Evaluating the bonding condition of NASA spray on foam insulation using audio frequency sound absorption measurements

by

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This is to certify that the master’s thesis of

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has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy
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CHAPTER 1 - INTRODUCTION

February 1st, 2003 will be a day that the whole world will remember. Even though the destruction of the space shuttle Columbia was not televised live, like the Challenger disaster on January 28th, 1986, the affect was still the same. Seven of the world’s most courageous people were lost including Israel’s first astronaut. Sixteen days earlier during the launch of space shuttle Columbia cameras recorded a suitcase size piece of Spray on Foam Insulation, referred to by the acronym SOFI (pronounced so-FEE), impact the left wing of Columbia. Figure 1.1 depicts the location of the SOFI that detached from the external tank (ET) and the place where it impacted the left wing.

Figure 1.1 - Shuttle Columbia before liftoff on January 16th, 2003
Scientists and engineers at National Aeronautical Space Administration (NASA) evaluated the video of the impact and determined it would not endanger the shuttle mission or the astronauts aboard. This was not the first time SOFI from the external tank had damaged the fragile heat protecting tiles that cover the space shuttle. During the first space shuttle flights, astronauts radioed during liftoffs about falling white-colored insulation from the external fuel tank hitting the shuttle's windows. After the first space shuttle flight 250 debris hits were found on the heat tiles that need to withstand temperatures up to 2300° F during atmospheric reentry. The problem with foam “shedding” continued, the second shuttle flight after the Challenger disaster resulted in Atlantis receiving more than 707 debris hits including 272 hits that were deemed “significant” because the size was larger than one inch in diameter. In 1989, Columbia was “significantly” damaged by a piece of foam 23 inches wide and 15 inches long [1]. The problem continued in 1997, NASA found more than 308 hits that included 132 hits that were deemed “significant”. Slashes in the tiles were up to 15 inches long and 1.5 inches deep into the 2 inch thick tiles. This depth was dangerously close to the aluminum skin of the space shuttle that melts at a much lower 350° F. After the 1997 flight, a total of 100 tiles had to be replaced before Columbia could attempt its next mission [2]. As shuttle flights continued successfully, the issue of heat tile damage from SOFI impacts was not deemed a “safety of flight” issue but a maintenance issue. The shuttles were examined after landing and broken heat tiles were replaced. That was until February 1st, 2003 when Columbia was destroyed upon reentering the atmosphere.

1.1 Background of SOFI
SOFI covers the entire surface of the external tank to maintain the temperature of rocket propellant at -423° F for liquid oxygen and -298° F for liquid hydrogen. The SOFI also insulates the tank so that ice does not form on the external tank while it is on the launch pad [3]. Ice formed on the external tank could melt and release during liftoff causing major damage to the fragile heat tiles that cover the space shuttle. Most of the foam is applied by machine but over three dozen of the 1900 workers at the Michoud Assembly Facility in east New Orleans, operated by Lockheed Martin and managed by NASA's Marshall Spaceflight Center, spray foam on the external tank manually. The foam is sprayed on manually in
regions where the tank geometry is complex. The most sensitive of these areas is at the bipod where the external tank connects to the orbiter. This is the area where foam detached and struck the left wing of Columbia [4]. According to Neil Otte, NASA’s chief engineer for the external tank "We can't look inside the foam, we have one sprayer spray while another watches; we have videotape and high-fidelity mock-ups to check the procedure; we have technique cards that tell them exactly what they have to do [5]." The procedures described by Otte can help minimize the imperfections in the SOFI but cannot prove they are eliminated.

1.2 Type of Imperfections
When the foam is sprayed onto the external tank three different types of imbedded defects are assumed to cause SOFI loss. The defect blamed for most of the SOFI "shedding" is cohesion failure. Cohesion failure occurs when the SOFI does not properly adhere to the external tank. During liftoff, the improperly bonded foam rips loose from the external tank because of large dynamic forces and causes damage to the heat tiles on the orbiter. Furthermore, voids or small air pockets inside the foam cause SOFI to release from the tank. If the void is close enough to the metal skin of the external tank, the air becomes liquefied due to the extreme cold of the liquid propellant. This liquid then expands rapidly during liftoff causing pieces of SOFI to be shot off the external tank toward the orbiter. Additionally the external tank stays on the launch pad for an extended period of time; small cracks in the SOFI form during this time allowing water to penetrate. This water penetrates to the super cooled tank, turns to ice and expands allowing more water to penetrate. These icy patches can also undergo rapid expansion during liftoff shooting off pieces of SOFI similar pockets of air.

1.3 Previous Work on SOFI Bonding Detection
Iowa State University through the Center for Nondestructive Evaluation (CNDE) has been using two different methods involving sound to detect the bonding condition of a small sample of SOFI. Dr. David Hsu used ultrasonic detection techniques to determine areas of disbond between the SOFI and aluminum used to represent the tank. When the ultrasonic
transducers were placed on opposite sides of the sample the disbonded areas were clearly visible. However, this method would not be practical when the tank is filled with liquid fuel. Dr. Hsu also implemented a pitch-catch method so that both transducers would be on the outside of the external tank. However, the spray application of the SOFI causes layered variations in the composition of the foam. Since the wavelength of the ultrasonic energy is small it is easily deflected along these layers. This deflection does not allow the ultrasonic signal to reach the SOFI/aluminum bond causing defects to remain hidden [6].

Matt McKee and Dr. Adin Mann investigated acoustic impedance below 10,000 Hz to determine SOFI bonding. Sound waves below 10,000 Hz are longer and can penetrate the SOFI unlike than shorter wavelength ultrasonic methods. A method developed by Allard [7] was used to examine the SOFI sample sent to Iowa State University. The method involved using two microphones close to the sample to determine the acoustic properties such as impedance and absorption. A slight difference was found when comparing the real impedance of the material over a bonded and unbonded section of foam. The difference was confined to a single point at 2650 Hz in the frequency spectrum and degraded when the sample was placed in a reverberant room instead of the ideal conditions of the anechoic chamber. The frequency spectrums were also noisy because of room reflections. The use of an impedance tube to shield the readings from background noise was also implemented but not refined.

Several other nondestructive methods have been used at locations besides Iowa State University. Rensselaer Polytechnic Institute located in New York has been using terahertz radiation (T-Rays) to examine a sample of SOFI. T-Rays are in the far infrared of the electromagnetic spectrum between microwaves and visible light. SOFI has a low enough refraction and attenuation to T-Rays to allow proper penetration into several inches of the sample. T-Rays have proven effective by identifying 49 out of the 57 defects built into the foam sample being researched including voids and debonds ranging from ¼ inch to 1 inch in size. T-Rays are also safe enough that the operator is in no danger from residual radiation [8]. The only drawback of terahertz radiation testing is the size of the equipment. Currently
the equipment used to conduct terahertz testing is the size of an office photocopier and costs £200,000 or $384,000 U.S. [9].

X-Ray backscattering and laser shearography have also provided limited ability to evaluate tank bonding condition. Laser shearography vibrates a material very slightly while a laser is beamed onto the surface of the material. A digital camera records any surface differences and a post processing program reveals any defects that are present. The laser system can scan an area of 32 inches by 36 inches every half a second and can detect flaws as small as 20 nanometers. This would allow the entire external fuel tank to be tested in 24 hours. Laser shearography equipment like T-Ray testing equipment is quite expensive. One laser shearography device costs around $175,000 [10]. Also Harry Wadsworth, a company spokesman for Lockheed Martin, stated laser shearography is unreliable and provides false positives. "In other words, when it is OK, sometimes it tells us it's not OK. It indicates flaws where none exists sometimes," he said [11]. Backscatter radiography detects the X-Rays that reflect from an object expose to X-Ray radiation. Traditional X-Ray technology records the X-Rays that pass through an object on radiographic film. The “backscatter” technique was developed for cases when it would be impossible to place the film on the opposite side of the object. Originally the technique was developed at the University of Florida to detect landmines for the military but also works on one sided objects like the external tank of the space shuttle. Two detectors record the photons scatter by the material and combines them into a single image that provides information about the bonding condition of the SOFI. Backscatter radiography successfully detected foam debonds and voids present in samples of SOFI. Backscatter radiography is rather slow only able to scan one square foot of material an hour and the initial cost of the equipment is approximately $100,000 [12]. Also special precautions have to be taken when working with X-Rays to ensure that the user is properly protected during examination of the foam.

1.4 Problem Statement
The focus of this thesis will be to refine the measurements conducted in the initial phase of audio frequency band testing to identify debonding at the SOFI/Aluminum interface by Matt
McKee and Dr. Adin Mann. Additional indicators such as the sound absorption coefficient will also be explored in addition to acoustical impedance. The impedance tube method that Matt McKee started at the end of his thesis will be explored. Early work involving the impedance tube, shown in Figure 1.2, indicates that environmental factors in the reverberant room can be minimized. The solid line represents the absorption coefficient calculated using an impedance tube for ½ inch thick polyethylene foam and the dotted line represents data obtained using the method implemented by Matt McKee.

