International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 7, September - 2012

FEM ANALYSIS AND EXPERIMENTAL VALIDATION OF THE ACOUSTIC PERFORMANCE OF A CENTRAL INLET SIDE OUTLET REACTIVE MUFFLER

A.P.Bhattu, A.D. Sahasrabudhe

Abstract: Noise from an IC Engine is the major source of noise pollution in the modern world. In recent years people have become more conscious of their working and living environment, resulting in mandatory restriction on sound emitted by automotive engines by many governments. This has resulted in research on muffler performance and size. The present paper deals with FEM analysis and experimental validation of the acoustic performance of a reactive muffler with side outlet. For the chosen model, the measured transmission loss was compared with analytical method and finite element method (FEM). Two load method is used for experimental work. Experimental results show good agreement with analytical and FEM results.

Keywords: Transmission loss, FEM, Two load method

INTRODUCTION

Accurate prediction of sound radiation characteristics from reactive muffler is of significant importance in automotive exhaust system design. The most commonly used parameter to evaluate the sound radiation characteristics of muffler is transmission loss (TL). Transmission loss is one of the most frequently used criteria of muffler performance because it can be predicted very easily from the known physical parameters of the muffler [1]. For achieving higher TL, the expansion ratio must be correspondingly higher. However, higher expansion ratio introduces an upper frequency limit up to which the plane behavior is valid [2]. When better performance is desired in the mid to high frequency region, the central inlet and side outlet chambers are helpful.

The transmission loss (TL) could be obtained by three methods: analytical, numerical, and experimental. However, practical muffler configurations generally have large cross sectional dimensions as well as complex geometries and analytical methods are cumbersome in the sense that the associated algebra is very complicated. Hence it is impossible to solve such problems by analytical methods [3].

The numerical methods are completely general and allow the analysis of all types of mufflers. But the results achieved by numerical tool i.e. by FEM may not be correct due to many reasons such as modeling errors, meshing errors, assumptions while solving the partial differential equations (solution errors), specifications of approximate boundary conditions, insufficient constraints, selection of meshing elements, types of meshing etc. Irrespective of these drawbacks numerical methods can be used for optimization of model of complicated shapes and cost involved is less compared to experimental methods. So general practice is to optimize the model by numerical methods and validate the result by experimental methods.

In general, experimental results are required for verifying the analytical and numerical predictions and also for evaluating the overall performance of a system configuration so as to check if it satisfies the design requirements [4]. In this research paper two load method is used for measuring transmission loss by experimental method.

ANALYTICAL APPROACH

For a propagating plane wave the characteristic impedance ρc is a real quantity, where ρ is density of air and c is speed of sound in air, and the acoustic pressure (p) and particle velocity (v) are in phase.

For the propagating plane wave (which is one dimensional wave) the wave equation is given by second order partial differential equation in x and t [5].

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}$$

The general solution to this equation is given by

$$p(x,t)=F(x-ct)+G(x+ct)$$

where t is the time and the function F(x-ct) represents waves moving in the positive x direction and G(x+ct) represents waves moving in the opposite direction.

When a sound wave is superimposed upon another wave of the same frequency but travelling in the opposite direction, a standing-wave sound field is generated.

For a given medium the acoustic impedance of a plane progressive wave is everywhere the same provided the size of wave front does not alter. The effect on the phase of a plane wave in a pipe when reflection occurs as a result of transmission to a larger cross section is analogous to that which is associated with reflection of sound going from dense medium to a rare medium. Likewise the transition from large cross section to small cross section is analogous to the passage of sound from a rare to dense medium.

