

Measurement and Simulation of Two-Inlet Single-Outlet Mufflers

Weam Elsahar and Tamer Elnady
Ain Shams University

ABSTRACT

In several applications, two-inlet single-outlet mufflers are possible to encounter in exhaust systems. They are usually used to merge two exhaust streams from two similar engines or from two sides of an engine. They have an advantage of reducing the back pressure on the engine(s). There is a lot of published research on the analysis of single-inlet single-outlet mufflers acting as a two-port. On the other hand, there are a few publications on the analysis of two-inlet single-outlet mufflers due to their complexity representing a three-port. A three-port is characterized by a 3×3 Scattering Matrix. The nine elements of this matrix represent the 3 reflection coefficients at each port, and the 6 transmission coefficients between the 3 ports in both directions. In this work, a two-inlet single-outlet muffler is studied. The elements of the scattering matrix were measured using the two-source two-microphone technique with and without flow. These elements were also calculated from 1D simulation using a set of two-port elements representing the internal dimensions of the muffler, and compared to those obtained from the measurement. A similar 1D simulation was performed using Flow two-ports in order to analyze the flow distribution inside the muffler and the pressure drop across both flow paths. The flow distribution is crucial to obtain accurate acoustic predictions. For all cases, there was a very good agreement between the measurement and the simulations.

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INTRODUCTION

The two-inlet single-outlet muffler configuration, is one of the common muffler forms used in exhaust systems. This configuration is usually used with V-type engines, where each bank of cylinders is connected to a separate exhaust pipe. This allows merging two streams of exhaust gas, while introducing low engine back pressure. The introduced back pressure is usually lower than the back pressure caused by other merging approaches such as using a Y-type junction. Moreover, this is a good alternative to a dual exhaust system, having a separate muffler connected to each of the two exhaust pipes.

Relative to the amount of published research on the analysis of single-inlet single-outlet mufflers acting as two-ports, fewer research work included simulations and measurement case studies where the acoustic performance of a multiport muffler was analyzed. This is despite having several research work offering formulations to solve acoustic multi-ports with arbitrary number of inputs and outputs [1],[2].

Several studies analyzed single-inlet two-outlet mufflers. Selamet and Ji [3] studied the attenuation performance of circular expansion chambers with single inlet and two outlets, using a 3D solution of the Helmholtz equation in circular ducts. Denia et. al [4] studied the acoustic behavior of elliptical single-inlet two-outlet mufflers using the mode matching method. They compared their results to FEM simulations and measurements investigating the effects of muffler length, eccentricity and relative location between the inlet and the outlet ducts. For the same muffler configuration, Wu et. al [5] used the modal meshing approach to predict the transmission loss of the

muffler. Mimani and Munjal in [6], investigated the acoustical behavior of semi-elliptical single-inlet multiple outlet mufflers. They managed to predict the transmission loss of this muffler by proposing a 3-D semi-analytical approach. This study also investigated the effect of pipe chamber length and the relative locations of the ports.

However, all these studies [3, 4, 5, 6] did not consider the more challenging two-inlet single-outlet muffler case. The difference in this case is that it is possible to have two different sources connected to each inlet. Thus, current definitions for acoustic performance measures as transmission loss and insertion loss need to be redefined for this case. Selamet and Ji [7] investigated the acoustic behavior of multiple inlet mufflers. They used a one-dimensional approach to estimate the transmission loss of the muffler. This study considered the effect of the geometry on the acoustic performance of the chamber. Hua et. al [8] extended the transmission and insertion loss definitions to include the multiple inlet case. These expressions for defining the transmission and insertion loss are based on the impedance matrix method by Munjal [2].

Most of the previous studies related to multiple-inlet mufflers had to define an exact solution for a specific muffler configuration. None seemed to propose a generic formulation to apply on a multiple-inlet muffler regardless to its configuration. Moreover, it seems that only Hua's work included acoustic performance measurements for a multiple-inlet case study. Åbom [9] considered a multiport case study where the active and passive properties of a T-junction were measured in a form of an active scattering matrix. The two

microphone technique was used for wave decomposition at each of the measured ports. This measurement technique can be applied to measure the acoustic properties of two-inlet single-outlet mufflers.

