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Sound transmission measurements through porous screens

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The two microphone transfer function technique is used to measure sound transmission properties of porous screens or membranes in a plane wave tube. This paper will compare sound transmission of porous screens from several manufacturers. Measurements are made with two different plane wave tubes, one of diameter 10.2 cm to measure frequencies between 100 Hz and 2 kHz, and the other of diameter 1.3 cm to measure frequencies between 2 kHz and 16 kHz. Multiple methods of transmission loss measurement and analysis are presented. Special considerations are made to account for the intrinsic losses in the smaller diameter tube.

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1. INTRODUCTION

Currently there are few companies in the market that strive to provide woven mesh that is not only water resistant, but also attempts to be acoustically transparent. Commercially available mesh provides small electronic transducers like drivers and microphones a level of water resistance while still minimizing acoustic degradation, but often the porous mesh is not sufficiently protective. Things like hearing aids and body worn cameras need thorough protection from liquids while still projecting or receiving sound efficiently. In developing microfabricated membranes, our goal was to provide better performance. There is a relationship between pore size and water pressure such that as pore size decreases, the water resistivity increases. If our microfabricated screens are to be applied as a liquid barrier for acoustic transducers, we must understand the acoustic impact of a smaller screen pore size. By comparing transmission loss in a plane wave tube for multiple acoustic screens, including those already commercially available, we can determine how suitable our membranes would be for acoustic transmission.

Three different membranes were tested, two that are commercially available for acoustic filtering (the two black membranes in Figure 1) and one developed by Precision Membranes (PM) with significantly smaller pore size and more open area (transparent membrane). The two black membranes have pore sizes of 21 μm and 18 μm, with open areas of 15% and 13% respectively, while the transparent membrane has 8 μm pores, though 25% open area.

Determining which measurement practices were best suited to our equipment was also a goal of the present work, as was obtaining clean results while still measuring in frequency ranges from 90 to 16000 Hz. Data analysis methods were studied using both an anechoic and non-anechoic termination, rigid wall losses in a tube, and microphone calibration techniques. The purpose of this paper is to present our findings and discuss our implementation of the transmission loss measurement techniques.

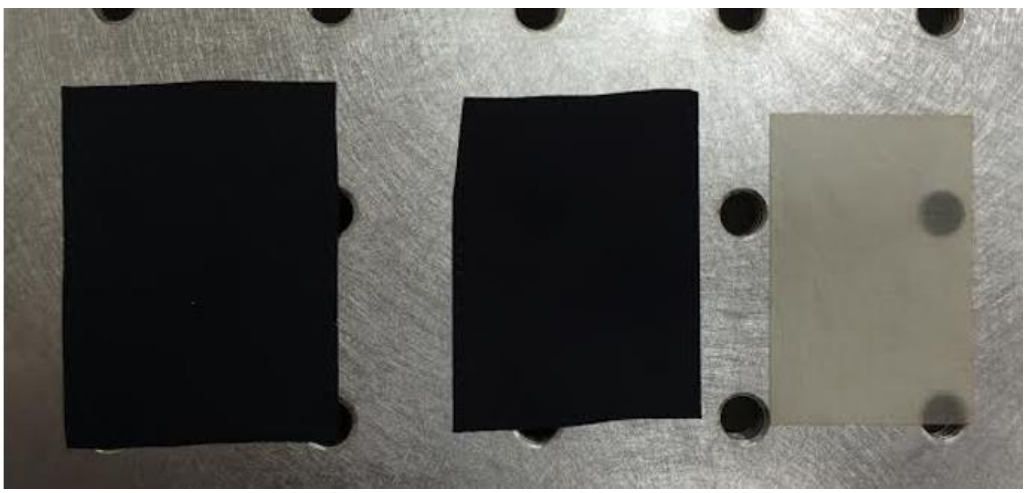

Figure 1: membranes from left: 21 μm pore (15% open area), 18 μm pore (13% open area), 8 μm pore (25 % open area).