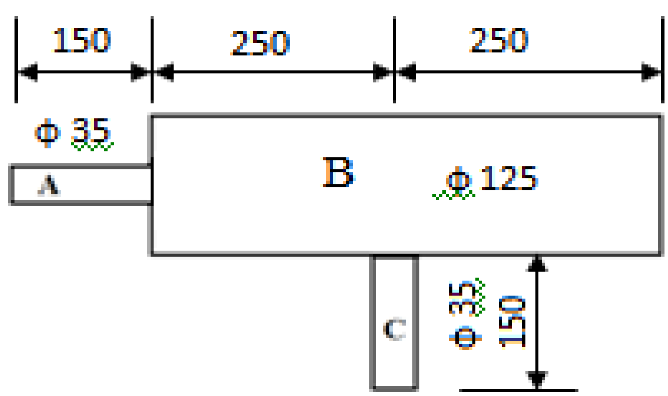


Figure 1. Single chamber central inlet side outlet muffler

Figure 1 shows a single chamber central inlet side outlet muffler which is used for analysis and experimentation. In this model a harmonic plane wave travelling in the positive x direction interferes with another plane wave travelling in the negative x direction at the centre of the chamber. The superimposition of two sound waves traveling in opposite directions is given by

$$p_1(t) + p_2(t) = A_1 sin(2\pi ft - kx) + A_2 sin(2\pi ft + kx)$$

where k is wave number

The first sine term in the equation represents a sound wave traveling in the positive x direction with amplitude A_1 and frequency f. The second sine term in the equation represents a sound wave traveling in the negative x direction with amplitude A_2 and identical frequency f. A.P.Bhattu and A.D. Saharabudhe [6] developed a general analytical formula of transmission loss for central inlet side outlet muffler considering the following assumptions:

1. The acoustic wave in the duct is a plane wave.
2. The viscosity effects and the gravity effects are neglected.
3. The radiation and convection of sound through the surface of the duct is negligible.
4. There is no reflection wave from the exit of the silencer.
5. Zero mean flow

$$TL = 10log_{10}[1 + \frac{1}{4}(2m - \frac{1}{2m})^2 sin^2(\frac{kl_B}{2})]$$

where m = area ratio, k =wave number, l_B =length of chamber, TL= transmission loss

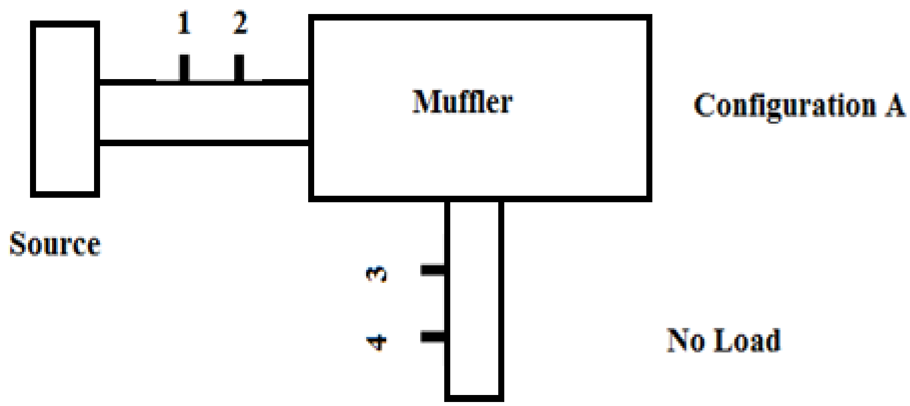
NUMERICAL APPROACH

Single chamber central inlet and side outlet muffler was numerically modeled by A.P.Bhattu and A.D. Saharabudhe [7] using parametric and linear solver assuming no fluid structure interaction and have shown that transmission loss calculated by modified transfer matrix elements and FEM show very good agreement in low and mid frequencies. They have compared numerically performance of single chamber central inlet and side outlet muffler with single chamber central inlet central outlet muffler and have shown that single chamber central inlet side outlet muffler gives transmission loss which is equivalent to transmission loss of single chamber central inlet central outlet muffler which is double in length and double in cross section area of expansion chamber.

