

Practical Considerations when using the Two-Load Method to Determine the Transmission Loss of Mufflers and Silencers

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ABSTRACT

The two-load method is commonly used to determine the transmission loss of a muffler or silencer. Several practical measurement considerations are examined in this paper. First of all, conical adapters are sometimes used to transition between impedance tubes and the muffler. It is demonstrated that the effect of adding the adapter can be quite significant at low frequencies especially if the adapter is short in length. The effect of changing the length of the adapter was examined via measurement and plane wave theory. Secondly, the effect of selecting the reference microphone was examined experimentally. It was found that measurements are improved by selecting a downstream reference. Finally, the effect of using different frequency response function estimation algorithms (H_1 , H_2 and H_v) was compared sans flow. This had little effect on the measurement.

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INTRODUCTION

Insertion loss is the metric typically used to assess muffler performance in the field. It is defined as the difference in sound pressure at a point near the termination with and without a muffler installed. Though insertion loss is easy to measure, it is a property of the source and termination impedances as well as the lengths of the inlet and outlet ducts and the muffler. Hence, insertion loss is a measure of the installed muffler attenuation for a particular exhaust system.

Transmission loss eliminates the effect of the inlet and outlet ducts. Indeed, insertion loss is equal to the transmission loss if the source and termination impedances are anechoic. Transmission loss is simpler to determine using analysis since an anechoic termination is easily applied as a boundary condition below the plane wave cutoff.

Measurement of transmission loss is trickier. Certainly, transmission loss is often roughly measured using either a very long downstream duct or a makeshift anechoic termination. However, it is difficult to create an anechoic termination that will be accurate over the full frequency range. For precise determination of transmission loss, the muffler must be measured at two different conditions. The two commonly used techniques are the two-load [1,2,3] and two-source [4] methods. In this work, the two-load method is examined exclusively though many of the conclusions made in this paper should be transferable to the two-source method.

The two-load method has been standardized in ASTM E2611-09 [5]. Although this standard is geared towards determining the transmission loss through a sound absorbing material, the algorithm and methodology can be applied to measuring muffler transmission loss. As noted in the standard, two different loads are selected.

Both Munjal [4] and Åbom [6] pointed out that a potential challenge is to find two different loads at all frequencies of interest. If the two loads are too close, the determined transmission loss is prone to error. The standard recommends using one absorptive load, which allows minimal reflection. The other preferred load is an open or closed termination where significant reflection of sound is anticipated.

Four microphones are mounted along the impedance tube with two upstream and two downstream of the muffler. A reference signal is selected prior to the test, which can be one of the four microphones, the source signal for driving the loudspeaker or a fifth microphone. Based on the reference selected, three or four transfer functions for each load are measured. From these transfer functions; the so-called four-pole parameters for the muffler can be determined along with the transmission loss.

In this paper, the two-load method is investigated in a number of ways. The cross-sectional area of the impedance tube is fixed and cannot be easily adjusted to fit the dimensions for different mufflers. A pair of conical adapters

is sometimes used to transition between impedance tubes and the muffler. The effect of using adapters is discussed.

Secondly, the selection of the reference is also investigated by comparing results for selecting upstream and downstream references. Reference signal selection is unaddressed in the ASTM standard.

When measuring the transfer functions, three different frequency response function algorithms can be adopted. The effect of using each of the different algorithms is also compared. All measurements discussed in the paper are sans flow at room temperature.

REVIEW OF TRANSMISSION LOSS MEASUREMENT

Figure 1 shows the transmission loss measurement setup schematically. A speaker is placed at the end of the impedance tube. Two microphones are mounted upstream and the other two microphones are mounted downstream. Two different termination loads are applied and four transfer functions are measured for each load, noted as $H_{1,ref}$, $H_{2,ref}$, $H_{3,ref}$ and $H_{4,ref}$.