Figure 1.2 – Comparison of microphones in impedance tube versus free field

Once the microphones were isolated in the impedance tube environmental factors such as outside noise sources and reflections were reduced producing a smoother more accurate frequency spectrum. The smoother spectrum allowed differences between the bonded and unbonded foam locations to be more apparent. Matt McKee’s indicator for the bonding condition was limited to one frequency because of the excessive background noise. Furthermore, the indicator shifted frequencies when the environmental conditions changed from the anechoic chamber to the reverberant room. This was counterproductive because
the indicator would need to be recalibrated every time the measurement environment changed. The impedance tube eliminated the effect of the background noise and environment as long as the background noise was at least 10 dBA lower than the sound level in the tube. This allowed the indicator to be more robust over a wider range of frequencies in different noise settings providing a better method to find SOFI defects. Furthermore, the impedance tube scanning system was designed to be a low cost, robust, and portable alternative to the earlier methods described so that it can be used on the factory floor during foam application or on the launch pad as a way to determine the bonding condition of the foam directly before liftoff.
CHAPTER 2 - THEORY

The work done in this thesis is an extension of the work conducted by Matt McKee under the supervision of Dr. J.A. Mann and supported by NASA under award No. NAG102098. Several assumptions are still considered valid such that the material is locally reacting and the SOFI acts as a finite duct. The development of these two assumptions can be found in the thesis submitted to Iowa State University by Matt McKee [13]. An impedance tube with two microphones was used to calculate the impedance and sound absorption coefficient of the SOFI foam. Two different algorithms, the Allard method [7] and ASTM E1050 standard [14], were used to compute the desired acoustic quantities. The methods were compared to determine the most effective computational method. This chapter will include the theory for the impedance tube, calculation methods and calibration procedures.

2.1 Impedance Tube

Impedance tubes are used to determine the absorption coefficient of materials when there is not enough material or space to conduct reverberant room tests (ASTM C432). Two different methods are available to determine the acoustical properties of a test sample in an impedance tube. The standing wave method ASTM C384 [15] utilizes a standing sine wave in the tube to determine the acoustic properties. This process is slow because individual frequencies need to be tested and compiled to determine overall values. The ASTM E1050 standard utilizes the transfer function between two closely spaced microphones to determine acoustical properties. The two microphone method was used for this thesis because all frequencies are excited and tested simultaneously dramatically increasing the speed of the test. Furthermore, impedance tubes are used to analyze acoustical material properties because the sample is isolated in the tube. Outside noise sources or room reflections do not affect the test results. The impedance tube also guarantees the sound waves in the tube
remain plane waves up to a limit determined by the tube diameter. The plane wave assumption needs to be satisfied for the two microphone method to work properly.

### 2.1.1 Impedance Tube Setup

The impedance tube setup pictured in Figure 2.1 is used for the ASTM E1050 standard.

![Impedance Tube Setup Diagram](image)

**Figure 2.1** – Standard impedance tube configuration for ASTM E1050

The impedance tube can be made from steel, brass, plastic or any other material that has high enough transmission loss so that the sound field in the tube is 10 dB higher than the background noise. The diameter of the tube needs to be sized according to the frequency range that is required for testing. Equation 2.1 provides the relationship for upper frequency limit and tube diameter [14].

\[
d < \frac{Kc}{f_u}
\]

where:
- \(f_u\) = upper frequency limit, hertz,
- \(c\) = speed of sound in air, m/s,
- \(d\) = diameter of tube, m, and
- \(K\) = 0.586 for circular cross section or 0.500 for rectangular cross section.

The length of the tube is not explicitly stated but the ASTM E1050 standard requires a minimum of three tube diameters from the sound source to the first microphone. However, Andrew Seybert, a pioneer in the two microphone method, states the minimum three tube diameters is marginal and suggests using at least 10 to 15 tube diameters to guarantee fully developed plane waves [16].
2.1.2 Microphone Size and Spacing

The size and spacing of the microphones used in the impedance tube also limits the maximum frequency that can be tested. Table 2.1 taken from the ASTM E1050 standard gives the maximum frequency based on microphone diameter [14].

Table 2.1 – Maximum frequency based on microphone diameter

<table>
<thead>
<tr>
<th>Nominal Diameter [inch]</th>
<th>Maximum Frequency [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
</tr>
<tr>
<td>1/2</td>
<td>5600</td>
</tr>
<tr>
<td>1/4</td>
<td>11500</td>
</tr>
</tbody>
</table>

The spacing between the two microphones must be less than the shortest half wavelength of interest. Figure 2.2 diagrams the variables of interest involving microphone spacing for the ASTM E1050 standard.

Figure 2.2 – Microphone spacing variables

Equation 2.2 gives the relationship between the maximum frequency of interest and microphone spacing. The ASTM E1050 standard recommends the maximum microphone spacing, $s$, be 80% of $c/2f_u$.

$$s \ll \frac{c}{2f_u} \quad [2.2]$$

where:
$f_u$ = upper frequency limit, hertz,
$c$ = speed of sound in air, m/s,
$s$ = microphone spacing, m.

The microphones should be mounted flush with the interior of the tube. The minimum distance, $l$, a microphone can be to a flat test sample is one-half a tube diameter. The
maximum distance is not stated but if the distance, \( l \), is too large the attenuation of the air in the tube may affect the impedance and absorption coefficient calculations [14].

### 2.1.3 Sound Source Specifications

The sound source signal should be random noise containing frequency components for the range needed for testing. The sound source should be mounted coaxially with the main tube. The amplitude of the frequency response does not have to be flat. A range of +/- 10 dB across the frequency range is sufficient [16]. If the sound source varies by more than +/- 10 dB an equalizer can be used to smooth the amplitude of the frequency response [14].

### 2.2 Calibration Procedure

The calculations for impedance and absorption coefficient involve a transfer function between microphones, any phase or amplitude mismatches would affect the final results. Specially matched microphones are not needed if a calibration procedure is followed before measurements are taken. The phase mismatches from both the microphones and equipment such as low pass filter, signal conditioner, and computer also need to be corrected.

#### 2.2.1 Magnitude Calibration

The methods used to determine the acoustic properties of materials only require a relative magnitude calibration between microphones. However, since a piston phone of known sound level was readily accessible in the lab an absolute calibration was done. The piston phone outputs a 1000 Hz tone at 94 dB relative to \( 20 \times 10^{-6} \) Pa or the lower limit of human hearing. The calibration constant was determined by summing all points in the auto-spectrum for the microphone from 900 Hz to 1100 Hz. The magnitude calibration, \( M \), can be found by using Equations 2.3 and 2.4

\[
V^2_{\text{sum}} = V^2_{\text{rms900Hz}} + \ldots + V^2_{\text{rms1100Hz}}
\]

\[
M = \frac{10^{\frac{94}{10}}}{V^2_{\text{sum}}}
\]

[2.3]

[2.4]
2.2.2 Equipment Phase Calibration

The equipment phase calibration is found by inputting the same signal to the data acquisition system and determining the phase difference. The signal inputted into the system was a wide band random noise source so all frequencies were excited. The equipment phase calibration setup appears in Figure 2.3.

![Diagram for equipment phase calibration](image)

**Figure 2.3 – Diagram for equipment phase calibration**

The following equations use $P$ to represent the pressure recorded by the microphone, $M$ is the magnitude calibration constant, $C$ is the known signal amplification, $V$ is the signal voltage recorded by the computer, and $\beta$ represents the phase of the signal due to the equipment. Equations 2.5 and 2.6 represent the recorded voltage signals for channel one and channel two of the data acquisition system.

\[
V_1(\omega) = P_1(\omega)M_1|C_1|e^{i\beta_1} \tag{2.5}
\]

\[
V_2(\omega) = P_2(\omega)M_2|C_2|e^{i\beta_2} \tag{2.6}
\]

If the data acquisition was ideal there would not be any phase difference between the voltage signals because the same signal was inputted into both channels. Any phase difference found in the cross spectrum of the two channels would be the phase error introduced by the equipment. For the following equation and remainder of this thesis the complex conjugate will be noted by an asterisk (*). The following equations assume frequency dependence similar to the $V(\omega)$ in Equations 2.5 and 2.6.

\[
V_1V_2^* = P_1P_2^*M_1M_2|C_1||C_2|e^{i(\beta_1-\beta_2)} \tag{2.7}
\]
Solving Equation 2.7 for the cross spectrum $P_1 P_2^*$:

$$G_{12} = P_1 P_2^* = \frac{V_1 V_2^*}{|M_1M_2C_1C_2|} e^{-j(\beta_1 - \beta_2)}$$  \[2.8\]

The phase difference between channels can be found by determining the phase of $G_{12}$. Equation 2.9 determines the equipment phase error denoted by $\phi_{eqpt}$. The notation Im indicates the imaginary part and Re indicates the real part of the complex value.

$$\phi_{eqpt} = \tan^{-1} \left( \frac{\text{Im}(G_{12})}{\text{Re}(G_{12})} \right)$$  \[2.9\]

2.2.3 Microphone Phase Calibration

The phase calibration for the microphones requires both microphones and assumes the microphone preamplifiers do not cause any phase differences. A random noise source was again used to excite all frequencies of interest. This method is also called the “switching” method because the microphone tips are switched half way through the calibration process.

