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Measurement of Small Fabric Samples using the Transmission Loss Tube Apparatus

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ABSTRACT

Small fabric membranes are used in mobile phones and earbud headphones to cover microphones and loudspeakers. The membranes provide protection against moisture, contamination, pressure changes, and physical intrusion. The membranes must also have minimal sound transmission loss which must be quantified. This paper describes the use of the tube apparatus to measure the normal incidence sound transmission loss and acoustic impedance across small fabric membrane samples. Methods are described for area change corrections and for minimizing the effect of membrane natural frequencies. The development of an accurate and efficient test methodology is important given the large number of devices manufactured and the lack of guidance in ASTM E2611-09 specific to testing these materials.

1 INTRODUCTION

This paper describes methods for measuring the normal incidence sound transmission loss and acoustic impedance across small fabric membrane samples using the transmission loss tube (impedance tube) apparatus. These materials are very thin and exhibit minimal sound transmission loss, and so present certain challenges in producing effective measurements.

A typical sound transmission loss tube apparatus set-up is shown in Fig. 1. The four microphone method uses two source tube and two receive tube microphones to decompose sound in the tube into so-called left-going and right-going plane waves. From this wave decomposition process, the pressure and particle velocity upstream and downstream of the sample is determined, which allows for the formation of the transfer matrix of the test article and subsequent calculations of its acoustic properties[1]. Given a fixed diameter of source and receive tubes, it is at times necessary to use conical adapters to test samples smaller than the given diameter[2].

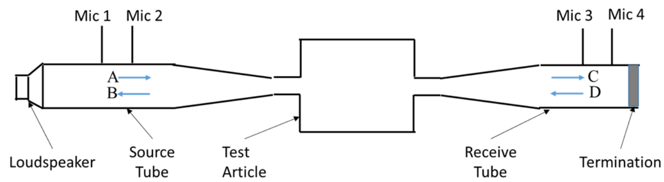

***Figure 1**: Schematic of impedance tube apparatus used to perform sound transmission loss (STL) measurements.*

Hardware used for testing included a Brüel & Kjær Type 4206T Impedance Tube Kit modified to include conical adapters and a Type 3160 LAN-XI Frontend with generator output. Software used for data acquisition was the Brüel & Kjær Type 7758 PULSE Acoustic Material Testing in a Tube, version 20.

A typical application for thin membrane materials is in the protection of acoustic transducers in mobile phones (see Fig. 2) from moisture, contamination, pressure changes and physical intrusion. However in this case it is desirable for the material to be highly acoustically transparent, so as not to detract from the performance of the transducer. In order to evaluate the materials for this application, acoustic transmission loss testing must be performed. ASTM E2611-09 does not provide any specific instruction with regard to these types of materials and their testing[3]; therefore it is important for an accurate and efficient test methodology to be developed.

***Figure 2**: Example of material application.*

2 SAMPLE PREPARATION

The manner in which a sample is prepared for testing can greatly affect the outcome of acoustic transmission loss measurements. One of the most important aspects of sample preparation is consistency across measurement sets. Preparing samples in a consistent and repeatable fashion reduces measurement uncertainty and allows for more accurate comparisons between sets of measurements. It is also important to achieve a "realistic" mounting condition. The sample should be mounted in a way that is representative of the end use, so as to produce meaningful test results.

Typically the sample is attached to a test fixture for ease of interface with the impedance tube apparatus. The test fixture used here was a ring shape, with outer diameter equal to 29mm (the inner diameter of the impedance tube apparatus) and an inner diameter of 20mm, as shown in

Fig. 3. The fixture functions as a sample holder and facilitates installation of the sample into the test apparatus. The non-woven fabric material and microporous expanded polytetrafluoroethylene (ePTFE) membrane material used in this work were provided by W. L. Gore & Associates. Thin films of polyurethane were also examined and were obtained commercially from Covestro.

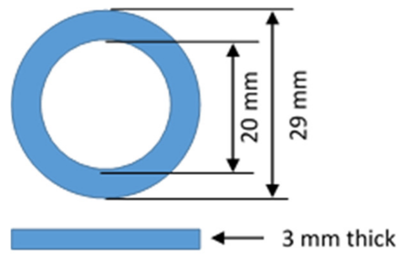

***Figure 3**: Schematic of the sample fixture used in the TL measurements*

Adhesion of the material sample to the fixture was achieved by the use of both double-sided and single-sided adhesive, cut to match the shape of the fixture. The double-sided adhesive bonds the sample to the fixture, and the single-sided adhesive leaves open the portion of the material to be tested, and aids in the alignment of the sample with the tube apparatus. The final stack-up is shown in Fig. 4.