In this work, a two-inlet single-outlet muffler was studied. The acoustic performance of the muffler was defined by a multi-port scattering matrix. The elements of the scattering matrix were determined experimentally using a set of two-source two microphone measurements with and without mean flow. Similarly, the scattering matrix of this muffler was calculated from a set of 1D acoustic two-port simulations and the results were compared to measurements. A similar 1D simulation was performed using Flow two-ports in order to analyze the flow distribution inside the muffler and the pressure drop across both flow paths [10], as the flow distribution is crucial to obtain accurate acoustic predictions for the with flow case study.

THEORY

Acoustic Multi-Port Scattering Matrix

A general representation for an acoustic two-port is a multiport. While a two-port have only one inlet and one outlet, a multiport can represent an element with any number of inlets and outlets. The general form of a multiport as shown in Figure 1 can be described using equation (1), where n indicates the number of ports of the multiport element.

$$\begin{bmatrix} p_1^- \\ p_2^- \\ \vdots \\ p_n^- \end{bmatrix} = \begin{bmatrix} S_{11} & \cdots & S_{1n} \\ \vdots & \ddots & \vdots \\ S_{n1} & \cdots & S_{nn} \end{bmatrix} \begin{bmatrix} p_1^+ \\ p_2^+ \\ \vdots \\ p_n^+ \end{bmatrix} + \begin{bmatrix} p_{s1}^- \\ p_{s2}^- \\ \vdots \\ p_{sn}^- \end{bmatrix} \quad (1)$$

Where as shown in Figure 1 p_n^+ and p_n^- represents the incident and reflected components of the pressure of the plane wave respectively, at the node indicated by the subscript number n . While p_{sn}^- indicates the element's source pressure propagating outwards the element at each node referenced by the subscript number n . The graphical representation of this multiport is shown in Figure 1.

The scattering matrix representation shown in equation (2), relates the pressure amplitudes travelling towards each port to the pressure amplitudes travelling outwards at each port. This representation is more convenient in some cases, as the scattering matrix can be written in terms of the different reflection and transmission coefficients of the given multiport. Where R is the reflection coefficient of the port designated by the subscript symbol and Tr is the transmission coefficient between the two-ports designated by the two numbers in the subscript respectively. In this study only the passive behavior of the muffler was studied, thus the term representing the source was eliminated in equation (2).

$$\begin{bmatrix} p_1^- \\ p_2^- \\ p_3^- \end{bmatrix} = \begin{bmatrix} R_1 & Tr_{12} & Tr_{13} \\ Tr_{12} & R_2 & Tr_{23} \\ Tr_{13} & Tr_{23} & R_3 \end{bmatrix} \begin{bmatrix} p_1^+ \\ p_2^+ \\ p_3^+ \end{bmatrix} \quad (2)$$

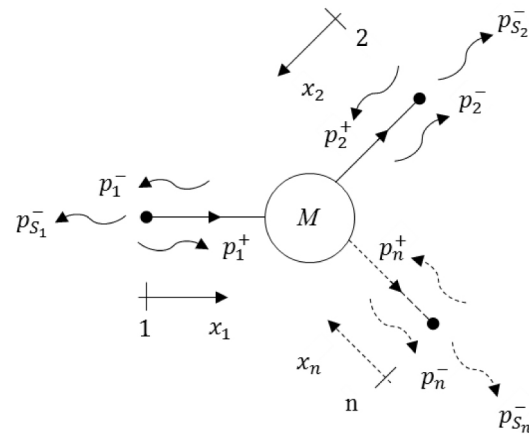


Figure 1. Scattering plane wave pressure representation for a Multi-port element showing the incident and reflected pressure wave components at each node.

Measuring the Elements of a Multiport Scattering Matrix

Figure 2 shows the multiport representation for the muffler used in this study. To obtain the elements of this 3×3 scattering matrix of such multiport using measurements, it is required to construct a three-port measurement setup.