2.2.3.1 Unswitched Condition

The microphones are initially placed over a wide band sound source on their original preamplifiers. The same terminology from section 2.2.2 is used with the addition of $\phi$ representing the phase introduced by the microphones. Figure 2.4 represents the unswitched microphone arrangement. The signal is assumed to be conditioned by the data acquisition system but the representation of the system in Figure 2.4 is omitted to maintain clarity.

![Microphones in unswitched arrangement](image)
Equations 2.5 and 2.6 are again used to determine the voltage output produced by the microphones but are modified to include the phase of the microphone in Equations 2.10 and 2.11.

\[
V_1(\omega) = P_1(\omega)M_1|e^{j\phi_1}|C_1|e^{j\beta_1} \tag{2.10}
\]

\[
V_2(\omega) = P_2(\omega)M_2|e^{j\phi_2}|C_2|e^{j\beta_2} \tag{2.11}
\]

Equation 2.10 is then multiplied by the conjugate of 2.11. Once again the quantities calculated are assumed to depend on frequency.

\[
V_1V_2^* = P_1P_2^*M_1M_2|C_1C_2|e^{j(\phi_1-\phi_2)}e^{j(\beta_1-\beta_2)} \tag{2.12}
\]

### 2.2.3.2 Switched Condition

The microphone switching method assumes that the pressures \(P_1\) and \(P_2\) remain constant throughout the calibration process. Figure 2.5 represents the microphones in the switched configuration.

![Microphones in switch configuration](image)

**Figure 2.5** – Microphones in switch configuration

The output voltages change according to Equations 2.13 and 2.14.

\[
V_1'(\omega) = P_1(\omega)M_2|e^{j\phi_2}|C_1|e^{j\beta_1} \tag{2.13}
\]

\[
V_2'(\omega) = P_2(\omega)M_1|e^{j\phi_1}|C_2|e^{j\beta_2} \tag{2.14}
\]
Equation 2.13 is then multiplied by the conjugate of 2.14.

\[ V_1^* V_2 = P_1 P_2^* M_2^* M_1^* C_1 C_2 e^{i(\phi_1 - \phi_2)} e^{i(\beta_1 - \beta_2)} \]  \[2.15\]

Equation 2.12 is then divided by 2.15.

\[ \frac{V_1^* V_2}{V_1^*} = \frac{P_1 P_2^* M_2^* M_1^* C_1 C_2 e^{i(\phi_1 - \phi_2)} e^{i(\beta_1 - \beta_2)}}{P_1 P_2^* M_2^* M_1^* C_1 C_2 e^{i(\phi_2 - \phi_1)} e^{i(\beta_1 - \beta_2)}} \]  \[2.16\]

Simplifying Equation 2.16 leaves only the microphone phase error.

\[ \frac{V_1^* V_2}{V_1^*} = e^{2i(\phi_1 - \phi_2)} \]  \[2.17\]

Finally the microphone phase error is found in Equation 2.18.

\[ \phi_{mic} = \frac{1}{2} \tan^{-1} \left( \frac{\text{Im}(e^{2i(\phi_1 - \phi_2)})}{\text{Re}(e^{2i(\phi_1 - \phi_2)})} \right) \]  \[2.18\]

The cross spectrum needed to determine the transfer function for subsequent calculations can be calibrated for magnitude and phase by Equation 2.19. The subscripts \( cal \) and \( mes \) represent the calibrated cross spectrum and the measured cross spectrum respectively.

\[ (G_{12}(\omega))_{cal} = (G_{12}(\omega))_{mes} |M_1 M_2| e^{-j(\phi_{mic}(\omega) + \phi_{phase}(\omega))} \]  \[2.19\]

### 2.3 Impedance/Absorption Calculations

Two different methods were used to determine the acoustical properties of the material being tested. The ASTM E1050 and Allard methods for determining impedance and absorption were both calculated and compared. The following sections develop the equations used for both methods. It is important the definition of the length from the material to the measurement plane is understood for each method because it differs from the ASTM standard to the Allard method.
2.3.1 ASTM E1050 Standard

Figure 2.6 defines the length, \( l \), used for ASTM E1050 calculations as the distance from the material sample to the center of the first microphone [14].

![Diagram of microphone setup](image)

**Figure 2.6** – Definition of \( l \) and \( s \) for ASTM standard

The cross spectrum of the microphones and auto spectrum of the input microphone were used to determine the transfer function \( H \). The input microphone is defined as the microphone closest to the sound source. For the setup shown in Figure 2.6, microphone one is the input microphone. Equation 2.20 represents the form of the transfer function used for calculations.

\[
H = \frac{P_2 P_1^*}{P_1 P_1^*} \tag{2.20}
\]

The angular frequency, \( \omega \), and the wave number, \( k \), are defined in Equations 2.21 and 2.22.

\[
\omega = 2\pi f \tag{2.21}
\]

\[
k = \frac{\omega}{c} \tag{2.22}
\]

Where:

- \( f \) = frequency, hertz, and
- \( c \) = speed of sound in air, m/s.

The complex reflection coefficient, \( R \), represented by Equation 2.23 can be used to determine the impedance and absorption of the test sample.

\[
R = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k(l+s)} \tag{2.23}
\]
Where:
\( s \) = spacing between microphones, m, and
\( l \) = distance from sample to center of closest microphone, m.

The normal complex impedance, \( Z \), can be found by Equation 2.24.

\[
Z = \rho c \frac{1 + R}{1 - R} \quad \text{[2.24]}
\]

The absorption coefficient, \( \alpha \), is calculated by Equation 2.25.

\[
\alpha = 1 - |R|^2 \quad \text{[2.25]}
\]

### 2.3.2 Allard Method

Figure 2.7 defines the length, \( l \), used for Allard calculations as the distance from the material sample to the measurement plane half way between the two microphones.

![Figure 2.7 - Definition of l and s for Allard standard](image)

The acoustical impedance defined by Equation 2.26 was calculated using a finite difference approximation. Where the \( ^\wedge \) symbol represents a vector quantity.

\[
Z = \frac{P}{\hat{u}} \quad \text{[2.26]}
\]

The pressure, \( P \), at the measurement plane is represented by Equation 2.27 and approximated by averaging the pressure at the microphones.

\[
P = \frac{P_1 + P_2}{2} \quad \text{[2.27]}
\]

The velocity at the midpoint is than approximated by Equation 2.28 assuming the acoustic field consists of plane waves.

\[
\hat{u} = -\frac{j}{\rho \omega} \frac{dP}{dx} \quad \text{[2.28]}
\]
Where:
\( \rho \) = the density of air, kg/m\(^3\), and
\( \omega \) = the angular frequency defined by Equation 2.21, rad/s.

The finite approximation of Equation 2.28 takes the form of Equation 2.29.

\[
\hat{u} = \frac{P_2 - P_1}{j \omega \rho s} \tag{2.29}
\]

Where:
\( s \) = spacing between microphones, m.

Substituting Equations 2.27 and 2.28 into 2.26 the impedance at the measurement plane, \( Z_M \), can be found.

\[
Z_M = j \omega \rho s \frac{P_1 + P_2}{2P_2 - 2P_1} \tag{2.30}
\]

The transfer function from Equation 2.20 can be substituted into Equation 2.30 to replace the pressure terms.

\[
Z_M = j \omega \rho s \frac{H + 1}{2 - 2H} \tag{2.31}
\]

Assuming the sound field consists of plane waves the impedance of the measurement plane can be projected onto the surface of the material to find the actual material impedance, \( Z \).

\[
Z = \frac{Z_M - j \rho c \tan \left( \frac{\omega d}{c} \right)}{\rho c - j Z_M \tan \left( \frac{\omega d}{c} \right)} \tag{2.32}
\]

The complex reflection coefficient, \( R \), can be found from the impedance of the material.

\[
R = \frac{Z}{\rho c} - 1 \quad \frac{Z}{\rho c} + 1 \tag{2.33}
\]

The absorption coefficient, \( \alpha \), is calculated by Equation 2.34.

\[
\alpha = 1 - |R|^2 \tag{2.34}
\]
CHAPTER 3 - EXPERIMENTAL SETUP

The experimental setup section includes the physical setup of the equipment such as dimensions and types of equipment used for calculating the impedance and sound absorption coefficient.

3.1 Calibration

The calibration of the two microphone system was conducted before impedance tube testing began. Figure 3.1 represents a block diagram of the equipment used for signal processing.