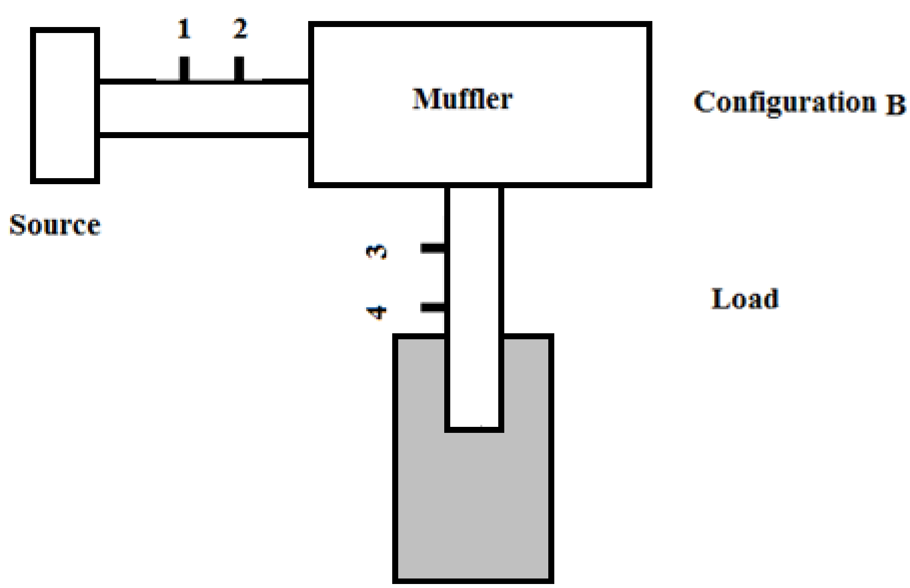
ISSN: 2278-0181
Vol. 1 Issue 7, September - 2012

EXPERIMENTAL APPROACH

Two Load Method [8] was used for experimental investigation. In the two load method, two loads should be different to keep results stable. Generally, two loads can be two different length tubes or a single tube with and without absorbing materials. In this work two loads were achieved by outlet tube with and without absorbing material as shown in Fig. 2. The two load method is based on the transfer matrix approach. Using the transfer matrix method, one can readily obtain transmission loss of any muffler by using four pole equations from the four positions of microphones.



Configuration (a) No load



Configuration (b) With load

Figure 2. Two configurations and schematic model of Muffler

Experimental Setup:

A schematic diagram of experimental set up for calculating TL of simple expansion muffler is shown in Fig. 3 and actual setup in Fig. 4. It consists of a noise generation system, noise propagation system and noise measurement system. The TL is measured by transfer function method. The setup has the following main components.

- Impedance Tube
- Data acquisition system
- Noise source with amplifier
- Sound pressure measuring microphones

