Optimization of Extended Inlet length and Extended Inlet diameter of Single Expansion Chamber Reactive Muffler with Extended Inlet and Extended Outlet for maximum Transmission Loss in specific frequency range

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Abstract

Internal combustion engines are a significant noise pollution source. The engines are used in a variety of manufacturing equipment, trains, and automobiles, among other things. Both noise from exhaust and noise caused by the friction from different components contribute the most to noise pollution. Mufflers are devices that reduce noise in exhaust systems. It is installed along the exhaust pipe to help with noise reduction. The current work attempts to optimize the Extended Inlet Length and Diameter in a Reactive Muffler with a Single Expansion Chamber with Extended Inlet and Outlet for maximum transmission loss in a specific frequency range. The Taguchi Method is used for optimization. The muffler's acoustic behaviour is thoroughly examined using: (1) the use of COMSOL Multi-Physics and the finite element method; and (2) The two-load approach was employed for experimental validation.

Keywords: *Transmission Loss, Reactive muffler, Finite Element Analysis, Taguchi Method, Experimental Analysis.*

1. Introduction

The two-load approach was implemented for experimental validation. hazards, engine noise pollution becomes a major concern. The most dangerous noise is exhaust noise. Noise levels above 80 decibels are harmful to humans. Mufflers of various types are used to dampen this noise. The construction and operation of mufflers determine the level of exhaust noise reduction. As a result, the design of the muffler is critical because it affects the engine's noise characteristics and fuel efficiency. The two types of parameters that describe the exhaust silencer are many Insertion Loss (IL) as well as Transmission Loss (TL). Transmission Loss (TL) is a popular criterion for muffler performance because it is easily predicted using the muffler's known physical parameters. Analytical, numerical, and experimental methods could all be used to calculate the Transmission Loss. Analytical methods are time-consuming because the associated algebra is complex, making it difficult for analytical methods to solve such problems [1][2]. Because numerical methods are general and can be used to analyse, they are often employed for the optimisation of models with intricate forms and are less expensive than experimental methods.

M.L.Munjal's The literature contains a detailed design procedure. [3]. In general, outcomes from experiments are utilised to validate analytical and numerical approach results, as well as to assess the overall model performance and assess whether it meets the design requirements [4]. The systematic and simple method to optimise the dimensions of a reactive muffler with Single Expansion Chamber and Extended Inlet and Extended Outlet using optimization tools (the Taguchi method) to improve the muffler's performance at specific frequency ranges is not reported at a very large scale in the available literature. This paper employs the Taguchi Method to optimize the dimensions of Extended Inlet in Single Expansion Chamber (SEC) reactive muffler with Extended Inlet as well as Extended Outlet. The variation in diameter of Extended Inlet and Extended Inlet Length are chosen as control elements in the initial design stage. The L-9 orthogonal array table is modified to identify the key components that work.

2. Taguchi Method

The Taguchi Method is an effective method for creating high-performance systems. The result is a tool which allows you to efficiently and methodically optimise designs for quality, performance, and cost. When design criteria are both qualitative and discrete, the Taguchi Method is more useful. Taguchi parameter design improves performance characteristics by adjusting design parameters and decreasing system sensitivity. Taguchi advises evaluating quality attributes that differ from desired values with the signal-to-noise (S/N) ratio. The primary premise of quality measurement is to minimise product performance variability due to noise factors, while increasing variability due to signal factors. As a result, maximising the product's signal-to-noise (S/N) ratio may be the goal of quality improvement efforts. In the S/N ratio analysis, there are three different categories of quality characteristics: 1st is lower-the-better 2nd is higher-the-better and 3rd is nominal-the-better. To maximize Transmission Loss, the higher the better quality characteristic is used in this case. Depending on the S/N analysis, every level of a procedure parameter has an associated S/N ratio that is determined. Because the current work produces Transmission Loss, a higher-the-better characteristic is required [5].

3. FEM Analysis

The basic procedure for the FEM analysis starts with CAD geometry. In this study, the gearbox loss of the silencer are calculated with the help of 3-D finite element approach. The assumed Mach number is zero. COMSOL Multiphysics is used for finite element analysis, which has no fluid-structure interaction. According to the COMSOL Multiphysics User's Manual, COMSOL A.B., both parametric and linear solvers are used. (2008) [6].

The Helmholtz equation is used to calculate the 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 denoted as the wavelength and ρ_0 is denoted as the density of the fluid and c_0 is denoted as the velocity of sound. In this study, the two-pole source term, q, which stands for acceleration per volume unit, equals zero. A parameterized solver with this equation can find a solution in its frequency domain.