![Signal path through signal processing system](image)

Figure 3.1 – Signal path through signal processing system

The equipment used in the setup consisted of two Brue! and Kjaer type 4939 microphones with sequential serial numbers 2389726 and 2839727. The preamplifiers and power supply were also Brue! and Kjaer Type 2807. After the power supply, the signal was low pass filtered to eliminate signal aliasing. The low pass filter/amplifier was a Stanford Research Systems Inc. model SR640. The signal was filtered at half the sampling rate according to the Nyquist frequency criteria. The sampling rate was varied throughout testing to observe different frequency ranges. The signal was amplified by 20 dB to give an input of 4 volts peak to peak to the data acquisition card. The National Instruments data acquisition card used to acquire data was a NI DAQCARD-6036E. The data acquisition card was able to
sample 200 kS/s with 16 bit analog inputs. The National Instruments program LabVIEW was used on a Gateway laptop to collect raw time signals and output the cross and auto spectrums of the two microphones.

The calibration procedures outlined in 2.2.2 and 2.2.3 were conducted to determine the phase error present in the system. A Bruel and Kjaer Sound Power Source Type 4205, picture in Figure 3.2, was used for calibration. The microphones were placed horizontally on the same plane above the sound source to ensure the same sound field was present on both microphones.

Figure 3.2 - Calibration setup

Figure 3.3 shows the typically phase error for the equipment and Figure 3.4 depicts the phase error from the microphone tips. The sampling rate for this example was 18,000 kHz. Aliasing begins to occur at 80% of the Nyquist frequency or approximately 7000 Hz. A linear least squares line was fit to the data to average the peaks present in the frequency spectrum. Due to aliasing the line was only fitted up to 7000 Hz. 800 averages were taken to remove any time dependence due to the random noise generator.
Figure 3.3 – Typical phase calibration curve for equipment

Figure 3.4 – Typical phase calibration curve for microphones
3.2 Impedance Tube

The impedance tube used for data collection was constructed of transparent cast acrylic and is depicted in Figure 3.5. Since the SOFI has to be tested while it is attached to the external tank a base was constructed to balance the tube on the sample for scanning. The tube was sealed to the SOFI with 3/8 inch wide by 3/16 inch thick closed cell PVC foam. The foam was purchased under the name Frost King Vinyl Foam Weatherseal Self Stick Tape Grey.

![Figure 3.5 - Impedance tube used for measurements](image)

The 1” tweeter used as the sound source was a Peerless 840277 shielded 1” ring dome tweeter. The dimensions of the longer, shorter and smaller tubes are presented in Figure 3.6, Figure 3.7, and Figure 3.8. All dimensions are in millimeters.

![Figure 3.6 - Impedance tube dimensions for long tube](image)
The tweeter on the impedance tube was band pass filtered to avoid damage to the tweeter from low frequency components. Figure 3.9 represents the path of the random noise signal to the tweeter.

Random noise from 0 to 20,000 Hz was generated from a General Radio Co. Type 1390-A signal generator. The noise was then sent through a band pass filter, General Radio Company 1952 Universal Filter, which had lower frequency limit of 1000 Hz and a higher frequency limit of 10,000 Hz. The lower limit was determined by analyzing several frequency spectra that showed no significant changes below 1000 Hz. The 10,000 Hz upper frequency limit was determined to cover all frequencies below the cut off of the impedance.
tube plane wave limit which for a one inch tube was approximately 8000 Hz. The band limited signal was amplified by a Bruel and Kjaer Type 2706 audio amplifier. The amplified signal was then outputted to the Peerless 840277 tweeter attached to the impedance tube. No enclosure was needed for the tweeter because the back was enclosed at the factory. The Peerless tweeter uses a powerful Neodymium magnet making the tweeter smaller and lighter than most tweeters available on the market allowing the impedance tube to be lighter and more portable. The microphones depicted in Figure 3.5 were flush mounted with the inside of the tube as stated in the ASTM E1050 standard.

3.3 Test Sample Setup

The SOFI sample sent to Iowa State University by NASA, shown in Figure 3.10, was mounted previously in a ¾ inch thick MDF baffle that was 4 foot x 4 foot. The SOFI was flush mounted with the top of this baffle supported by a frame made from 2 inch by 4 inch pine. A ¼” piece of foam was placed between the pine frame and test sample to reduce any vibrations caused by the incident sound waves. The baffle was initially used to prevent edge reflections. Several markings on the surface of the SOFI sample pictured in Figure 3.10 were enhanced by black dots in Microsoft Word because they were not clear on the photograph.

![Figure 3.10 - SOFI test sample with MDF baffle](image)
The sample was tested in a reverberant room with no effort to reduce the background noise. The room was the Acoustics Lab in Howe Hall Room 0316 at Iowa State University. The room had concrete floors, open ceiling with exposed ventilation ducts and pipes. Experiments on the SOFI were conducted while other tests such as underwater transducer tests and skid loader fan noise tests were being conducted. Also no effort was used to isolate the lab during experiments from closing doors or student conversations.

3.4 Test Sample

The test specimen was a 22 inch long by 22 inch wide by 2 inch thick sample of SOFI that was sprayed onto a 1/8 inch thick piece of aluminum that also measured 22 inches long by 22 inches wide. Two Teflon pads were placed on the aluminum backing before the foam was sprayed onto the aluminum to represent disbonds. However during Dr. Hsu’s initial testing the Teflon pads did not appear to cause foam debonding. Dr. Hsu used a thin piece of metal to create a 1 inch wide by 5.5 inch long separation at the SOFI/aluminum interface. Matt McKee also created a similar disbond during his testing that measured 2 inches wide by 8 inches long. Figure 3.11 depicts the size and locations of cuts on the SOFI. The black dots and black dotted lines indicate markings on the surface of the SOFI and the gray boxes indicate the assumed dimensions of the disbonds. Exact locations for the inserted NASA Teflon pads were not given but the locations are approximated by the Teflon Pad squares.

![Diagram of the foam side of SOFI sample from NASA](image)
CHAPTER 4 - IMPLEMENTATION

Before testing of the NASA SOFI sample began the impedance tube was tested to determine if the tube and processing algorithms were working properly. After impedance tube qualification was completed, testing on the SOFI began. Results from SOFI testing are presented in this chapter to familiarize the reader with the calculations used to determine the acoustical properties of the SOFI.

4.1 Testing of Impedance Tube

Andrew Seybert provided a simple test to determine if the impedance tube and equations were working properly. The end of the impedance tube is capped with a closed tube of know length similar to Figure 4.1. The length $L_o$ is not important as long as the value is known accurately.

Following the development from the previous chapter Equation 4.1 holds for a closed tube.

$$\text{Im}\left(\frac{Z}{\rho c}\right) = \frac{-1}{\tan kL_o}$$

[4.1]

The experimental and theoretical values for the closed end tube agree closely from 1000 Hz to 6000 Hz. The lower frequencies do not coincide below 1000 Hz because frequencies below 1000 Hz were filter and signal aliasing begins to dominate at 7000 Hz. Figure 4.2
represents experimental and theoretical results for $l = 0.025$ meters and $L_o = 0.0144$ meters [16].

![Graph](image)

**Figure 4.2** – Experimental versus theoretical results for closed end tube

Several foam samples were also tested to determine if the impedance tube was working correctly. Even though the exact absorption values were not known the trend of values in Figure 4.3 shows evidence the tube was working correctly. The $\frac{1}{2}$ inch thick polyethylene foam absorbed the least amount of sound while the 1 inch polyethylene foam was more absorbent and the 1 inch Sonex foam absorbed the most sound. Since sound absorption depends on thickness for the same type material the results indicate this trend occurs in the impedance tube for the $\frac{1}{2}$ inch and 1 inch polyethylene samples. The Sonex foam is special acoustic foam designed specifically for sound absorption. The high sound absorption of this material in the impedance tube provides further evidence the impedance tube and post processing algorithms are working correctly.
4.2 ASTM E1050 Standard Sample Calculations

This section will detail sample calculations for the ASTM E1050 standard. The purpose of this section is to familiarize the reader with typical results from the theory presented in section 2.3.1. Figure 4.4 is provided as a reference and represents the same setup at in section 2.3.1.

Figure 4.3 – Absorption coefficient of foam samples used for testing

Figure 4.4 – Definition of $l$ and $s$ for ASTM standard
The equations from section 2.3.1 will also be provided as a reference to make the sample calculations easier to follow. Equation 4.2 represents the form of the transfer function used for calculations.

\[ H = \frac{P_2P_1^*}{P_1^*P_1} \]  \[4.2\]

The auto spectrums \( P_1P_1^* \) and \( P_2P_2^* \) recorded by the microphones in the impedance tube are depicted in Figure 4.5. The sample data provided is for a section of assumedly bonded SOFI.

![Figure 4.5 - Auto spectrums of microphone channels one and two](image)

The magnitude and phase of the cross spectrum between the two microphones \( P_2P_1^* \) used to calculated the transfer function in Equation 4.2 are represented in Figure 4.6 and Figure 4.7 respectively.
Figure 4.6 – Cross spectrum magnitude of microphone channels one and two

Figure 4.7 – Cross spectrum phase of microphone channels one and two
The magnitude of the transfer function $H$, defined by Equation 4.2, is presented in Figure 4.8. The phase of the transfer function $H$ is represented by the phase of the cross spectrum in Figure 4.7. Since the auto spectrum $P_i P_i^*$ does not have an imaginary component it does not introduce any phase changes.