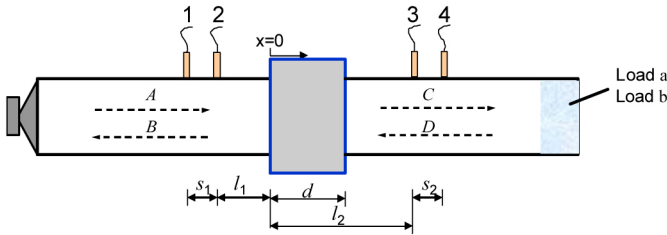


Figure 1. Two-load transmission loss test setup.

Wave Decomposition Data Processing

There are two methods to process the measured transfer functions to obtain transmission loss. The first method, which has been standardized in Reference 5, is based on wave decomposition. By applying wave decomposition at both the upstream and downstream tubes, the wave strength A , B , C , and D can be determined as

$$A = j \frac{H_{1,ref} e^{-jkl_1} - H_{2,ref} e^{-jk(l_1+s_1)}}{2 \sin ks_1} \quad (1a)$$

$$B = j \frac{H_{2,ref} e^{jk(l_1+s_1)} - H_{1,ref} e^{jkl_1}}{2 \sin ks_1} \quad (1b)$$

$$C = j \frac{H_{3,ref} e^{jk(l_2+s_2)} - H_{4,ref} e^{jkl_2}}{2 \sin ks_2} \quad (1c)$$

$$D = j \frac{H_{4,ref} e^{-jkl_2} - H_{3,ref} e^{-jk(l_2+s_2)}}{2 \sin ks_2} \quad (1d)$$

For each load (a or b), pressure and particle velocity at two ends of the sample or muffler are expressed as

$$p_0 = A + B \quad (2a)$$

$$u_0 = (A - B) / \rho c \quad (2b)$$

$$p_d = C e^{-jkd} + D e^{jkd} \quad (2c)$$

$$u_d = (C e^{-jkd} - D e^{jkd}) / \rho c \quad (2d)$$

The four-pole matrix based on pressure and particle velocity can be written as

$$T = \begin{bmatrix} \frac{p_{0a} u_{db} - p_{0b} u_{da}}{p_{da} u_{db} - p_{db} u_{da}} & \frac{p_{0b} p_{da} - p_{0a} p_{db}}{p_{da} u_{db} - p_{db} u_{da}} \\ \frac{u_{0a} u_{db} - u_{0b} u_{da}}{p_{da} u_{db} - p_{db} u_{da}} & \frac{p_{da} u_{0b} - p_{db} u_{0a}}{p_{da} u_{db} - p_{db} u_{da}} \end{bmatrix} \quad (3)$$

where the subscripts a and b denote the two different loads. Then, the transmission loss is expressed as

$$TL = 20 \log_{10} \left| \frac{1}{2} \left(T_{11} + \frac{T_{12}}{\rho c} + \rho c T_{21} + T_{22} \right) \right| \quad (4)$$

The algorithm used is identical to that for the two-source method.

Four-Pole Matrix Data Processing

The other well-known method for processing data follows References 4 and 7 and was originally used for the two-source method. Instead of the four-pole matrix for the sample, the four-pole matrix between microphones 2 and 3 is calculated. The four-pole parameters can be written as

$$A_{23} = \frac{\Delta_{34} (H_{32a} H_{34b} - H_{32b} H_{34a})}{\Delta_{34} (H_{34b} - H_{34a})} + \frac{D_{34} (H_{32b} - H_{32a})}{\Delta_{34} (H_{34b} - H_{34a})} \quad (5a)$$

$$B_{23} = \frac{B_{34}(H_{32a} - H_{32b})}{\Delta_{34}(H_{34b} - H_{34a})} \quad (5b)$$

$$C_{23} = \frac{(H_{31a} - A_{12}H_{32a})(\Delta_{34}H_{34b} - D_{34})}{B_{12}\Delta_{34}(H_{34b} - H_{34a})} - \frac{(H_{31b} - A_{12}H_{32b})(\Delta_{34}H_{34a} - D_{34})}{B_{12}\Delta_{34}(H_{34b} - H_{34a})} \quad (5c)$$

$$D_{23} = \frac{(H_{31a} - H_{31b}) + A_{12}(H_{32b} - H_{32a})}{B_{12}\Delta_{34}(H_{34b} - H_{34a})} B_{34} \quad (5d)$$