2. PLANE WAVE TUBE CONSIDERATIONS

For testing, the membranes (also referred to as screens) were mounted approximately halfway along an acoustic plane wave tube, as shown in Figure 2. We first used the two microphone transfer function technique developed by Chung and Blaser[1] in 1980 to decompose the upstream and downstream sound fields in order to calculate upstream and downstream reflection coefficients. Chung and Blaser's technique assumes the following conditions are met. Firstly, the plane wave tube must have an anechoic termination. Secondly, the microphones mounted in the tube must be more than a tube diameter away from any boundary, such as the driver or screen itself. Cross-modes generally decay sufficiently in the tube about one tube diameter length away from a boundary.[2] If these conditions are met, transmission loss (TL) is measured as

$$TL = 20\log_{10}\left|\frac{e^{jks} - H_{12}}{e^{jks} - H_{34}}\right| - 20\log_{10}|H_{23}|, \quad (1)$$

where $H_{12} = \frac{P_1(f)^* P_2(f)}{P_1(f)^* P_1(f)}$ and is the transfer function between microphones one and two, and $H_{34} = \frac{P_3(f)^* P_4(f)}{P_3(f)^* P_3(f)}$, the transfer function between microphones three and four. H_{23} is the transfer function between microphones two and three and is equivalent to $\sqrt{\frac{S_{33}}{S_{22}}}$ where S_{33} is the autospectrum from microphone three.

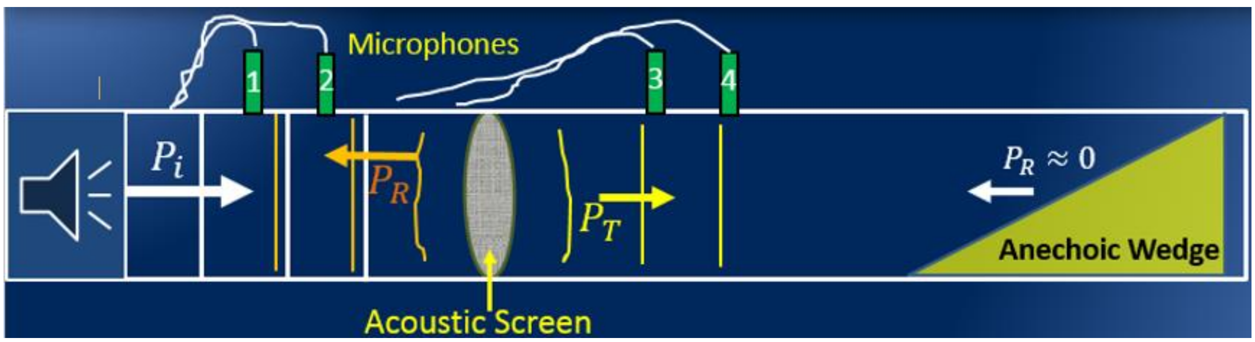

Figure 2: Schematic of plane wave tube with acoustic screen mounted mid-tube. P_i is the incident pressure wave, P_R the pressure wave reflected from the screen, and P_T is the pressure wave transmitted through the screen. Plane waves form in the tube within a tube diameter of hitting a boundary.

Chung and Blaser established a technique for factoring out differences in microphone gain and phase by physically switching microphones as part of the testing process. To implement this, a frequency sine sweep was emitted from the driver with the microphones in their original positions, while simultaneously measuring the transfer functions for each set of microphones ($H_{12}^o, H_{34}^o, H_{23}^o$). Then the microphone positions were physically switched (first switched with second and third switched with fourth), and the sine sweep was run again (H_{12}^s, H_{34}^s). Lastly, the first and fourth microphones were replaced in their original positions and a third sine sweep was run with the second and third microphones switched (H_{23}^s). By taking the geometric mean of the transfer functions from each configuration (the original and switched), we can divide each original microphone transfer function by the mean to eliminate the impact of any phase and amplitude mismatch between the microphones. An example of this is shown in terms of the transfer function between microphones one and two in equation (2).

$$H_{12} = \frac{H_{12}^o}{\sqrt{H_{12}^o * H_{12}^s}}. \quad (2)$$

The pipe diameter can only restrict acoustic propagation of cross-modes below the first cross mode resonance frequency (often called the cutoff frequency, f_c) where d is the pipe diameter (or side length for rectangular cross-section tubes), and c is the speed of sound in the tube (air at 290 K and 1.01 atm). This is shown in equations (3) and (4) for a circular and rectangular cross-section tubes respectively

$$f_c = \frac{0.586c}{d} \qquad (circular\ pipe) \tag{3}$$

$$f_c = \frac{0.5c}{d}. \qquad (rectangular\ pipe) \tag{4}$$

The anechoic wedge is also a limiting factor for testing procedures. An anechoic wedge is considered to be anechoic if it can absorb 99% of the incident energy (absorption coefficient of 0.99 or a pressure reflection coefficient of 0.1).[3] The length of the anechoic wedge is the primary factor that determines the low frequency limitations of an anechoic wedge but the taper angle also matters. A commonly used criterion is that the low frequency anechoic limit of a wedge occurs when the wedge length is approximately 1/3 the length of a wavelength. Further design considerations are given in Reference 3.

