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An Overview of Acoustic Investigation of a Dual Expansion Chamber Reactive Muffler

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Abstract: ***Noise pollution is a significant environmental issue, particularly with diesel engines, which generate considerable noise due to their high compression ratios. In India, the Central Pollution Control Board (CPCB) has set permissible noise limits of 75 dB for four - wheelers and 80 dB for two - wheelers. To adhere to these standards, reducing noise levels is crucial. One effective method is the use of mufflers, which are designed to attenuate the sound produced by exhaust gases. The efficiency of a muffler in reducing noise depends on its design and operational characteristics. Additionally, mufflers can influence factors such as fuel efficiency and vehicle emissions, necessitating a thorough evaluation of their design before production and implementation. Various parameters, including perforations, back pressure, insertion loss, and transmission loss, play a vital role in determining muffler performance. This review focuses on identifying a muffler design that can effectively minimize noise levels while also reducing back pressure to prevent any adverse effects on engine performance. Special emphasis is placed on the acoustic analysis of a twin expansion chamber reactive muffler, considering different parameters to optimize transmission loss.***

Keywords: Dual Expansion Chamber Reactive Muffler, Backpressure, Numerical Analysis, Experimental Analysis, Transmission Loss

1. Introduction

Internal combustion engines produce sound pulses during combustion, which can be mitigated using either reactive or absorptive mufflers. Reactive mufflers work by creating impedance mismatches to reflect sound waves, while absorptive mufflers rely on materials that absorb sound energy. The performance of an exhaust muffler is commonly evaluated using parameters such as Transmission Loss (TL) and Insertion Loss (IL), with TL being a critical factor in characterizing the muffler's sound attenuation properties. Prolonged exposure to noise levels above 80 dB can lead to significant health risks, highlighting the importance of designing mufflers that effectively reduce noise while maintaining engine performance, fuel efficiency, and low emissions. Figure 1 shows dual expansion chamber reactive muffler [1], [2], [3].

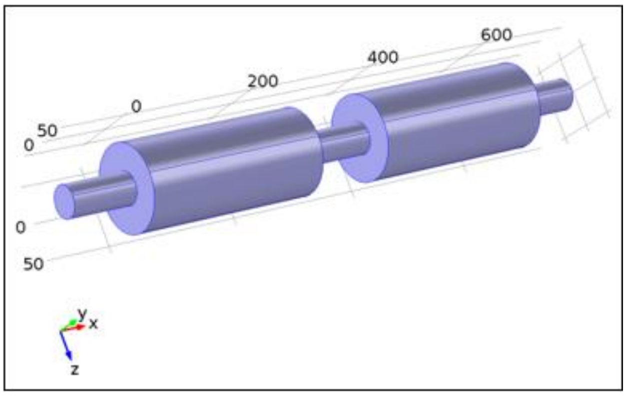

Figure 1: Dual Expansion Chamber Reactive Muffler

1.1 Types of Mufflers

Absorptive Mufflers: Utilizing absorption mechanisms, these mufflers reduce sound energy. Characterized by simpler designs and relatively lower back pressure, they excel in attenuating noise at higher frequencies but may exhibit limitations in reducing noise generated by exhaust gases at specific frequencies.

Reactive Mufflers: Comprising resonating and expansion chambers, reactive mufflers are engineered to decrease sound pressure levels at targeted frequencies, operating on the principle of impedance mismatch. Their construction aims to achieve optimal noise reduction.

Combination Muffler: A combination muffler integrates both reactive and absorptive elements to effectively reduce noise. This hybrid design leverages the strengths of both principles, combining sound absorption and reflection to optimize performance. Typically, a combination muffler consists of components such as chambers, baffles, and sound - absorbing materials, strategically arranged to enhance their noise - dampening capabilities. These mufflers are widely used in various applications, including automotive exhaust systems, motorcycles, generators, and industrial equipment, where comprehensive and efficient noise control is required. By blending the benefits of reactive and absorptive designs, combination mufflers provide a versatile solution for reducing exhaust noise.

2. Literature Review

In their study, Dr. Ravindra Ingle, J. M. Jadhav, V. S. Manvi, M. A. Sawant, and V. D. Talekar developed three models of a double expansion chamber reactive muffler designed for a single - cylinder stationary engine operating at 3000 RPM with a power output of 7.5 BHP. The research aimed to reduce low - frequency noise emissions by designing and analyzing reactive mufflers featuring double expansion chambers, focusing on improving transmission loss and noise attenuation.

