Ultrasonic, Normal-Incidence Insertion Loss through Common Building Materials Using Continuous-Wave Excitation

Physics 492R Capstone Project Report

By: Jayrin Farley

Advisor: Dr. Brian E. Anderson

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ABSTRACT

Transmission loss measurements of building materials at audible frequencies are commonly made using various techniques such as plane wave tubes or as a panel between reverberant rooms. These measurements provide vital information for noise isolation control in architectural acoustics. However, not much has been done to explore airborne ultrasonic sound transmission through common building materials. Technologies and products that utilize ultrasonic frequencies are becoming increasingly more common. This paper will present various measurements of the ultrasonic, normal-incidence insertion loss for various building materials over a frequency range of 28 kHz – 90 kHz. The materials tested include: medium density fiberboard, Styrofoam, galvanized steel, and polycarbonate plastic. Results show that the insertion loss is approximately 10 dB less than predicted by the theoretical mass-law transmission loss. This paper will also discuss the challenges involved in making such measurements.

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I. INTRODUCTION

Transmission loss (TL) is a measurement of the noise insulation of a material. It is the ratio of incident sound power to transmitted sound power expressed in dB.[1] Transmission loss measurements of building materials at audible frequencies (20-20,000 Hz) are commonly made.[2,3,4] These measurements are typically made by placing a small sample in a plane wave tube[5,6,7,8,9] (for example, see the recent work done in references 5, 6, 7, 8, and 9) or by placing a panel between reverberant rooms[10,11,12,13] (for example, see the recent work done in references 10, 11, 12, and 13). Not much is known about air-borne transmission loss over the ultrasonic frequency range of 28 kHz - 90 kHz. Research has been done in the field of underwater transmission loss at ultrasonic frequencies.[4, 14-15] Ultrasonic transmission loss studies in air have been done on biological materials, but over a much higher frequency range (>200 kHz).[16,17]

For plane wave tubes, the length and cross-sectional area of the tube are determined based on the wavelength of the signal to be tested. The smaller the wavelength, the smaller the required cross section of the plane wave tube to avoid the first cross mode, and vice versa. It is not feasible to construct a plane wave tube small enough to be appropriate for testing ultrasonic signals.

To make a measurement using coupled reverberation chambers, the partition is placed in between the two chambers. A sound source produces noise in a source room, and sound is transmitted through the partition into the receiving room. The reverberation time of the receiving room must be determined beforehand. The spatially-averaged sound pressure levels in the two rooms are measured and the difference between the two values gives the transmission loss of the partition. Transmission loss can also be determined using only one reverberation chamber with an anechoic or free-field receiving room. In this method, the incident and transmitted sound intensities are measured instead. According to Bies and Hansen, this second method using only one reverberation chamber provides more accuracy than the first method.[18] This technique may be attempted in future research on ultrasonic transmission but will require some careful consideration of how to design an ultrasonic reverberation chamber.

In an anechoic chamber, TL measurements can be made with either pulsed signals or continuous-wave (CW) signals. In each case, a signal is emitted from a source loudspeaker, and the incident sound pressure level (SPL) is measured, as well as the transmitted, or downstream SPL. An insertion loss measurement, which approaches a TL measurement, is measured only at a downstream microphone location with the partition in place and without. The advantage of the insertion loss technique is that the absorption of the propagating waves does not have to be accounted for (important for ultrasonic frequencies) since the propagation distance is the same. Pulsed signal measurements are unaffected by diffraction around the partition with the experiment designed to yield sufficient time separation, whereas CW signal measurements may be affected by diffraction around the partition. We chose to use CW signals to get continuous averaging due to time varying instabilities in our ultrasonic source transducers.

In general, ultrasonic measurements in air can be difficult to make. Absorption at ultrasonic frequencies can be orders of magnitude higher than absorption at audible frequencies, making distances from the source an important consideration. Also, it may be difficult to find the necessary equipment. Not many transducers are made that emit in ultrasonic frequencies. Those that are made are generally narrowband, making it challenging to analyze in octave bands or even third-octave bands. Additionally, in order to measure ultrasonic frequencies, one needs an analyzer with a sufficiently high sampling frequency. Perhaps one of the biggest challenges is that the sensitivity of the majority of commonly available microphones significantly drops off in the ultrasonic range. Other challenges come in the difficulty of finding an appropriate testing facility. Some anechoic chambers may not be anechoic above 20 kHz if a perforated metal mesh is used to contain/protect the wedges.