The muffler's Transmission Loss is calculated using the equation below;

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

Where, p_{in} and p_{out} indicates the acoustic impacts at the Inlet and Outlet, which are estimated as

$$p_{in} = \int_{\Omega}^{1} \frac{{p_0}^2}{2\rho c_0} \mathrm{dA} \tag{3}$$

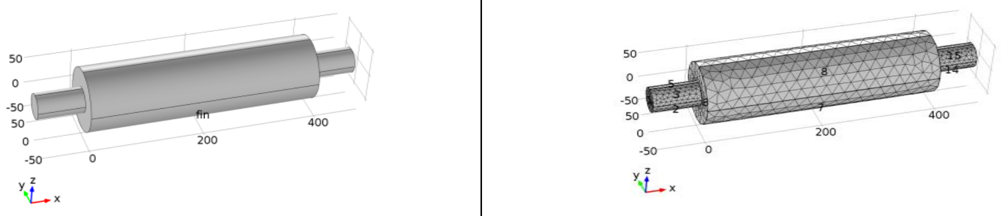
$$p_{out} = \int_{\Omega}^{1} \frac{|p_c|^2}{2\rho c_0} \mathrm{dA} \tag{4}$$

The pressure value at the Inlet, p_0 is set to 1 bar.

According to the following equation, the model uses good hard wall boundaries at solid borders.

$$\left(-\frac{\nabla_p}{\rho}\right).\mathrm{n}=0 \tag{5}$$

The model and meshed model of the SEC muffler is as shown in figure 1.

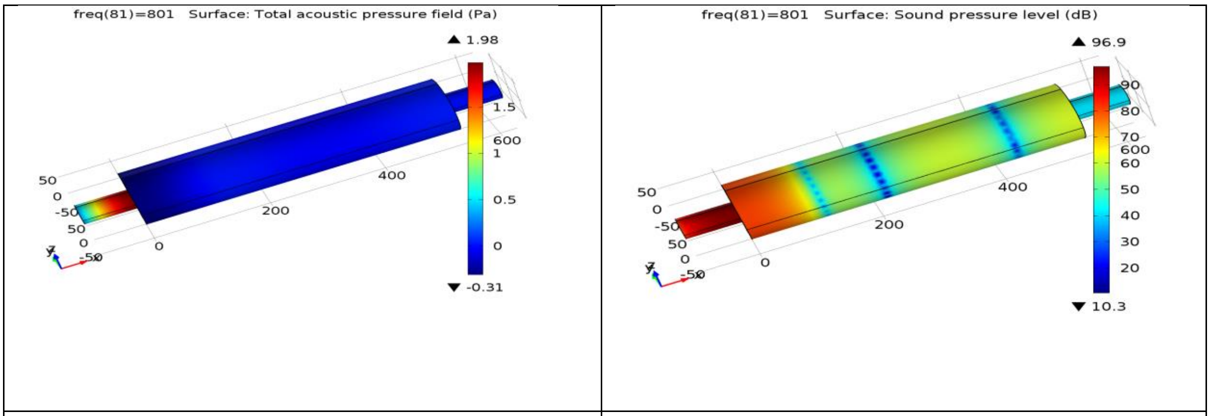


a) Model

b) Meshed Model

Figure 1 Model and meshed model of the SEC muffler

The entire frequency range of 1-1600 Hz is considered in the analysis, with a frequency spectrum of 650-850 Hz. The speed of sound is presumed to be 343 metres per second, and air has a density of 1.2 kg per cubic metre. Tetrahedral elements and automatic meshing are employed in the meshing process. A minimal resolution of 12 elements per wavelength is an element size of the finite element domain.



Acoustic Pressure

Sound Pressure Level

Figure 2 Acoustic Pressure and Sound Pressure Level for muffler

Figure 2 shows the acoustic pressure and sound pressure levels for a muffler at a specific frequency range. It can be observed that, the sound pressure level at the inlet of a muffler is about 90 dB and that at the outlet of a muffler is 45 dB. This is due to the attenuation of sound waves inside the muffler.