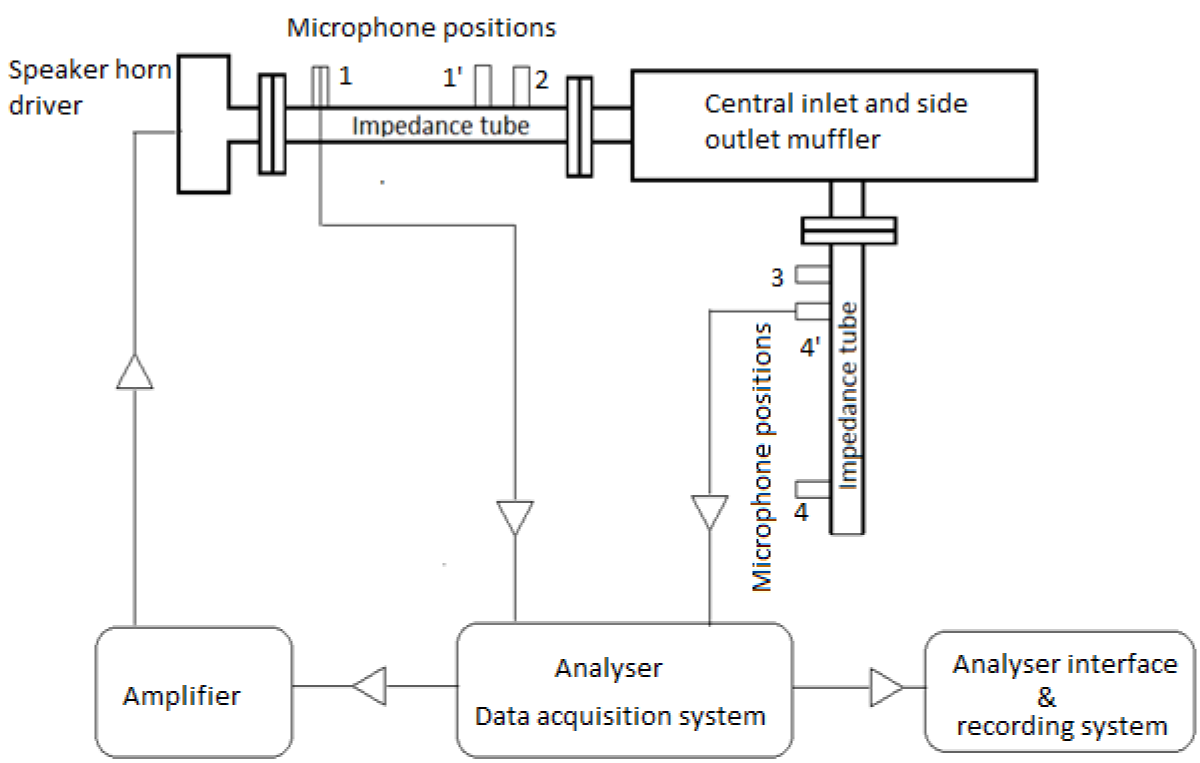


Fig. 3 Schematic Diagram of Experimental set up with its components

ISSN: 2278-0181
Vol. 1 Issue 7, September - 2012

Experimental Procedure [8]:

Experimentation for pressure measurement mainly consists of analyzer setting and data processing for TL calculation. The experiment is performed for frequency range of 50 to 3400 Hz. The measurements are taken in two slots with two locations 1-1' and 4-4' as shown in figure respectively to cover desired frequency range [9]. The locations 1-2-3-4 are used for measuring pressure in frequency range 50-400 Hz, while the locations 1'-2-3-4' are used for measuring pressure in frequency range of 400-3400 Hz. The first set of readings is taken for no load condition with both frequency ranges and same procedure is repeated for with load condition. Two microphones are used for measurement, which are sufficient for measurement of transfer function between sound pressures measured at two locations. One microphone is placed at location 3 and other placed at location 1, 2 and 4 respectively to get transfer function H_{31}, H_{32} and H_{34} with respective locations. All other locations except locations where microphones are inserted are sealed with pins to avoid sound leakage. The sound leakage is tested and wax is used to seal these leaks. The obtained transfer functions are then directly used in four-pole element calculations to get TL.

Neglecting flow of air, the four poles for elements 1-2 can be expressed as

$$\begin{bmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{bmatrix} = \begin{bmatrix} \cos kl_{12} & j\rho c \sin kl_{12} \\ \dfrac{j \sin kl_{12}}{\rho c} & \cos kl_{12} \end{bmatrix}$$