**Figure 4.8** – Magnitude of transfer function $H$

The complex reflection coefficient, $R$, represented by Equation 4.3 can be used to determine the impedance and absorption of the test sample.

$$ R = \frac{H - e^{-jks}}{e^{jks} - H} e^{j2k(l+s)} $$  \[4.3\]

Where:
- $s$ = spacing between microphones, m,
- $l$ = distance from sample to center of closest microphone, m
- $\omega = 2\pi f$ the angular frequency, rad/s,
- $f$ = frequency, hertz,
- $k = \frac{\omega}{c}$ the wave number, and
- $c$ = speed of sound in air, m/s.
The complex reflection coefficient was separated into the real and imaginary component for graphing. Figure 4.9 represents the real component of the complex reflection coefficient. Figure 4.10 displays the imaginary component of the reflection coefficient.

![Graph of real reflection coefficient](image)

**Figure 4.9** – Real component of reflection coefficient

Once the complex reflection coefficient is calculated the impedance and absorption coefficient can be calculated. The normal complex impedance can be from Equation 4.4.

$$Z = \rho c \frac{1 + R}{1 - R}$$  \[4.4\]

Where:
- \(\rho = \text{density of air, kg/m}^3\),
- \(c = \text{speed of sound in air, m/s, and}\)
- \(R = \text{complex reflection coefficient.}\)

Figure 4.11 displays the real component of the acoustical impedance and Figure 4.12 displays the complex component of the acoustical impedance.
Figure 4.10 – Imaginary component of reflection coefficient

Figure 4.11 – Real component of acoustical impedance
The absorption coefficient can be found by Equation 4.5 which utilizes the magnitude of the complex reflection coefficient.

\[ \alpha = 1 - |R|^2 \]  \hspace{1cm} [4.5]

Figure 4.13 presents the average absorption coefficient for the SOFI over a bonded location.

**4.3 Allard Method Sample Calculations**

The Allard method uses the same auto spectrum, cross spectrum, and transfer function as the ASTM E1050 standard. However, instead of computing the complex reflection coefficient the Allard method determines the impedance at the midpoint, a distance \( l \) from the sample represented in Figure 4.14, between the two microphones and projects that impedance onto the surface of the material assuming the acoustic field in the tube is planar. Figure 4.14 depicts the experimental setup for conducting tests with the Allard method. The transfer function from Equation 4.2 is used to determine the impedance of the measurement plane between the two microphones.
The transfer functions represented in Figure 4.8 is substituted into Equation 4.6 to determine the complex impedance at the measurement plane. Figure 4.15 represents the real acoustical impedance at the midpoint of the two microphones. Figure 4.16 depicts the imaginary impedance at the midpoint of the two microphones.

\[ Z_M = j\omega ps \frac{H + 1}{2 - 2H} \]  

[4.6]
Figure 4.15 – Real acoustical impedance at the measurement plane

Figure 4.16 – Imaginary acoustical impedance at the measurement plane
The measurement plane impedance is projected onto the surface of the material using Equation 4.7.

\[
Z = \frac{Z_M - j\rho c \tan \left( \frac{\omega l}{c} \right)}{\rho c - jZ_M \tan \left( \frac{\omega l}{c} \right)} \tag{4.7}
\]

Figure 4.17 and Figure 4.18 respectively represent the real and imaginary impedances projected onto the surface of the SOFI.

![Figure 4.17](image)

**Figure 4.17** – Real acoustical impedance at the surface

After the surface impedance is calculated, it can be substituted into Equation 4.8 to determine complex reflection coefficient, \( R \). Figure 4.19 represents the real reflection coefficient at the surface of the SOFI.

\[
R = \frac{Z}{\rho c} - 1 \tag{4.8}
\]
Figure 4.18 – Imaginary acoustical impedance at the surface

Figure 4.19 – Real reflection coefficient at the surface
Figure 4.20 represents the imaginary component of the reflection coefficient. The absorption coefficient, $\alpha$, is calculated in Equation 4.9 by using the magnitude of the complex reflection coefficient. The sound absorption coefficient is plotted in Figure 4.21.

$$\alpha = 1 - |R|^2$$  \[4.9\]

![Graph](image.png)

**Figure 4.20** – Imaginary reflection coefficient at the surface

### 4.4 Background Noise

Several tests over the one inch SOFI disbond were conducted to ensure that background noise does not effect the calculation of the acoustical sound absorption coefficient. The impedance tube was placed over the one inch disbond while the wide band noise source from the experimental setup chapter produced white noise from 100 Hz – 10 kHz. A Radio Shack sound level meter (Catalog Number 33-2050) was used to measure the sound level inside and outside of the impedance tube. The sound level in the impedance tube was determined by placing the microphone of the sound level meter in the end of the tube. The external noise was measured a distance of one meter from the wide band noise source. The initial sound level in the tube was louder than 126 dBA.
The exact value could not be determined because the maximum sound level the meter could measure was 126 dBA. Figure 4.22 proves the background level does not affect the absorption coefficient if the sound level inside of the tube is at least 34 dBA higher than outside of the tube. The sound level inside of the tube was decreased while leaving the background noise at 92 dBA to determine the sound level needed in the tube to produce accurate results. Four different sound levels inside of the tube were compared starting at 112 dBA. The 112 dBA sound level results were indistinguishable from data in Figure 4.22. However, as the sound level in the tube approached the background noise level the smooth absorption coefficient spectrum deteriorated significantly as demonstrated in Figure 4.23. The absorption coefficient calculated at tube levels of 92 dBA and 82 dBA do not produce precise enough data for proper evaluation of the spectrums. The sound level inside of the tube needs to be at least 10 dBA above the background noise to produce accurate results. The sound level inside of the tube remained at the initial setting of 126+ dBA to ensure environmental noise does not affect the absorption coefficient spectrums.

Figure 4.21 – Absorption coefficient
Figure 4.22 – Tube sound level 126+ dBA with varying background levels

Figure 4.23 – Background sound level 92 dBA with varying tube sound levels
CHAPTER 5 - RESULTS

After impedance tube qualification was completed, testing on the SOFI began. The impedance and absorption coefficient of the SOFI over known unbonded sections were calculated and compared to areas of the SOFI that was assumed to be adhered to the aluminum backing properly. This chapter includes initial scan results, the creation of an indicator to determine unbonded areas from bonded areas, the result of a scan of the entire surface using the developed indicator, and the relationship between the absorption peaks and size of the SOFI defect.

5.1 Comparison of Allard and ASTM Calculations

The Allard method and ASTM E1050 standard were compared to determine which processing method would be the most successful to determine the bonding condition of the SOFI. The same data was inputted into both the Allard and ASTM algorithms and the results were compared. Figure 5.1 and Figure 5.2 compare the absorption coefficient and acoustical impedance of the material. The results show that both methods of calculation are almost identical. The only difference was a slight shift in the higher frequencies but the results remain consistent if the same method is used. This shift may be caused by the measurement plane shift between the two measurements. The ASTM E1050 measures the distance from the center of the closest microphone to the sample and the Allard method uses the midplane of the two microphones from the sample as a reference. Since both methods produced the same spectrum relative to the shift the ASTM E1050 method was used for subsequent calculations because it was specifically developed for use in an impedance tube.
Figure 5.1 – Allard method versus ASTM method for absorption coefficient

Figure 5.2 – Allard method versus ASTM method for acoustic impedance
5.2 Absorption Coefficient versus Acoustical Impedance

According to the ASTM E1050 standard the measurement of the microphone spacing and distance from the material being tested to the center of the first microphone must be known to a tenth of a millimeter [14]. This is especially important for the impedance calculation because the length is part of the phase component in Equation 2.23. However, the surface of the SOFI is not uniformly flat over the whole tank. This presents a problem in calculating the impedance unless the distance from the surface of the SOFI to the center of the closest microphone is measured accurately. A simple alternative to purchasing equipment to measure the distance from the SOFI to the microphone would be to calculate the absorption coefficient. The absorption coefficient is more robust because it only involves the magnitude of Equation 2.23 and not the phase. Figure 5.3 shows the impedance of the same location on the SOFI sample but has offset from the initial position of +1 millimeter, -1 millimeter, and +2 millimeters. These values are all possible while scanning the test sample because of the uneven top surface.

![Figure 5.3 – Impedance calculation with offsets](image-url)
The impedance changes considerably with minor variations in the length from the sample to the center of the microphone. The dip in the acoustical impedance at 3250 Hz begins to degrade with larger offsets from the true distance. Conversely, Figure 5.4 depicts no change in the absorption coefficient even with distance offsets from the true value. This more stable behavior led to calculations that only involved the absorption coefficient.