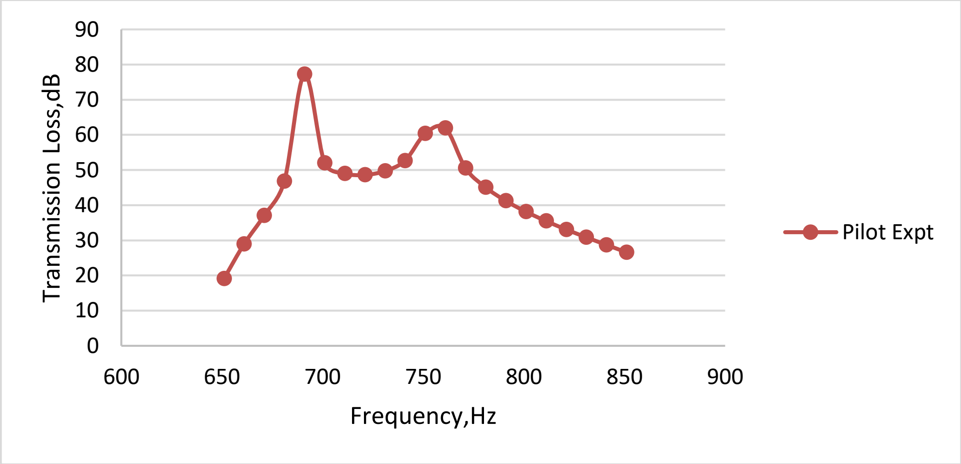


Figure 3 Transmission Loss of muffler for pilot experiment

Figure 3 depicts the Transmission Loss curve for the pilot experiment**.** Throughout the 650-850 Hz frequency range, the average Transmission Loss is around 44 dB. The study's goal is to improve the muffler's Transmission Loss in this frequency band by optimising the Extended Inlet length and Extended Inlet diameter.

4. Optimization of Muffler

A. Model

The specific frequency range of 650–850 Hz is selected for the 4-cylinder, 1500 rpm engine. Optimization is performed for this engine for the specific frequency range of 650–850 Hz. This is the requirement of the industry to determine the TL at this frequency range for the engine. Figure 4 shows the configuration of the SEC muffler model with Extended Inlet and Extended Outlet. The Inlet and Outlet pipes on the upstream and downstream sides have a diameter d1 and 44 mm respectively, while the main chamber diameter is 120mm. The corresponding lengths of The outlet and inlet pipes are maintained at 95 mm. The length of the chamber of a muffler is 540 mm. Two factors are chosen for optimization at the start of the design experimentation process. Figure 4 depicts the Extended Inlet length L1 and Extended Inlet Diameter d1.

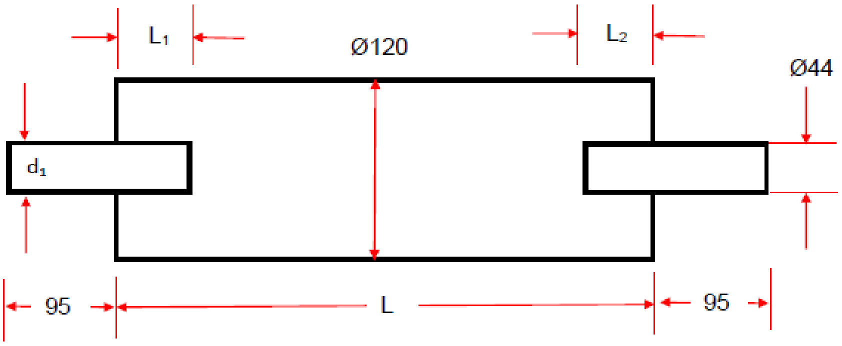


Figure 4 Configuration of the muffler model with Extended Inlet and Outlet

B. Selection of Control parameters and levels

This method started with a pilot experiment. The muffler parameters are chosen based on a review of the literature and by evaluating parameters' effects on transmission loss. The literature review serves as the foundation for determining the levels of factors. To determine the standard as well as reference value at treatment condition 1, each factor is examined at level 1. The treatment condition that follows includes running factor L1 at level 2 while retaining the other factors at level 1. As a factor in the third treatment circumstance, d1 is examined at level 2, whilst the other elements remain at level 1. This procedure is repeated until all of the factors at level 1 have been run. L1 and d1 are the Extended Inlet length and diameter respectively, for the Single Expansion Chamber muffler. L1 and d1 are control parameters in this model. As an initial guess, L1 is set to 270 mm, and d1 is set to 44 mm in the pilot experiment. L1 was adjusted from 0 to 270 mm in 10 mm increments. The Extended Outlet Length L2 is kept at 105mm and Extended Outlet diameter is kept at 44 mm. Models were built and tested in COMSOL using these dimensions. The greatest transmission loss was observed at L1 = 110 mm. Keeping L1 at 110 mm, d1 is varied from 29 to 64 mm in 5 mm steps. At d1 = 59 mm, the maximum TL occurs. Finally, the pilot experiment yielded the dimensions L1 = 110 mm, d1 = 59 mm [7].

From the pilot experiment, final levels of control parameters were decided to refer to Table 1.