The four poles for elements 2-3 can be expressed as

$$\begin{bmatrix} A_{23} & B_{23} \\ C_{23} & D_{23} \end{bmatrix}$$

where

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

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

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

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

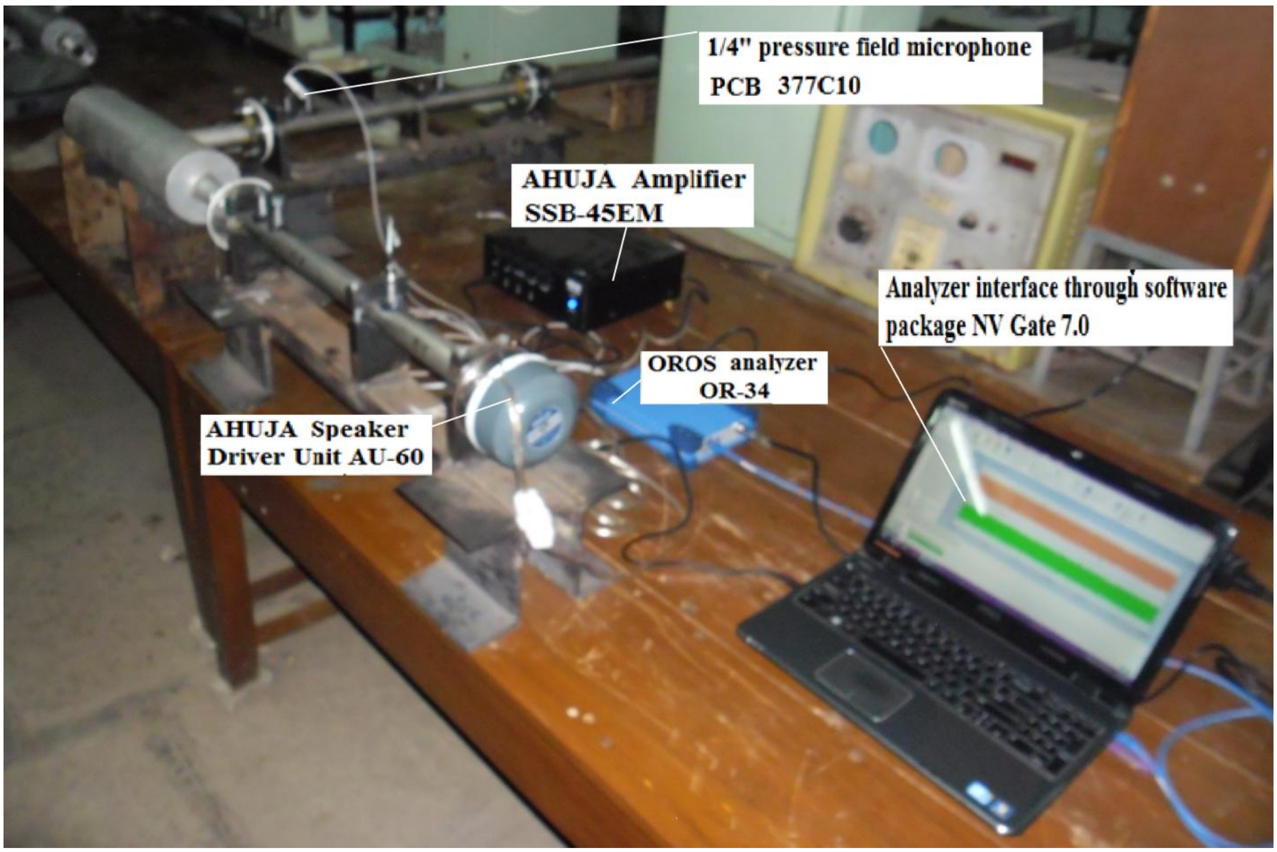
$$TL = 20\log_{10}\left(\frac{1}{2}\left|A_{23} + \frac{B_{23}}{\rho c} + \rho c\, C_{23} + D_{23}\right|\right)$$

The term H_{ij} represents transfer function between P_i and P_j ($H_{ij} = P_j / P_i$).

The four poles for elements 3-4 can be expressed as

$$\begin{bmatrix} A_{34} & B_{34} \\ C_{34} & D_{34} \end{bmatrix} = \begin{bmatrix} \cos kl_{34} & j\rho c \sin kl_{34} \\ \frac{j \sin kl_{34}}{\rho c} & \cos kl_{34} \end{bmatrix}$$

By using two microphones with random excitation transmission loss can be calculated experimentally.



a. Configuration without load

b. Configuration with load

Fig. 4 Experimental setup for two load method

RESULTS AND DISCUSSION

The acoustic attenuation of central inlet side outlet reactive muffler is expected to depend on the geometric characteristics. For this configuration the dimensions of muffler are chosen in such a way that length of chamber is exactly equal to $\frac{\lambda}{2}$. (λ wavelength corresponding to frequency of interest and trough occurs at that frequency in case of simple muffler) and the centre point of chamber is $\frac{\lambda}{4}$ where $sin\ (\frac{kl_B}{2}) = 1$ which gives maximum value of transmission loss.

