The Design and Creation of the Texas Christian University Impedance Tube

THE DESIGN AND CREATION
OF THE TEXAS CHRISTIAN UNIVERSITY
IMPEDANCE TUBE

by

Claire Elrod

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OF THE TEXAS CHRISTIAN UNIVERSITY

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Project Approved:

Supervising Professor: Hubert Seth Hall, PhD

Department of Engineering

Robert Bittle, PhD
Department of Engineering

Michael Faggella Luby, PhD

Department of Teaching and Learning Sciences

ABSTRACT

The two-microphone impedance tube test method is a well-established and widely used technique for determining the acoustic absorption coefficient of materials. This method uses two closely spaced microphones to simultaneously measure the incident and reflected sound waves. A two-microphone impedance tube measurement system made of 6061-T6 Aluminum with a diameter of 3 inches, a 0.5 inch wall thickness, and microphones spaced 2.7 inches apart has been constructed for undergraduate research at Texas Christian University (TCU). These geometrical values suggest a usable frequency range of 50 Hz to 2637.77 Hz as referenced in ASTM Standard E1050-19. Validation of the system was achieved by taking measurements on Owen Corning Type 705 pressed fiberglass board with a 1-inch thickness and comparing them to absorption data provided by the manufacturer. Additional validation measurements were taken without a test sample in place. All validation tests suggest that the TCU impedance tube is an accurate measurement system.

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INTRODUCTION AND MOTIVATION

This paper outlines the process taken to successfully design, construct, and test a two microphone impedance tube. An impedance tube is a device that is used to measure the absorption coefficient and the impedance of a material. It is the most commonly used device to measure these characteristics because it allows for the measurements to occur in well-defined and controlled conditions [1]. Another benefit to the impedance tube is that it has a relatively simple design, meaning there is a straightforward method to customize the device to the desired parameters. Each one corresponds to a geometric property of the tube itself, which are all defined in the ASTM E1050-19 Standard, so it is easy to design to the needed specifications. There are two main types of impedance tubes, ones that use a single microphone and ones that use multiple microphones. Both operate on the same basic principles but, the single microphone impedance tube can only test one frequency at a time while a multiple microphone impedance tube can test multiple frequencies at a time. The simplest form of a multiple microphone impedance tube is one that uses two microphones. Because of this and its straightforward design process, the two microphone impedance tube was chosen.

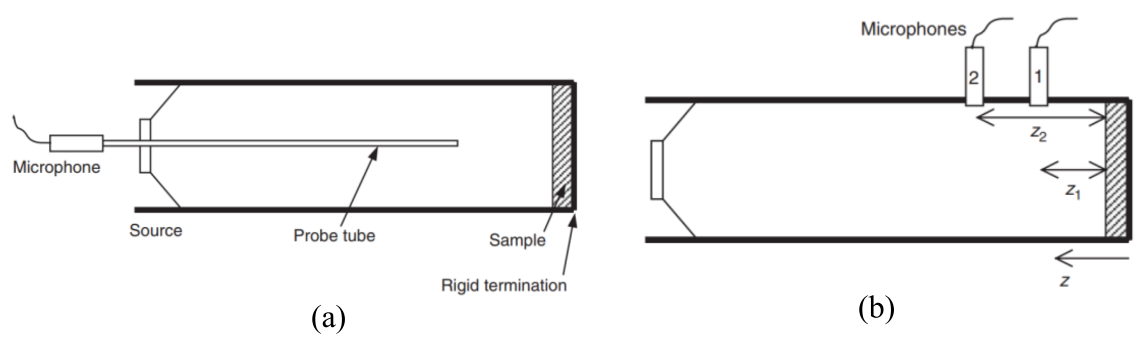

Figure 1: (a) Single Microphone Impedance Tube (b) Two Microphone Impedance Tube

The motivation for this project is to create a tool for the TCU Engineering Department to use to support its students and faculty via laboratory experiments and research. The impedance tube will allow for students to have the opportunity to research and learn about acoustics in a way they never have before. It will also allow the faculty to support those students in deepening their understanding of materials' acoustic properties and continue their own research.

This project provides a completed and calibrated two-microphone impedance tube with usable frequency range of 50 Hz to 2637.77 Hz. This paper explains the design and fabrication of said impedance tube and the methods used to validate its operation and data acquisition.

BACKGROUND

Before jumping into the design, it is important to have an understanding of the fundamental acoustic concepts pertaining to impedance tubes. As previously mentioned, an impedance tube is a device that measures a material's absorption coefficient and impedance. The absorption coefficient refers to a material's ability to absorb acoustic energy and is typically between 0 and 1. The less absorbing a material is, the smaller its absorption coefficient is and the more absorbing it is, the higher the coefficient is. It is also heavily angular dependent, meaning it changes depending on the angle of the sound wave. Different measurement methods address the angular dependency. The Sabine diffuse room method [2] provides an average over all incident angles. Impedance tubes, in general, focus on 0° incident absorption, also known as normal incidence. Acoustic impedance is similar to electrical impedance. It refers to a material's ability to resist the transmission of acoustic waves within and through it to a different medium just like electrical impedance refers to a component's ability to let current flow through it. These two properties are key to understanding the basics of acoustics and knowing these for a certain material allows for a deeper understanding of it and its uses.