In addition to anechoic frequency considerations, if microphones are not spaced appropriately in the tube, the acoustic data obtained is flawed. In Figure 3, the microphones are spaced too close to one another in order to detect any difference between amplitudes and phases for long-wavelengths. In this case, the microphones need to be placed further apart to detect the wave. In Figure 4, the microphones are too far apart to detect the short wavelength, and a spatial aliasing effect occurs. In this instance, the microphones need to be closer together to accurately record the shorter wavelengths. To combat these issues, Bodén and Åbom[4] specify a certain range of frequencies for a given microphone spacing, according to the equation

$$0.1\pi < ks < 0.8\pi, \tag{5}$$

where k is the acoustic wavenumber and s the physical distance between the microphones in each pair (1 and 2, 3 and 4). This equation allows one microphone spacing to span three octaves of measurement bandwidth (a factor of 8).

Figure 3: If microphones are spaced too closely relative to the wavelength, they can't detect wave amplitude differences.

Figure 4: If microphones are spaced far apart relative to the wavelength, they detect a larger wavelength than is actually present.

3. PLANE WAVE TUBE TESTING

For our experiments we used two plane wave tubes. The tube shown in Figure 5 is 10 cm (4 inches) in inner diameter and covers a bandwidth of 50 Hz to 2000 Hz, if two different microphone spacings are used. The low frequency microphone spacing of 30 cm covers 50-400 Hz and the higher frequency spacing of 5 cm covers 350-2000 Hz. The removable plugs allowed us to move the microphones to these distances. This tube also has a tapered anechoic termination for frequencies down to roughly 90 Hz.

Because the 10 cm diameter tube is anechoic over the frequency range of 50-2000 Hz, Chung and Blaser's technique was very straightforward in this plane wave tube. However, to examine higher frequencies, a smaller tube was required with a higher cutoff frequency, such as that shown in Figure 6. It is roughly half a meter long with an inner side length (square cross section) of 0.95 cm (3/8 inch). Two microphone spacings were incorporated in this tube as well, with the total bandwidth of the tube encompassing frequencies from 1000-16000 Hz to provide an overlapping frequency range of 1000-2000 Hz between both tubes. A microphone spacing of 17 mm measured the bandwidth from 1000-8000 Hz and a spacing of 7 mm measured frequencies from 2250-16000 Hz. 6.4 mm microphones (Quarter-inch diameter) were placed on opposite sides of the tube in order to obtain a small enough spacing. An attempt was made to carve a small anechoic wedge for the tube termination, though it was not as anechoic as desired. In addition, the tiny inner-diameter meant we could no longer ignore thermoviscous losses along the tube boundaries. As a consequence of these two problems, we could no longer use Chung and Blaser's method.

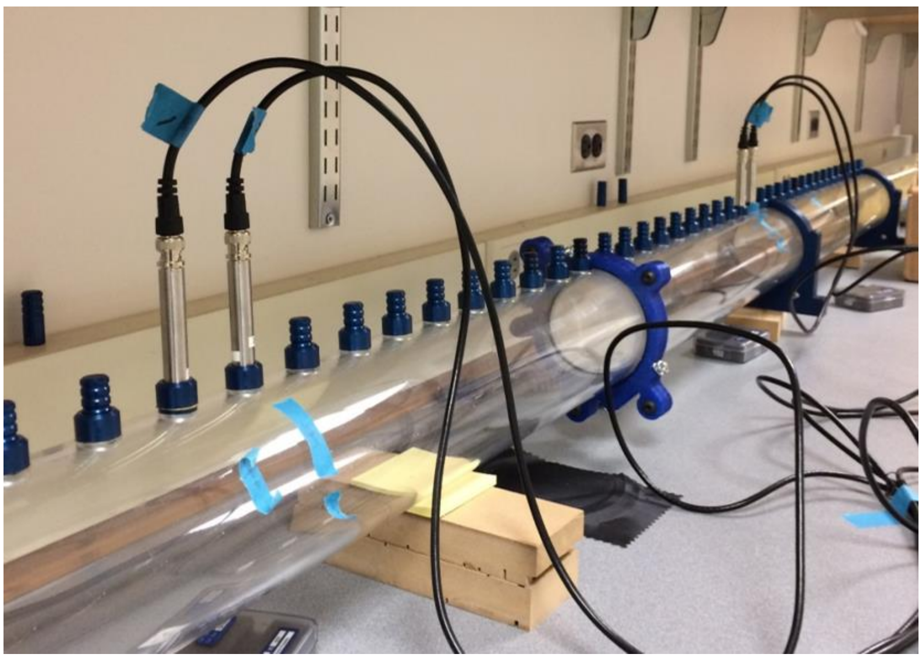

Figure 5: Plane wave tube with a 10 cm inner diameter. There is an opaque membrane mounted at the center junction.

