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An additional configuration to standard ASTM E2611-09 for measuring the normal incidence sound transmission loss in a modified impedance tube

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This paper presents a three-microphone two-load (3M2L) method for measuring the normal incidence sound transmission loss of a noise control system or material in a modified impedance tube. In the standard ASTM E2611-09, the downstream section of the impedance tube includes two microphones flush with the interior surface of the tube and the proposed four-microphone two-load (4M2L) method to assess the normal incidence sound transmission loss requires the use of two arbitrary acoustic terminations. The method presented here is conceptually identical but (i) the downstream section is reduced to a simple movable rigid backing with one microphone flush mounted on it and (ii) the two arbitrary acoustic terminations are replaced by two air cavities. It thus requires one microphone less and fewer transfer functions. The standard switching technique used to correct the variations between the three microphones is validated on a symmetrical air layer. The proposed 3M2L method is then applied to a non-symmetrical specimen and validated compared to the standard 4M2L method.

1 Introduction

The normal incidence sound transmission loss (*nSTL*) is an important indicator used to assess the sound insulation property of noise control systems (e.g., sound barrier samples, mufflers, expansion chambers, and resonators). This measurement of the *nSTL* has been standardized in ASTM E2611-09[1]. It uses a plane wave tube instrumented with four microphones and a termination of adaptable acoustic load. For any specimen, the four-microphone two-load (4M2L) standard method can be applied for measuring its transfer matrix and *nSTL*. The two loads are typically a minimally reflecting termination (e.g., anechoic termination), and a termination reflecting a portion of incident wave (e.g., open termination). A minimum of 6 transfer functions need to be measured.

An additional configuration to those described in standard ASTM E2611-09 (see Table 2 in [1]) has been recently published [2] and is described here. This configuration uses three microphones in a slightly modified classical impedance tube, the third microphone being flush mounted on the movable hard termination. Furthermore, the proposed method requires fewer transfer function measurements (4 in the general case) than the standard method. The two acoustic loads are in this case two different air cavities. The purpose of this paper is to present this simple additional configuration and how it can be used in conjunction with (or in complement to) standard ASTM E2611-09.

2 Theory

A schematic view of the modified impedance tube is shown in Figure 1. The apparatus consists of a finite-length hard walled impedance tube with uniform inner cross-section. The tube features a loudspeaker (source) at one end and a movable hard termination at the other end. The loudspeaker is used to generate a plane wave field in the impedance tube. There are two microphones flush mounted upstream the test sample and one microphone flush mounted on the hard termination. Downstream the sample, an air cavity is added. The thickness of the cavity is adjusted with the movable hard termination.

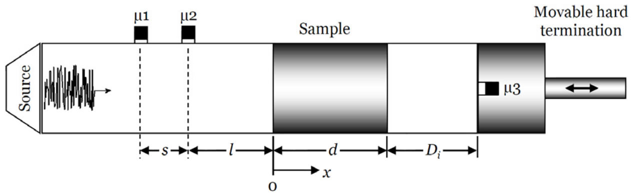

Figure 1: Measurement configuration.

Now, suppose a unit amplitude incident plane wave with time dependence of the form exp($j\omega t$), where $j=\sqrt{-1}$, ω is the angular frequency, and t is the time. The acoustic pressure p_i(x) and particle velocity u_i(x) upstream ($x\leq 0$) and downstream ($x\geq$d) the test sample are respectively given by

$$p_i(x)=e^{-jkx}+R_i e^{jkx}, u_i(x)=\frac{1}{Z_s}\left(e^{-jkx}+R_i e^{jkx}\right), \qquad (1)$$

and

$$p_i(x)=2A_i e^{-jkL_i}\cos\left(k\left(x-L_i\right)\right),$$
$$u_i(x)=-j2\frac{A_i}{Z_s}e^{-jkL_i}\sin\left(k\left(x-L_i\right)\right) \qquad (2)$$

where subscript i=a,b and refers to a value obtained with an air cavity of thickness D_i, L_i=d+D_i, d is the thickness of the sample, Z_s and k are the complex specific acoustic impedance and complex wave number of the air in the tube, R_i is the complex sound reflection coefficient at the surface of the sample (i.e. at x = 0), and $2A_i$ is the maximum pressure amplitude of the standing wave downstream the sample. The two air cavities D_a and D_b are the two loads of the proposed 3M2L method. The geometrical variables are also defined in Figure 1. Note that Z_s and k account for viscous and thermal dissipation effects at the tube walls. For the setup shown in Figure 1, the reflection coefficient is given by

