THREE-MICROPHONE TWO-CAVITY METHOD FOR MEASURING SOUND TRANSMISSION LOSS IN A MODIFIED IMPEDANCE TUBE

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1. INTRODUCTION

The normal incidence sound transmission loss (*nSTL*) is an important indicator to assess the sound insulation property of acoustic materials. A literature review of the main methods used to measure the *nSTL* using a plane wave tubes is given elsewhere by the authors[1]. Today, the two most recognized methods are the four-microphone two-load (4M2L)[2] and one-load (4M1L) methods[3]. While the 4M2L method is a general method, the 4M1L method is limited to materials being geometrically symmetric and invokes the reciprocity principle[4].

In an attempt to reduce the number of microphones, a method based on two upstream microphones only was proposed[5]. However, when tested experimentally, the method has singularities that are not yet resolved[6]. For symmetrical materials, this difficulty was circumvented by adding a third microphone on the hard termination cap backing the sample[7,8]. The resulting three-microphone method was proved to be efficient for characterizing the dynamic properties. In parallel to the present work, Rodriguez *et al.*[9] presented a generalization of the latter three-microphone method (the 3M-TMTC method). However, their approach is restricted to samples with flat and symmetrical surfaces as the third microphone is in direct contact with the sample. The present paper describes a general three-microphone two-load (3M2L) method which generalizes the three-microphone methods. It may be seen as a particular case of the 4M2L method when the surface impedances of the two loads are known.

2. THEORY

A schematic view of the modified impedance tube used in the proposed 3M2L method is shown in Figure 1. The apparatus consists of a finite length rigid walled impedance tube with circularly shaped and uniform inner cross-section. The tube features a loudspeaker (source) at one end and a movable piston (rigid end) 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 rigid end. Two different air cavities of thickness D_i $(i=1,2)$ are inserted between the sample and the rigid end. Assuming a unit amplitude incident plane wave with time dependence of the form $\exp(j\omega t)$, the acoustic pressures p(x) and velocities u(x) upstream and downstream the test sample are respectively given by

$$\left.\begin{aligned} p(x) &= e^{-jk_0 x} + R_i e^{jk_0 x} \\ u(x) &= \left(e^{-jk_0 x} - R_i e^{jk_0 x}\right)\Big/ Z_0 \end{aligned}\right\} \text{ for } x \le 0$$
$$\left.\begin{aligned} p(x) &= 2A_i e^{-jk_0 L_i} \cos\left(k_0 (x - L_i)\right) \\ u(x) &= \left[-j2A_i e^{-jk_0 L_i} \sin\left(k_0 (x - L_i)\right)\Big/ Z_0\right] \end{aligned}\right\} \text{ for } x \ge d \qquad (1)$$

where subscript i 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, $Z_0 = \rho_0 c_0$ is the characteristic acoustic impedance of ambient air with ρ_0 and c_0 the density of air and the speed of sound wave in air respectively, k_0 is the wave number in air, R_i is the complex sound reflection coefficient at the surface of the sample (i.e. at $x = 0$), $2A_i$ is the maximum pressure amplitude of the standing wave downstream the sample, and $j^2 = -1$. The geometrical variables are defined in Figure 1. The reflection coefficient R_i is obtained from,

$$R_i = \left(H_{12}(D_i) - e^{jk_0 s}\right) e^{2jk_0 L} \Big/ \left(e^{-jk_0 s} - H_{12}(D_i)\right), \qquad (2)$$

$H_{12}(D_i)$ is the transfer function between microphones 1 and 2 (i.e., p(µ1) /p(µ2)) 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 surface of the sample. Using Eq.(1), the transfer function H_{31} between microphones 3 and 1 (i.e., p(µ3) /p(µ1)) is written as

$$H_{31}(D_i) = 2A_i e^{-jk_0 L_i} \Big/ \left(e^{jk_0 (L+s)} + R_i e^{-jk_0 (L+s)}\right), \qquad (3)$$

which yields the following expression for A_i

$$2A_i e^{-jk_0 L_i} = H_{31}(D_i)\left(e^{jk_0 (L+s)} + R_i e^{-jk_0 (L+s)}\right). \qquad (4)$$

Using the transfer matrix relation, the acoustic pressure and velocity at $x = 0$ and $x = d$ can be linked as,

$$\begin{Bmatrix} 1 + R_i \\ (1 - R_i)/Z_0 \end{Bmatrix} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{Bmatrix} \cos(k_0 D_i) \\ j \sin(k_0 D_i)/Z_0 \end{Bmatrix} 2A_i e^{-jk_0 L_i}. \qquad (5)$$

Now, if two measurements are successively done with cavities of thickness D_1 and D_2, Eq.(5) yields four linear relations and four unknowns. The four unknowns are the transfer matrix coefficients. Solving the system of linear equations yields the transfer matrix coefficients and the transmission coefficient of the test sample is deduced from,

$$\tau = 2e^{jk_0 d} \Big/ \left(T_{11} + T_{12}/Z_0 + Z_0 T_{21} + T_{22}\right) \ . \qquad (6)$$

$$nSTL = -10\log_{10}|\tau|^2 \qquad (7)$$

As one can note, only two measurements and three microphones are required for measuring *nSTL*. The procedure is not limited to symmetrical samples and does not invoke the reciprocity principle[4].