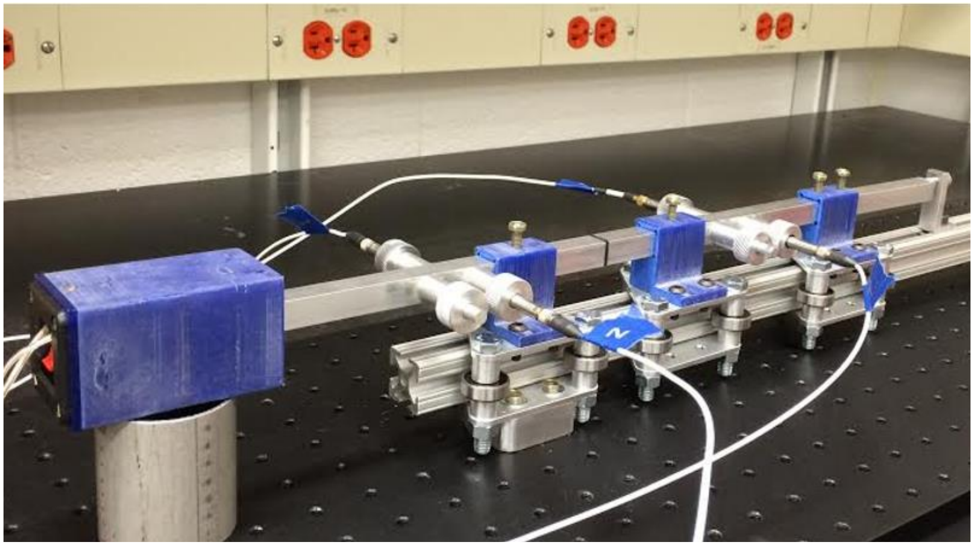

Figure 6: Plane wave tube with inner side dimension of 0.95 cm. Microphones are pictured mounted on opposite sides of the tube.

4. TRANSMISSION LOSS ANALYSIS TECHNIQUES

In 2000, Song and Bolton[5] developed the two-load transfer matrix technique, eliminating the requirement of an anechoic termination as long as the tube was capable of supporting two different termination conditions (two loads). Because of the need for transfer functions from two different loads, the testing process takes twice as long, and the formulation uses transfer functions between a reference signal off of the generator and the microphones, a technique that doesn't easily allow for microphone switching calibration. In their work, they used amplitude and phase matched microphones to avoid microphone inconsistencies.[6]

A extension method to the two load technique was developed in 2009 by Salissou and Panneton.[7] This technique uses a combination of wave decomposition (similar to Chung and Blaser) in addition to two different loads (like Song and Bolton). In addition, the transfer functions in the formulation are easily adapted to support microphone switching calibration. The transmission coefficient (τ) and TL equations are shown below.

$$\tau = H_{23}\left(1 - r_2 r_b e^{2jk_0 D_2}\right)\frac{e^{jk_0L_1} + r_1 e^{-jk_0L_1}}{e^{-jk_0L_2} + r_b e^{jk_0L_2}}, \tag{6}$$

$$TL = -20\, log_{10}(\tau). \tag{7}$$

In the transmission coefficient, H_{23} is the transfer function between microphones two and three (on opposite sides of the membrane), r_2 is the reflection coefficient at the back of the membrane, r_b is the reflection coefficient at the tube termination, and r_1 is the reflection coefficient at the front of the membrane. L_1 and L_2 are the distances from the membrane to the closest microphone upstream and downstream of the membrane respectively. A full formulation, including details of the transfer functions H_{12} and H_{34} from both loads, is included in the 2009 paper.

To account for the thermoviscous losses, we implemented a complex wavenumber into our data processing. This process is described in sections 8.8-8.9 of Kinsler and Frey's *Fundamentals of Acoustics*.[8]

As an example of how the two different loads appear visually, Figure 7 shows the small plane wave tube with both the semi-anechoic termination and an open termination. Figure 8 shows a membrane mounted in the plane wave tube.