$$R_i=\frac{H_{12}(D_i)e^{jks}-1}{1-H_{12}(D_i)e^{-jks}}e^{2jkl}, \qquad (3)$$

where $H_{12}(D_i)$ is the measured transfer function between microphones 2 and 1 ($p_i(\mu_2)/p_i(\mu_1)$) with an air cavity of thickness D_i, s is the spacing between microphones 1 and 2, and l is the distance between microphone 2 and the front face of the sample. In a similar manner, one can deduce coefficient A_i by introducing transfer function $H_{13}(D_i)$ between microphones 3 and 1 ($p_i(\mu_3)/p_i(\mu_1)$). This yields

$$2A_i e^{-jkL_i}=H_{13}(D_i)\left(e^{jk(l+s)}+R_i e^{-jk(l+s)}\right). \qquad (4)$$

According to Eqs. (1) and (2), calculating R_i and A_i from Eqs. (3) and (4) allows a complete description of the sound field in the air inside the impedance tube presented in Figure 1.

For any specimen, Eq. (22) of standard ASTM E2611-09 gives the transfer matrix **T** of the specimen in terms of the pressure and particle velocity on its both faces (at x=0 and at x=d). For the sake of clarity, this equation is repeated here with the used notations:

$$\mathbf{T} = \frac{1}{p_a(d)u_b(d) - p_b(d)u_a(d)} \times \begin{bmatrix} p_a(0)u_b(d) - p_b(0)u_a(d) & p_b(0)p_a(d) - p_a(0)p_b(d) \\ u_a(0)u_b(d) - u_b(0)u_a(d) & p_b(d)u_b(0) - p_b(d)u_a(0) \end{bmatrix} \quad (5)$$

where pressures and velocities are derived from Eqs. (1)-(4) for two different loads. For cavity load $i=a,b$, they are given by

$$\begin{aligned} p_i(0) &= -2je^{jkl}\frac{H_{12}(D_i)\sin(k(l+s)) - \sin(kl)}{H_{12}(D_i)e^{-jks} - 1}, \\ u_i(0) &= \frac{2je^{jkl}}{Z_s}\frac{H_{12}(D_i)\cos(k(l+s)) - \cos(kl)}{H_{12}(D_i)e^{-jks} - 1}, \\ p_i(d) &= -2je^{jkl}\frac{H_{13}(D_i)\sin(ks)\cos(kD_i)}{H_{12}(D_i)e^{-jks} - 1}, \\ u_i(d) &= \frac{2je^{jkl}}{Z_s}\frac{H_{13}(D_i)\sin(ks)\sin(kD_i)}{H_{12}(D_i)e^{-jks} - 1}. \end{aligned} \quad (6)$$

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Consequently, the application of the 3M2L method to obtain the transfer matrix **T** of any specimen will require only 4 transfer function measurements, which is two measurements less than the 4M2L standard method.

Before testing experimentally the three-microphone configuration, a singularity specific to the 3M2L method is underlined. Combining Eqs. (5) and (6), one can show that **T** is not determined when $\cos(kD_a)\sin(kD_b)=\cos(kD_b)\sin(kD_a)$. To avoid this, a condition on the difference between the depths of the cavities must be fulfilled. This condition is $|D_a-D_b|<\pi/k\approx172/f_u$, where f_u is the upper frequency limit of the tube in hertz to ensure plane wave propagation.

3 Experimental setup

To implement the 3M2L method, a 44.45-mm diameter tube is used. The tube has three sections: upstream (235-mm long), sample holder, and downstream. The downstream section is terminated with a 30-mm thick sliding piston – the piston acts as a hard wall and is made of steel. In the upstream section, two microphones are flush mounted as shown in Figure 1. A third microphone is flush mounted directly on the hard termination, as depicted in Figure 1. The distance between microphone 1 and 2 is s=25.2 mm and the distance between microphone 2 and the front surface of the test sample is l=45.5 mm. Precise measurements of these distances have been carried out using the method proposed by Katz [3]. This latter method is based on the frequency determination of the nulls of the transfer functions between microphones 1, 2 and microphone 3, respectively H_{31} and H_{32}. These transfer functions are easily measurable using the proposed setup of Figure 1 without sample and placing the movable piston at position x=0. The cavity thickness downstream the sample is fixed by moving the hard termination conveniently. With the used setup, the working frequency range for this study is 150–4100 Hz. To implement the 4M2L standard method, the same setup is used; however the downstream section is replaced by a two-microphone instrumented 360-mm long tube. The two downstream microphones are separated by a distance s=25.6 mm and flush mounted on the tube extension. The distance between the back surface of the sample and microphone 3 is l_2. The two termination loads are selected to have relatively different reflection coefficients to yield good results. The first load is a partially anechoic termination. It is constructed using a 1.5-m long cylindrical tube filled with low density wool. The wool is arranged in a way that its density increases gradually as the acoustic wave propagates in the tube. The second load is a 25.4-mm thick melamine foam backed by a rigid cap.