Table 1 Control parameters and their levels for SEC muffler model

Regulatory Parameters	Level 1	Level 2	Level 3
Extended Inlet Length,L1	105	110	115
Extended Inlet diameter,d1	54	59	64

Table 2 L9 Orthogonal Array

Treatment Condition	Extended Inlet Length,L1	Extended Inlet Diameter,d1	Response
1	105	54	90.214
2	105	59	99.583
3	105	64	89.92
4	110	54	66.748
5	110	59	65.264
6	110	64	63.831
7	115	54	60.569
8	115	59	59.26
9	115	64	57.864

L1 and d1 are the factors.

Taguchi established a family of fractional factorial experiments (FFE) matrices, which can be employed in various situations. In this situation, a possible matrix is the 9 Trial Orthogonal Array (OA), which is labelled as the L9 matrix. The true power of using an OA is its ability to assess multiple factors in minimal tests. Table 2 mentions the L9 Orthogonal Array. In the designation L9, the number 9 signifies the degree of freedom, the total number of conditions for treatment (TC), and the number of rows. The maximum number of factors that can be used is shown at the top of the orthogonal array, which in our case is two. The levels are denoted by the numbers 1 and 2. If the array has more levels, the numbers 3, 4, 5, and so on are utilized. Other schemes, such as -, 0-, and +, are available. Using these control parameters, the L9 orthogonal array is prepared using Minitab software and tabulated as shown in Table 3.

Table 3 L9 Table of Taguchi for Frequency Range (1-1600Hz)

Treatment Condition	Extended Inlet Length,L1	Extended Inlet Diameter,d1	Response TL in dB	Square of TL
1	105	54	90.214	8138.566
2	105	59	99.583	9916.774
3	105	64	89.92	8085.606
4	110	54	66.748	4455.296
5	110	59	65.264	4259.39
6	110	64	63.831	4074.397
7	115	54	60.569	3668.604
8	115	59	59.26	3511.748
9	115	64	57.864	3348.242
			Total =653.253	49458.62

Using this table the effect of individual parameter on Transmission Loss can be analysed.

C. Result and discussion

The Taguchi analysis is carried out using Minitab software. Figure 5 depicts the Main Effects plot, which shows the effect of individual muffler parameters on TL from L9 as calculated from Table 2. As L1 increases, the mean of the means value decreases; as d1 increases, the mean of the mean value first increases to its maximum and then decreases.

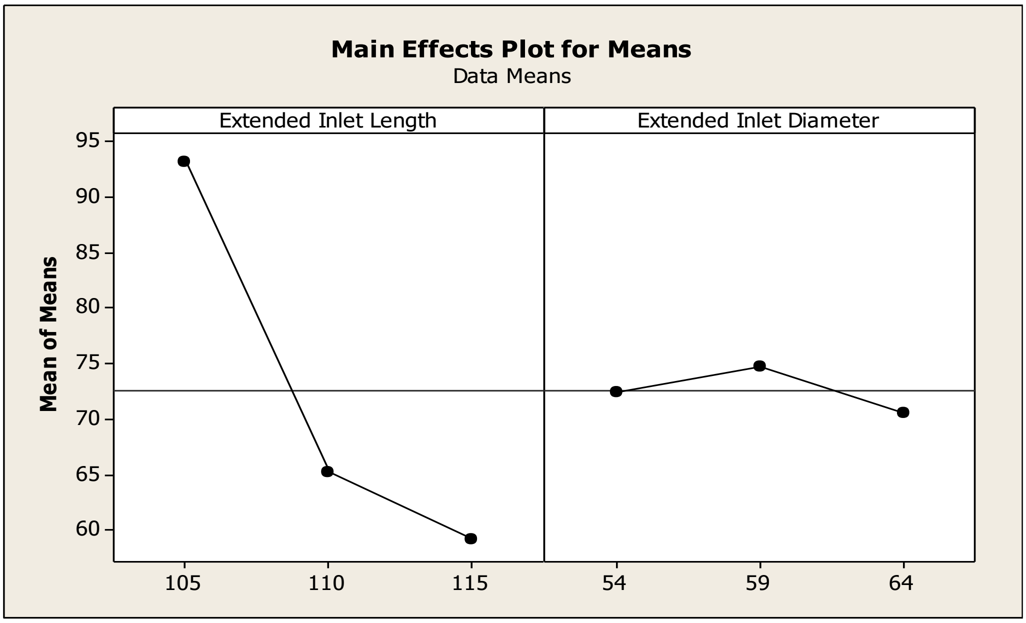


Figure 5 Main Effect plot for Means for frequency ranges

D. Taguchi Analysis

For single-objective response optimization, Taguchi analysis of the SN ratio is used. Using the Taguchi method to quantify quality parameters that deviate from what is desired instead of the SN ratio. Applying the experimental results of various responses, a signal to noise (or S/N) ratios is computed. The characteristics of 'higher the better' are applied to the reactions that should be maximised. For responses that are to be minimised, the 'lower the better' character is employed. The following are the different types of Signal to Noise (S/N) ratios:

For the 'Higher the better' strategy, the SN ratio is determined as

$\eta = -10 \log [(1/n) * \Sigma (1/yi^2)]$

The "Lower the better" strategy's SN ratio is calculated as

$\eta = -10 \log [(1/n) * \Sigma (yi^2)]$

The "nominal-the-better" strategy's SN ratio is calculated as

$\eta = 10 \log ((y^2)/ \sigma^2)$

Where, n is the number of observations, y is the appropriate response, and η is the resultant SN ratio.

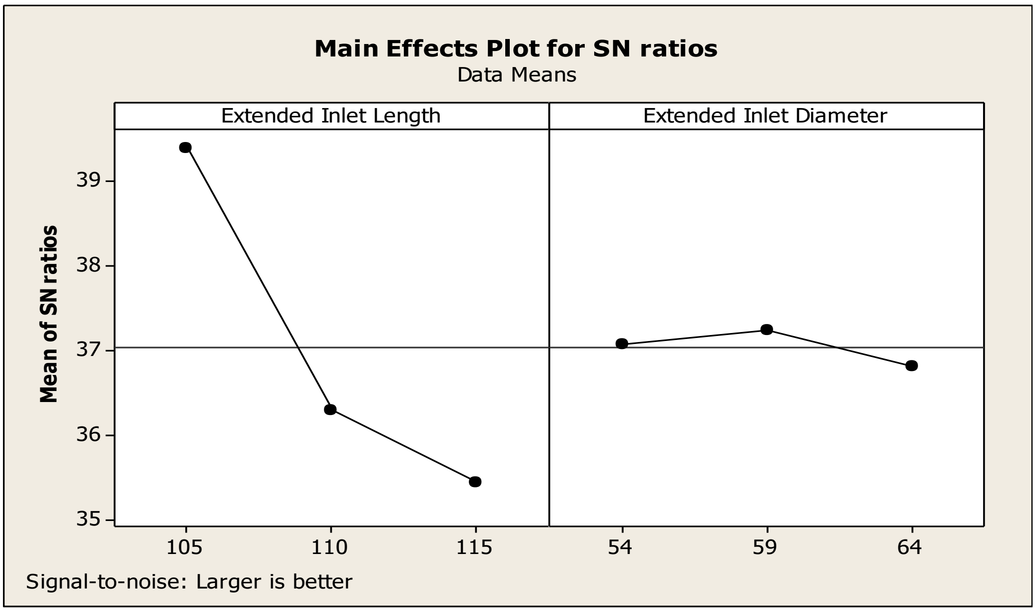


Figure 6 Main Effect plot for SN ratios for frequency ranges.

From the S/N ratio plot (refer Figure 6) by using MINITAB software, it can be concluded that L1 and d1 are major parameters that affect the performance of a muffler. For the current work, the "Larger is better" condition is adopted. This is the reason that the best Transmission Loss is one with higher value and which provides a lower sound level. Therefore (the S/N) ratio of this Transmission Loss is required to be maximum.

From Figure 6, it can be observed that, the SN ratio is maximum for L1=105 mm, for d1=59 mm. Thus, it is clear that, the optimal values of the Extended Inlet length (L1) is 105 mm and Extended Inlet diameter of the muffler (d1) is 59 mm.

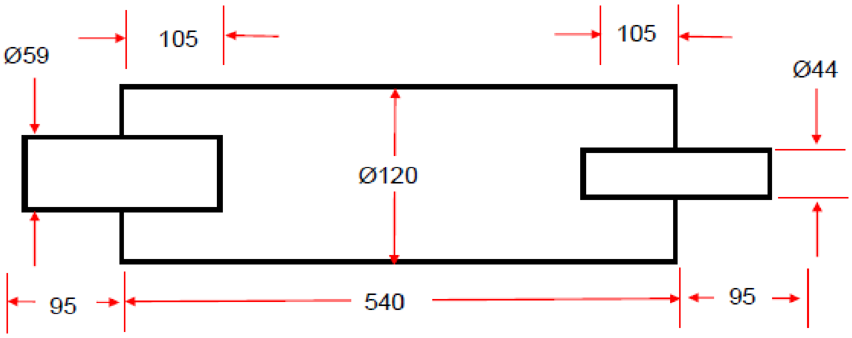


Figure 7 Optimum Configuration of Muffler

The optimum configuration for the muffler is as shown in figure 7.The Extended Inlet Length is 105 mm and Extended Inlet diameter is 59 mm.