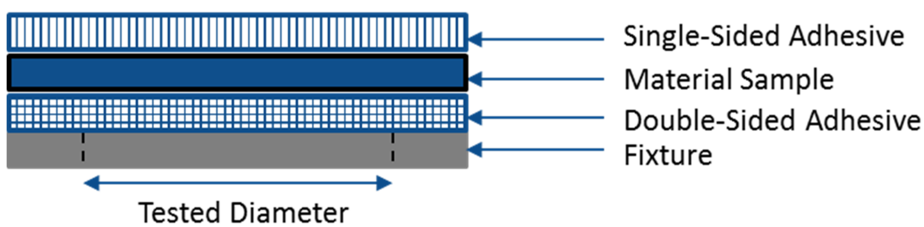

***Figure 4:** Adhesive stack-up showing how material under test is attached to fixture.*

In general, thin polymeric materials used for portable electronic venting applications are not self-supporting and can easily wrinkle or be inadvertently tensioned during the preparation process. Excess tension on the sample can exacerbate membrane modes which causes large peaks in the transmission loss data. This type of behavior is illustrated in Fig. 5, which shows the transmission loss of commercially available non-porous polyurethane thin films. One sample was prepared so that the active area of the membrane was under a "neutral" tension state, whereas the other was prepared with excess tension. The large peaks seen here are the result of the membrane mode behavior of the sample.

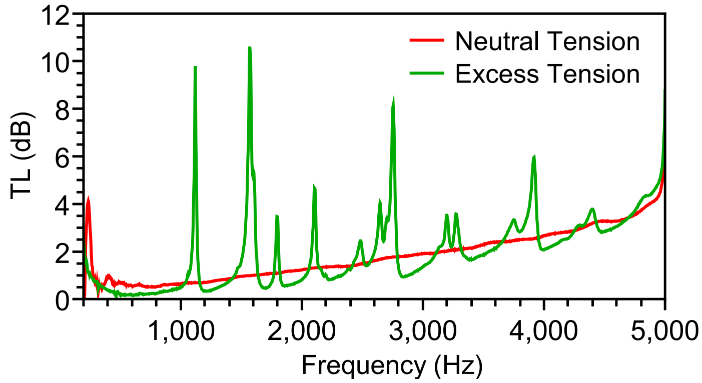

Figure 5*: Transmission loss (TL) vs. frequency plot for non-porous polyurethane membranes prepared with neutral (red) and excess (green) tension. The diameter and thickness of the membrane were 20mm and 25 µm, respectively.*

For thin membrane materials, it is best to first lay the material flat, apply the double-sided adhesive to the fixture, and then apply the fixture to the material to be tested. Again, the goal is to consistently capture the membrane on the fixture with a minimal amount tension. As shown in Fig. 6, the samples are planar (i.e. not baggy) and free of wrinkles.

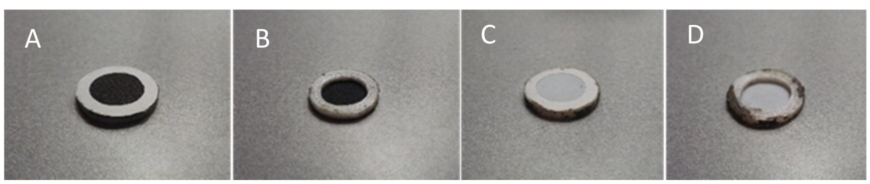

Figure 3*: Picture of sample mounting, top and bottom views (Left A-B: non-woven material – 250 µm thick, Right C-D: thin microporous ePTFE membrane – 9 µm thick)*

In laying the material flat, it may be helpful to lightly "brush" the wrinkles out with a strip of paper or similar thin flexible material. The material can then be cut to match the outer diameter of the fixture, taking care to avoid deformation of the material, as this could change the material properties and thus the acoustic performance of the material. Lastly, the single-sided adhesive can be applied. Samples prepared in this manner will be appropriately tensioned so that transmission loss due to membrane mode behavior is minimized.