where $H_{ij} = p_j / p_i$. A_{ij} , B_{ij} , C_{ij} , and D_{ij} are the corresponding four-pole parameters between microphone i and j , and $\Delta_{ij} = A_{ij}D_{ij} - B_{ij}C_{ij}$. Since additional tube extensions at the inlet and outlet do not modify the transmission loss, the transmission loss can be expressed as

$$TL = 20 \log_{10} \left| \frac{1}{2} \left(A_{23} + \frac{B_{23}}{\rho c} + \rho c C_{23} + D_{23} \right) \right| \quad (6)$$

In the authors' opinion, the wave decomposition method is simpler to use and program. Moreover, it can be used to directly determine the four-pole parameters for the muffler.

CONICAL ADAPTER EFFECT

Plane Wave Theory with Conical Adapters

Assuming a pair of conical adapters is utilized to transition between the impedance tube and the muffler in the measurement, the measured transfer matrix $[T_{total}]$ below the cutoff frequency includes the pair of adapters and the muffler itself. It is expressed as

$$[T_{total}] = [T_{cone1}] [T_{muffler}] [T_{cone2}] \quad (7)$$

where $[T_{cone1}]$ and $[T_{cone2}]$ are the transfer matrices of the upstream and downstream adapters respectively. $[T_{muffler}]$ is the transfer matrix of the muffler. The transfer matrix of the divergent conical tube with length l , and radii r_u and r_d (shown in Figure 2) can be written as [8]

$$[T^d] = \begin{bmatrix} T_{11}^d & T_{12}^d \\ T_{21}^d & T_{22}^d \end{bmatrix} \quad (8)$$

where

$$T_{11}^d = \frac{x_2}{x_1} \cos(k_0 l) - \frac{\sin(k_0 l)}{k_0 x_1} \quad (9a)$$

$$T_{12}^d = j \frac{x_2}{x_1} \sin(k_0 l) \quad (9b)$$

$$T_{21}^d = j \frac{x_1}{x_2} \left(1 + \frac{1}{k_0^2 x_1 x_2} \right) \sin(k_0 l) - j \left(1 - \frac{x_1}{x_2} \right) \frac{\cos(k_0 l)}{k_0 x_2} \quad (9c)$$

$$T_{22}^d = \frac{\sin(k_0 l)}{k_0 x_2} + \frac{x_1}{x_2} \cos(k_0 l) \quad (9d)$$

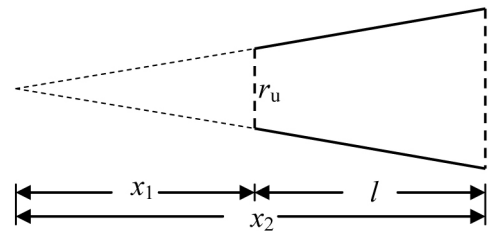


Figure 2. The dimensions of a divergent conical adapter.

The transfer matrix of the convergent conical tube is similar and can be written as

$$[T^c] = \begin{bmatrix} T_{22}^d & T_{12}^d \\ T_{21}^d & T_{11}^d \end{bmatrix} \quad (10)$$

By solving Equation 7, the transfer matrix of the muffler is

$$[T_{muffler}] = [T_{cone1}]^{-1} [T_{total}] [T_{cone2}]^{-1} \quad (11)$$

The transmission loss of the muffler is then calculated using

$$TL = 20 \log_{10} \left(\frac{1}{2} \left| T_{11}^{muffler} + \frac{T_{12}^{muffler} S_o}{\rho c} + T_{21}^{muffler} \frac{\rho c}{S_i} + T_{22}^{muffler} \frac{S_o}{S_i} \right| \right) + 10 \log_{10} \left(\frac{S_i}{S_o} \right) \quad (12)$$

where S_i and S_o are the cross-sectional area of the inlet and outlet of the muffler, respectively. ρ is the air density and c is the speed of sound.

The measured transmission loss is only valid below the cutoff frequency. If the muffler is smaller than the impedance