Ultrasonic frequencies are increasingly being used in the medical industry and in other industries. In medicine, ultrasound is used in sonograms, ultrasonic tomography, lithotripsy and therapy. In other industrial applications, ultrasound is used for cleaning, mixing, soldering, drilling, the detection of flaws in solid objects, acoustical holography, and a variety of chemical applications.[19] Electronic devices, such as laptops and cell phones also emit ultrasonic noise (ex. the switching frequency of some DC to DC transformers generates vibrations and acoustic radiation).

It has been proposed that ultrasonic sound may have detrimental effects to hearing,[20,21,22] even though humans are unable to hear it. Pilot studies involving dental hygienists exposed to ultrasonic noise from cleaning equipment suggest that ultrasonic exposure causes hearing loss, especially in the higher audible range.[23] With many technologies and products emerging that use ultrasound, the results of the current study could have a vital impact on future product development. If ultrasound does, in fact, affect hearing, such devices would need to be enclosed in a material that does not transmit ultrasonic sound.

The results of the current study could also have an important impact in the field of nondestructive testing and evaluation. One example from this field is that if an electronic device that emits ultrasonic sound were encased inside a container, and the transmission loss of that container were known, then the device, and/or the state of that device, could be identified without ever needing to disassemble or destroy the box, assuming the electronic device radiates sound at sufficient levels. Nondestructive testing would provide a way to determine if these electronic devices are working properly without requiring that the container be opened.

This paper reports on normal-incidence air-borne ultrasonic (28-90 kHz) sound transmission through various common building materials, including medium density fiberboard (MDF), Styrofoam, galvanized steel, and polycarbonate plastic.

II. EXPERIMENT

Three ultrasonic emitters are used as the sources in this experiment. These sources are denoted A, B, and C, with 40 kHz, 58 kHz, and 75 kHz respective center frequencies. A photograph of the three sources is shown in Fig. 1. The dimensions and parameters of these sources are given in TABLE I.

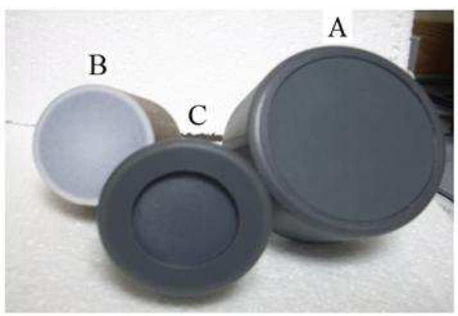

FIG. 1. Photograph of three ultrasonic sources used in this paper.

TABLE I. Dimensions and parameters of ultrasonic sources.

Source	Center Frequency	Diameter (cm)	-6dB Beam Width		
			28 kHz	40 kHz	50 kHz
A	40 kHz	7.14	12.7°	8.0°	9°
			50 kHz	56 kHz	71 kHz
B	58 kHz	4.45	7.5°	11.25°	6.25°
			71 kHz		90 kHz
C	75 kHz	4.6	7°		7.5°

The receiver used is a type-1 precision, ¼ in., prepolarized, ICP, condenser microphone with a specified flat-frequency response of up to 100 kHz. The materials under test include: medium density fiberboard, Styrofoam, galvanized steel, and polycarbonate plastic. Figure 2 is a photograph of the four materials used in this project. The physical properties, including density and size are given in TABLE II.

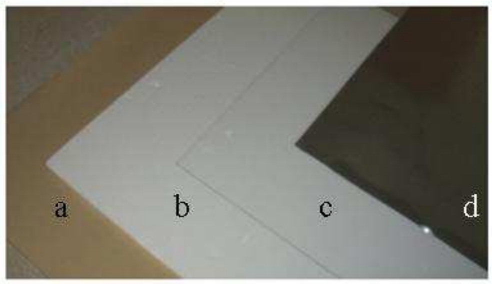

FIG. 2. Photograph of partitions tested in this experiment. a.) medium density fiberboard, b.) Styrofoam, c.) polycarbonate plastic, d.) galvanized steel.

TABLE II. Table of physical dimensions and properties of partitions tested.