The impedance tube measures these quantities by simultaneously measuring the incident and reflective sound waves, generated by a speaker at one end and reflected by the material being tested located at the other end, with two spaced microphones. This approach was first suggested by Seybert and Ross [3]. The technique is restricted to a frequency range where only planar waves exist in the tube. Planar acoustic waves are sound waves that only propagate in one direction and have a constant amplitude and phase [4] unlike spherical acoustic waves which travel radially in multiple directions. For this frequency range, the plane was assumption ensures that only normal incidence is considered in the measurement.

DESIGN

Key Parameters

There are several parameters that need to be considered when designing an impedance tube. While each one is individually outlined in the ATSM E1050 – 19 Standard, the key parameters are the testable frequency range, maintaining plane waves withing the tube, and keeping the tube airtight.

The testable frequency range is made up of a lower frequency limit and an upper frequency limit. The lower frequency limit is dependent on the spacing between the two microphones. The standard recommends that the microphone spacing should be about one percent of the wavelength of the desired lower frequency limit [5]. Since the wavelength (λ) of a given wave can be found by dividing the velocity of that wave by its frequency, the wavelength of an acoustic wave would be the speed of sound divided by frequency of the wave. Hence, the lower frequency limit (f_{lower}) of a two microphone impedance tube can be found using the following equation:

$$(1)\ f_{lower} = 0.01\frac{c}{s}$$

Where: c = speed of sound in m/s (343 m/s) and s = microphone spacing in meters.

A frequency of 50 Hz was chosen for the lower frequency limit. The microphone spacing that aligns with 50 Hz can be found by rearranging Equation 1 to solve for s. This results in a microphone spacing of 0.0686 m or 2.7 inches The upper frequency limit (f_{upper}) depends on the inner diameter of the tube. The formula given in the ATSM standard is:

$$(2)\ f_{upper} = 0.586\frac{c}{d}$$

Where: c = speed of sound in m/s (343 m/s) and d = inner diameter of tube in m

The inner diameter of the tube used to construct this impedance tube is 3 inches, which is 0.0762 m. Plugging this value into Equation 2 results in an upper frequency limit of 2637.77 Hz. Thus, the frequency range of the TCU impedance tube is 50 Hz – 2637.77 Hz.

Maintaining planar acoustic waves in the tube is done by constraining the length of the tube. More specifically, the distance between the sound source and the first microphone must be at least three times the diameter of the tube, and the distance between the second microphone and the material being tested must be at least two times the diameter. These specific distances allow for the waves to fully develop into plane waves. With this in mind, distances of 15 inches (five times the diameter) and 9 inches (three times the diameter) were chosen for the length of tube between the speaker and first microphone and the length from second microphone and the material, respectively.

Keeping the tube airtight is important because it affects the quality of the data measured. Escaping sound would lead to erroneous lower microphone levels and an over prediction of the absorption coefficient. Unlike the previous two parameters, this one does not align with a geometric feature of the tube itself. It is a detail that needs to be remembered at all times but especially when designing the microphone holders, speaker housing, and the material housing since those three parts need to be removable and easy to access. Different tactics and designs were used to keep the tube airtight at each location. For the microphone holders, silicone O-rings were put around the microphone in the holder, so that when it is attached to the tube, the O-ring is compressed. For the speaker and material housing, a flat rubber ring with a 3 inches inner diameter and 4 inches outer diameter was adhered to the end on the tube where they attached. When compressed, the silicon and rubber create a seal and fill any gaps between the aluminum pieces keeping all the sound generated by the speaker inside the tube.

Each of the four main parts of the impedance tube are discussed in the next subsections. Each section will cover the details of each component, its construction, and a computer aided design (CAD) model. The four main parts of the impedance tube are the tube body, microphone holders, and the speaker and material housings.

Tube Body

The tube body is the area of the tube where wave propagation takes place and is where the microphones are located. The tube is made of 6061-T6 Aluminum and, as previously mentioned, has an inner diameter of 3 inches with a 0.5 inch wall thickness. The total length of the tube body is a result of the microphone spacing and the distances between the speaker and first microphone and the second microphone and the material. The total length of the tube body is 26.7 inches.

The tube body also features two threaded counterbore holes for the microphones. The holes are counterbored because it allows for the microphone to sit flush with the inside of the tube while also allowing the microphone holder to be secured into the tube. Additionally, two aluminum rings with an inner diameter of 4 inches and a 0.5 inch thickness were attached to the ends of the tube body. Each of these rings has three through holes that allow for the speaker and material housings to be attached to the tube with bolts.

