Numerical Analysis on Improving Transmission Loss of Reactive Muffler using Various Sound Absorptive Materials

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Abstract:
Finite element analysis approach is used to determine the transmission loss for an optimized geometry of reactive multi-chamber muffler. The pressure acoustics theory is involved in the present problem and it examines the wave nature of sound and also the intensity with which it propagates. COMSOL Multiphysics software was used for modelling and analysis. The acoustics module with parallel study in frequency domain was utilized to study the flow and acoustic behaviour of the reactive muffler. Various absorptive liner materials were considered for the muffler and the transmission losses were compared. In addition to the above, the thickness of liner and inlet pressure were varied in order to have profound work for discussion. The validation of predicted transmission loss is in good agreement with the referred experimental data. The result for different types of absorptive liner materials was tracked in comparison with the muffler without liner. The average transmission loss was found to be increased by 8% with the introduction of absorptive liner with 10mm thickness. Finally, the calculated sound pressure level with total acoustic pressure field and streamlines intensity provide insight of the physics involved.

Keywords: Reactive Muffler, Transmission Loss, Numerical, and Absorptive Materials

1. Introduction:
Sound is playing a major role in an automobile especially when we consider it at the exhaust end and muffler is widely used to treat this sound by damping it. At sufficiently high level it grows into noise becoming unacceptable by human ear and may hit threshold of pain. In this technology driven world efforts are being made to keep this vehicular exhaust noise in the confined limit [1, 2]. Moreover, various optimization techniques [1, 3] are used to further condition this noise by maximizing the average transmission loss. Colin Hansen [4] described about the fundamentals of acoustics and explained the physics dealt with propagation of sound. It also discusses one of such technique by introducing absorptive material liner which captivates the noise considerably.

Muffler [5-7] is an acoustic soundproofing device basically acting as an expansion chamber to lower the loudness of sound pressure created by an internal combustion engine. Muffler is engineered to suppress the high intensity acoustic pulse and adequately attenuates the noise. Muffler design [8-10] is about calculating the proper volume for expansion and constructing series
of passages, chambers in such a fashion that enables the sound wave to interfere destructively thus cancelling out waves at higher frequencies.

Reactive mufflers [10-12 & 6] are one which reflects the sound waves to cause interference and are tuned harmonically. One of the parameter in determining muffler performance is transmission loss [11] which is defined as the difference of sound in decibels at entry and exit end of muffler. Similarly, attenuation is measured through transmission loss which gives the damping in dB as a function of frequency. Absorptive material reduced the acoustic energy of a sound wave as the wave propagates through closed volume by reducing the amplitude of the reflected waves. They are used as an interior lining and find application in aircraft, automotive, ducts, closed chambers etc.

To investigate the past work, a brief review of previously published literatures is presented. Daniela Siano and Fabio Bozza [3] has experimented on performances of a commercial three chamber muffler and simulated it with a three-dimensional boundary element method and also with a one-dimensional approach. When it comes to the scope of CAE tools, Shitalkumar and Gangadhar [13] worked on balancing the conflict between noise and back pressure. Middelberg and Barber [14] used CFD as a platform to test the acoustic performance of expansion chamber mufflers and the results were closely followed with experimental data. Xiang and Zuo [10] developed a two dimensional (axial direction and radial direction) analytical approach to calculate the transmission loss value. Based on the literature review, it can be concluded that only a handful of research articles are available on reactive mufflers. The effect of lining material with its thickness on increasing the transmission loss has not been studied in the past. Hence, a detailed study on multi-chamber reactive muffler with various linings is proposed for the present study.

The objective of this paper is to increase the transmission loss by studying the effect of various absorptive liner materials on muffler. For achieving this goal an optimized design of multi chambered reactive muffler with two baffles is taken as an input model for the study. Model used by Xiang and Zuo [10] is used as a reference to validate as well as to compare the results of absorptive liners in the present study. Initially, the geometry is validated for transmission loss at various frequencies using COMSOL [15] Multiphysics software emphasizing on pressure acoustics module. Absorptive muffler liners as used in others work [16, 17 &12] such as glass wool, polyurethane foam (PU foam) and rock wool were incorporated in the present simulations. These materials possess unique physical properties like apparent density, flow resistivity, mean fibre diameter etc. Consequently, to enhance the study the thickness of liner material was varied and also the effect of increased inlet pressure was examined.