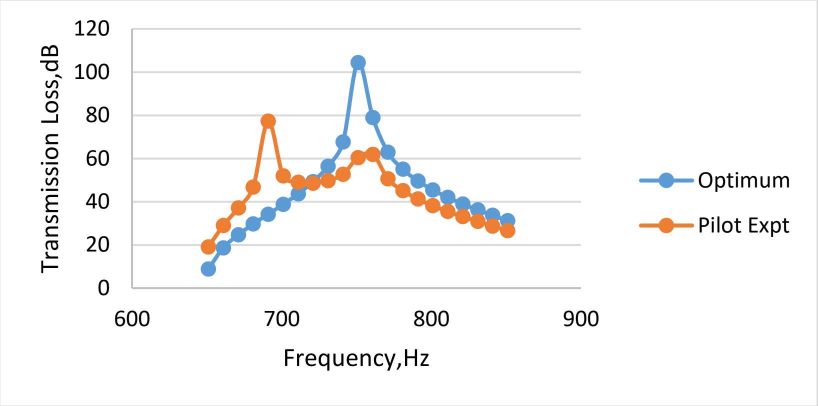
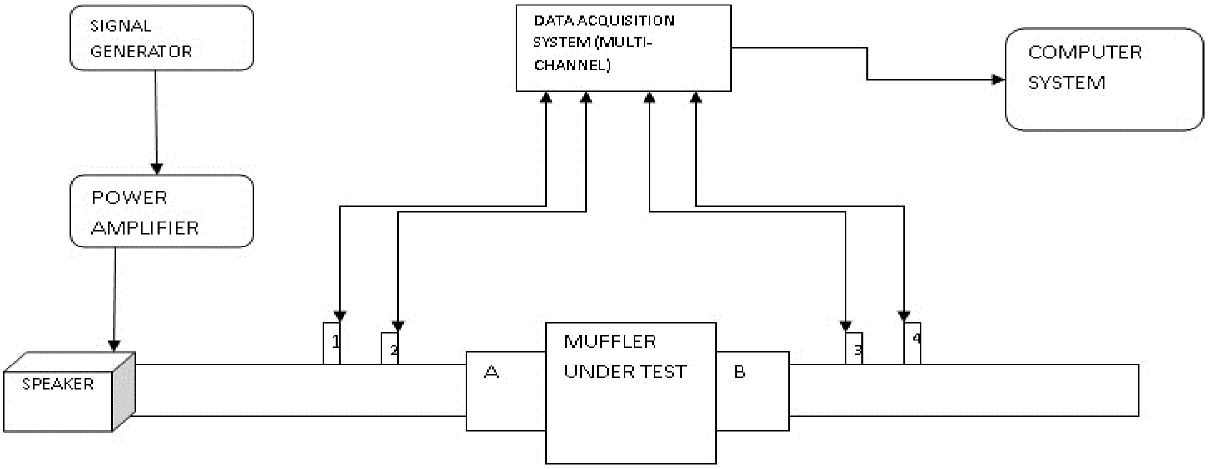


Figure 8 Transmission Loss for SEC Muffler Model for specific frequency range (650 Hz to 850 Hz)

Figure 8 shows results for the SEC Muffler Model for a specific frequency range (650 Hz to 850 Hz). It is observed that the Transmission Loss (TL) curve for the pilot experiment shows troughs at 651 Hz, 721 Hz, and 851 Hz, while crests occur at 691 Hz and 761 Hz. The impedance mismatch occurs at 651 Hz, 721 Hz, and 851 Hz, due to which sound waves travelling in the opposite direction cancel each other out, leaving a very minor sound. This indicates that the sound wave entering the muffler at this frequency is completely attenuated. The highest TL for the said geometry of the SEC muffler model is 77.21 dB at 691 Hz. The average TL of the muffler model is 43.4 dB. The optimum Transmission Loss curve shows broadband Transmission Loss for the specific frequency range. The maximum Transmission Loss found to be 104.46 dB at 751 Hz, and the average TL of the muffler model is 45.23 dB.

5. Experimental Analysis

The optimised model is verified in the experiment analysis using the Two Load method.
Figure 9 depicts the experimental setup.