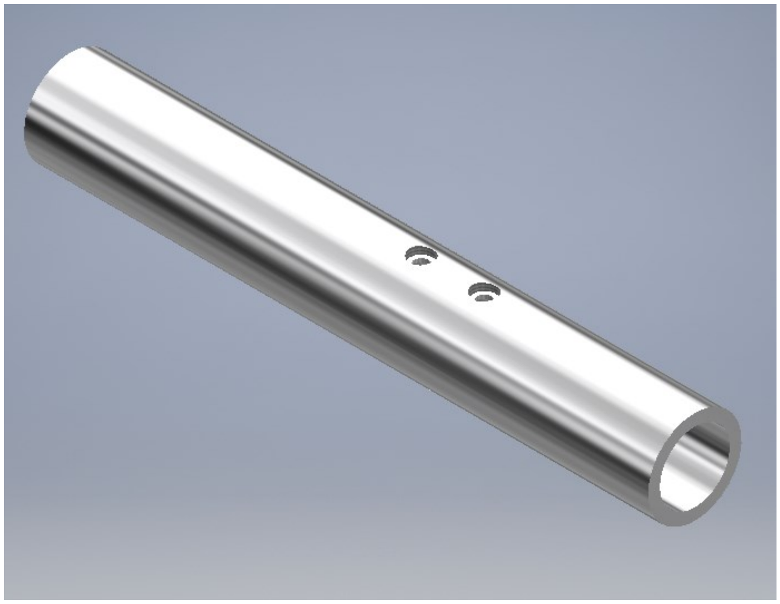

Figure 2: Tube Body CAD Model

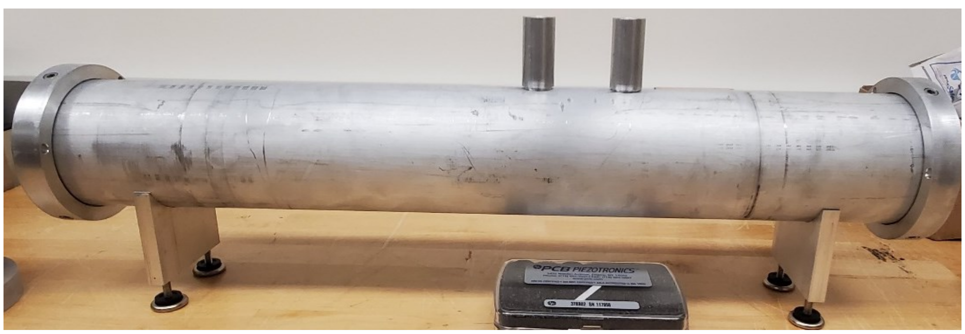

Figure 3: Tube Body

Legs were created to support the tube body. These are made out of 3.5 inches wide and 0.5 inch thick piece of 6061-T6 Aluminum. There is a 4 inch circular cut out of the top that allows for the legs to cradle the tube body. Two swivel-leveling mounts were added to each leg for stability and adjustability.

<u>Microphone Holders</u>

The microphone holders attach the microphones to the tube body and hold them steady. They are made of a 6061-T6 Aluminum tube with an inner diameter of 0.53 inches and outer diameter of 1 inch that was cut to be just under 3 inches. The outside of the bottom end of the holder is threaded to match the counterbore holes in the tube body. This allows the microphone holder to seamlessly twist into and out of the tube. This allows for the compression of the previously mentioned silicon O-ring that seals the opening in the tube and keeps sound inside. The O-ring also fits so well around the microphone and inside the holder that it is enough to hold the microphone snuggly and securely. While these microphone holders were made to hold the specific PCB microphones TCU has, any industry-standard 0.5. inch diameter microphone can be used.

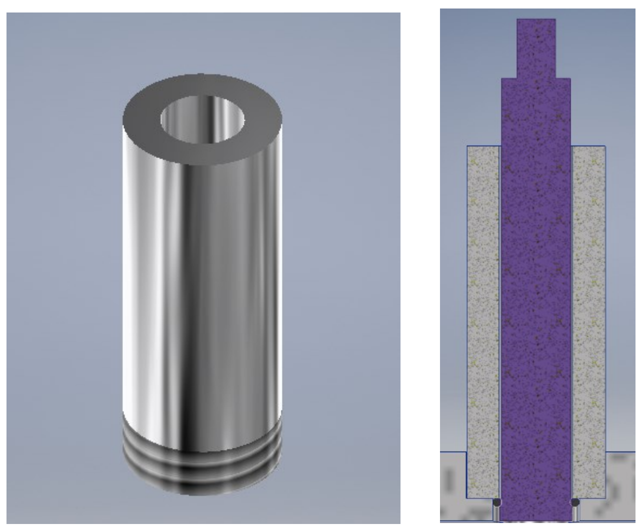

Figure 4: (a) Microphone Holder CAD Model (b) Cross-Section View

Figure 5: Microphone Holder

Speaker and Material Housings

The speaker and material housings are similar. They are both made from the same 6061-T6 Aluminum tube that tube body was made from. They also both have the same 4 inch aluminum rings attached to the ends of them, so they can attach to the tube body. The material housing has an as-built length of 2 inches. To support the verification test with a 1 inch sample, a 1 inch thick backing plate of 6061 Aluminum was placed behind the same to ensure reflection back through the test sample. The tube can accommodate sample thicknesses up to 2 inches with the use of varying thickness backing plates. Samples greater than 3 inch thickness would require a longer material housing. To close off the ends of the housings that are not connected to the tube body, 3D printed end caps were attached. These end caps have a 4 inch diameter and a 0.125 inch thickness. The speaker housing has an additional 3D printed ring that aligns with the inside of the tube body. This ring has a cutout that matches the mounting plate of the speaker and allows for it to be secured to the speaker housing.

