INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

OPEN ACCESS

Received: 03-11-2022

Accepted: 18-01-2023

Published: 11-02-2023

Citation: Suratwala N, Kulkarni M (2023) Effect of Variations in Diameter of Extended Inlet on Transmission Loss of Single Expansion Chamber Reactive Muffler with Extended Inlet. Indian Journal of Science and Technology 16(6): 401-408. https://doi.org/10.17485/IJST/v16i6.2123

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Effect of Variations in Diameter of Extended Inlet on Transmission Loss of Single Expansion Chamber Reactive Muffler with Extended Inlet

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Abstract

Objectives: Muffler with extended inlet has an additional dimension of variable compared to normal mufflers, that is the diameter. Understanding the effect of change in this diameter value affects Transmission Loss. Muffler used for experimentation is a reactive muffler, which cancels the noise waves using reflection phenomenon. Comparison of Computer Aided Engineering (CAE) in experiments to signify the technology advancement. **Methods:** MATLAB program is created for running the data and analytical solution. Finite element analysis with COMSOL Multiphysics using 3D model of muffler and computer aided engineering is done considering boundary conditions. The real experiment is carried out to evaluate confidence in simulated results where two load method is applied. **Findings:** Experimental setup results are showing results close to Numerical analysis. Analysis of the study suggest increase in diameter leads to rise in transmission loss. The experimental results of selected dimensions setup also prove same. Various geometric variation in muffler have effect of 10 to 30% on TL, while changing diameter from 10 to 20 mm of extended inlet raise the peak of TL to almost double and increase the average TL by 28%. **Novelty:** A diameter variation in extended inlet is an empty space in literature till now. This research combines analytical and experimental setups and comparison of results leads to a strong conclusion toward better muffler design.

Keywords: Transmission Loss (TL); Single Expansion Chamber reactive muffler; Numerical analysis; Twoload method; Acoustics

1 Introduction

Residential areas face major issues if loud noise producing engines or machines are placed in nearby. Equipment with IC engines produces loud noise in exhaust. It has been well-known that for humans, the noise level should be below 80 dB (decibels). Therefore, component called muffler is used for attenuation of noise. Any device used for noise reduction, has number of parameters which defines the effectiveness. Therefore, the design of the muffler plays an important role as it affects the noise cancellation properties and fuel efficiency of the engine. Insertion Loss (IL) and Transmission Loss (TL) are used to describe muffler ability to reduce noise. Mostly, Transmission Loss is used in studies. It is calculated using equations derived from power input and output. The numerical techniques are prepared considering majority of parameters and permit the evaluation of all kinds of mufflers. They also help to optimize the physical model for most effectiveness. Also, numerical methods are cheaper and quicker for achieving approximate results. The mufflers with various shape, size and dimensions are studied to understand the various parameters. Specifically, one research study with in homogeneous microperforated panels (iMPPs) inside an extended inlet and outlet muffler concluded that depth of air cavity has effect on Transmission Loss. The results were validated by comparing simulations and experimental data[(1)]. Similar study carried out on muffler with tapered section for side outlet. Simulation results from FEA are matching with analytical approach with error less than 1%. This suggests the analytical approach with FEA simulations can provide results almost exactly same to real life experiments[(2)]. Above study discusses the effect of air-cavity depth on muffler results and the simulations of inhomogeneous material applications, while it does not provide any insights on the diameter or shape of muffler and their effects. Studies about significance of various parameters' and their effect on Transmission Loss are going on. A review on various muffler parameter and performance is discussed in another research article[(3)]. Methodology of research mentions number of experiments using change in parameter and result findings. It also discusses application of various computer tools like FORTRAN for efficient and accurate analytical solutions in past. Nowadays highly accurate and quicker tools are available with 3D simulations. Detailed research with variation in diameter of muffler will be interesting subject to implement methodology for experimentation. For better TL, various experimental results are used to create a mathematical equation. TL depends upon the material property of muffler, geometrical dimensions, number of reflecting surfaces, pressure varying shapes, extension or application of multiple chambers, etc. Many mufflers have extended porous tube with inlet and outlet tubes inside chamber. This porous tube method has significant effect on TL compared to use of non-porous tubes. Approximately based no single or double expansion chamber porous tubes raise the TL of muffler from 25% to 30%[(4)]. A series of experiments suggest that the length of expansion chamber should be between 1.2 to 1.7 times of diameter of chamber[(5)]. Final experiment results and optimization leads to conclusion that most suitable value for length of muffler should be equal to 1.3 times diameter. Inside muffle chamber various hollow or porous tubes or reflecting surfaces or baffle plates are used to increase TL. Application of V-shape baffle plates placed internally of chamber are proved to be very effective compared to other methods[(6)]. V- shape baffle plates are around 20% more efficient than common hollow tube method used for automotive mufflers. This helps in making decision of inner chamber size, shape and dimensions. The effect of variation in diameter will be helpful in deciding the size of muffler for best suitable design with less space.

