

Experimental Acoustic Characterization of Double-Inlet and Single-Outlet Muffler

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ABSTRACT

The acoustic performance of mufflers with single-inlet and single-outlet are well described using Insertion Loss (IL) and Transmission Loss (TL). These parameters represent the acoustic damping on the engine emission and on the incident pressure wave respectively. However, for mufflers with multi-inlet these parameters depend also on the sources characteristics, as consequence their use is quite difficult.

In the present work the acoustic performance of a double-inlet and single-outlet muffler are experimentally evaluated in terms of reflection and transmission coefficients of each port of the muffler itself. These coefficients are used to evaluate the Insertion Loss of the manifold muffler taking into account specific sources on the inlets.

The characteristic coefficients are also used to predict the acoustic emission of the manifold muffler using a known engine source on the two inlets. The resulting acoustic emission is compared with the measured one on the corresponding experimental test.

Therefore, in the present work, the experimental procedure and test rig adopted to estimate the acoustic characteristic coefficients are shown.

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INTRODUCTION

Currently, the acoustic performances of internal combustion engines mufflers have been widely studied. It is known that the main acoustic parameters describing muffler performances are the Transmission Loss (TL) and Insertion Loss (IL). The first one evaluates the acoustic attenuation on the incident acoustic field and the second one measures the loss on external acoustic radiation of the engine coupled with the muffler.

Many analytical and experimental studies have investigated the effects of geometry on the acoustic attenuation of single inlet and single outlet mufflers. Ferrara et al. [1] show a wide experimental campaign on the TL estimation of different simple muffler geometries with one inlet and one outlet. The authors have used the multi-microphone method [2] for the wave decomposition and the two-source technique [3] to evaluate the TL, all tests are performed without flow and at ambient temperature. In particular, the results have showed the effects of thin walls on the TL trend. A significant study on the fluid-structure interaction on an muffler has been presented by Siano et al. [4], they shows a numerical and experimental analysis on the acoustic attenuation of an automotive muffler. The muffler has one inlet and one outlet, and it is made up of three chambers, two extended concentric tube resonators and perforated ducts coupled with fibrous acoustic damping material. The authors have used the boundary element method (BEM) to predict the acoustic attenuation performance of the muffler. The numerical model

has demonstrated an excellent agreement with experimental results, considering also the fluid-structure interaction between the acoustic pressure field and the thin walls of the muffler.

Other studies have used the finite element method (FEM) in spite of BEM. An early study of Craggs [5] have showed the application of the FEM method for the performance evaluation of a simple reactive muffler. Several studies follow the same path, using the FEM method for the analysis of the acoustic performance of mufflers or air intake systems, confirming the use of this numerical method in place of experimental test rigs to validate the results of a more common 1D code. The 1D codes are largely used to investigate the behavior of the acoustic filters, in particular in the low-middle frequency ranges, achieving good results and low computational time. Indeed, the works of Ferrara et al. [6] and Montenegro et al. [7] have illustrated the good agreement between the 1D simulation and the experimental measure of TL of a muffler and an air intake system respectively.

All above-mentioned studies may be gathered together in an wide branch of study which is focused on the analysis of the numerical model capabilities to predict the acoustic performance of a muffler. Considering also the physical phenomena due to fluid structure interaction or a pulsating gas flow, that can have effects on TL trends. On the other hand, all this studies have been carried on mufflers with

two ports. To this day, there aren't many works on the TL analysis of mufflers with multiple inlet/outlet and about their advantages or disadvantages in place of a two port system.

The work of Selamet et al. [8] shows an early study on a muffler with single inlet and double outlet. The authors have developed a three-dimensional analytical approach to determine the TL of a circular expansion chamber with double outlet, in absence of mean flow. The authors studied the influence of geometry and the locations of the outlets on the acoustic attenuation trend and compared the results with a BEM analysis. The authors have proved that the disposition of the outlet ports compared to the inlet port deeply affect the TL of the muffler, especially after the first tridimensional acoustic mode of the chamber.

A similar study is presented by Wu et al. [9], the authors use the transfer matrix method (TMM) to predict the TL of a single-inlet/double outlet cylindrical expansion chamber muffler. They focused on improving the transfer matrix method by means of the modal meshing approach. In order to consider also the higher order wave modes that can become predominated when the dimensions of chambers are significantly bigger than the ducts diameter and when the outlet ports are not symmetrically placed compared to the inlet port.