2. Model building and experimental validation:

A multi-chamber reactive muffler shown in Figure 1 is taken for validation for the course of this study. Design of muffler is a complex phenomenon and moreover it may involve trial and error method to find the best suitable design considering the problem statement [9].
Following Table 1 shows the optimized variables of a reactive multi chamber muffler as discussed by Longyang Xiang [5].

| Variable | Optimized value (mm) |
|----------|----------------------|
| r1       | 25.4                 |
| r2       | 67.3                 |
| r3       | 20.2                 |
| r4       | 28.7                 |
| lb       | 136.5                |
| ld       | 47.2                 |
| lf       | 56.2                 |

This optimized design claimed the increase in transmission loss by around 136 %. To validate the results similar geometry was built using COMSOL designer.

3. **Muffler geometry and mesh:**

The geometry has a single inlet and outlet with same radii at openings. The muffler is chambered and separated with two baffles of different radii. These chambers vary in length and thus is an optimized geometry obtained series of iterations performed for different lengths and radius [5]. The modelled geometry for optimized variables is shown in Figure 2.
Figure 2: Muffler geometry

The transparent view of the geometry as shown in Figure 3 give clear vision on position of baffle plates and separated chamber.

Figure 3: Transparent view of muffler geometry

The meshing was done in the form of free tetrahedral with finer mesh. Complete mesh consists of 145102 domain elements, 20668 boundary elements, and 1032 edge elements as observed in figure 4.
Figure 4: Meshed geometry of reactive muffler

4. Pressure acoustics study and numerical analysis:

The Pressure Acoustics, Frequency Domain interface is used to compute the pressure variation for propagation of acoustic waves in fluids at quiescent background conditions. It is suited for all frequency-domain simulations with harmonic variations of the pressure field. The physics interface solves the Helmholtz equation in the frequency domain for given frequencies. Boundary conditions include sources, non-reflecting radiation conditions, impedance conditions, periodic conditions. The model Equation 1 is a slightly modified version of the Helmholtz equation for the acoustic pressure [6, 10].

\[ \nabla \cdot \left( \frac{\nabla p}{\rho} \right) - \frac{\omega^2 p}{c^2 \rho} = 0 \]  

(1)

where \( p \) is pressure, \( \rho \) is the density, \( c \) is the speed of sound, and \( \omega \) is the angular frequency.

Transmission (TL) = \( \log_{10} \left( \frac{P_{in}}{P_{out}} \right) \)  

(2)

Where, \( P_{in} \) is inlet pressure and \( P_{out} \) is outlet pressure

The plot of transmission loss Vs frequency of referred experiment in comparison with our calculated result in COMSOL is plotted in Figure 5 [11]. The inlet conditions are standard atmospheric conditions of 1 bar pressure and 250 C. It shows how the optimized geometry has more transmission loss over original geometry.
Similarly, optimized geometry modelled in COMSOL showed comparable results at frequencies with highest transmission loss value and as well followed the pattern of graph as shown in Figure 5. The graph is plotted for frequency range between 1000Hz to 3500Hz with step size of 50. The comparison of numerical data with experimental data shows better agreement for the peaks and an overall fair agreement. Assumption of data like inlet pressure conditions, step size of frequency etc. contribute for the minor change in pattern of graph as these conditions weren’t mentioned in the reference literature. The following results were also obtained from acoustical analysis.

**Figure 5:** TL Vs Frequency comparison between referred result and calculated result.

**Figure 6:** Total Acoustic pressure field
The total acoustic pressure field, sound pressure level and streamlines with intensity are shown in Figures 6, 7 and 8 respectively. The reduction in noise due to the optimized model is shown using the lower values of acoustic pressure field and sound pressure level in the muffler exit. Streamlines show a complex flow path inside the reactive muffler.