1, 2, 3, 4- Microphones,
A, B-Diffuser

Figure 9 Set up for Experimental Analysis

The three systems that make up the experimental setup are noise creation, sound transmission, and noise measurement.

The sound source, amplifier, FFT analyzer, and impedance tube are the main components of the setup. The microphone positions are denoted by numbers 1, 2, 3, and 4 in the diagram. The stiff impedance tube has evenly spaced measurement points. The sound is transmitted by this tube. The other end of this impedance tubes is connected to the test muffler, and a sound source has been attached to the other. Because we're interested in both incident and transmitted waves, we've connected a muffler with two impedance tubing on either side. The FFT analyser is utilised as a data acquisition system. Pressure data from microphones is collected by this system and sent to a data storage system for recording. It also has an analyzer-connected output channel that is connected to the speaker. The speaker receives the random noise signal from the analyser via the amplifier. Since each frequency has an equal power density of noise, the random noise signal (white noise signal) is used. 120 dB of sound is produced by a strong sound source. Because the Transfer function technique is used, two microphones are used.

5.1 Theory of Two Load Method

For the experimental analysis of mufflers, Z. Tao and Mr. A. F. Seybert (2003) used the Two load method [8]. The Two-Load Approach employs the Transfer Matrix Approach. By resolving four-pole equations starting from the four microphone positions, one can quickly determine the Transmission Loss of any muffler using the transfer matrix method. The two loads used in this method should be distinct in order to maintain stable results. With without absorbing material, the Outlet tube is used in this study to achieve the two loads, as shown in Figure 10.

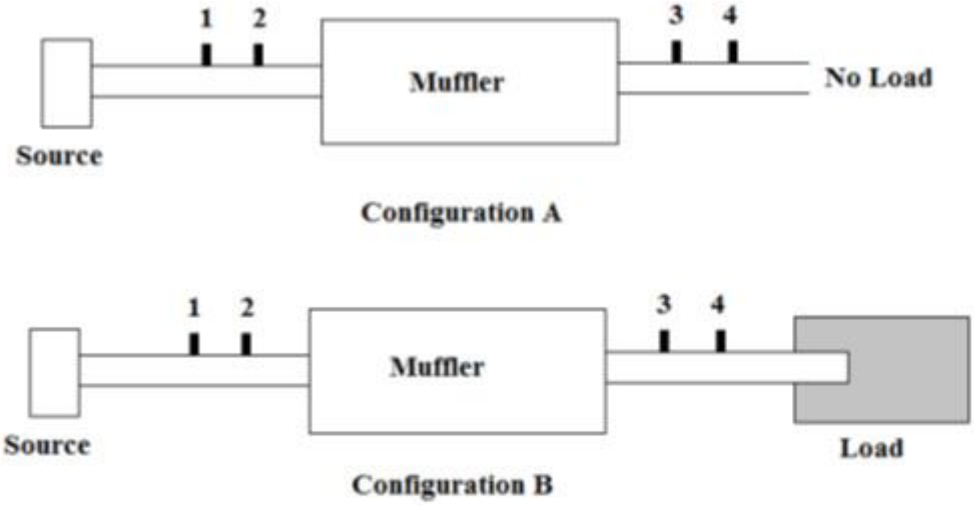


Figure 10 Configurations for TWO Load method

The Transmission Loss of a Muffler can be calculated using the Transfer Matrix Approach by solving using four microphone positions to solve four pole equations [9][10]. In the absence of air flow, the four poles for elements 1-2 can be expressed as

$$\begin{bmatrix} A_{12} & B_{12} \\ C_{12} & D_{12} \end{bmatrix} = \begin{bmatrix} cos kl_{12} & j\rho c sin kl_{12} \\ \frac{j sin kl_{12}}{\rho c} & cos kl_{12} \end{bmatrix} \quad (6)$$

The following are four poles of elements 2-3

$$\begin{bmatrix} A_{23} & B_{23} \\ C_{23} & D_{23} \end{bmatrix} \quad (7)$$

Where,

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

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

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

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

$$\begin{bmatrix} A_{34} & B_{34} \\ C_{34} & D_{34} \end{bmatrix} = \begin{bmatrix} cos kl_{34} & j\rho c sin kl_{34} \\ \frac{j sin kl_{34}}{\rho c} & cos kl_{34} \end{bmatrix} \quad (8)$$

The term H_{ij} represents transfer function between P_i and P_j ,where

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

A final Transfer matrix appears as followed after cascading these matrices.

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

The Transmission Loss is calculated as

$$TL = 20\log_{10}\left[\frac{1}{2}\left(\left|A_{14} + \frac{B_{14}}{\rho c} + \rho c C_{14} + D_{14}\right|\right)\right] \quad (10)$$

Transmission Loss can be determined experimentally with two microphones and the random excitation technique.