There are very limited studies focusing on extended inlet muffler. Therefore, the research focus on diameter of inlet extension will lead more detailed design methodology. Muffler is noise reducing assembly. Experimental results are measured using microphones. For theoretical understanding, using real life conditions variables are formed which are implemented in various equations to develop a mathematical model of noise reduction. The number of variables are high and with large number of elements, it becomes more complicated and time consuming to find accurate values. Computer program MATLAB provides significant support in such calculations. These results are then compared with FEA and real-life experiments.

2 Methodology

2.1 Theoretical Analysis

Transmission Loss (TL) is calculated according to the empirical formula given below for theoretical analysis of single expansion chamber reactive muffler.

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

Where,

m = Expansion ratio = cross-sectional area of expansion chamber to cross-sectional area of inlet & outlet pipe.

k = Wave number = $\frac{2\pi f}{c}$

c = Velocity of sound (in m/s)

l = Length of expansion chamber (in m)

TL = Transmission Loss; dB

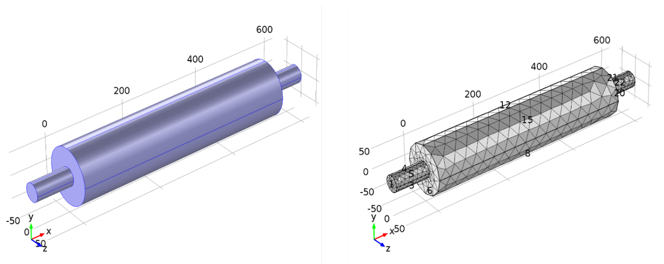
In theoretical analysis, various design parameter used for basic model of muffler are indexed below and Transmission Loss is evaluated.

a. The length of expansion chamber is kept constant i.e., L = 535 mm.

b. The diameter of expansion chamber is kept constant i.e., D = 120 mm.
c. The diameter of inlet and outlet pipe connected to expansion chamber is kept constant i.e., d = 40mm.
d. The length of inlet pipe and outlet pipe connected to expansion chamber is kept constant i.e., l_1 = 90 mm and l_2 = 90 mm
e. The length of Extended inlet = 240 mm
f. The diameter of extended inlet is varied from 10 mm to 50 mm with step size of 10 mm.
The MATLAB script is prepared, and for the purpose of analysis the frequency range is set from 1 to 1600 Hz.

2.2 Numerical Analysis

A 3D muffler model in form of CAD was drafted for simulation. The Figure 1 displays the CAD model and FE model of single expansion chamber reactive muffler using COMSOL Multiphysics. In this simulation, mean flow of the muffler is ignored. Meshing is done using "Auto" in Tetrahedral Elements [6,7].



3D CAD　　　Meshed Model

Fig 1. Model and meshed model

Well-known acoustic Helmholtz empirical equation is used to estimate sound pressure P,

$$\nabla.\left(\frac{1}{\rho_0}\nabla_p - q\right) + \frac{k^2}{\rho_0}p = 0 \tag{1}$$

Where, $k = \frac{2\pi f}{C_0}$ is the wavelength, ρ_0 is the density of the fluid and c_0 is the velocity of sound, q is the two-pole source term which means acceleration per unit volume and equals to zero in this study. With this equation, a solution on frequency domain can be found using parametric solver. The transmission loss of the muffler is calculated using following equation.