Material	Width (cm)	Height (cm)	Thickness (mm)	Density (kg/m^3)	Wave Speed (m/s)	1st Thickness Resonance (kHz)
Plastic	134.62	91.44	2.82	1160		
Styrofoam	132.08	121.92	17.50	21		
MDF	121.92	124.46	12.70	751	2260	88.99
Steel	121.92	91.44	0.31	7540	6167	9946.89

The thickness resonances are calculated using the general equation for half wavelength resonators with the same boundary conditions on each end of the resonator:

$$f_n = \frac{nc}{2L}, \; n = 1,2,3\ldots, \qquad (1)$$

where n is the mode number, c is the speed of sound in the material, and L is the thickness. The speed of sound, c, is calculated using the equation for the bulk longitudinal sound speed as follows:

$$c = \sqrt{\frac{E(1-\sigma)}{(1+\sigma)(1-2\sigma)\rho}}, \qquad (2)$$

where E is the Young's modulus, ρ is the density, and σ is the Poisson's ratio of the material.

The insertion loss measurements presented in this paper are made in an anechoic chamber on the campus of Brigham Young University. A photograph of the anechoic chamber is shown in Fig. 3. The wedges in this chamber are made of exposed foam. This makes the room less reflective at ultrasonic frequencies than wedges covered with perforated metal coverings. The working dimensions of the room are 3.00 m x 2.38 m x 2.59 m. The anechoic chamber was previously qualified as being anechoic over the range of 150 Hz to 5 kHz using ISO 3745-2003. For ultrasonic measurements the chamber needed to be further qualified from 28 kHz to 90 kHz to ensure that it absorbs sound over the frequency range of interest. A modified qualification procedure to ISO 3745 was used with CW excitation, yielding reasonably anechoic results. For further information on the chamber qualification see appendix A.

FIG. 3. Photograph of the anechoic chamber used with exposed foam wedges. The door to the chamber is open in this photograph.

Insertion loss, IL, is calculated by measuring the sound pressure level (SPL) without the partition in place and subtracting the sound pressure level measured with the partition in place

$$IL = SPL_{without} - SPL_{with}. \tag{3}$$

The experiment is set up by placing a source at a fixed location at one end of the chamber. The microphone is placed at a fixed location on the opposite end of the chamber. The partition under test (PUT) is held in place by small clamps to allow consistent replacement of PUTs and easy insertion and removal of the PUT between measurements. The source is aligned (necessary for highly directional sources) by placing the transparent polycarbonate plastic partition in the holders between the source and receiver and using a laser pen. The plastic partition reflects part of the laser light and allows part of it to transmit through the partition. The laser is attached to the top of the source, and the source is rotated until the laser reflected exactly back onto itself. A similar method is used to align the microphone with the source by placing a laser on top of the receiver and rotating the receiver until the laser light is both transmitted onto the source face and also reflected back onto itself. A photograph of the experimental set-up is shown in Fig. 4.

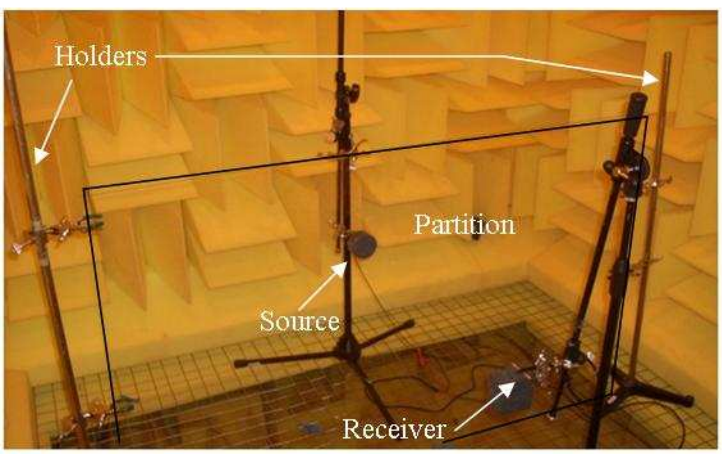

FIG. 4. Photograph of the experimental set up with the polycarbonate plastic partition in place, and source A as the ultrasonic emitter. The edges of the partition were outlined to make it more visible to the viewer.