The same four-channel analysis system and ¼-inch MPA416 BSWA microphones are used to conduct all measurements. The analysis system uses a USB Fireface UC sound card driven by a MATLAB script which generates, acquires, and processes the signals. The input signals from the microphones are stored on 24 bits by the sound card with a sampling frequency of 44.1 kHz. The MATLAB script processes the signals to obtain the required transfer functions. The output signal is a white noise and the source is a 4-in. loudspeaker. Each characterization test is the average of 50 repeated measurements, and uses a linear weighting. For the 3M2L method, three microphones (μ_1, μ_2, μ_3) and four channels (ch_1, ch_2, ch_3, ch_4) are used for measuring the required four transfer functions ($H_{12}(D_a)$, $H_{13}(D_a)$, $H_{12}(D_b)$, $H_{13}(D_b)$). Each microphone μn (n=1, 2, 3) is connected to channel ch_n to form measurement line $\mu_n ch_n$, and ch_4 is the output source signal. For correcting the measured transfer functions for amplitude and phase mismatches between the three measurement lines, the sensor-switching technique as described in ASTM E2611-09 is used. Here line $\mu_1 ch_1$ is the reference line. Consequently the calibration is successively made between $\mu_1 ch_1$ and $\mu_2 ch_2$ and between $\mu_1 ch_1$ and $\mu_3 ch_3$ using microphone positions 1 and 2. For the 4M2L method, the one-microphone two-channel configuration given in Table 2 of ASTM E2611-09 is used. In this case, the output source signal on ch_4 is the transfer function reference. Here, μ_1 is connected to ch_1 and moves successively to microphone locations 1 to 4 for measuring the required eight transfer functions (i.e., four for each load). Since the same microphone is used, no correction on the transfer functions is required.

4 Results

4.1 nSTL of an air layer and calibration of the setup

With a view to validate both the transfer function correction technique discussed in the previous section and the 3M2L test procedure, an air layer (d=80 mm) is first tested. The air layer is placed at the sample position shown in Figure 1. The sound transmission loss of an air layer is 0 dB (at least on a small distance when neglecting losses) and its transfer matrix is theoretically known. Its coefficients are: $T_{11}=T_{22}=\cos(kd)$, $T_{12}=jZ_s\sin(kd)$, and $T_{21}= j\sin(kd)/Z_s$. The thicknesses of the two air cavities (i.e., the two loads) are D_a=25.4 mm and D_b=50.8 mm. These cavities respect the singularity condition of the 3M2L method (i.e. $|D_a - D_b| < 172/f_u \rightarrow$ 25.4 mm<42 mm). Figures 2 and 3 present the 3M2L measurement results between 150 and 4100 Hz in terms of the real and imaginary parts of the transfer matrix coefficients respectively. Figure 4 presents the 3M2L measurement of the *nSTL*.

With the used microphones, one can note that if the transfer functions are not corrected, poor results are obtained compared to the theoretical results. On the contrary, using the standard sensor-switching correcting technique, a good correlation is obtained between the 3M2L and the theory. Moreover, one can note that the symmetry of the material is preserved with the 3M2L measurements, i.e. $T_{11}=T_{22}$. Nevertheless, a slight divergence can be observed at high frequencies on the *nSTL* (less than 0.3 dB) due to viscous losses around the movable termination, and a loss in accuracy when approaching the lower frequency limit of the system.

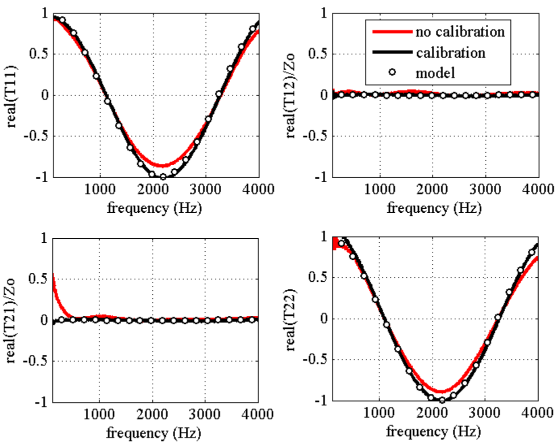

Figure 2: Real part of the 80mm air layer transfer matrix.

