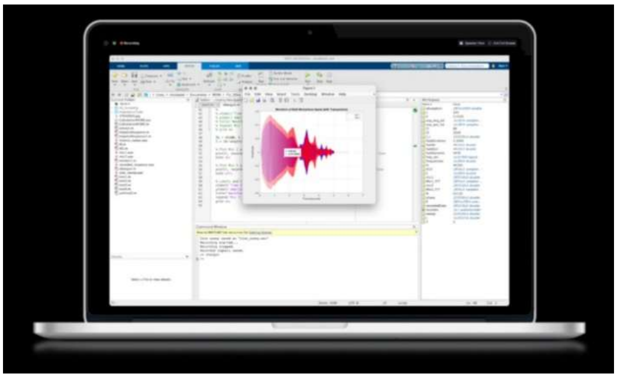

Figure 5. Excerpt of data acquisition workflow using the custom graphic user interface with the built impedance tube.

2.2.3 Compute Fast Fourier Transform (FFT)

The recorded waveforms are transformed into the frequency domain using a Fast Fourier Transform (FFT) to compute the transfer function between the two microphone positions. From this relationship, the complex reflection coefficient is derived, capturing the proportion of reflected to incident sound energy. The normal-incidence absorption coefficient (α) is then calculated as $\alpha = 1 - |R|^2$, representing the fraction of energy absorbed by the test specimen at each frequency. Fig 6 illustrates the MATLAB workflow for calculated absorption coefficients.

Figure 6. Excerpt of data calculation using the custom graphic user interface with the built impedance tube.

2.2.4 Retrieve and Save Microphone Data

The final step of the Data Acquisition process plots the absorption curve across the audible spectrum, yielding a quantitative profile of the material's acoustic performance under standardized conditions.

2.3 Data Analysis and Calibration

While the prototypical impedance tube and data acquisition system performed effectively, it was important to compare its results with those from a professional laboratory setup to assess accuracy and reliability. Two 3D-printed material specimens were designed and fabricated to demonstrate distinct material properties (Fig 7).

Figure 7. Distant view of selected material samples (Left: Plastic fiberboard and Right: Plastic flatboard).

The specimens were subsequently evaluated using both the prototypical impedance tube and an industry-standard testing apparatus, a Brüel & Kjær Type 4206 impedance tube to compare their acoustic performance and validate the proposed measurement approach (Fig 8).

Figure 8. Selected material samples at Riverbank Testing Laboratories.

The results from both test configurations were compared to assess the correlation between the prototypical impedance tube and the industry-standard testing apparatus (Fig 9). While the low-cost apparatus proved effective for comparative analysis and iterative design exploration, it consistently reported higher absorption coefficients than the reference system. One possible source of deviation was the attenuation of sound energy due to minor air gaps in the setup and uncontrolled variations in testing conditions.

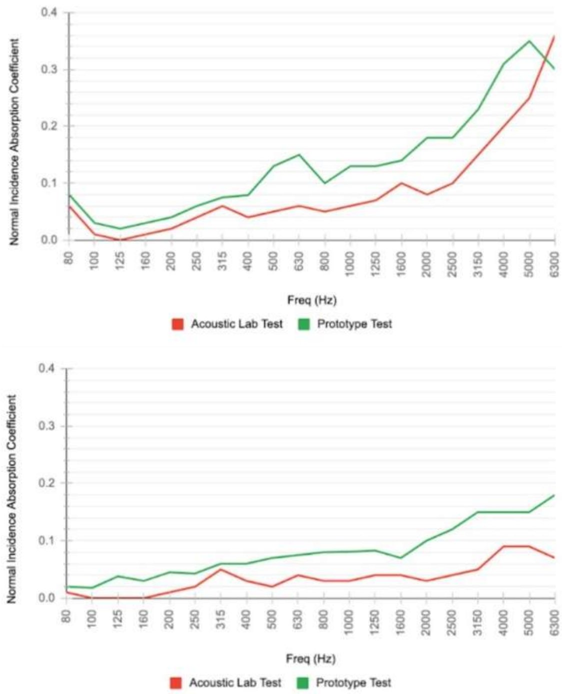

Figure 9. Comparison of acoustic-lab and custom-built impedance tube test results (Top: Plastic fiberboard and Bottom: Plastic flatboard).