5. Results and discussion:

Numerical simulations have been performed with three absorptive muffler liner materials such as glass wool, polyurethane foam (PU foam) and rock wool and with different thicknesses of liner material in order to understand the effect of these variants and reduce the transmission
5.1. Effect of different absorptive liner material on transmission loss:

Absorptive materials are used to impart acoustic damping which increases the average transmission loss (TL). The most important parameter which determines sound-absorptive and sound-transmitting properties of acoustic materials is the flow resistivity ($R_f$). This flow resistivity depends on mean fibre diameter, density of material and apparent density of material as mentioned in Equation 3. In this paper three different absorptive material are taken into consideration and its influence is studied. These materials are affixed in the form of liner to the muffler keeping the geometry unchanged with the thickness liner as 10 mm. The $R_f$ value can be determine by following formula

$$R_f = \frac{3.18 \times 10^{-9} \rho_{ap} 1.53}{d^2}$$

(3)

Where, $R_f$ is the flow resistivity in kg/m³·s, $\rho_{ap}$ is the apparent density of material in kg/m³ and $d$ is mean fibre diameter in m

Poro-acoustics study is dedicated to deal with absorbing material behavior and damping enters the Eq.1 as a complex speed of sound, $c_c = \omega/k_c$, and a complex density, $\rho_c = k_c Z_c/\omega$, where $k_c$ is the complex wave number and $Z_c$ equals the complex impedance. The modified geometry of muffler with attached liner is shown in Figure 9.

**Figure 9:** Geometry with 10mm thick liner
5.1.1. Case 1: Glass wool liner:

Considering the glass wool material for this case with $d$ as 10μm and $\rho_{ap}$ as 12 kg/m$^3$. The flow resistivity comes out to be 1424.2 kg/(m$^3$·s). The plot for transmission loss Vs frequency is shown in Figure 10 which compares the muffler with and without glass wool absorptive liner.

![Figure 10: TL comparison for Glass wool liner](image)

5.1.2. Case 2: PU Foam liner:

The flow resistivity of this material is 10001 kg/m$^3$·s which is much higher than that of glass wool. The values of $d$ and $\rho_{ap}$ is 6μm and 22 kg/m$^3$ respectively. The graph is plotted for PU foam material and the variation is compared in Figure 11.
5.1.3. Case 3: Rockwool liner:

Rockwool material is highly dense with flow resistivity of 21156 kg/(m³·s). Figure 12 shows the plot for rockwool liner material.

Fig. 11. TL comparison for PU Foam liner

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Figure 12: TL comparison for Rockwool liner
5.2. Effect of variation in liner thickness:

Liner thickness is another important parameter as it is necessary to evaluate the amount of material required and as to what extent it should be used. Higher wavelength sound can be absorbed with thicker material as mentioned by Hoda S. Seddeq [8]. We have considered two different liner thickness 5mm and 15mm with respect to original 10mm of liner thickness for PU foam material and studied its influence. Following obtained result is plotted below in Figure 13.

![Image of TL comparison for change in liner thickness](image)

**Figure 13:** TL comparison for change in liner thickness

5.3. Effect of inlet pressure:

As we know the exhaust gases in engine are released at pressure more than the atmospheric pressure condition and hence it becomes necessary to find the muffler performance at this varied pressure. For this study, basic geometry without any liner material is considered whereas inlet pressure condition are increased to 1.3 bar and 1.6 bar. Intensity magnitude is the power of sound wave per unit area. The following plot of intensity magnitude is obtained shown in Figure 14 and Figure 15. It is observed that power is incoming sound wave increases with increase in inlet pressure.
Figure 14: Intensity magnitude for 1.3 bar inlet pressure

Figure 15: Intensity magnitude for 1.6 bar inlet pressure

6. Conclusion:

Transmission loss is an important performance parameter signifying extent to which incoming sound pressure is treated. To manage this acoustic quieting this paper has successfully executed sound absorptive liner analysis on reactive muffler. The optimized geometry of muffler was comfortably validated in COMSOL Multiphysics software. This paper presents finite element analysis approach with an integrated study of pressure acoustics and poro-acoustics.

It enabled to understand acoustical behavior of reactive multi chamber muffler under application of sound absorptive material liner. Sound absorptive material has good damping properties which changes with change in material as a function of flow resistivity $R_f$. [8]. The transmission loss (TL) behavior is studied considering the effect of different absorptive liner material which yield an increment in transmission loss by 7.91% for a frequency range from 1000Hz to 3500Hz. Further, the influence of change in thickness of liner material and inlet pressure was analyzed. It was observed that the sound power is very sensitive to increase in pressure. This optimization
technique is reliable and can be applied to various fields of automotive application for increasing the transmission loss and reducing the noise effectively.

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