3. EXPERIMENTAL TESTS AND RESULTS

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 ($H_{12}(D_1)$, $H_{13}(D_1)$, $H_{12}(D_2)$, $H_{13}(D_2)$). Each microphone μ_i is connected to channel ch_i to form measurement line $\mu_i ch_i$, 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.

As a first validation the 3M2L, an air layer (with $d = 80$ mm) seeing as a symmetrical sample is tested. The air layer is placed at the sample position shown in Figure 1. From Figure 2, one can note that if the transfer functions are not corrected, poor results are obtained compared to the theoretical results. From Figure 3 one can see that the three methods (3M2L, 4M2L and 3M-TMTC) compare very well. However, the 3M-TMTC shows a singularity at 2157 Hz, due to the tested resonant air layer which shows a zero particle velocity at $x = 0$ when $f = c_0/2d$ (here, $c_0 = 345$ Hz, and $d = 80$ mm).

Next, a 20-mm thick step discontinuity (see Figure 4) seeing as a non-symmetrical sample is tested and compared to the standard 4M2L method and 3M-TMTC method. One can note that similar results are obtained between the 3M2L and 4M2L methods, however 4M2L is noisier compare to 3M2L. The 3M2L results are also noisier compared to those of the air layer, due to the fact that the step discontinuity is quite reflective. In this case, microphones 1 and 2 may coincide with pressure nodes and microphone 3 may have a poor signal-to-noise ratio. The problem may be larger in 4M2L since microphone 3 is always at a maximum pressure in the 3M2L; which is not the case for the 4M2L. The 3M-TMTC results are not so good. This is due to the fact that the sample is backed on the rigid termination. In this case, microphone 3 is in the near field.

ACKNOWLEDGEMENTS

N.S.E.R.C., REGAL, and ALCAN supported this work.

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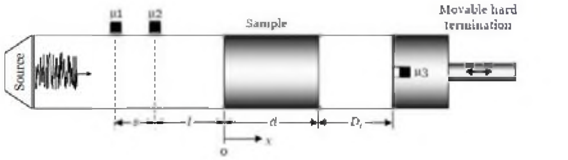

Figure 1: Experimental setup of the 3M2L

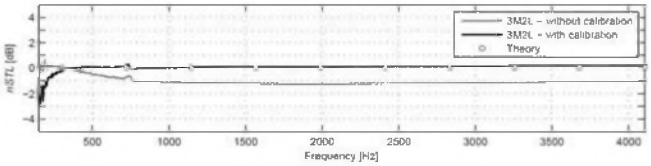

Figure 2: nSTL of a symmetrical sample (80-mm air layer). Comparison between the theory and the proposed 3M2L method with and without sensor-switching calibration

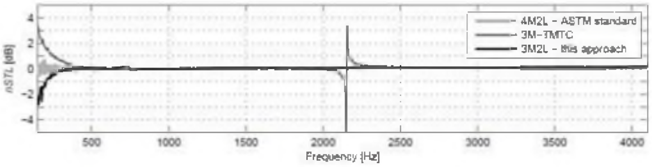

Figure 3: nSTL of a symmetrical sample (*80-mm* air layer). Comparisons between the proposed 3M2L method, the standard 4M2L method, and the 3M-TMTC method

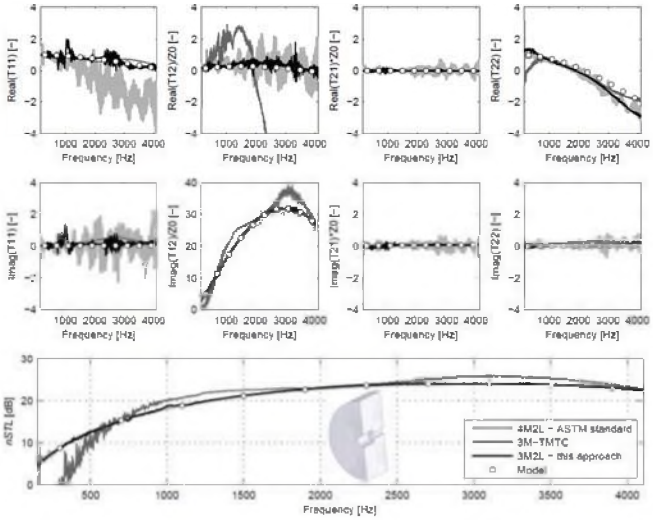

Figure 4: Transfer matrix coefficients and nSTL of an asymmetrical sample (step discontinuity). Comparisons between the proposed 3M2L method, the standard 4M2L method, and the 3M-TMTC method.