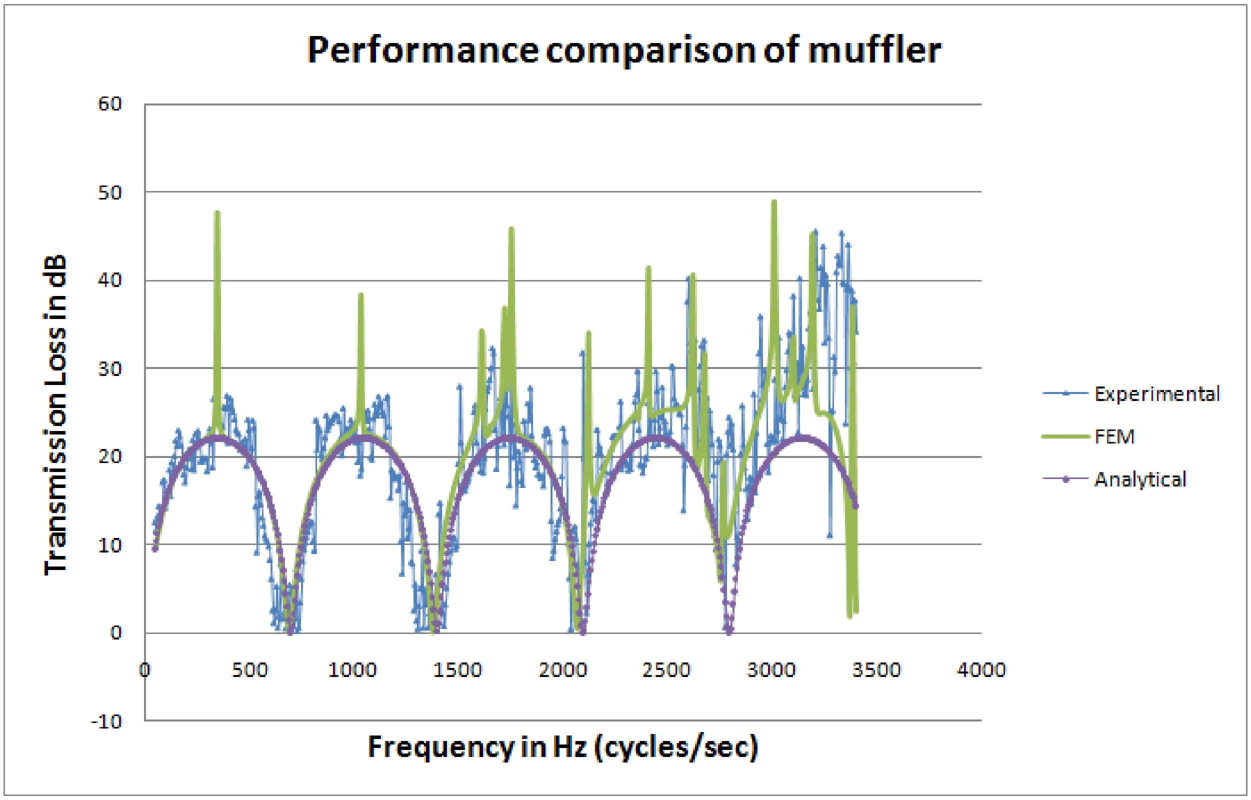


Figure 5 Comparison of TL for a central inlet side outlet muffler by different methods

Figure 5 shows TL comparison for a central inlet side outlet muffler by different methods**.** In analytical method it is assumed that the wave is planar throughout the frequency range but this assumption is not valid as cut on frequencies are excited in high frequency range. The measured results by experimental method agreed with the FEM results.

CONCLUSIONS

In this work paper analytical and FEM results of central inlet side outlet muffler are verified by experimental method.

The experimental results show good agreement with the analytical results and numerical results**.** The deviation of the experimental results from the numerical results may be due to leakage of sound from the surrounding and problems in generating true random (white) noise from the FFT.

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