Conical adapters are used to transition from the diameter of the impedance tube apparatus to a different test diameter. The sample/fixture assembly is mounted between two cones so that the measurement of the 20mm sample may be performed using the 29mm diameter impedance tube apparatus. The top side of the sample fixture assembly faces in the upstream direction when installed in the tube apparatus. The single-sided adhesive is used to aid in the alignment of the sample in the assembly. Once aligned, the assembly is sealed with clay to eliminate acoustic leakage and then secured with gaffers tape before installing in the tube apparatus. It would be helpful in the future to design fixtures in such a way as to streamline the alignment, sealing, securing, and installation processes.

Figure 7: *Conical adapters and fixture assembly used in the transmission loss measurements.*

The ideal size of cones is a balance between length and upstream/downstream area ratio[1, 2]. For example, increasing the length of the cones improves the low frequency performance[1] of the cones but increases viscous and thermal losses at the cone/air boundary layer. Increasing the area reduction ratio increases measurement error and decreases signal to noise[1, 2].

To ensure an accurate measurement, it is important that there is no acoustic leakage around the cones or fixture. Even with well-designed fixtures, it may be necessary to use clay to improve the sealing performance. The effect of the conical adapters (including the thermal and viscous losses at the cone-air boundary layer) and fixture can and should be removed in post-processing by the transfer matrix method[2, 4].

3 MEASUREMENT

To improve the accuracy of the measurements, an equalization correction was applied to the sound source so that the frequency spectrum within the tube was as flat as possible. The frequency response within the tube is largely dependent on the end boundary condition; therefore equalization was performed using an anechoic termination and without any sample or conical adapters installed, in order to avoid any reflection effects. The microphone closest to the source was used as the equalization reference.

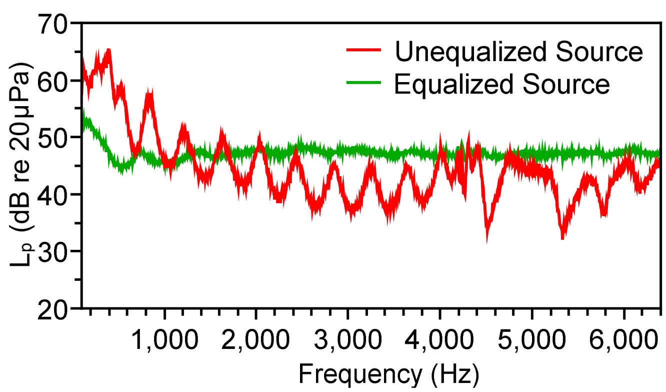

Figure 4: *Sound level L_p vs. frequency for an equalized (green) and unequalized (red) sound source as measured by the first upstream microphone (anechoic termination, empty tube).*

In practice, when measurements are being made, the observed spectrum of the first upstream microphone will not be as flat as the equalized spectrum shown in Fig. 8. When a sample is installed in the tube apparatus the upstream microphone measures both direct sound from the loudspeaker and reflections in the tube caused by the presence of the sample. An example of the expected spectra can be seen below in Fig. 9. Regardless, the direct sound incident on the sample is equalized.

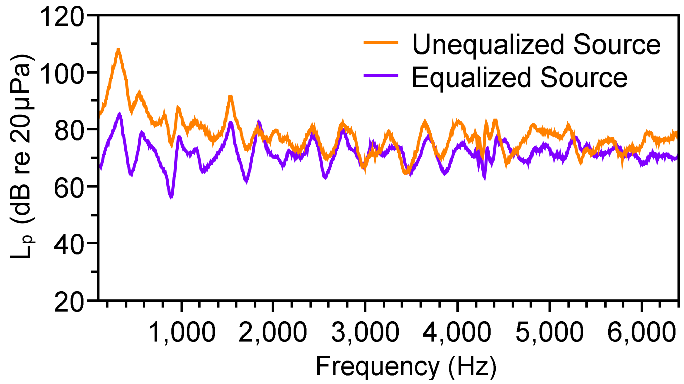

Figure 9: *Sound level L_p vs. frequency for an equalized (blue) and unequalized (red) sound source as measured by the first upstream microphone (anechoic termination, with sample).*

The purpose for this source equalization is twofold. First, a flat frequency content incident on the material under test minimizes the effect of any non-linear excitation of the sample. As the tube will have pressure minima and maxima due to its geometry, equalizing the source avoids excitation levels that are significantly larger or smaller at certain frequencies than at others. Second, a flat frequency spectrum allows for a straightforward interpretation of what the excitation level is. Overall and total levels of the spectrum can be misleading because they are susceptible to being dominated by large peaks caused by pressure maxima in the tube apparatus. For example, two spectra may have equivalent overall levels, though the frequency content of each is very different. In prescribing the use of an equalized spectrum, it is possible to also prescribe an appropriate excitation level.