![Figure 5.4](image_url)  
**Figure 5.4** – Absorption coefficient calculation with offsets

### 5.3 Effect of Sealing Impedance Tube to Foam Surface

The impedance tube needed to be sealed consistently against the surface of the foam to produce results that depended only on the material properties. If the tube was not sealed properly the air gap between the tube and foam dominated the final results. Figure 5.5 shows the results of different sealing conditions. If the air gap was significant such as 2 millimeters between the tube and foam, the air gap dominated the absorption coefficient. If the tube was placed in contact with a surface that was uneven different amounts of air leakage would occur. This leakage caused significant variations from location to location.
If the impedance tube was sealed to the SOFI with a soft foam gasket that filled in possible air gaps the results became more uniformed and depended on the behavior of the material and not the air gap. The material used to seal the impedance tube to the SOFI also affected the measurement of the absorption coefficient. The magnitude of the results across the entire sample stayed consistent if the same type of seal was used. Figure 5.6 shows the differences between sealing conditions. The noisiest absorption coefficient spectrum corresponded to the no seal case. This was a result of the uneven SOFI causing uneven air leakage around the end of the tube. The \( \frac{3}{16} \)" foam seal was used for testing because it was the standard size available and would not indent or mar the surface of the foam during scanning.

5.4 Comparison of Long and Short Impedance Tubes

Short and long impedance tubes were constructed to determine if the impedance tube could be made shorter to make the system more portable.
The ASTM E1050 standard requires only three tube diameters from the sound source to the closest microphone [14]. Seybert however suggests this is the minimal distance and 10 to 15 tubes diameters may be required to fully develop plane waves at the test sample [16]. The short and long tube dimensions in Chapter 3 were used to determine the effect of tube length. Figure 5.7 presents the differences between the different lengths. Both tubes presented similar results as far as peak development was concerned but the short tube was noisier at the edges of the valid frequency range. The long tube also appeared to provide a larger absorption peak. As Seybert stated the plane waves in the short tube may not be fully developed which may lead to more noise in the frequency spectrum. This noise led to the longer impedance tube being used exclusively to reduce the frequency spectrum noise to as low as possible.
Figure 5.7 – Long tube compared to short tube measurements

5.5 Initial SOFI Frequency Spectra

Initial testing was used to compare the frequency spectra from unbonded sections to assumedly bonded sections. The initial testing using the ASTM E1050 standard showed promising results in the frequency range between 1000 Hz and 4000 Hz. Figure 5.8 demonstrates peaks in the absorption coefficient at 2200 Hz for the 2 inch by 8 inch cut and at 3235 Hz for the 1 inch by 5.5 inch cut. Three scans of different bonded locations were included as a reference on Figure 5.8.

5.6 Absorption Peak Indicator

An algorithm was developed to determine if a peak in the absorption coefficient spectrum was “significant”. A “significant” peak was a peak that indicated a disbond between the SOFI/aluminum interface. A maximum indicator would not work for the spectrum present in Figure 5.8 because of the upward slope of the curve. Also the peaks in the absorption coefficient appeared at different frequencies for different sized cuts.
This behavior also had to be corrected during indicator development. Initially several scans of assumed bonded locations were averaged to determine the average absorption coefficient spectrum. After scanning the entire sample, all points taken on the test sample were included in the average absorption coefficient calculation. Each individual spectrum was normalized by dividing the individual spectrum by the average spectrum. Figure 5.9 depicts the normalized spectrum. This normalization allowed the absorption peaks to be found by determining the maximum value of the spectrum. Several weighting strategies were used to further separate “significant” peaks from noise. After the absorption coefficient spectrums were normalized, the spectrums were aligned from 1000 Hz to 1500 Hz. Initial scans determined the behavior in this region was consistent and no “significant” peaks were present in this frequency band. The spectrums were aligned by finding the average absorption from 1000 Hz to 1500 Hz and subtracting that mean from the mean normalized absorption coefficient spectrum. Figure 5.10 performs this shift on the data presented in Figure 5.9. The mean shift in the absorption coefficient may be a result of the physical distance between the SOFI and closest microphone shifting slightly.

**Figure 5.8** – Initial absorption coefficient results
The shift may occur over surface defects, such as dents, on the surface of the SOFI or because the surface of the sample was not uniformly flat. The maximum peak in the frequency spectrum was found after normalization and mean shifting was complete. The initial spectrums indicated a peak a width of approximately 500 Hz. Using this observation, a 500 Hz wide frequency band centered at the maximum was integrated from the nominal absorption spectrum to the individual absorption spectra. This integration acted as a weighting system by returning a larger value for significant peaks. Figure 5.11 diagrams the indicator and sum weighting. The arrows between the one inch cut line and the bonded location line represent the area of integration used for calculations. Figure 5.11 represents a close up of the one inch cut absorption spectrum presented in Figure 5.10. The grid lines were omitted for arrow clarity. An additional weighting factor was added to further separate the “significant” peaks from noise. The maximum difference, which usually occurred at the maximum absorption value, between the individual absorption spectra and the nominal absorption spectra was multiplied by the area between the two curves.
Figure 5.10 – Normalized mean shifted absorption coefficient

Figure 5.11 – Diagram of sum indicator
If the maximum value of the absorption spectra was within 250 Hz of the useful frequency range limits the integration was terminated before unreliable data appeared. The useful frequency range for Figure 5.10 was determined to be 1000 Hz to 4000 Hz. This was determined from Nyquist criterion and observations of the noise in the spectrum. If the maximum peak was present at 3900 Hz the indicator would be calculated from 3650 Hz to 4000 Hz.

5.7 Scan of Entire Sample

One of the main objectives of this thesis project was continue the work Matt McKee started by completing a scan of the entire sample of SOFI. The method Matt McKee utilized was rather cumbersome and time consuming so only scans of certain sections of SOFI were completed. The scanning of the SOFI was conducted by hand using the impedance tube with a \( \frac{3}{16} \) inch foam sealed base. An automated system was available but it was only able to scan objects in a vertical orientation. The SOFI would require remounting to be vertically scanned and new equipment would need to be implemented to provide a slight retraction of the impedance tube while moving the tube from location to location to preserve the integrity of the foam seal. Manual scanning was implemented to save time and money since repeated scans of the whole sample was not needed. The 22 inch by 22 inch sample of SOFI was scanned using a 2 centimeter by 2 centimeter square grid. The data acquisition parameters included a sampling rate of 10,000 Hz, frame size of 1024 points, 128 ensemble averages, a signal amplification of 20 dB, and the low pas filter cut off of 5000 Hz. Figure 5.12 displays the 2-D scan of the SOFI sample using the absorption peak indicator developed earlier. If the indicator value is high it is more likely that the section of SOFI contained a disbond. White boxes were superimposed on the 2-D scan to represent the locations of the 1 inch and 2 inch wide cuts. The high values of the absorption indicator correlate with the areas of know disbons in the SOFI/aluminum interface. The higher values of the absorption indicator along the 0 X Coordinate resulted from improper sealing of the tube to the SOFI sample. The MDF baffle in this area was not completely flush with the top of the SOFI sample. The 2 inch and 4 inch square pads that were inserted by NASA do not appear on
the scan of the sample. This was consistent with the earlier ultrasonic scans performed by Dr. Hsu.

\[ \begin{align*}
\text{Figure 5.12} & \quad \text{2-D scan of SOFI sample to locate disbonds} \\
\end{align*} \]

### 5.8 Void Detection

The ability to detect voids in the SOFI was also investigated using the sound absorption coefficient. Since only one sample of SOFI was available to Iowa State University for testing the use of an alternate foam material with similar acoustical characteristics was examined for testing purposes. The use of alternate foam would allow testing of several different void sizes, shapes, and locations without further compromising the SOFI sample provided by NASA. Two inch thick yellow extruded polystyrene (EPS) foam (McMaster Carr PN: 9255K3) was studied as a possible replacement. The EPS, mainly used to insulate houses, had the same thickness, color, and similar composition as the SOFI indicating that it may have similar acoustic properties.
5.8.1 Qualification of EPS

Testing of the absorption coefficient of the EPS was conducted to determine if the acoustical properties of the EPS were similar to the SOFI. The EPS was cut into four inch squares for testing. The four inch squares were cut to match the size of the bottom of the impedance tube apparatus. The assumption of the SOFI being a locally reacting surface, meaning the acoustical properties are dominated by a small test area and not the entire sample, allowed the samples to remain small. The two inch EPS was tested under a “bonded” and “unbonded” condition and compared to the bonded SOFI. The “unbonded” condition involved placing the EPS on a ½” thick sheet of plywood, which represented a reflective surface, and testing the acoustical properties. The bonded condition involved adhering the EPS to the same ½” sheet of plywood with 3M Super 77 spray adhesive and testing the acoustical properties. The spray adhesive allowed for uniformed bonding similar to how the SOFI is attached to the external tank. Figure 5.14 suggests that the EPS and SOFI have similar acoustical properties. The unbonded EPS acoustical properties almost match the properties of the SOFI up to 3000 Hz and the bonded polystyrene mimics the straight absorption curve with a slight shift upward at lower frequencies. A disbond similar to the two inch disbond in the SOFI was created to further ensure proper acoustical behavior of the EPS. The EPS was bonded to the ½” plywood after a 2.00 inch wide by 0.13 inch deep air gap was created with a hot wire saw. Figure 5.13 depicts the side view of the gap created in the EPS where W represents the width and D represents the depth.