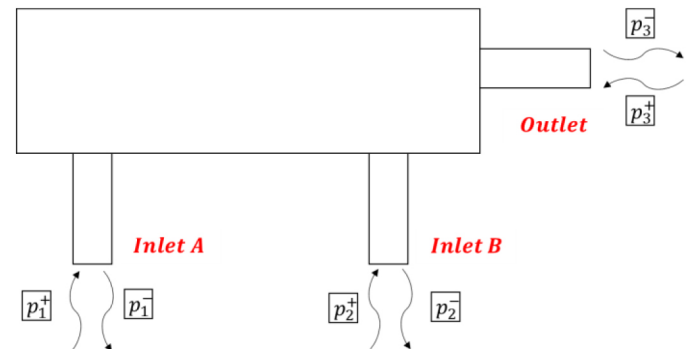


Figure 2. Schematic representation of the two-inlet muffler single-outlet muffler used in this study. The figure shows the scattered pressure wave components at each port.

In this setup, each of the three ports is connected to an excitation source (loudspeaker), and the two-microphone method need to be applied at each of these ports. To measure all the elements of the scattering matrix, three measurement runs need to be performed. In each run, one of the sources is activated, while the incident and reflected pressure values at each node p_1^+ , p_2^+ , p_3^+ , p_1^- , p_2^- and p_3^- are measured simultaneously. Substituting these pressure values in equation (2), 3 equations can be obtained from each run. This results in a total number of 9 equations for the 3 runs, which corresponds to the number of unknown elements in the 3×3 scattering matrix. To cover a wide range of frequencies, three microphones might be used at each port to allow different microphone spacing (low frequency spacing and high frequency spacing). In this case, a total of 9 microphones and 9 data acquisition channels need to be measuring simultaneously in each measurement run. These requirements were not available in this case study. However, for this three port element, the elements of the 3×3 scattering matrix can be obtained using a combination of measurement steps, where the pressure values are measured simultaneously at two

ports only and the third port is connected to a long pipe extension to reduce the reflections at this port. For this system, 2 equations can be extracted from each measurement run. As the pressure values are available at only two of the three ports, it will require at least 5 runs with different boundary conditions to get the 9 equations for the elements of this scattering matrix.

The following three measurement steps will provide 6 different boundary conditions, and thus 12 equations to extract the scattering matrix elements through. This over determination in these three extra equations, will provide redundant results for R_1 , R_2 and R_3 . In the first measurement step inlet A is connected to the upstream of the two-port measurement setup, inlet B is connected to the downstream of the setup and the muffler output is connected to a pipe extension. This step will cover two measurements runs, one with the source connected upstream and another when the source is connected downstream. Figure 3 shows how the first measurement step was configured. Similarly, the other measurement steps were configured by alternating the ports at which the upstream measurement section, downstream section and the pipe extension are connected.

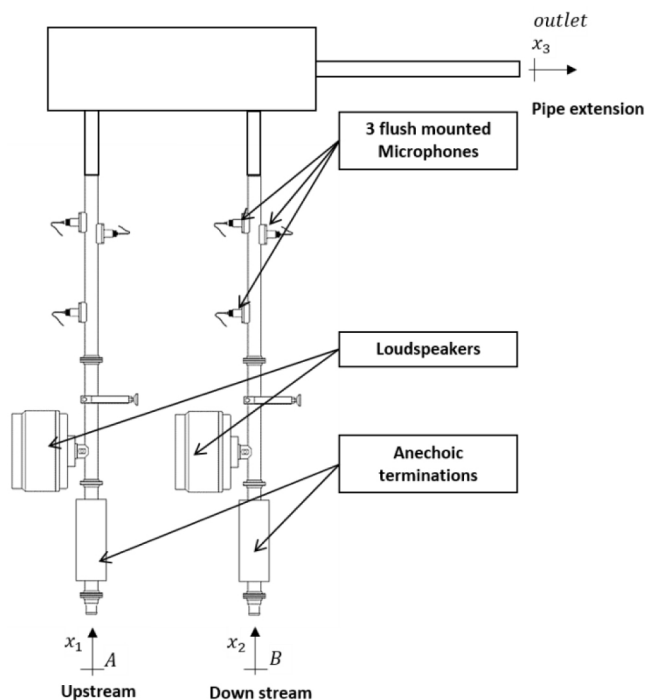


Figure 3. Schematic showing how the studied two-inlet muffler is connected to the two-port measurement setup in the first measurement step.