Typical normal incidence transmission loss measurements are performed on materials or mufflers that provide levels of transmission loss in excess of 10-20dB. Given that small fabric samples are typically very nearly acoustically transparent materials, providing transmission loss of less than 5dB, the source levels in the tube apparatus need not be as high as for muffler systems. Source levels that are too high can cause non-linear excitation of the samples, which is exhibited by a "crackling" noise and poor coherence between microphones in the tube apparatus. It was found that for small fabric samples, the spectrum levels at the microphone closest to the source should be centered around 70-75dB (re: 20 µPa) across the measured frequency span. This level avoids any non-linear excitation of the sample, and is sufficiently high to produce an accurate measurement.

Testing was performed using the 2-load, 4 microphone method for measuring normal incidence transmission loss. The 1-load method was considered as it is more similar in boundary condition to the source equalization process than the 2-load method. However, the 1-load method necessitates the use of a sufficiently anechoic termination at all measured frequencies, which can be a challenge to achieve. The 2-load method eliminates this necessity by simply requiring two different termination loads[3]. The measured results were seen to be appropriately similar between 1-load and 2-load methodologies.

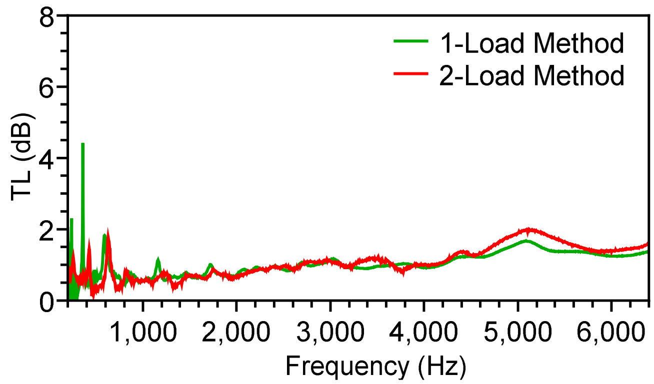

Figure 5: *Transmission loss vs. frequency plot for a microporous ePTFE membrane measured using the 1-Load (green) vs 2-Load (red) method. The diameter and thickness of the membrane was 20mm and 9 µm, respectively.*

4 DATA ANALYSIS

The effects of the fixture assembly and conical adapters must be removed in order to produce transmission loss results for the material sample alone. The fixture used for this testing was comprised of a cone that reduces the test inner diameter from 29mm to 20mm, the sample holder which has an inner diameter of 20mm and a thickness of 3mm, and another cone that expands the test inner diameter from 20mm to 29mm to interface with the remainder of the tube apparatus. In order to remove the effect of this fixture from the measured data, the transfer matrix method[4] as described in [2] is used.

The output from the adapter removal processing is the four-pole transfer matrix elements of the material under test. This information is then used to calculate transmission loss and acoustic impedance across the sample. The transmission loss, given the transfer matrix elements, is calculated as follows[5]:

$$TL = 10\log_{10}\left(\frac{1}{4}\left|T_{11} + \frac{T_{12}}{\rho_0 c} + \rho_0 c T_{21} + T_{22}\right|^2\right) \quad (1)$$

In most cases, it is sufficient to use the theoretical transfer matrices when correcting for the effect of conical adapters. However, when analyzing materials with very low transmission loss (< 5dB), accuracy of the measurement can be improved by accounting for viscous and thermal losses at the cone/air boundary layer. The influence of the conical adapters on the measured TL spectrum – with and without additional losses taken into account – for an ePTFE membrane is shown in Fig. 11. Additional losses due to the use of the conical adapters were accounted for in the post-processing by adding a damping term to the complex wavenumber of air. Note that the increased TL bump at 5 kHz is an artifact of the measurement apparatus.