Also Mimani and Munjal [10] have analyzed the TL of an elliptical muffler with single inlet and multi-side outlet, using a 3D semi-analytical formulation. The authors have found the guidelines for optimizing disposition of the inlet and outlet ports to improve the TL trend in a large frequency range. The disposition of outlets can interact with the acoustic modes inside the chamber and contributes to reduce the flow-induced noise at the tail pipe. Furthermore, the relative disposition of the inlet and outlet ports influences the higher order modes inside the volume of muffler, as demonstrated by Younghyun [11].

About the acoustic analysis of mufflers with two ports at the inlet, the work of Selamet and Ji [12] can be considered very significant. The authors have studied how the TL of a muffler with double inlet port and single outlet port can be conditioned by the relative phase information between the two incident waves at the inlets. In their results Selamet and Ji shows that if the two incident waves are generated in-phase, out-of-phase or with a phase shift of 90 degree, will produce three different TL trends already starting from low frequencies. Following that, Hua et al. [13] have shown an interesting comparison between two numerical methods for evaluate the TL and the IL of a muffler with double inlet and single outlet: the impedance matrix approach and the superposition approach. The authors have generalized the formulations of these parameters also for mufflers with multi-inlet and multi-outlet port and in conclusion they have showed as this parameters are strongly dependent on the amplitude ratio and phase difference between sources. Confirming the results of the previous studies.

In the present study, the authors analyze the acoustic attenuation performance of a motorcycle muffler with double-inlet and single outlet, the aim is the evaluation of the acoustic performances exploiting the widely used parameter Transmission Loss. The TL is defined independently from the characteristic of the source. This

parameter expresses the acoustic power reduction that is produced by the silencer on the acoustic field, considering the total acoustic incident power at the inlet and the total acoustic power transmitted at the outlet [14].

The muffler under study when it works has two incident acoustic fields, one for each port. More in detail, the silencer analyzed is commonly used as exhaust manifold for a twin engine, therefore, the incident acoustic wave at the two inlets have a phase shift which is a function of the engine timing and the engine speed. As result the mutual interference, constructive or destructive, between the two incident waves inside the muffler can modify its TL.

In the present work, it is proposed a new expression of the TL that takes into account the phase shift between the incident waves on the two inlets and the acoustic characteristics of the muffler in terms of the transmission coefficients between the inlets and the outlet. Such definition allows to express the TL still independently from the other source characteristics: intensity and impedance.

The scattering coefficients, such as transmission and reflection ones, are evaluated by means of a series of experimental tests. Starting from the experimental approach adopted for the characterization of the T-junction [15]-[16], the experimental procedure has been designed to evaluate the scattering coefficients between each couple of ports. Measuring the incident and reflected waves for each test, it can be written an algebraic system where the unknowns are the scattering coefficients. The experimental procedure uses the multi-microphones technique to measure the incident and transmitting waves, and the two-source method to evaluate the four pole parameters of the muffler [17].

The effectiveness of scattering matrix is evaluated using itself to predict the acoustic emission radiated into the ambient. Two time-shifted acoustic fields are generated on the inlets of the muffler and measuring the resulting acoustic field with a free-field microphone placed near the outlet of the muffler. The free-field data are compared with the one obtained by a lump parameter system that simulate the test experimental configuration.

TRANSMISSION LOSS DEFINITION

The Transmission Loss (TL) is a parameter that does not depend on the source and presumes an anechoic termination at the downstream section of the acoustic filter. It is defined as the difference between the acoustic power level at the inlet and at the outlet respectively, as expressed in Eq. 1.

$$TL = L_{Wn} - L_{Wout} = 10 \log \left(\frac{W_n}{W_{out}} \right) [dB] \quad (1)$$

where L_{Wn} is the total incident acoustic power level at the inlet and L_{Wout} is the acoustic power level at the outlet port; more in detail, the subscript n indicates the number of inlets whereas the subscript out indicates the outlet port. In the present work, the case study is a two-inlet and single outlet motorcycle muffler, its central body is made

up of two chambers connected by a resonator duct. In Fig. 1 a simplified sketch of the muffler is depicted, where t_{ij} is the transmission coefficient between i - and j -port while the r_i is the reflection coefficient of the i -port. In Fig. 2 is depicted the 3D CAD of the muffler under test, the two inlet ducts 1 and 2 enter in the chamber while the single outlet duct 3 connects the chamber with tail pipe.