Two-Inlet Muffler Two-Port Model

A two-port model was constructed for each of the measurement steps described before. SIDLAB, [11] which is a software based on the two-port theory and implements the formulism developed by Glav and Åbom [1], was used for these simulations. Figure 4 shows a detailed section view for the muffler considered for this study.

The two-port network is the same for all the steps, but the terminations of the two-port network were reconfigured for each study step. Different volumes inside the muffler were discretized into acoustic two-ports as shown in Figure 5.

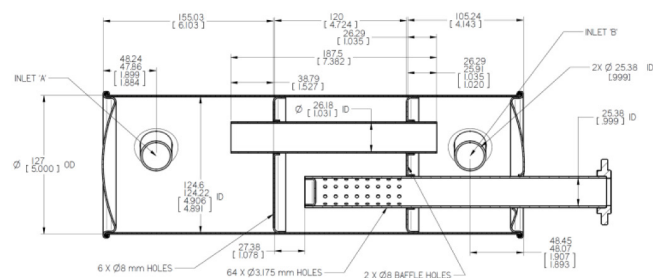


Figure 4. Detailed section view of the studied muffler.

For step 1 the two-port network is shown in Figure 6. The elements are indexed according to the corresponding volumes numbered in Figure 5. Consider the muffler to be divided into three main chambers, the first chamber from the left where inlet A is extended into, the last chamber to the right where inlet B is extended into and the middle chamber where the outlet pipe is extended from. The three chambers are separated by two perforated plates represented by elements 10 and 12 [12]. The symbols representing the elements in the two-port networks in Figures 6, 7 and 8 are described in Table 1.

For study step 1 as shown in Figure 6, the upstream point of the two-port network was set to node number 1 (inlet A), the downstream was set to node number 11 (inlet B) and node 15 from the outlet pipe was connected to the pipe extension element number 16 and the one port open end termination element number 1. Similarly, study steps 2 and 3 were configured as shown in Figure 7 and Figure 8.

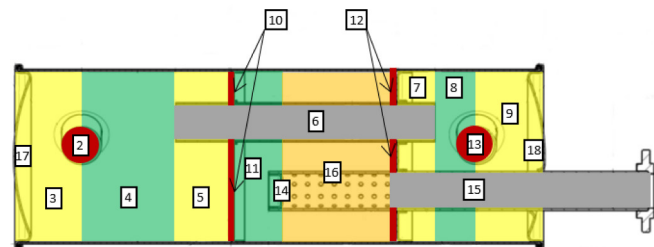


Figure 5. Schematic showing the studied two-inlet muffler divided into volumes, to be represented as two-port elements.

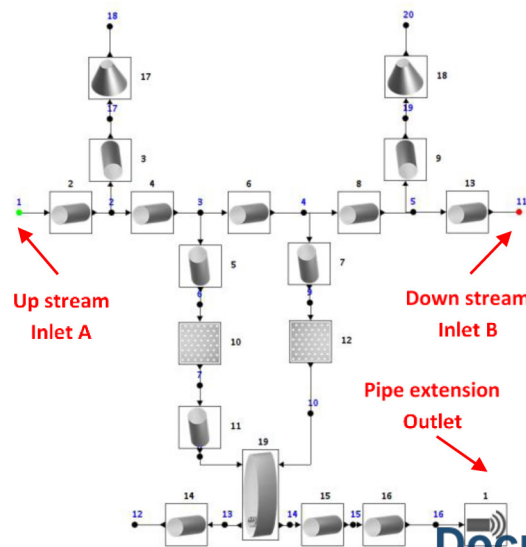


Figure 6. Two-port network representation for the two-inlet muffler in study step 1.