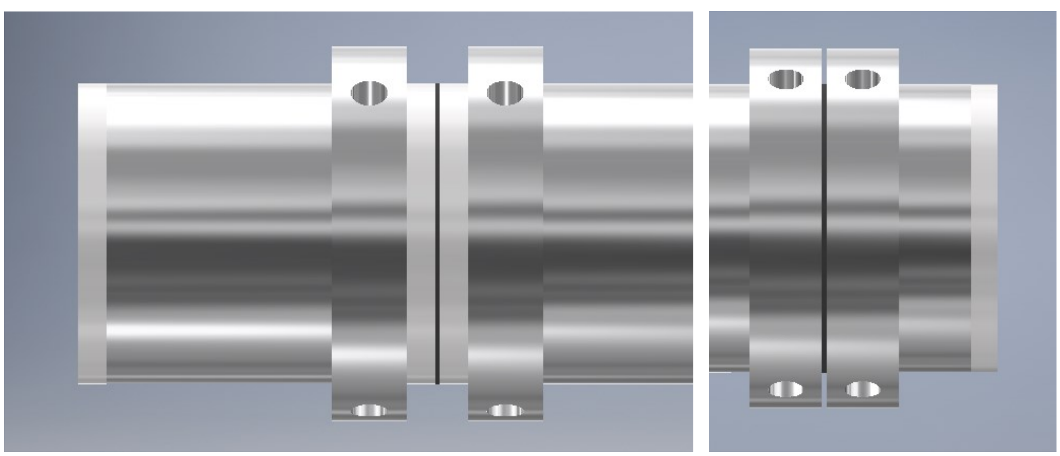

Figure 6: (a) Speaker Housing CAD Model (b) Two Material Housing CAD Model

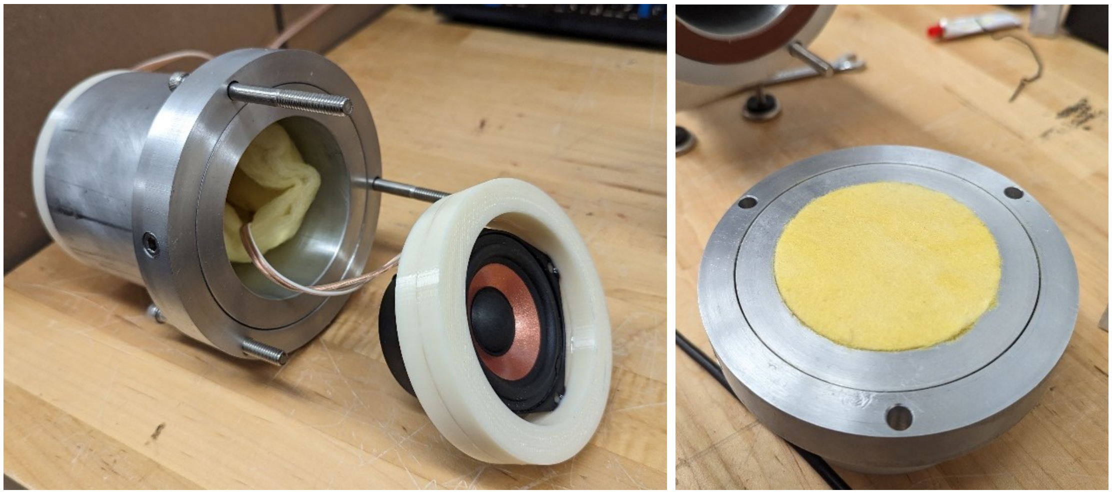

Figure 7: (a) Speaker Housing (b) Two Material Housing

Below is a picture of the completed TCU Impedance Tube and its CAD model. The detailed CAD drawings that were given to TCU machine shop to create these pieces are located in the Appendix.