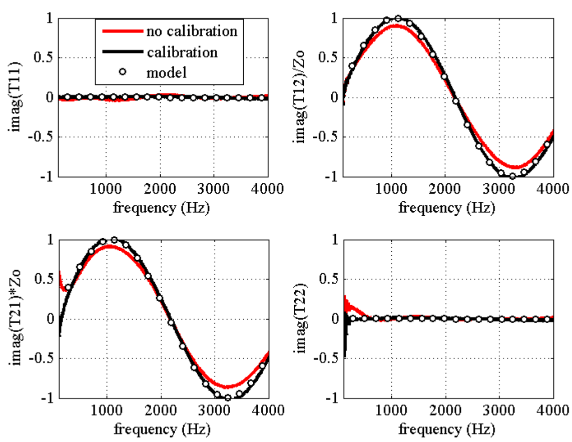

Figure 3: Imaginary part of the 80mm air layer transfer matrix.

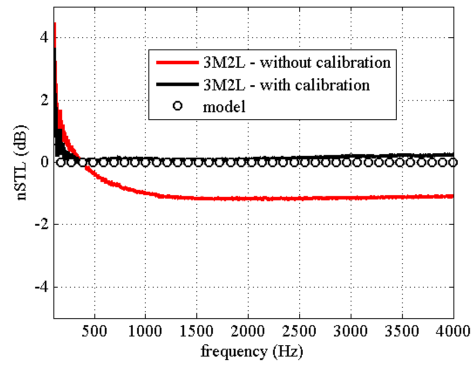

Figure 4: nSTL of the 80mm air layer.

These first results show that using the standard sensor-switching technique as described earlier is appropriate to correct transfer functions H_{12} and H_{13} of the 3M2L method, even if microphone 3 is used at 90° compared to microphones 1 and 2.

4.2 nSTL of an non-symmetric bi-layer sample

A two-layered poroelastic sample made up from a 51-mm thick melamine foam (porosity: 0.980±0.005 and airflow resistivity: 10800±100 N.s.m^{-4}) and a 37-mm thick mineral wool (porosity: 0.970±0.005 and airflow resistivity: 18000±500 N.s.m^{-4}) is used to validate the proposed 3M2L method on a non-symmetrical sample.

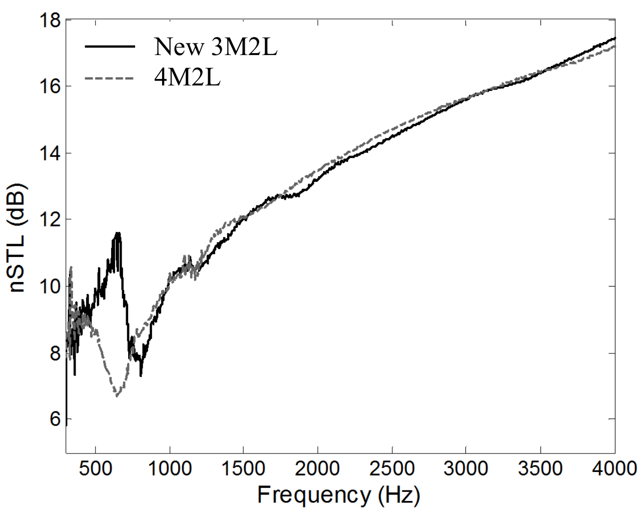

Figure 3: nSTL of the two-layered sample. Comparison between the results obtained with the proposed three-microphone method (3M2L) and the general four-microphone two-load method (General 4M2L).

Figure 3 shows that the two methods are in good agreement. The deviation observed between the two transmission loss curves around 700 Hz is due to the change of the boundary conditions that affect the elastic frame resonance of the sample. In fact, the sample was reinstalled between the 3M2L and 4M2L tests.

5 Conclusion

This paper presented a simple three-microphone configuration which complies with standard ASTM E2611-09 for measuring the sound transmission loss and transfer matrix of acoustical materials. This configuration uses three microphones in a slightly modified classical impedance tube, the third microphone being flush mounted on the movable hard termination. The standard sensor-switching technique is used without any modification, even if microphone 3 is used at 90° compared to the other 2 microphones. ASTM E2611-09 can be complemented with this additional three-microphone configuration, if its Eq. (22) is used with Eq. (6) of this paper.

Acknowledgments

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References

[1] ASTM E2611-09, "Standard test method for measurement of normal incidence sound transmission of acoustical materials based on the transfer matrix method," American Society for Testing and Materials (2009)

[2] Y. Salissou, R. Panneton, O. Doutres, "Complement to standard method for measuring normal incidence sound transmission loss with three microphones*", J. Acoust. Soc. Am.* 131(3), EL 216 (2012)

[3] B.F.G. Katz, "Method to resolve microphone and sample location error in the two-microphone duct measurement method," *J. Acoust. Soc. Am.* 108, 2231-2237 (2000)