A CW sine-wave signal is emitted from each source. For each measurement the partition is inserted and the sound pressure level is recorded. The partition is then removed and the sound pressure level is recorded again. The insertion loss is found using Eq. (3). Measurements are taken at the 1/6-octave band center frequencies. Overlapping measurements are made at frequencies on the upper and lower ends of the sources' operation ranges. With source A, measurements are taken at 28, 31.5, 35.5, 40, 45, and 50 kHz. With source B, measurements are taken at 45, 50, 56, 63, and 71 kHz, and with source C measurements are taken at 71, 80, and 90 kHz. For the Styrofoam, MDF, and galvanized steel partitions measurements were also taken at 63 kHz with source C. However, this measurement could not be made with the polycarbonate plastic partition in place because the transmitted SPL could not be distinguished from the noise floor. The 1/6-octave bands for each source were chosen such that bands would overlap between the sources.

A two-channel, HP 35670A Dynamic Signal Analyzer is used to take sound pressure level measurements over a frequency span of 0 to 102.4 kHz with a resolution of 1600 lines. The measurements are taken with 40 averages in time. Each measurement takes approximately 45 seconds in time (in part due to analyzer processing time). Without the partition in place the signal to noise ratio (SNR) ranges from 37 dB to 74 dB, depending on the source used and the proximity of the emitted frequency to the transducer's center frequency. With the partition in place the SNR range is from 1 dB to 20 dB for the polycarbonate plastic, medium density fiberboard, and galvanized steel partitions (though the majority of the measurements had at least a SNR of at least 5 dB). The average signal to noise ratio for these three partitions is approximately 5 dB and quite distinguishable from the noise floor. The range for the signal to noise ratio of the Styrofoam partition is much higher than that of the other three partitions due to the lower degree of transmission loss through the Styrofoam. The signal to noise ratio ranges from 16 to 48 dB, with an average ratio of 28 dB for the Styrofoam PUT.

III. RESULTS AND DISCUSSION

Theoretical values for the transmission loss of each partition are found using the well known normal-incidence mass law:

$$TL = 10\log\left(\left[\frac{m\omega}{2\rho_0 c}\right]^2 + 1\right) \quad , \tag{4}$$

where m is the mass of the partition, ω is the angular frequency, ρ_0 is the density of the fluid through which the sound is propagating, and c is the speed of sound in the fluid.

The mass law and measured insertion loss data are shown in Fig. 5. The measured data generally increases as 6 dB per frequency octave as does the mass law theory. The three solid lines shown on the graphs correspond to the three sources used. In Fig. 5(a), the measured IL values start out nearly 20 dB below the theoretical values. Between 35.5 kHz and 63 kHz there is much less deviation between experimental and predicted values. Above 63 kHz, measured IL values once again begin to diverge significantly from the values predicted by the mass law. In Fig. 5(b), IL values obtained using both source A and B are considerably lower than the theoretical TL values. However, the values obtained using source C better correspond with the prediction. Figure 5(c) shows increasing insertion loss values from 28 kHz to 45 kHz. From 45 kHz to 90 kHz measured IL values generally tend to decrease in value. In Fig. 5(d), experimental insertion loss values measured with sources A and B better correlate with theoretical values. Insertion loss values obtained at 80 kHz and 90 kHz diverge more from theory.