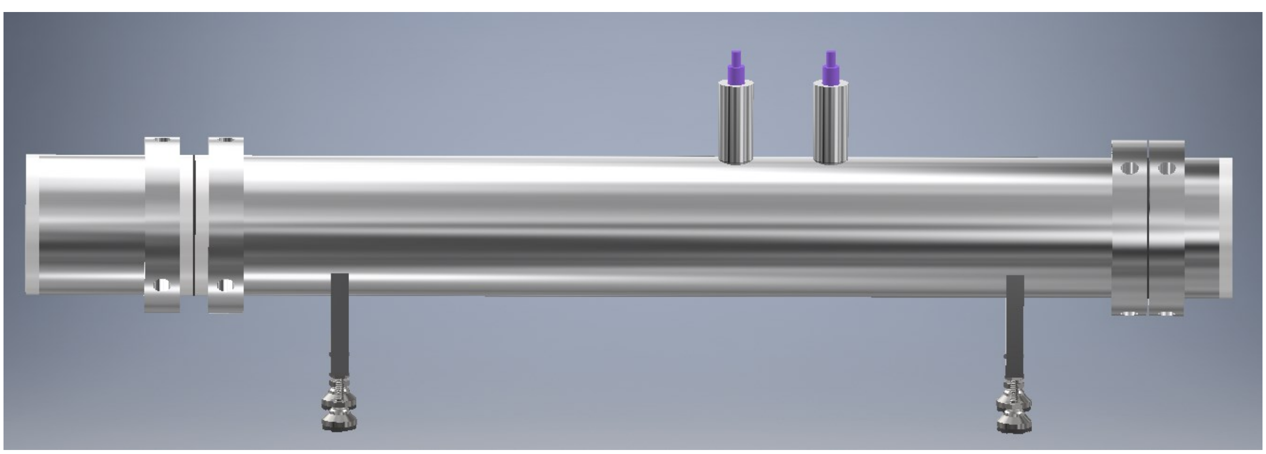

Figure 8: Completed TCU Impedance Tube CAD Model

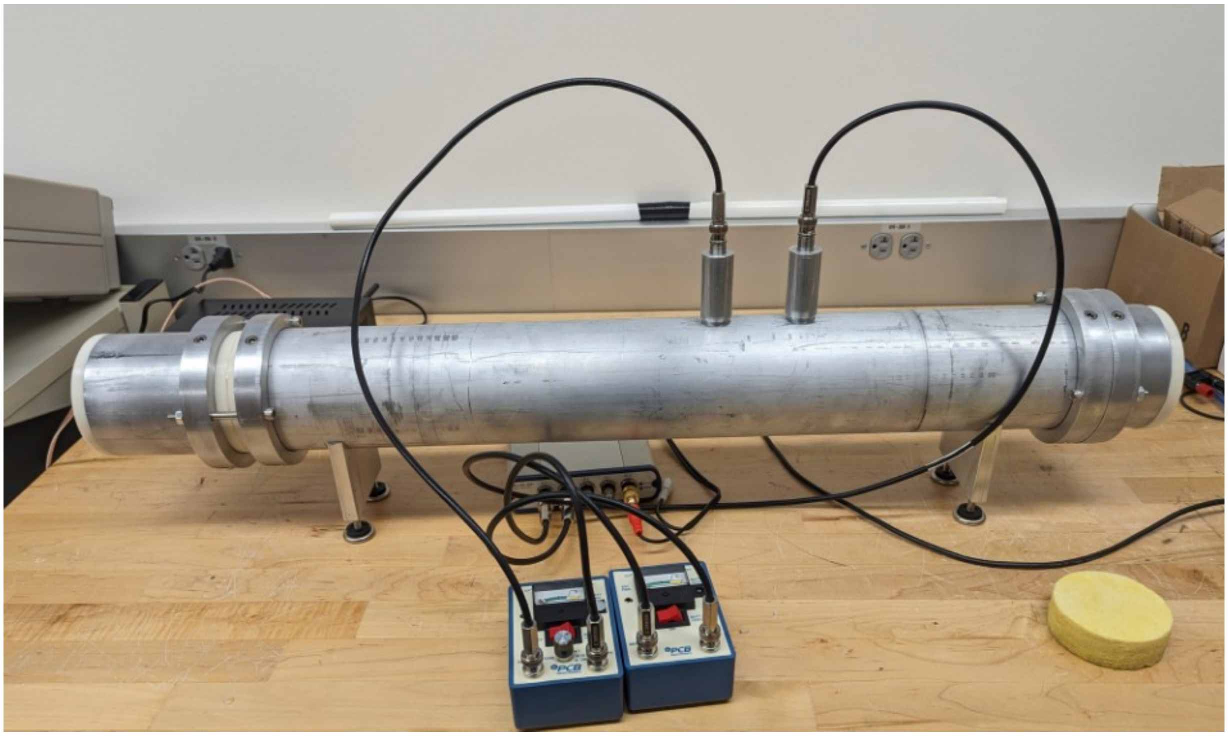

Figure 9: Completed TCU Impedance Tube

TESTING AND VALIDATION

Testing Setup and Process

A validation test was performed on Owens Corning Type 705 pressed fiberglass board to prove the accuracy of the TCU impedance tube. This pressed fiberglass is a common type of sound absorbing foam and can be found in recital halls, theatres, and recording studios. It is made of "inorganic glass fibers with a thermosetting resin binder and formed into a semi-rigid rectangular board" [6].

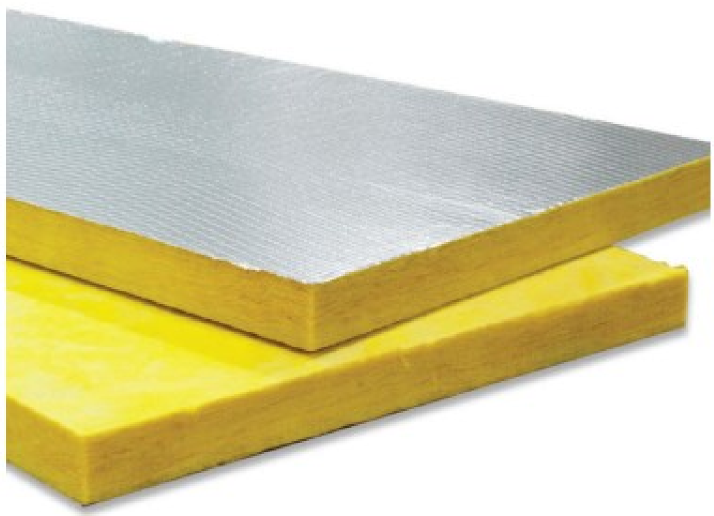

Figure 10: Owens Corning Type 705 Pressed Fiberglass Board

For verification testing, a 1 inch thickness was chosen for the fiberglass board. It was cut into a 3 inch diameter circle and inserted into the material housing which was then attached to the tube body. The speaker signal was run through a Pyle PTA 4 Stereo Power Amplifier to allow for signal to be enhanced. A key part of the testing set up is the microphone phase calibration. To do this, a G.R.A.S Type 51AB acoustic calibrator was used on both of the PCB microphones (378B02 and Y378A13) simultaneously to ensure that the phase measurement made from each was aligned. Once the microphones were properly set up, they were plugged into a NI USB – 4431 which was the data acquisition device used for this test.