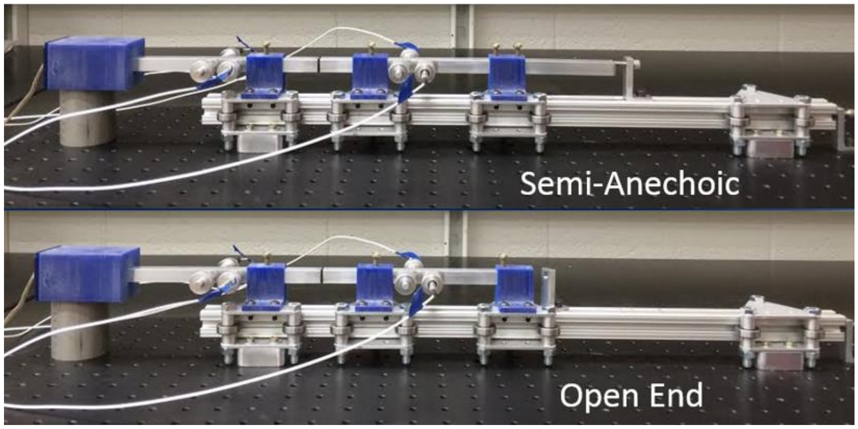

Figure 7: 0.95 cm inner dimension plane wave tube, shown first with the semi-anechoic termination, and then with an open end.

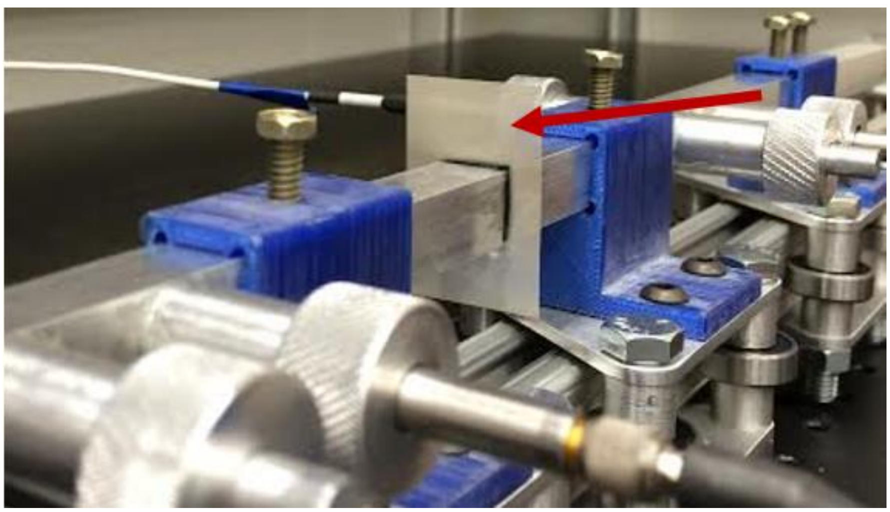

Figure 8: 0.95 cm inner dimension plane wave tube, shown with an 8 μm pore membrane mounted at the middle of the tube, as pointed out by the red arrow.

5. RESULTS

Figure 9 shows the transmission loss (TL) vs frequency for the three screens depicted in Figure 1. The dashed black vertical lines indicate a transition between microphone spacings in the same tube. The solid black vertical line is the transition between tubes. It is important to note that because the two tubes had such drastically different diameters, the membranes were also measured at two different sizes. This means that the natural resonances of the membranes were different between the two tubes simply due to the differences in sizing. Looking at the transmission loss curves, the purple line indicates the PM microfabricated membrane with 8 μm pores, and the blue and yellow are the screens commercially available at the moment. All three of these membranes illustrate acoustic-mass like behavior with a slow rise in TL as frequency increases. Most