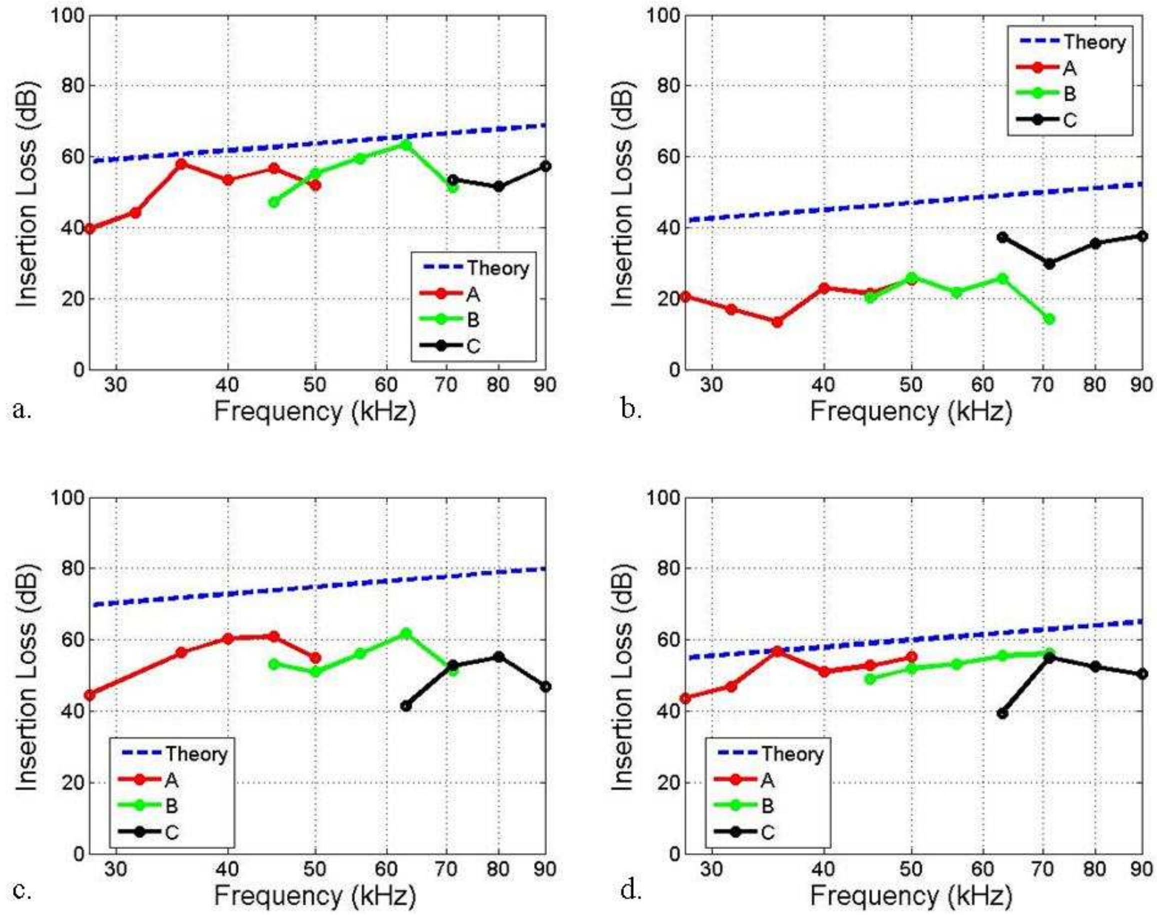

FIG. 5. Insertion loss vs. frequency plots for the four materials tested. (a) Polycarbonate plastic, (b) Styrofoam, (c) Medium density fiberboard, (d) Galvanized steel. Measured data is compared to theoretical transmission loss values.

For all partitions it can be seen that overlapping insertion loss values obtained using different sources do not generally coincide. In Fig. 5(c), the experimental IL values measured with both source B and source C at 63 kHz differ by 19.9 dB. The reason for the disagreement for overlapping frequencies is unknown but is likely due to the lower signal to noise ratios with the partitions in place.

It is possible that these results may display the effects of resonances in the thicknesses of the partitions tested. The wavelengths of the ultrasonic frequencies may be small enough to actually excite resonances in the partitions in the thickness dimension. The first thickness resonances for the medium density fiberboard and galvanized steel partitions are given in TABLE II. These thickness resonances may be the cause of the decrease in measured insertion loss values at higher frequencies for medium density fiberboard, as seen in Fig. 5(c).

Based upon the popular model for diffraction around barriers proposed by Kurze and Anderson,[24] it is determined that the diffraction around the partition is minimal, and perhaps nonexistent practically speaking. The estimated diffraction around the partition would result in approximately no measured insertion loss through the partition since the diffracted waves are attenuated by the about the same amount as the transmitted wave. Since the measurements presented here show significant IL we conclude that diffraction around the partition edges is likely only to have a minor effect on IL accuracy or no effect at all. Further testing with additional techniques will need to be done to determine the extent of diffraction effects on these results.

Other effects seen in the results may arise from problems in the misalignment of the source and receiver. The floor of the anechoic chamber is made of metal wire mesh, with 2 in. square gaps between the wires. This makes it difficult to properly align the source and receiver in both the vertical and horizontal directions because the floor does not provide a solid base. Misalignment off of normal incidence could potentially result in less IL due to the coincidence effect which occurs only off of normal incidence.

IV. CONCLUSION

Measurements of ultrasonic, normal-incidence insertion losses have been presented in this paper for common building materials. These measurements may have an impact on future product design and development. These measurements will also be fundamental in expanding our knowledge of air-borne transmission loss at ultrasonic frequencies. To the authors' knowledge this work represents the first study of the ultrasonic air-borne transmission properties of structural panels up to 90 kHz.