![Diagram of EPS and Plywood with dimensions](image)

**Figure 5.13** – Dimensions of air gap created in EPS

This gap demonstrated similar behavior to the two inch disbond in the NASA SOFI. The peak in the absorption coefficient appeared over the same frequency range as the SOFI disbond. Figure 5.14 compares the disbonded conditions in the SOFI and EPS. The black dashed line box encompasses the frequencies of correlation.
Figure 5.14 – Comparison of SOFI and two inch EPS with no air gaps in foam

Figure 5.15 – Comparison of SOFI and two inch EPS with similar air gap size
5.8.2 Comparison of Bonded and Unbonded EPS
The effect of bonding the EPS to the ½" plywood board was investigated to determine the best way to test the EPS samples. Three different EPS samples were tested on the ½" plywood before bonding and again after bonding to determine how the samples were affected. The samples were bonded using the 3M Super 77 spray adhesive to ensure uniformed bonding. Figure 5.16 and Figure 5.17 demonstrates the EPS behaves more consistently when bonded to the surface. The number and location of peaks in the absorption spectrum become more uniformed once the samples were bonded to the plywood surface. The significant difference in the absorption spectrum indicates the assumption of a locally reacting surface may be incorrect. The absorption spectrum was not only affected by the size of the air gap but also how the sample was bonded. The air gaps listed in the legends of Figure 5.16 and Figure 5.17 were located next to the plywood as indicated in Figure 5.13.

**Figure 5.16** – Sample unbonded (gap size indicated in legend by W x D from Figure 5.13)
5.8.3 **Effect of Measurement Location over Void**

The effect of different measurement locations were tested over a sample of EPS that had a 2.00 inch by 0.94 inch air gap created next to the bonding surface. Measurements were taken in five different locations indicated by the top view of the sample in Figure 5.18. The tube was aligned so that the inside diameter of the impedance tube was tangent to the edges of the air gap.

**Figure 5.17** – Sample bonded (gap size indicated in legend by W x D from Figure 5.13)

**Figure 5.18** – Location of tube over gap (C=Center, L=Left, R=Right, T=Top, B=Bottom)
The results for the measurement locations were split into two plots Figure 5.19 and Figure 5.20 to help maintain clarity. The EPS that did not contain a gap was added as a reference on both plots. The measurement location affects the size and location of peaks in the absorption spectrum. This result reinforces the idea that the material does not locally react. The location relative to the side or end of the void contributed to peak size and location. If the sample was locally reacting the peak size and location would only be affected by the void directly below the impedance tube and not by the surrounding EPS. However, the peaks in the absorption coefficient appear to be centered around 2650 Hz except for the bottom edge measurement location. Proceeding absorption coefficients were taken over the center of all air gaps to maintain uniformity between measurements.

![Figure 5.19](image)

**Figure 5.19** – Effect of measurement location over gap (legend W x D from Figure 5.13)

### 5.8.4 Voids in EPS Away from Bonding Surface

Voids away from the bonding can surface occur in the SOFI applied to the external tank. If this method is to be successfully implemented on a large scale defects away from the bonding surface will also need to be detected.
The ability to detect gaps away from the bonding surface was investigated by creating volumetric voids in the EPS samples. The defects were created by heating aluminum bars and melting away the foam to create the defect. Figure 5.21 exhibits the absorption spectrums for two different sized volumetric defects. The size of the defect appears to effect the location and size of the absorption peaks.

**5.9 Absorption Peaks Frequency Spectrum Correlation**

The peaks in the absorption spectrum appear at different locations for different sized defects. The advantage to correlating the peaks in the absorption coefficient to the size of the defect would be to provide more information with less scanning time. If it was decided only a defect larger than two inches by two inches was a problem the distance between scans could be increased and only peaks in a certain frequency range would be examined.

**Figure 5.20** – Effect of measurement location over gap (legend W x D from Figure 5.13)
5.9.1 Defects at the Bonding Surface

The artificial dis bonds created at the bonding surface of the SOFI sample resulted in absorption peaks at 2200 Hz for the two inch wide disbond and at 3235 Hz for the one inch wide disbond. Different sized dis bonds were created in the EPS to determine if the defects in the foam can be related to absorption peaks. A hot wire saw was used to make all the defects in the EPS. The length of the hot wire required the cuts to be four inches long or the length of the EPS samples. The hot wire was so long it deflected during cutting causing the defects to vary size from end to end. The depth of the defect was measured from the center of the EPS sample where the sound measurements were taken to maintain uniformity during analysis. Figure 5.22 represents data taken over five different defect depths that are approximately two inches wide. The data for the two inch wide cuts does not provide a simple relationship between the air gap size and the location of the absorption peaks. Initially the 0.13 inch and 0.25 inch air gaps the absorption peaks appear to shift to higher
frequencies for larger gaps. However, larger gaps such as the 0.50 inch and 0.88 inch gaps appear at lower frequencies.

![Absorption Coefficient vs Frequency](image)

**Figure 5.22** – Two inch wide gaps on bonding surface (legend W x D from Figure 5.13)

The one inch wide gaps appear to be more uniformed than the two inch wide defects. One cause for the uniformity may be due to the one inch wide defects had larger bonded areas to the ½” plywood. According to Figure 5.23 the absorption peaks stay at higher frequencies than the two inch wide defects. The one inch wide defects remained centered around 3500 Hz close to 3235 Hz where the one inch disbond in the SOFI appeared. The peaks appear to shift to lower frequencies as the depth of the air gap increases. The increasing volume of the air gap may also contribute to the resonant frequency similar to a Helmholtz resonator. The half inch wide defects in the EPS did not appear as peaks in absorption spectrum. Figure 5.24 does not show any absorption peaks in any of the spectrums. The reason for this may be due to the defects not dominating the cross sectional area of the tube unlike the one inch and two inch wide defects.
Figure 5.23 – One inch wide gaps on bonding surface (legend $W \times D$ from Figure 5.13)

Figure 5.24 – Half inch wide gaps on bonding surface (legend $W \times D$ from Figure 5.13)
Half inch polyethylene foam was used to further provide information about the absorption spectrum when a single condition does not dominate the cross sectional area of the tube. Four different cases were examined in a closed impedance tube. As Figure 5.25 demonstrates, the absorption coefficient relies heavily on the material that dominates the cross sectional area of the impedance tube. The sound absorption was proportional to the type of material present in the tube cross section. For example, as wider strips of half inch polyethylene were placed in the impedance tube the sound absorption became proportionally greater. Using this observation, the data for the half inch wide defects were recalculated without using an algorithm to account for any mean shift in the absorption spectrums. Figure 5.26 shows a uniformed shift below the EPS that contained no gap indicating that the absorption may be proportional to type of material that dominates the cross sectional area of the impedance tube.

![Graph showing absorption coefficients for different foam sizes.](image)

**Figure 5.25** – Different sizes of ½” polyethylene foam
The peaks of the absorption spectrum were compiled into a table to determine if the frequency peaks depended on the material resonance or air gap resonance. Since acoustical waves cause resonant conditions at quarter wavelength increments such as 0.25, 0.50, 0.75, 1.00, 1.25, etc. times the actual wavelength from the frequency spectrum these conditions were investigated. The center frequency and frequency band where the absorption coefficient deviated from the average absorption spectrum were analyzed. Table 5.1 gives an average error of 207% when trying to correlate the depth of the air gap to the center of the absorption peaks. The wavelength was calculated by dividing the speed of sound in air by the center frequency. The quarter and half wavelength resonances were analyzed because they were the closest length to the actual air gap depth. The amount of error in calculations suggested the peaks in the absorption spectrums were not caused by the air gap depth.

Figure 5.26 – Figure 5.24 uncorrected for mean shift
Table 5.1 - Resonance of air gap assuming $c = 343 \text{ m/s}$

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Table 5.2 - Resonance of air gap assuming $c = 343 \text{ m/s}$

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Table 5.2 determined the closest resonant length to the actual air gap depth from the width of the absorption peak not just the center frequency. The air gap resonance error only improves by 3% to 204%. The resonant frequency of the material was also investigated to determine if the material was dominating the resonant condition of the absorption measurements.

Table 5.3 - Resonance of center frequency assuming $c = 411$ m/s

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The average error from Table 5.3 was approximately 22% or nine times less than errors for the air gap calculations. The resonant length of the material was also calculated assuming the speed of the sound in the material was approximately 411 m/s. Since the value of the speed of sound in the EPS was not known 411 m/s was used because it was reasonable and produced the minimum amount of error. The speed of sound value of 411 m/s is reasonable because it is faster than the speed of sound in air because it has a higher density. In addition, the speed of sound was not as fast as a denser material such as steel which has a speed of
sound of 5960 m/s [17]. This speed of sound value was also close to the ultrasonic speed of sound in the SOFI that Dr. Hsu calculated as 500 m/s.