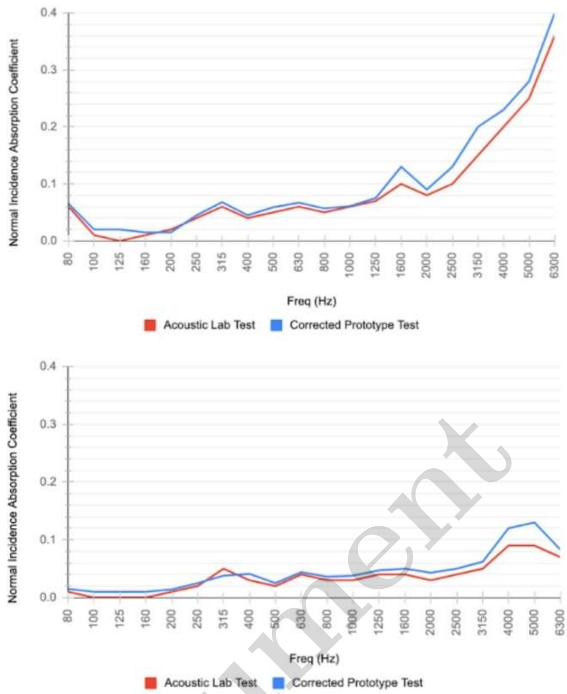

Figure 10. Comparison of recalibrated acoustic-lab and custom-built impedance tube test results (Top: Plastic fiberboard and Bottom: Plastic flatboard).

3. Acoustic Recalibration

To recalibrate the low-cost setup, absorption coefficient data from both systems were compared using statistical metrics, and correction curves were integrated into the MATLAB script to improve measurement accuracy. Fig 10 compares the custom-built system after applying the correction coefficient with the standardized systems, highlighting their alignment.

To ensure consistency and minimize environmental interference, measurements using the proposed system were conducted in rooms with ambient sound levels below 60 dB. The results demonstrate an increased effectiveness of the system in aligning the custom setup's outputs with those of the standardized apparatus.

4. Conclusions

The developed *Accessible Acoustics* framework combines accessible off-the-shelf components with computational workflows to facilitate rapid iteration, enabling the evaluation and refinement of material designs based on their acoustic performance. Beyond technical validation, the research demonstrates that low-cost instrumentation can generate meaningful, repeatable acoustic data while lowering barriers to participation. It reframes measurement as a design medium rather than solely a verification tool, enabling designers to engage material behavior, formulate new inquiries, and build iterative feedback loops. computational interface linking material pedagogical platform, and experimentation with architectural curation and decision-making. By lowering the economic threshold required to generate acoustic data, the research situates itself at the intersection of design computation, collective intelligence, and digital commons. It proposes future open-source dissemination of its hardware specifications and calibration methods, framing acoustic measurement as a shared resource rather than a proprietary capability. As tools become more accessible, experimentation becomes more distributed, enabling emergent forms of collective intelligence. The project ultimately frames computational tools not only as instruments of analysis, but as infrastructures for participation that broaden collaboration among designers, educators, researchers, and communities in sound-driven architectural design.

5. Acknowledgments

This work was funded by the 2025 Ventulett NEXT Fellowship at Georgia Institute of Technology, School of Architecture and 2023–25 Ann Kalla Professorship at Carnegie Mellon University, School of Architecture. The authors are grateful to Zackery Belanger and Shahin Vassigh, for sharing invaluable insights and Catie Newell, for continued mentorship.

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