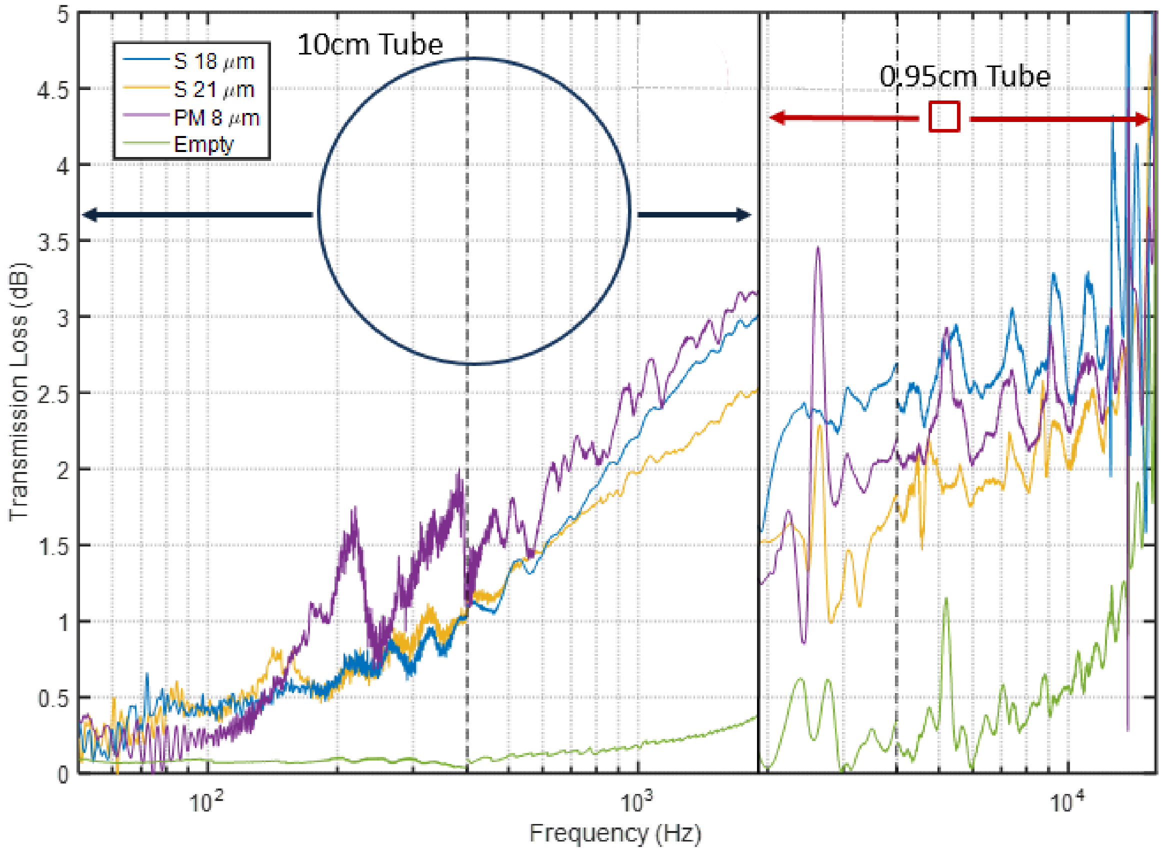

Figure 9: Transmission loss results from 3 membranes (blue, yellow, and purple) and the empty tubes (green). The dashed vertical lines indicate a transition between microphones spacings in the same tube. The solid vertical line is the switching point between the two different tubes. The blue circle and red square roughly show the relative difference in size between the two tubes used for measurement.

importantly, the membrane with 8 μm pores is performing nearly as well as the membranes with larger openings. In the large tube, the 8 μm mesh has a TL an average of 0.2 dB higher than the 18 μm mesh, while in the small tube, the 8 μm mesh TL is 0.5 dB lower than that of the 18 μm mesh. This was calculated by averaging the $10^{TL/10}$ values for each membrane in each tube, then subtracting the dB values obtained from each average. With the 8 μm pore membrane we were able to achieve the target TL which was to match the commercially manufactured polymer mesh.

Examining the TL from the empty tube, shown in green, there are still finite losses despite our attempts to account for thermoviscous losses. The fact that the empty tube has any losses at all suggests that there might be minor losses we are not accounting for or need to fix in our measurement process, such as flanking losses caused by minute gaps in tube sealing or imperfections in tube or microphone positioning.

There is also some question about our membrane positioning and sealing techniques. Especially in the small tube, membrane tensioning and position could have been inconsistent as the load was changed, giving slightly inaccurate acoustic results after data were analyzed.

6. CONCLUSION

A measurement system has been presented that measures transmission loss in the frequency range from 90-16000 Hz. Thermoviscous losses were accounted for and microphone switching calibration was used to ensure accurate amplitude and phase information. For the small plane wave tube, a two load method was implemented, capable of determining TL without an anechoic termination. The porous screens (membranes) tested essentially exhibit acoustic mass-like behavior up to 16 kHz, and more importantly, the membrane with a smaller pore size matched the acoustic performance of other less water-resistive membranes. In the future, sample tensioning and mounting techniques will be examined in order to ensure proper continuity across testing and a sufficient seal in the plane wave tubes.

7. ACKNOWLEDGMENTS

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