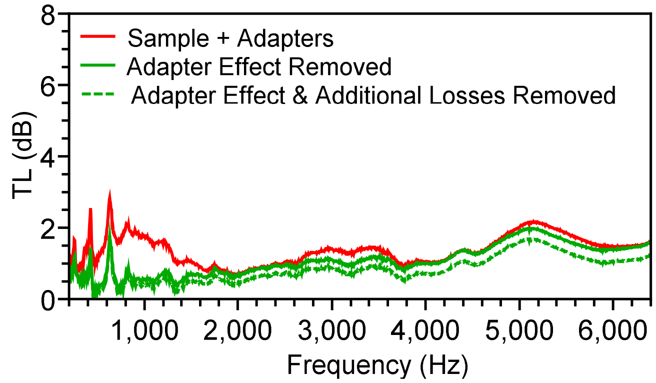

Figure 6: *Effect of conical adapters and viscous/thermal loss at adapter-air boundary layer on measured TL for a microporous ePTFE membrane. The diameter and thickness of the membrane was 20mm and 9 µm, respectively.*

The acoustic impedance across the sample, or transfer impedance, is given by the difference in the ratios of pressure to particle velocity upstream and downstream of the sample:

$$z_{tr} = \frac{P_1}{V_1} - \frac{P_2}{V_2} \tag{2}$$

Where the subscripts 1 and 2 indicate upstream and downstream faces of the sample, respectively.

The transfer impedance of the material under test may be calculated from the reflection coefficient of the material with an anechoic backing[6]. The reflection coefficient, given the transfer matrix elements, is calculated as follows[6]:

$$R = \frac{T_{11} + \left(\frac{T_{12}}{\rho_0 c}\right) - \rho_0 c T_{21} - T_{22}}{T_{11} + \left(\frac{T_{12}}{\rho_0 c}\right) + \rho_0 c T_{21} + T_{22}} \tag{3}$$

The transfer impedance is then calculated according to equation 4, below[6].

$$z_{tr} = \rho_0 c \left(\frac{1+R}{1-R} - 1\right) \tag{4}$$

Measured transfer impedances of the nonwoven fabric material and ePTFE membrane material are shown in Fig. 12.

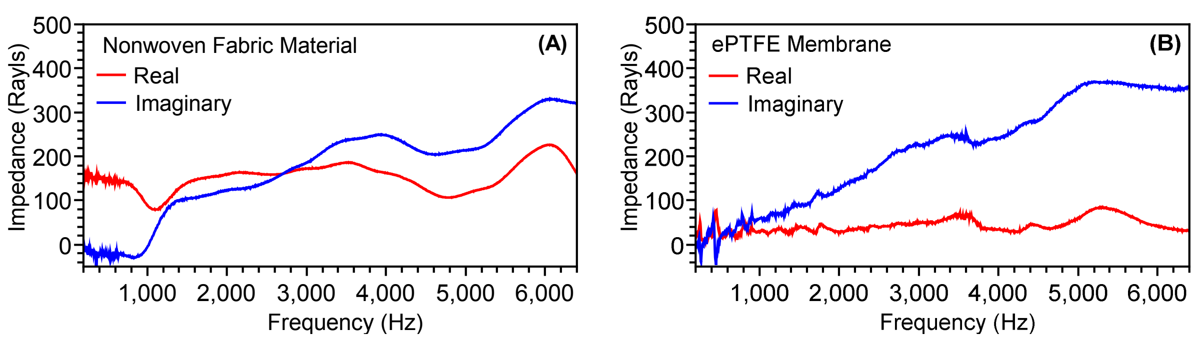

Figure 7: *Real (red) and imaginary (blue) parts of the complex transfer impedance for a 250-µm-thick nonwoven fabric (A) and a 9-µm-thick ePTFE membrane material (B). Sample diameter was 20 mm.*

Transfer impedance measurements are helpful in determining engineering direction for material design and improvement. For example, comparing the real and imaginary parts of the calculated transfer impedance provides an understanding of the physical interactions between the incident sound and the sample under test. Frequencies at which the real, or resistive, part of the impedance is dominant indicate that sound energy is primarily being dissipated by the sample. Frequencies at which the imaginary, or reactive, part of the impedance is dominant indicate that the transmission loss of the sample is due to its mass and stiffness properties.

5 CONCLUSIONS

Measuring the transmission loss and acoustic impedance of small fabric samples presents an added challenge over typical thick material samples or muffler systems. This paper has illustrated some basic guidelines for improved accuracy and success of these measurements. These guidelines include:

- Mounting the test samples without tension is important because membrane modes can cause peaks in the transmission loss spectra which make data interpretation difficult.
- The excitation pressure amplitude is important for these materials, so using low levels and source equalization is recommended.
- Post-processing the raw measurement results using the transfer matrix technique is important to remove the effect of the cones at low frequency and to remove the effect of viscous and thermal losses which are significant.

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