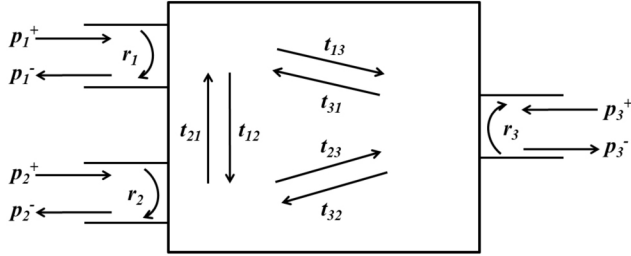


Fig. 1. Schematic of a double inlet and single outlet.

More in detail, the global acoustic power at the inlet (W_n) is the sum of the acoustic power on the two ports 1 and 2, as expressed in Eq.2:

$$W_n = W_1 + W_2 = \frac{|p_1^+|^2}{Y_1} + \frac{|p_2^+|^2}{Y_2} \quad (2)$$

Where p_i^+ is the incident acoustic wave at the i -port and $Y_i = \rho c / A_i$ is the characteristic acoustic impedance expressed as the ratio of sound speed (c), density (ρ) and duct area (A_i). In the same way, the acoustic power transmitted at the outlet is expressed in Eq.3:

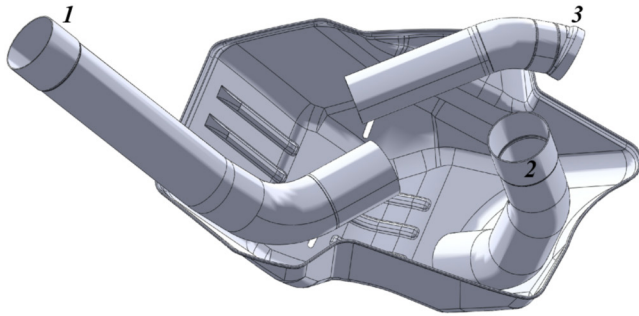


Fig. 2. 3D-CAD of the muffler under test without the upper shell

$$W_{out} = W_3 = \frac{|p_3^-|^2}{Y_3} \quad (3)$$

where p_3^- is the transmitted wave on the downstream section. Thus, substituting the Eq. 2 and Eq. 3 into the Eq. 1, considering the equivalence between the areas ($A_1 = A_2 = A_3$) the TL expression can be rearranged as showed in Eq.4:

$$TL = 10 \cdot \log_{10} \left(\frac{|p_1^+|^2 + |p_2^+|^2}{|p_3^-|^2} \right) \quad (4)$$

The transmitted wave at the outlet (p_3^-) can be expressed as function of the incident waves at the inlet (p_1^+ and p_2^+) by means of the scattering coefficients of the muffler, as depicted in Eq.5:

$$p_3^- = t_{13}p_1^+ + t_{23}p_2^+ \quad (5)$$

relating to Fig. 1, t_{13} and t_{23} are the transmitted coefficient between the first and third port and between the second and third port respectively. Substituting Eq.5 into the Eq.4 the TL becomes only function of the inlet incident pressures and of the acoustic characteristics of the muffler, Eq.6.

$$TL = 10 \cdot \log_{10} \left(\frac{|p_1^+|^2 + |p_2^+|^2}{|t_{13}p_1^+ + t_{23}p_2^+|^2} \right) \quad (6)$$

Considering a twin-cylinder engine, a good hypothesis on the two acoustic sources (p_1^+ and p_2^+) is that they should have the same amplitude but not the same phase, because there may be a phase shift between the two cylinders. Therefore, the two incident waves can be expressed as in Eq.7:

$$p_1^+ = p^+ \quad p_2^+ = p^+ \cdot e^{i\phi(f, RPM)} \quad (7)$$

where p^+ is the amplitude of the single plane wave at the frequency f and ϕ is the phase shift between the two waves produced by the phase shift between the two cylinders.

Substituting Eq.7 in Eq.6 it is possible to express the TL as a function of the characteristics of the muffler and the phase between the two sources look at Eq.8, the relative phase will be related to the engine timing and engine speed.

$$TL = 10 \cdot \log_{10} \left(\frac{2}{|t_{13} + e^{i\phi(f, RPM)} t_{23}|^2} \right) \quad (8)$$

Evaluation of the Phase Shift

The relative phase between the two sources has a strong relevance on the value of the TL, as seen in Eq. 8, its value depends on engine specifications and on the frequency of the acoustic wave analyzed. Considering a two cylinder motor engine, the time shift between the openings of the exhaust valves of the two cylinders depends on the mechanical angle and on the crankshaft speed, as shown in Eq.9:

$$\delta t = \frac{\alpha_{mec}}{2\pi} \cdot \frac{60}{n_s/2} \quad (9)$$