This test also used LabView to assist in data acquisition while MATLAB was used to process the data and determine the absorption coefficient. The LabView graphical user interface (GUI) allows for the user to choose the desired input signal the speaker will emit and to record the data measured by the two microphones. For this test, a chirp signal was used as the input signal to allow for testing of the entire usable frequency range at one time. The chirp signal tested a frequency range of 10 – 3200 Hz. Once LabView recorded all the data, it exported it to a MATLAB matrix data file. A MATLAB script was then run on the data that passed it all through the proper equations, shown below. Its output was another matrix file containing the absorption coefficient at a given frequency for the Owen Coring Type 705 pressed fiberglass board.

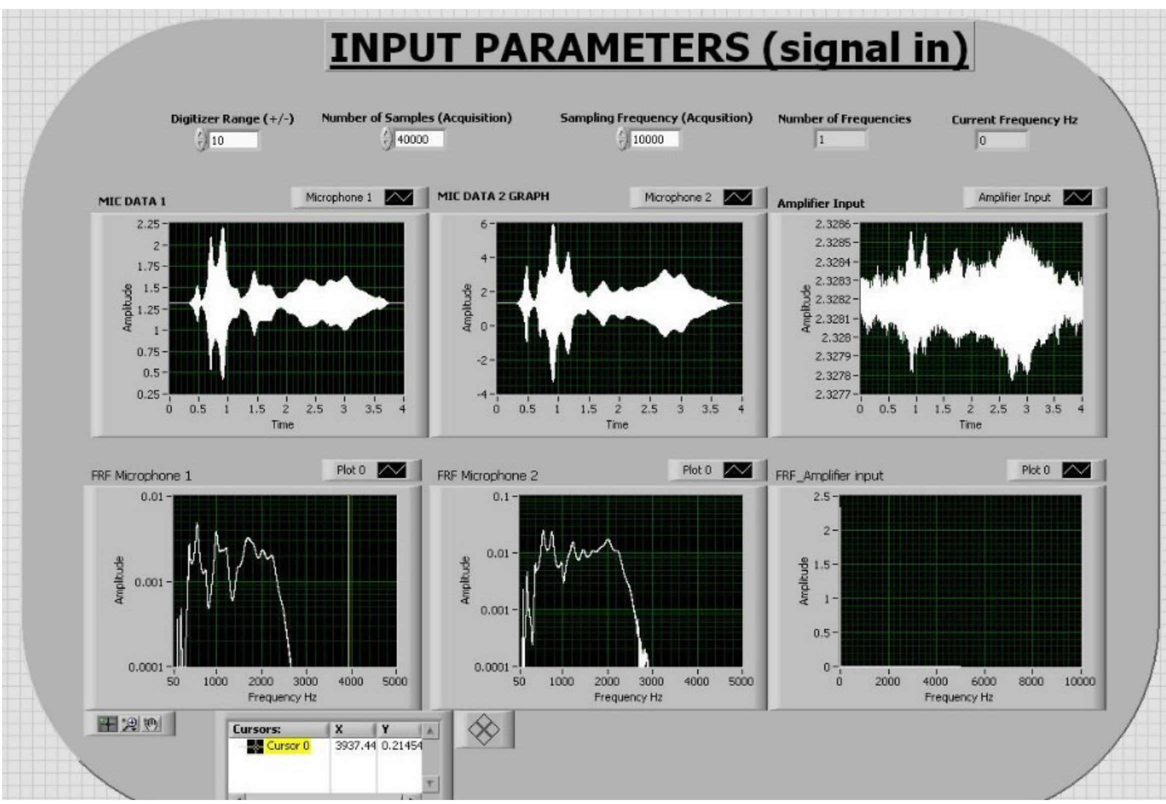

Figure 11: (a) LabView Measured Data (Signal In) GUI

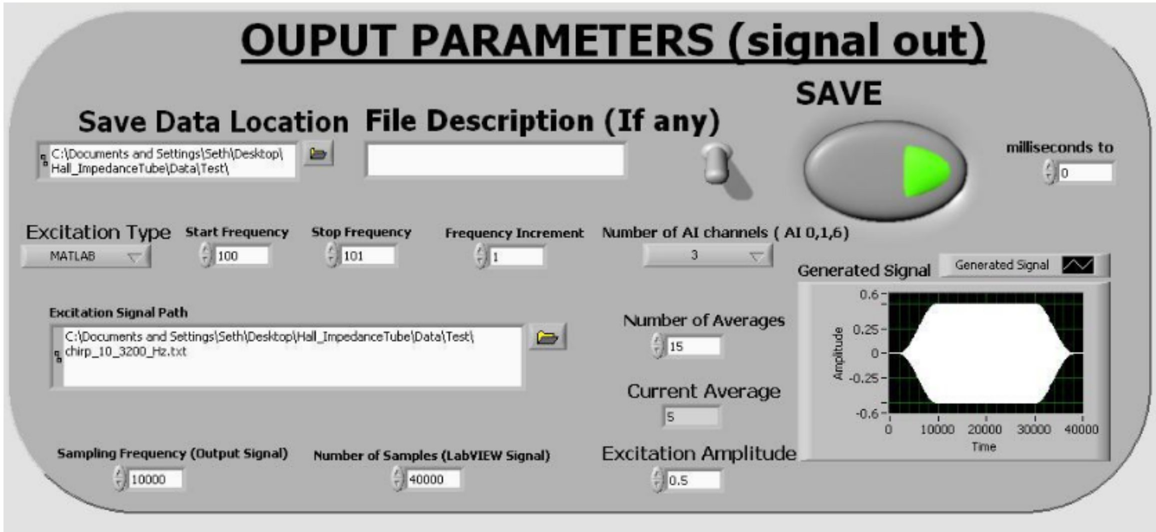

Figure 11: (b) LabView Output (Signal Out) GUI

$$\hat{H}_{12}(f) = \frac{p_2}{p_1} = \frac{e^{-i\hat{k}x_2} + \hat{R}e^{i\hat{k}x_2}}{e^{-i\hat{k}x_1} + \hat{R}e^{i\hat{k}x_1}}$$

$$\hat{R} = \frac{\widehat{H_{12}} - e^{-jk(x_1 - x_2)}}{e^{jk(x_1 - x_2)} - \widehat{H_{12}}} e^{j2kx_1}$$

$$\alpha = 1 - \left|\hat{R}\right|^2$$

Figure 12: Transfer Functions and Key Equations Applied

<u>Results</u>