The study employed both theoretical and experimental methods. Theoretical analysis was conducted using the Transfer Matrix Method and MATLAB software. Preliminary measurements of the source frequency were taken at two different distances, guiding the design of three distinct models (A, B, and C). Models A and B were designed for a source frequency of 800 Hz, while model C targeted a frequency of 600 Hz. In model A, the tube and chamber lengths were both set at 95 mm. Model B extended the chamber length to 130 mm, and model C further increased it to 170 mm. The tube diameter was fixed at 44 mm, and the chamber diameter at 100 mm. MATLAB simulations provided the transmission loss (TL) values for the models: 25.31 for model A, 23.70 for model B, and 23.74 for model C.

Experimental evaluation utilized the Four Pole Matrix Method over a frequency range of 400 Hz to 1600 Hz, with the VA - Lab IMP software measuring the absorption coefficient and TL of each model. A comparison of theoretical and experimental results revealed that model A achieved the highest TL, making it the most effective among the three designs. Minor deviations between the experimental and theoretical results were noted, attributed to factors such as sound leakage, measurement errors, and the rough surface finish of the muffler materials.

Overall, the research highlighted the effectiveness of double expansion chamber reactive mufflers in attenuating low - frequency noise from stationary engines. The integration of theoretical modeling with experimental validation offered comprehensive insights into the performance characteristics of the muffler designs [4], [5], [6].

In their paper, *"A Review of Current Techniques for Measuring Muffler Transmission Loss, "* Z. Tao and A. F. Seybert examined three methods for determining the transmission loss (TL) of mufflers: the Decomposition method, the Two - Source method, and the Two - Load method. The experiments were conducted using an expansion chamber muffler and a double expansion chamber muffler with an internal connecting tube.

In the Decomposition method, an expansion chamber muffler was analyzed by placing three microphones at specific points: two on the inlet tube and one on the outlet tube. The TL was measured across a frequency range of 100 - 1500 Hz, and the experimental results were compared with numerical simulations obtained through the Boundary Element Method (BEM). For the Two - Source method, both muffler types were used, and four microphones were positioned—two on each side of the muffler. The sound source was repositioned to create two configurations, and the experimental results were again compared with BEM simulations. The Two - Load method also utilized four microphones and analyzed both muffler types within the same frequency range, but it did not require repositioning the sound source.

The findings revealed that the Decomposition method showed significant deviations from BEM results across the entire frequency range, largely due to the lack of a good anechoic termination. This limitation makes the method unsuitable for accurately determining the four - pole parameters of a muffler, and measuring insertion loss (IL) is recommended instead. The Two - Source method, however, exhibited strong alignment between experimental and BEM results, making it a reliable approach. The Two - Load method, while slightly less accurate than the Two - Source method, proved easier to implement as it eliminated the need to shift the sound source.

Overall, the study concluded that the Two - Source method is the most preferable technique for measuring TL, providing a balance of accuracy and practicality. The research underscores the strengths and limitations of each method, offering valuable guidance for selecting appropriate measurement techniques in muffler analysis [7], [8], [9].

Mahesh V. Kulkarni and Dr. Ravindra B. Ingle conducted a study to evaluate muffler transmission loss using finite element analysis for a single expansion chamber reactive muffler. The chamber length was fixed at 400 mm with a diameter of 110 mm, while the inlet and outlet pipes had a constant length of 44 mm and a diameter of 80 mm. The volume of the expansion chamber remained constant. Transmission loss was calculated using the Transfer Matrix Method for theoretical analysis, and COMSOL Multiphysics software was used for the numerical analysis, where the muffler's geometry was defined, meshed with tetrahedral elements, and sound pressure was calculated using the Helmholtz equation. Four muffler models with different inlet and outlet configurations were tested, and the highest transmission loss was achieved when both the inlet and outlet sections were extended. The theoretical and numerical analysis results were consistent, indicating that extending both sections resulted in the best performance, with similar transmission loss observed whether the inlet or outlet was extended [10], [11], [12].

Mahesh V. Kulkarni and Dr. Ravindra B. Ingle designed a double expansion chamber muffler to investigate the impact of extended inlet and outlet placement on transmission loss. The muffler models were designed using COMSOL Multiphysics software, and the transmission loss was analyzed using the Finite Element Method. The models featured expansion chambers with a length of 270 mm and a diameter of 120 mm, while the external connecting tube was 110 mm long, and the inlet and outlet pipes had a diameter of 44 mm. Three different configurations were tested: the first model had extended inlets in both chambers, the second had extended outlets, and the third combined an extended inlet in the first chamber with an extended outlet in the second. Numerical analysis, using tetrahedral elements for meshing and the Helmholtz equation for sound pressure calculations, was conducted over a frequency range of 1 - 1600 Hz, with a 1 bar inlet pressure. Results showed that the third model, which combined both extended inlet and outlet sections, achieved the highest transmission loss and sound attenuation. These findings were validated through experimental analysis using a setup that included a Sound Source, Amplifier, FFT Analyzer, and Impedance Tube, with the Two Load method employed for measurements. The experimental analysis covered a frequency range of 1 - 2000 Hz, and results obtained from both Finite Element and experimental analyses were in excellent agreement [13], [14].