$$TL = 10\,log\left(\frac{P_{in}}{P_{out}}\right) \tag{2}$$

Where, P_{in} and P_{out} denotes power at inlet and outlet, which are calculated as,

$$p_{in} = \int_{\varphi}^{1}\frac{P_{0^2}}{2pc_0}dA \tag{3}$$

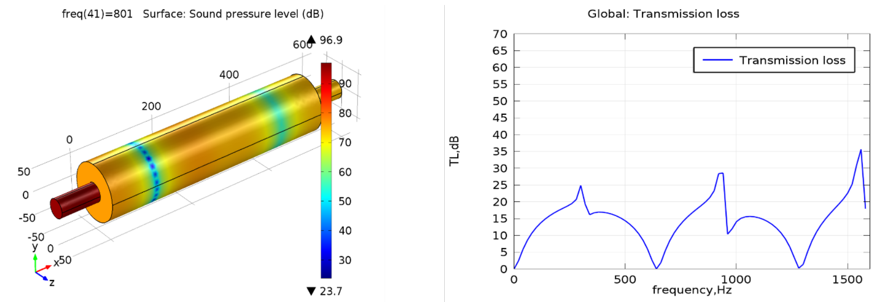
$$p_{out} = \int_{\varphi}^{1}\frac{|P_c|^2}{2pc_0}dA \tag{4}$$

The inlet pressure value P_0 is set to 1 bar.

The model uses sound hard wall boundary conditions at the solid boundaries as by following equation,

$$\left(-\frac{V_p}{P}\right).n = 0 \tag{5}$$

The numerical analysis is carried out for the frequency range of 1-1600 Hz. the results are shown in the form of graph in Figure 2
.



Acoustic Pressure distribution

Transmission Loss curve

Fig 2. Results of Numerical analysis

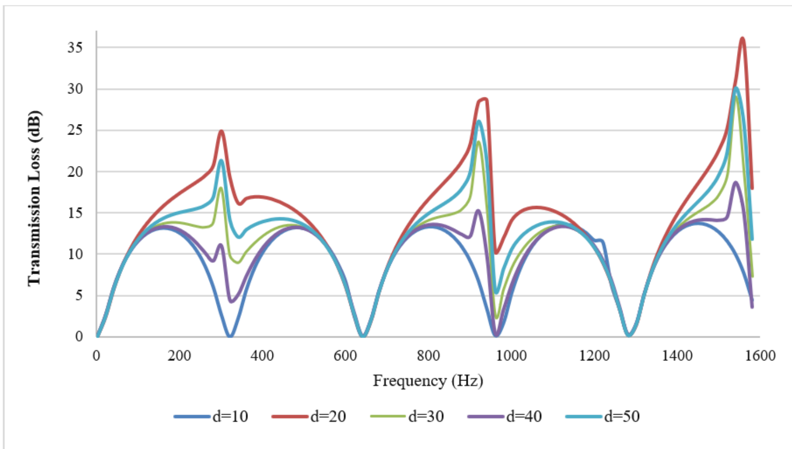


Fig 3. Comparison of Numerical transmission loss

The Figure 3 is comparison of transmission loss obtained using numerical analysis for various diameters in Frequency domain. The muffler model with Extended Inlet diameter 10 mm has troughs at 321 Hz, 641 Hz, 961 Hz and 1281 Hz, which are due to less amount of noise. The model with extended inlet diameter of 20 mm shows troughs at 641 Hz, and 1281 Hz and peaks at 301 Hz, 941 Hz and 1561 Hz. These peaks are due to occurrence of impedance mismatch at the related frequency, which in turn provides maximum attenuation. It can be observed that, the muffler models with extended inlet diameter 30 mm, 40 mm and 50 mm shows same troughs and peaks at the frequencies mentioned for muffler model with extended inlet diameter 20mm, but the peaks have relatively lower magnitude. The maximum attenuation is provided by muffler model with extended inlet diameter of 20 mm; therefore, it is the optimum model.