The measured insertion loss values suggest that more sound is being transmitted than the mass law predicts. In all four of the partitions tested, measured insertion loss values were lower than those predicted by the mass law by 10 dB on average but in some cases by as much as 20 dB. The reason why the measured values are so much lower than the theoretical values may be due to minor diffraction effects, misalignment off of normal incidence (resulting in a coincidence effect), and/or thickness resonances.

Future work on this project will include repeatability measurements to ensure that the results obtained in this experiment are valid and reproducible. Further testing will also be done to determine the extent of the effect diffraction has upon measured insertion loss values. The results presented here will be verified using additional transmission loss techniques.

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APPENDIX A

The standard method for qualifying an anechoic chamber is to take frequency spectrum measurements and record the one-third octave band sound pressure levels at 10 cm increments along four diagonals of the room (see ISO 3745-2003). For lower frequencies (5 kHz – 40 kHz), the hyper tweeter of a Mackie speaker is used with an HP Analyzer to emit a swept sine wave along each of the four diagonals, over the frequency range of 4.5 kHz to 45 kHz. Measurements are taken in 1/3 octave bands. Ultrasonic sources A, B, and C are used to qualify the chamber above 45 kHz. Originally these sources were assumed to be very narrow band, so the room was tested only at their center frequencies of 40 kHz, 58 kHz, and 75 kHz.

In order to be considered anechoic the sound pressure levels must decay over distance as

$$20\log_{10}\frac{A}{r} + B \pm 3dB \qquad (5)$$

where A and B are constants and r is the distance from the source to the microphone.

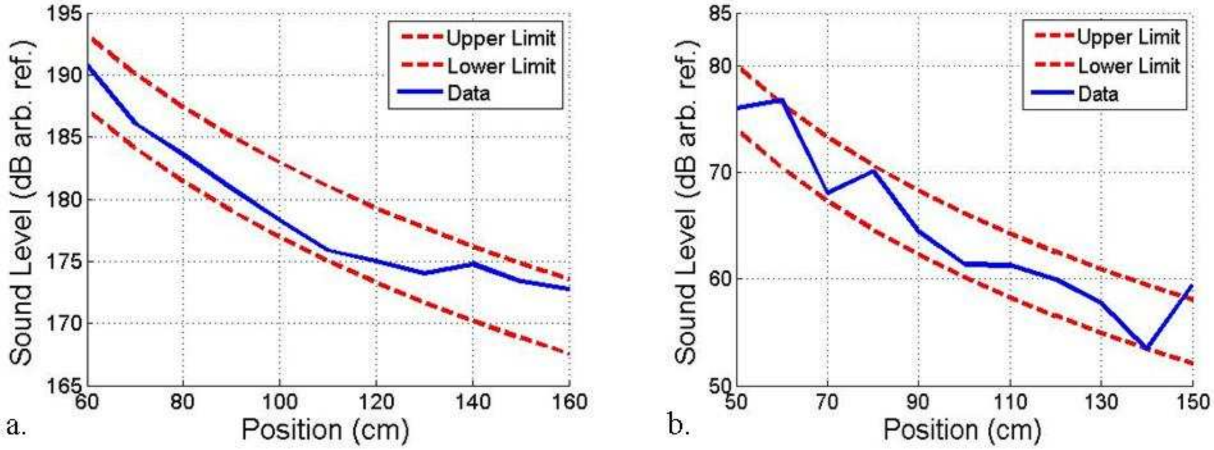

FIG. 6. (a) Qualifying fit for 8 kHz along the xyz axis. (b) Qualifying fit for 75 kHz along the xz.

From 5 kHz to 40 kHz the chamber qualified as anechoic, as shown in Fig. 6. For each of the four diagonals, the graphs of measurements taken at 40, 58, and 75 kHz each had one or two data points that fell outside of the given range. This unfortunately does not allow the room to be qualified as completely anechoic at these frequencies. However, the room can be considered nearly anechoic. The data taken fit well enough within the range to be deemed appropriate for the scope of this project. It was later discovered that these sources are not nearly as narrow band as originally thought. Future research will include re-qualifying the chamber in 1/3 octave bands from 40 kHz to 90 kHz. This will hopefully minimize the outlying points on each fit.

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