Mahesh V. Kulkarni and Ravindra B. Ingle conducted a study using the Finite Element Method (FEM) to examine the acoustic performance of a double expansion chamber reactive muffler, focusing on the effect of varying the outlet distance on transmission loss. Ingle employed COMSOL Multiphysics software for the analysis, where the muffler design parameters were kept constant: the length of the expansion chambers was 270 mm, the external connecting tube length was 110 mm, and the diameter of the expansion chambers was 120 mm. The inlet and outlet pipes were set at a diameter of 44 mm, with the volume of the expansion chamber remaining constant. The Helmholtz formula was used to calculate sound pressure, and numerical analysis was performed over a frequency range of 1 Hz to 1600 Hz. Four different models were analyzed, each altering the outlet distance from the end plate of the second chamber: Model - 1 had the outlet at L/2, Model - 2 at L/3, Model - 3 at L/6, and Model - 4 at 2L/3. The results indicated that modifying the outlet distance significantly affected the transmission loss, especially in the low to mid - frequency ranges. Model - 1 demonstrated the best acoustic performance, with a broad transmission loss spectrum and effective trough uplift after the first low attenuation region, achieving the goal of maximizing transmission loss. The study concluded that COMSOL Multiphysics software proved to be an effective tool for analyzing muffler acoustics, allowing for the assessment of various parameters such as sound pressure levels, the distribution of total acoustic pressure, iso - surfaces, and transmission loss [15], [16], [17].

Mahesh V. Kulkarni and Ravindra B. Ingle analyzed a double expansion chamber reactive muffler using finite element methods. The muffler consists of two resonator chambers with centrally connected inlet and outlet pipes, each 95 mm long and 44 mm in diameter. The chambers and connecting tube share a length of 95 mm, with chamber cross - sections measuring 110 mm in diameter. Simulations were performed in the frequency domain using time - harmonic pressure acoustics, applying three boundary conditions: sound hard walls, combined incoming and outgoing plane waves, and directional outgoing waves. Physics - controlled meshing, with element sizes ranging from 1.9 mm to 26.1 mm, revealed pressure variations indicating resonance. Maximum transmission loss occurred between 800–900 Hz, with reduced damping above 1501 Hz. Experimental validation employed the two - load method, using systems for noise generation, propagation, and measurement [18]

Mahesh V. Kulkarni and Akshay Vijay Shinde designed three reactive muffler models to evaluate the effects of design variations on transmission loss.

1) **Model 1**: Extended inlet and outlet with a single baffle plate, featuring a chamber diameter of 60 mm, length of 560 mm, and tube diameter of 22 mm. The baffle plate, positioned centrally, had an outer diameter of 60 mm and an inner diameter of 22 mm.
2) **Model 2**: Double baffle plates with the same muffler dimensions, except the circumferential diameter of the baffles was reduced by 5 mm. The plates were symmetrically placed near the chamber ends.
3) **Model 3**: Three baffle plates of varying circumferential diameters, positioned equidistantly within the chamber, maintaining the dimensions of Model 2.

COMSOL Multiphysics and the Finite Element Method (FEM) were employed for numerical analysis, using tetrahedral meshing and the Helmholtz equation to calculate sound pressure across a 1–1600 Hz frequency range. Results showed Model 1 provided the highest transmission loss, indicating superior noise reduction.

For experimental validation, a dual - chamber muffler with extended inlet and outlet designs was tested using the Two Load Method with a Transfer Matrix framework. The setup included a sound source, amplifier, FFT analyzer, and impedance tube, with measurements taken in 1–2000 Hz frequency range using four microphones. FEM and experimental results showed close alignment, with minor deviations due to sound leakage and surface imperfections [19], [20], [21].

Patil Sandip S., Patil Sudhir M., Bhattu Ajay P., and Sahasrabudhe A. D. developed a scheme to enhance muffler noise reduction using the Taguchi method. Performance was evaluated in LMS Virtual Lab 10 - SL 1, with designs modeled in Pro - E Wildfire 4.0 and meshed in Hyper Mesh. Acoustic behavior and transmission loss were analyzed through harmonic FEM in SYSNOISE.
Two design stages were examined:

1) **First Stage**: Control factors included extended inlet/outlet lengths, baffle position, and baffle hole diameter. A baffle was added to a simple expansion chamber, and transmission loss was optimized.
2) **Second Stage**: A choke tube was introduced, significantly improving transmission loss. Taguchi analysis optimized factors like choke tube dimensions, inlet/outlet lengths, and baffle placement using the "higher the better" SN ratio for quality assessment.