The absorption coefficient data was then plotted on the same set of axes as the manufacturer supplied absorption coefficient data as well as the absorption coefficient measured by another impedance tube created by Dr. Hubert Seth Hall in 2016 while he was at the Catholic University of America (CUA) [7]. This second data set was added because the manufacturer supplied data was not measured with an impedance tube, so adding the CUA impedance tube data allows for a comparison with a known accurate impedance tube. Below are the resulting plots.

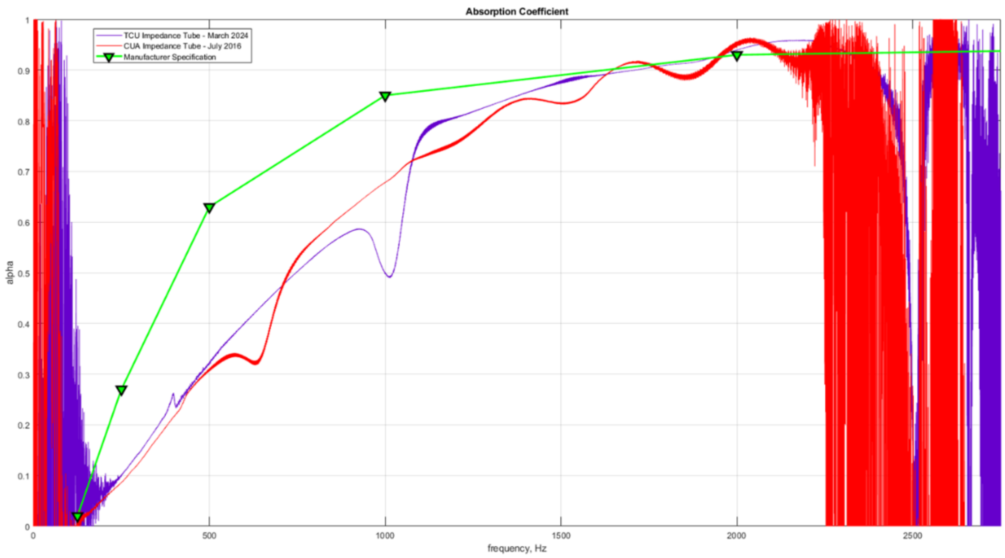

Figure 13 (a): Low Frequency Focus

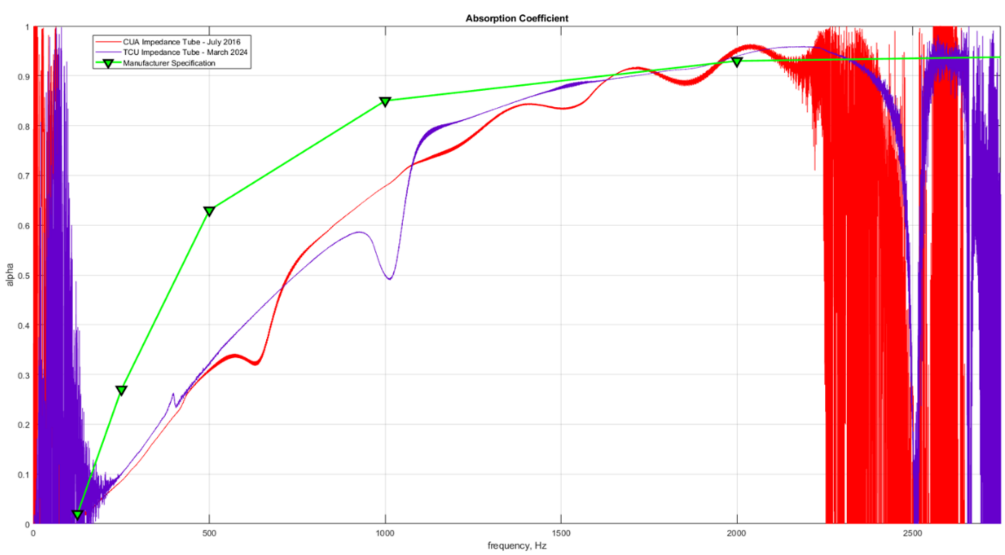

Figure 13 (b): High Frequency Focus

As seen in the plots above, the TCU impedance tubes lines up with both the CUA impedance tube and the manufacturer specification. An obvious observation is that both impedance tubes show a lower absorption coefficient than the manufacturer specified data. This is because, as previously noted, the manufacturer supplied data is measured using a different method. It was found using the Sabine diffuse room method. This test features the use of a room set up in a specific manner to allow for reverberation and adequate diffusion. This measurement test is vastly different from the impedance tube method and typically leads to larger absorption coefficients than would be found by using the impedance tube method as it is an average absorption over all incident angles versus only at normal incidence [2].