6. Procedure for Experimental Analysis

The process for conducting experiments, according to the International Standard (10534-2), includes configuring the analyzer and processing data to measure the TL. [11]. One to two thousand hertz (Hz) of frequency was used for the experiment. Location 1-2-3-4 measure the pressure of sound between 1 and 400 Hz, whereas Locations 1'-2-3-4 measure it between 400

Hz-2000Hz.

Figure 11 Experimental set up

To obtain transfer functions H31, H32, as well as H34 with their respective locations, at position 3, a microphone is positioned and the others at locations 1, 2, and 4. Figure 11 depicts the setup for calculating Transmission Loss.

7. Results and Discussion

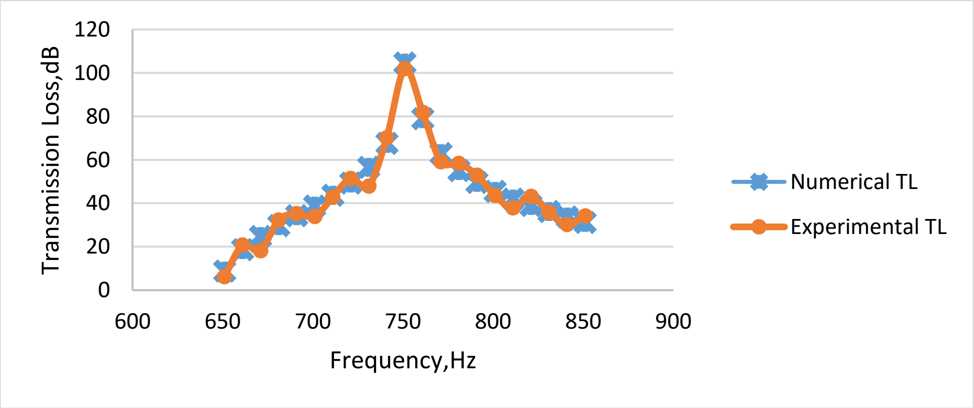


Figure 12 Comparison of TL for numerical and experimental analysis

Figure 12 compares the Transmission Loss obtained using Finite Element Analysis to the Transmission Loss discovered through experimentation in the targeted frequency band. The Experimental Transmission Loss (TL) curve is seen to have small troughs at 671 Hz, 701 Hz, 731 Hz, 811 Hz, and 841 Hz, as well as crests at 661 Hz, 721 Hz, 751 Hz, and 821 Hz. The peaks show the maximum Transmission Loss at relative frequency. These peaks are obtained due to an impedance mismatch, which causes destructive interference. The impedance mismatch occurs at 661 Hz, 721 Hz and 751 Hz and 821 Hz, due to which sound waves travelling in the opposite direction cancel each other out, leaving a very minor sound. This indicates that the sound wave entering the muffler at this frequency is completely attenuated.

The highest TL for the said geometry of the DEC muffler model is 101.89 dB at 750 Hz. The average TL of the muffler model is 44.64 dB for Experimental analysis and 45.23 dB for Numerical analysis.

The experimental and FEM results are in good agreement. The impedance tube's imprecise surface finish quality, difficulty in producing white noise from FFT, and sound leakage into the environment around it may be to blame for the little discrepancy between the experimental and FEM results.

8. Conclusion

In this study, the maximum Transmission Loss of a single expansion chamber reactive muffler was determined. The Extended Inlet length and diameter are optimised using the Taguchi method. FEM analysis was carried out using Comsol Multiphysics, and The Two Load Method was used to conduct experimental analyses. The results of the two analyses are compared, and they agree well. The ideal muffler dimensions are determined by the S/N ratio analysis using the "larger-the-better" characteristic for maximum Transmission Loss at the design frequency. According to Taguchi optimization, Extended Inlet length of 105 mm and Extended Inlet diameter of 59 mm imparts maximum Transmission Loss at specific frequency range in consideration. It is observed that, Extended Inlet length and diameter dimensions are crucial for increasing Transmission Loss at the specific frequency ranges. The Taguchi method of optimization is concluded to be an effective tool for optimising the Chamber with Single Expansion Reactive muffler with Extended Inlet as well as Extended Outlet for maximum Transmission Loss in a specific frequency range.

Statements and Declarations

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Competing interests

There are no declared competing interests of the author that are pertinent to the subject matter of this work.

Data Availability Statement

The authors attest that the publication [and/or] its supplemental materials have the data necessary to support the findings of this investigation.

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