Optimal parameters were identified for single and two - chamber mufflers. For a single - chamber muffler, optimal dimensions were L1 = 0.100, L2 = 0.25, L3 = 0.100, and diameter = 0.03. For a two - chamber muffler with a choke tube, L1 = 0.100, L2 = 0.25, L3 = 0.050, L4 = 0.100, and d3 = 0.03.

Transmission loss was experimentally measured using the two - load method across 50–400 Hz and 400–3400 Hz frequency ranges. Sound leakage was addressed to ensure accuracy. Transfer functions from experiments and FEM analysis showed close agreement. ANOVA revealed the choke tube diameter as the most influential factor (76.15%), followed by its length (16.99%). The study highlighted the importance of design parameters and demonstrated effective muffler configurations for noise reduction [22], [23], [24].

Parag S. Khanzode and Mahesh V. Kulkarni designed and optimized a double - chamber muffler to achieve maximum transmission loss at 800 Hz. A CAD model was created and analyzed using FEA software, with meshing ensuring six elements per wavelength and a maximum element size of 35.7 mm. Perforations were added to the extended inlet and outlet sections, and acoustic analysis was conducted with sound hard wall boundary conditions.

The study found the highest transmission loss at the second chamber's extended inlet (L3). Additional perforations were tested in this region, varying diameter (3–12 mm), porosity (5–15%), and perforation length (70–200 mm). FEA simulations identified optimal parameters: 4 mm diameter, 17.5% porosity, and 110 mm perforation length. Taguchi analysis, using S/N ratios, further refined these parameters. Redesigning the muffler with optimized parameters resulted in a significant improvement in transmission loss, increasing by 130% from 43.479 dB to 100.13 dB at 800 Hz. Experimental validation using the two - load method confirmed the FEA results, showing close agreement. This demonstrates the effectiveness of the optimized design in enhancing acoustic performance [25], [26], [27].

Nilesh A. Ghodke and Mahesh V. Kulkarni utilized the Taguchi Method to design a muffler and analyzed its exhaust back pressure using Computational Fluid Dynamics (CFD). Three models were developed to study the effects of internal geometry on muffler performance. CFD simulations showed that pressure was highest at the inlet and gradually decreased along the tube, reaching its lowest at the outlet, driven by airflow velocity changes.

For experimental validation, an axial flow fan, gate valve, water manometer, and the muffler were used. Airflow was regulated with the gate valve and measured with an anemometer. Back pressure measurements from experiments closely matched CFD predictions, with minor discrepancies attributed to the omission of frictional pressure drops in CFD simulations. This study demonstrated strong alignment between computational and experimental results for all models, highlighting the reliability of the designs. [28].

Mahesh V. Kulkarni and Dr. Ravindra B. Ingle analyzed a double expansion chamber (DEC) reactive muffler with a side outlet using COMSOL Multiphysics to study the impact of outlet placement on transmission loss. The muffler design featured constant parameters: chamber length (270 mm), connecting tube length (110 mm), chamber diameter (120 mm), and pipe diameter (44 mm), with a fixed chamber volume.

Numerical analysis was conducted across a 1–1600 Hz frequency range using the Helmholtz formula to calculate sound pressure at an inlet pressure of 1 bar. Four models were tested, varying the side outlet's distance from the second chamber’s end plate:
1) Model - 1: L/2
2) Model - 2: L/3
3) Model - 3: L/6
4) Model - 4: 2L/3

Results revealed that outlet position significantly influenced transmission loss in the low to mid - frequency range. Model - 1, with the outlet at L/2, exhibited the best acoustic performance, achieving broad transmission loss and effectively reducing troughs in attenuation.

The study demonstrated that COMSOL Multiphysics is a powerful tool for analyzing muffler acoustics, enabling detailed evaluation of parameters such as total acoustic pressure distribution, sound pressure levels, and transmission loss [29].

3. Conclusion

This research investigates the design and performance optimization of a double expansion chamber reactive muffler. It was observed that incorporating extended inlet and outlet sections significantly enhances Transmission Loss (TL) by providing additional space for sound wave reflection and interference, thereby improving noise reduction. The study also explores the impact of adding perforations to these extended sections. Varying the porosity while keeping the perforation diameter and length constant proved effective in dissipating sound energy through friction and turbulence, further reducing noise transmission. Additionally, the integration of baffles was analyzed as a means to further enhance TL. Strategically positioning baffles along the inlet section or within the muffler redirects exhaust gas flow, increasing sound wave reflections and interactions, which contribute to greater noise attenuation. In conclusion, the study demonstrates that the performance of a double expansion chamber reactive muffler can be significantly improved through the implementation of extended sections, perforations, and baffles. These design modifications collectively optimize TL, resulting in enhanced noise reduction and muffling efficiency.

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Competing interests
The author have no competing interests to declare that are relevant to the content of this article.

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