2.3 Experimental Analysis

Further, verification of the analytical model with outstanding acoustics performance is carried out using the Two Load approach in the experiment analysis. Figure 4 depicts the experimental set-up, there are three parts to the experimental setup: a noise creation system, a noise propagating system, and a noise measurement system. The Sound Source, Amplifier, FFT Analyzer, and Impedance Tube are the main components of the system. Microphone are placed at positions 1, 2, 3, and 4 as shown in Figure 4. The impedance tube is a rigid tube containing consistent spacing between measuring locations. This tube serves purpose of sound propagation medium. The sound source is linked to one end of the Impedance tube, while the test muffler is coupled to the other. We've linked the two impedance tubes on both sides of the muffler since we're interested in both incident and transmitted waves. The FFT analyzer is connected as the Data Acquisition (DAQ) System. This system collects pressure data from microphones and stored all in storage system. The Analyzer also has an output channel that is connected to a speaker. The random noise signal is produced by the Analyzer and transmitted to the speaker via the amplifier. Because the random noise signal or white noise signal has same power density at each frequency. To produce 120 dB of noise, a high-powered sound source is used. Since the Transfer Function Method is used, also known as Generalized Matrix Method (GMM). This method requires an understanding in complex functions, as optimization of geometrical parameters are done by changing the dimensional value.

2.4 Method of two loads

Using the transfer matrix approach, one may simply determine the transmission loss of any muffler by solving four pole equations from the four microphone positions [4,8]. Two loads in this procedure should be different to keep the observation data stable. Figure 4 depicts how the output tube with and without absorbing material is used to obtain the two loads in this study.

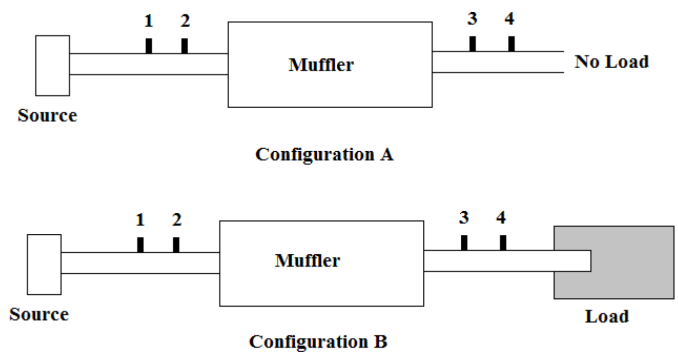


Fig 4. Configurations for TWO Load method

The acoustic output of a muffler can be analyzed through equations, based on above four microphone positions to calculate transmission loss. The four poles for elements 1-2 can be stated as

$$\begin{bmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{bmatrix} = \begin{bmatrix} \cos k\, l_{12} & j\rho c \sin k l_{12} \\ \dfrac{j \sin k\, l_{12}}{\rho c} & \cos k\, l_{12} \end{bmatrix} \tag{6}$$

The equation (7) states four poles for elements 2-3 as

$$\begin{bmatrix} A_{23} & B_{23} \\ C_{23} & D_{23} \end{bmatrix} \tag{7}$$

Where,

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

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

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

The equation (8) describes four poles for elements 3-4 as

$$\begin{bmatrix} A_{34} & B_{34} \\ C_{34} & D_{34} \end{bmatrix} = \begin{bmatrix} \cos k l_{34} & j\rho c \sin k l_{34} \\ \dfrac{j \sin k l\, l_{34}}{\rho c} & \cos k\, l_{34} \end{bmatrix} \tag{8}$$

The transfer function between P_i and P_j is stated by the term H_{ij},as

$$H_{ij} = \frac{P_j}{P_i}$$

The final Transfer matrix is stated as follows

$$\begin{pmatrix} A_{14} & B_{14} \\ C_{14} & D_{14} \end{pmatrix} = \begin{pmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{pmatrix} \begin{pmatrix} A_{23} & B_{23} \\ C_{23} & D_{23} \end{pmatrix} \begin{pmatrix} A_{34} & B_{34} \\ C_{34} & D_{34} \end{pmatrix} \tag{9}$$

The Transmission Loss is given by

$$\mathrm{TL} = 20 \times \log_{10}\left[\frac{1}{2}\left(\left|\mathrm{A}_{14} + \frac{B_{14}}{\rho c} + \rho c \mathrm{C}_{14} + \mathrm{D}_{14}\right|\right)\right] \tag{10}$$

The equation (10) is used for calculating experimental Transmission Loss.