Another observation of note is that there is a lot of noise in the data at lower frequencies for the TCU impedance tube as seen in Figure 13 (a). This noise is due to the small size of the speaker used. The Douk audio speaker used has a diameter of 2.5 inches and is not large enough to produce a high quality low frequency tone. Another key observation is that the TCU impedance tube is better at high frequencies than the CUA tube. This can be seen in Figure 13 (b). This is because the CUA impedance tube has a larger diameter than the TCU tube, so it has a lower upper frequency limit. The CUA impedance tube has a diameter of 3.5 inches which implies an upper frequency limit of 2260.94 Hz whereas the TCU impedance tube has a diameter of 3 inches which corresponds to a 2637.77 Hz upper limit. Because of this, the TCU impedance tube aligns more with the manufacturer's data at higher frequencies.

An interesting phenomenon to look at is the hitch in the data around 1000 Hz. This hitch should not appear there, but a similar event occurs in the CUA impedance tube around 700 Hz. This hitch is most likely there because it could be a modal property of the aluminum tube itself. The CUA tube was of a similar 6061 Aluminum construction as to the TCU tube. It is probable that 1000 Hz and 700 Hz are resonant frequencies of the tubes causing them to vibrate in a way that interferes with the readings.

CONCLUSIONS AND FUTURE WORK

Overall, the TCU impedance tube proved to be an accurate tool to measure the absorption coefficient. It is made of a 6061-T6 Aluminum tube with a 3 inch diameter and 0.5 inch wall thickness which leads to an upper frequency limit of 2637.77 Hz. It has a microphone spacing of 2.7 inches which corresponds to a lower frequency limit of 50 Hz. The TCU impedance tube was validating by performing testing on Owen Coring Type 705 pressed fiberglass board, and the result was an accurate measurement of its absorption coefficient as compared to both the manufacturer data and a data from another impedance tube. Thus, the TCU impedance tube is a valid and accurate way of measuring the absorption coefficient of a material.

Some recommendations for future work and improvements include upgrading to a larger, higher quality speaker that would allow for sufficient data to be taken at low frequencies to further prove that the impedance tube is successful at those frequencies. Another recommendation is to run a Finite Element Analysis (FEA) modal study on the aluminum tube to confirm the hypothesis that the hitch in the data is due to a modal property of the tube.

The TCU impedance tube is a tool that opens the door to new acoustic research for TCU Engineering and can be used for years to come.

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APPENDIX

Testing Equipment

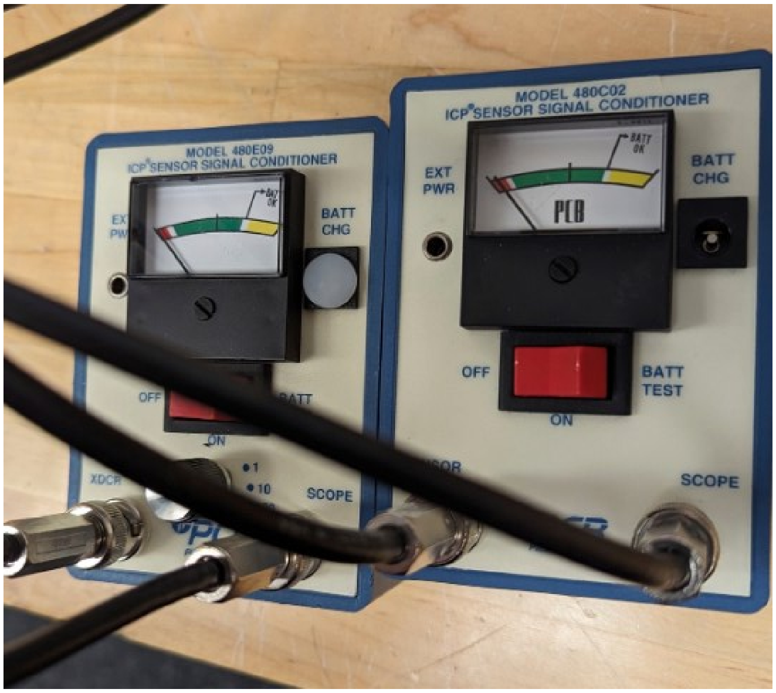
- Pyle PTA 4 Stereo Power Amplifier

- G.R.A.S Type 51AB acoustic calibrator

- Casella CEL – 120 Acoustic Calibrator

- NI USB – 4431 Data Acquisition Unit

- ICP Sensor Signal Conditioner (480C02 and 480E09)



- PCB microphones (378B02 and Y378A13)

Detail Drawings