**Table 5.4 - Resonance of frequency band assuming c = 411 m/s**

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Table 5.4 considered the whole frequency band that deviated from the average absorption coefficient instead of using only the center frequency value. The percent error decreased by about half to 12% when the whole frequency band was considered. This reduction in error could be due to the fact the air gap depths created in the EPS samples were not uniformed over the entire cross section of the impedance tube because of deflection from the hot wire saw. Table 5.5 calculated the resonant condition in the impedance tube as a function of frequency. The long impedance tube which was 18.75 inches long from the tweeter to the surface of the sample material correlates to the absorption peaks assuming the resonance condition in the tube changes due to the impedance of the material being measured. The average error between the resonant frequency of the tube and the actual tube length was 1.32%.
Table 5.5 - Tube resonance of center frequency assuming $c = 343$ m/s

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5.9.2 Defects Away from the Bonding Surface

The voids away from the bonding surface were examined to determine if a relationship between the air gap size and location existed. The method for creating the holes in the center of the foam led to the hole being unparallel from the top of the sample. This was advantageous so that the relationship between the depth of the defect and absorption peaks could be analyzed. Figure 5.27 depicts a cross section of the EPS samples with the centered defects.

![Figure 5.27](image)

**Figure 5.27** – Dimensions to centered air gap created in EPS
The distance $D_1$ refers to the unflipped condition and $D_2$ represents the condition when the EPS sample was flipped. Figure 5.28 illustrates the difference between the two different air gap depths for the defect that was 1.75 inches wide and 0.50 inches deep. The method to create the largest defect was too inconsistent to determine the exact depth of the defect. Measuring the defect from the end of the EPS sample indicated a uniformed depth for both sides of the sample but upon visual inspection this was not the case. Large variations in the depth was present along the length of the cut but could not be measured accurately because of the location in the middle of the EPS sample.

Figure 5.28 – EPS sample with largest defect away from bonding surface

Figure 5.29 does not show differences in the absorption spectrum even though the distance $D_1$ (0.61 inches) and $D_2$ (1.14 inches) differ by 0.53 inches. The defect was indicated by a higher absorption at frequencies above 2500 Hz but no significant peak shifts are present to relate the depth of the defect. Figure 5.30 provided a shift in the amplitude of the absorption coefficient and a shift in the resonant peaks for the smallest defect away from the bonding surface. The change in $D_1$ (1.08 inches) and $D_2$ (0.75 inches) differed by only 0.33 inches.

```markdown
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<th>Frequency [Hz]</th>
<th>Absorption Coefficient $\alpha$</th>
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<tr>
<td>4000</td>
<td>0.4</td>
</tr>
</tbody>
</table>
```

**Figure 5.28** – EPS sample with largest defect away from bonding surface
but provided shifts in the absorption spectrums. The resonant absorption peak shifted by 250 Hz from 3250 Hz to 3500 Hz when the sample was flipped over.

![Graph showing absorption coefficient vs. frequency for samples with and without gaps](image)

**Figure 5.29** – EPS sample with medium defect away from bonding surface

The quarter wavelength resonances for the two peaks corresponded to 1.24 inches (13% error) for the initial measurement and 1.16 inches (35% error) for the flipped measurements. These values did not provide the exact depth values for the EPS but were within the error margin previously determined. Drill bits were used to create defects in the foam that were smaller than the cross sectional area of the impedance tube. The mean shifts in the absorption spectrums, depicted in Figure 5.31, at lower frequencies for the 0.25” and 0.38” holes centered in the EPS samples indicate the defect was detected. Slight shifts in the absorption spectrum from 2775 Hz for the 0.25 inch hole and 2470 Hz for the 0.38 inch hole also indicates detection. The locations of the peaks do not correspond to the depths that the holes were created which was approximately one inch from the measurement surface. The quarter wavelength resonances of 1.46 inches and 1.64 inches contained errors of 32% and 39% respectively.
Figure 5.30 – EPS sample with smallest defect away from bonding surface

Figure 5.31 – Different sized holes centered in EPS samples
5.10 Half Inch Impedance Tube

An impedance tube was constructed from ½" ID cast acrylic to determine if smaller defects would be apparent with a tube that had a smaller diameter. Figure 5.32 identifies the same resonant peak for the one inch wide disbond in the SOFI as the one inch diameter tube. The two inch disbond however is not as visible with the smaller tube. The mean absorption coefficient also is higher than the one inch tube. This was most likely due to the seal material dominating more due to the smaller cross sectional area. The impedance tube was also tested over the EPS samples. The impedance tube demonstrates the absorption peak behavior over the samples. Next the half inch impedance tube was tested over the smaller defects created in the SOFI. Two small holes measuring 0.25 inches and 0.38 inches were created in the center and next to the bonding surface respectively. The results in Figure 5.34 resemble the results presented in Figure 5.25 for different sized strips of ½” polyethylene foam in a closed impedance tube but does not produce absorption peaks like the larger disbands.

![Graph](image)

**Figure 5.32** – Results from half inch impedance tube over SOFI
Figure 5.33 – Results from half inch impedance tube over EPS

Figure 5.34 – Results from half inch impedance tube over holes in SOFI
CHAPTER 6 – SUMMARY AND CONCLUSION

The summary section in this chapter summarizes the decisions made throughout the results section. The summary was designed as a quick overview and the specific details were not reported. The conclusion section gives the main ideas drawn from the data. The future work section describes what should be done to make the process more robust and additional applications of the impedance tube method.

6.1 Summary

The use of an impedance tube to determine the presence of defects in the NASA spray on foam insulation (SOFI) was investigated. The ASTM E1050 standard was chosen over the Allard method to determine the acoustical properties of the SOFI. Both methods produced identical results so the ASTM method was used because it was developed for impedance tubes. The audio frequency acoustical absorption was used instead of the acoustical impedance because variations in the length between the foam sample and microphones did not affect the absorption results unlike impedance. The impedance tube needs to be sealed to the SOFI so that the air gap between the tube and foam does not dominate the absorption calculations. The long impedance tube was used instead of the short tube because the short tube introduced slightly more measurement noise. The initial frequency spectra of the SOFI detected peaks in the absorption coefficient spectrum over the artificially created disbonds. The scan of the entire sample resulted in detecting only the artificial disbonds and only produced false positives when the impedance tube was not sealed properly near the edges. Expanded polystyrene (EPS) was used as a substitute during testing so that different sized defects could be tested without further compromising the single sample of SOFI provided by NASA. The EPS provided acoustical behavior similar to the SOFI. The impedance tube method proved not to be totally locally reacting. The bonding condition of the surround EPS changed the sound absorption spectrum. Voids away from the bonding surface were
detectable using the impedance tube method. The correlation between the sizes of the defect depended more on material resonance than air gap resonance. The smaller diameter impedance tube provided similar behavior when compared to the larger diameter tube. Defects smaller than the cross sectional area of the impedance tube provided a shift in the absorption spectrum instead of resonant peaks.

6.2 Conclusions
Defects in the SOFI can be detected by calculating the audio frequency sound absorption frequency spectrums. The use of an impedance tube reduces the environmental factors such as background noise and acoustic reflections. This noise reduction allows resonant peaks in the absorption spectrum to be detected over a wide frequency band instead of the single frequency indicator used during earlier research. Both disbonds on the bonding surface and volumetric voids on and away from the bonding surface were detected. The correlation of absorption peaks to defect size depended more on material resonance than on the resonance of the air gap. However, the large error between the material thickness and resonant length suggests that the peaks are not only dependant on material thickness. The location of the tube relative to the edge of the defect and the bonding condition of the surround SOFI also affect the location and size of the absorption peaks. The resonance of the impedance tube appears to be a valid indicator of absorption peak location but the relationship between the tube resonance and defect size needs to be determined. The defects smaller than the cross sectional area of the tube shifts the absorption spectrum without causing resonant peaks. This was caused by the bonded material dominating the calculations instead of the defect dominating the cross sectional area of the tube. The EPS was a valid substitute for SOFI testing because the acoustical behavior was similar when comparing the acoustical absorption and appearance of resonant peaks.

6.3 Future Work
Continued work on correlating the frequency peaks to the defect size should be conducted. The relationship between the peaks and defect size would help the scanner determine if the defect would need to be corrected with less scanning. Another sample of SOFI should be
scanned to verify the absorption peak behavior occurs on all SOFI samples and not just the sample obtained by Iowa State University. A sample with defects of various sizes should be examined to help correlate the peaks in the frequency spectrum to defect size. Different thicknesses should also be tested to verify the defect indicators are not dependent on the foam being two inches thick because the foam sprayed on the external tank of the space shuttle does not consist of only two inch thick foam. The thickness of the foam varies from location depending on geometry. When the EPS foam is used for future testing the defects should be made more uniformly by using a hot wire saw with less wire deflection or a mill should be used to obtain uniformity. The smaller diameter impedance tube should continue to be investigated to help identify the defects smaller than one inch. The impedance tube method could also be used for any application that involved a sound absorbent material adhered to a reflective surface. The bonding of foam sprayed into or onto objects such as refrigerators, conventional ovens, storm doors, or walls of a home could be tested for uniformity.
REFERENCES