2.5 Procedure for Experimental Analysis

Fig 5. Actual experimental set up

Figure 5 shows the actual experimental setup from Laboratory. The experiment is conducted in the spectral region of 1-2000 Hz. Locations 1-2-3-4 quantify sound pressure in the 1-400 Hz frequency range, while Locations 1'-2-3-4' quantify sound pressure in the 400 Hz to 2000 Hz frequency range. According to International Standard (10534-2), the technique for experimental analysis comprises of configuring the Analyzer and Data Processing for measuring the TL [8,9]. One microphone is set at site 3 and the others at locations 1, 2, and 4 to get transfer function H31, H32, and H34 with respectable placements.

3 Results and Discussion

Muffler is attached with 4 microphones, 2 on inlet tube while 2 on outlet tube. The various studies done in past have also followed same setup and method of experimentation to observe the results. Figure 6 is a comparison between experimental and simulation results. The experimental result of muffler has fluctuation in values as real environmental condition has a greater number of variables than the number of variables that are considered for simulation. The curve approximation shows a similarity in result between experimental and simulation. Muffler with porous tube inlet has maximum TL around 20 dB, while change in diameter improved the maximum TL significantly. Even tapering and extension of side outlet only improves the muffler TL by little percentage.

The troughs are obtained at 641 Hz and 1281 Hz - the points of local minimum. The muffler model showing uplifted troughs is considered as good model. The crests are observed at 321 Hz, 941 Hz and 1581 Hz - the crest means point of local maximum. The maximum transmission loss indicates that, minimum noise is radiated at the specified frequency. The experimental results and FEM results shows good agreement. The small difference in the experimental outcome from that of the FEM result is attributable to sound leakage from the impedance tube, FFT white noise production issues, impedance tube imprecise surface finish consistency [10–13]. Apart from extended inlet other geometrical parameters are researched very deeply and the scope in improvement is very limited for them. The diameter of inlet extension provides a good opportunity to work for more efficient design.

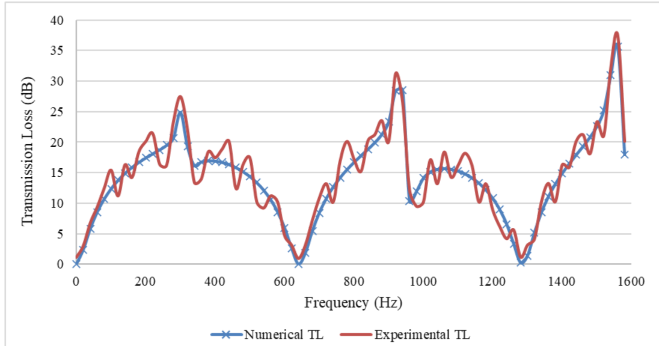


Fig 6. Comparison of Numerical and Experimental TransmissionLoss

4 Conclusion

In this research paper, acoustic analysis of extended inlet with variation in diameter in the single expansion chamber reactive muffler is analysed using different methodologies Viz Numerical analysis and Experimental analysis. The COMSOL Multiphysics is used for modelling, meshing and finite element analysis. The frequency domain is used for the analysis. In the Experimental analysis, Two Load method is used. Loads are varied without making change in position of source. It is observed that, with increase in extended inlet diameter, the average Transmission Loss increases up to 20 mm by 28%. Although, TL reduces for 30 mm and for 40 mm while increases for 50 mm. Therefore, comparatively, an effective value of 20 mm is the best suitable for this configuration. The result of Numerical analysis for optimum muffler is validated with Experimental analysis and it is perceived that, they are in good agreement with each other up to 94%. The cross verification of simulation and experimental results shows the confidence in above conclusion. Based on experiment and numerical simulation, it is proved that varying the diameter of extended inlet tube does affect Transmission Loss. Aim of the research is changing TL with varying inlet extension diameter and comparing the real-life component with FEA results. One aim highlights benefit of diameter variation on Transmission Loss and other leads positive conclusion that Computer Aided Engineering (CAE) are providing good accuracy in results.

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