Vehicle Double-chamber Muffler Optimization for Weight and Performance Improvement

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ARTICLE INFO	ABSTRACT
	The present study aims to optimize a two-chamber muffler's geometry and improve its acoustic performance. Mufflers with a circular cross-section are used in this study and then underwent the vibroacoustic analysis using COMSOL Multiphysics software. Several geometries, including a reference model and new ones, are designed and their geometry is optimized by Parametric and grid optimization methods, which are the software's optimization methods. First, the reference paper is validated to ensure the simulation produces the least error. The results obtained in this study have a good match with those of the reference. Then, by changing dimensions such as length, diameter, and inner design of the mufflers, the best geometry in terms of transmission loss and bandwidth was selected and compared with the results acquired by the reference model. It was found that the acoustic performance of the optimized design (two-chamber muffler with four inner tubes) outperforms the model used in the reference. That is, the results indicate that the optimized design is able to attenuate sound up to 78dB in the range of 0 to 500Hz, 45dB higher than that of the conventional model. Further, the muffler's weight is reduced by a quarter, using a 0.9mm thickness.

1. Introduction

Working similarly to resonators, silencers play an indispensable role in a vehicle's exhaust noise. Despite their simple schematic, they require a complex procedure to be designed for each individual type of vehicle. Its importance in the reduction of noise generated by the exhaust system has drawn researchers' attention in recent years, with the aim of weight reduction, simplicity, and fuel consumption improvement. There are generally three types of mufflers namely; dissipative mufflers, reflective mufflers, and a combination of the first two models. The first one controls the level of the noise of the exhaust system by absorbing the acoustic wave energy, while the second one, as its name implies,

reflects the incoming acoustic wave in the opposite direction. The main focus of recent studies conducted is on single-chamber and two-chamber mufflers, and some of them are herein reviewed. Vegad, et.al. [1], investigated the change in the Delta angle and its effect on a reflective muffler's acoustic performance. They showed that the sound pressure lever reduces up to 38dB. Elsayed, et.al. [2], analyzed the change in transmission loss by altering the baffles' dimensions. In this study, they covered parameters that had not been discussed in previous studies such as baffle cut ratio, perforation numbers, and their pattern. It was shown that the larger the baffler becomes, at lower frequencies the transmission loss peak occurs. A simulation-based study conducted by Gaonkar, and et.al. [3] revealed that extending the input pipe into

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the expansion chamber results in a 75% improvement in noise reduction, ensuring a wide bandgap frequency. Sonkule, and et.al. [4] experimentally investigated the acoustic efficiency of a single-chamber expansion muffler. The results obtained have a good match with those of theoretical and computational methods. More studies have been carried around double-chamber reflective silencer. Guo, and et.al. [5], proposed a two-dimensional method predicting acoustic performance of multi-chamber reflective resonators. Experimentally and computationally validated, results showed that this method anticipates the transmission loss in shorter time. Meanwhile, Fang, and et.al. [6], proposed a coupling method based on subdomain division technique for silencers with variable cross-section in length direction. In this method, the silencer is divided into several subdomain and the impedance matrix are calculated. Comparing the results obtained from the proposed method with those of experimental and theoretical indicated that the proposed method can accurately determine the transmission loss in shorter time. Sagar and Munjal [7], explored the performance of a double-muffler with H-type shape and using the matrix transfer method. Kulkarni, and et.al. [8] [9], investigated the double-chamber expansion muffler's transmission loss using acoustic pressure. It was shown that the noise can be mitigated by 30dB in frequency of 800Hz. Chang, et.al.[10] utilized a 3D expansion wave equation to reduce the frequency bandgap as a four-pole matrix. It was shown that the silencers' acoustic performance was reversely related to the diameter the of inlet and outlet. EbrahimiNejad, and et.al. [11], conducted a systematic examination on single- and double-chamber muffler comprising various baffles geometry and size in order to determine the best model for noise control purposes. They designed several models and numerically determined their TL efficiency. A reference model was first validated to ensure the simulation generates accurate results. Results indicated that 75% of circular baffles attenuate the noise up to 58dB, while the figures for rectangular baffles was 67dB. Bujana, and et.al. [12], designed a new model of two-chamber muffler with particularly designed perforation, and they could reduce the noise by 58dB. Madhukar, and et.al. [13], designed a muffler with several baffles in it. They investigated the effects of changing the baffles position and realized that the noise can be attenuated as well as having less complex structure. Trinh, and et.al. [14], compared the acoustic performance of three types of silencers, namely sing-chamber, multi-chamber, and multi-chamber with perforated tubes. They concluded the designing perforation on multi-chamber design outperforms other types of silences in terms of reducing the noise. Shirode, and et.al.

[15], experimentally and numerically showed that adding baffles to single-chamber mufflers performed better in noise attenuation than those without baffles. Damyar, and et.al.[16] experimentally explored transmission loss of a double-chamber expansion muffler. Results acquired by the Impedance tube revealed that the designed muffler performs well in noise attenuation. Zhao, and et.al [17], analyzed the problem of a muffler's acoustic performance being weakened by the airflow secondary noise based on the Large Eddy Simulation (LES). First, they investigated the unsteady flow in the chamber by using LES and performed an acoustic analysis to figure out the noise properties. They experimentally and theoretically showed that noise can be reduced up to 18% by modifying the interior geometry of the chamber. In another study, in contrast to other ones in which the chamber's wall are treated as rigid, they investigated the effect of the acoustic-solid coupling, the chamber's mode shape, other facts such as shell thickness and porous media material lining on muffler transmission loss. The results showed that increasing the shell thickness, using double insert-pipe could improve the muffler acoustic performance [18]. Secgin, and et.al [19], performed an optimization analysis on the number and the position of the baffles inside the muffler. They were the first ones who used the simplex centroid mixture designs, which is a type of response surface method. The evaluation of the mathematical optimization equations obtained from ABAQUS software indicated that the greater number of baffles are inserted inside the muffler, the lower level of noise is transmitted. Trong, and et.al. [20], analyzed the effect of the interior geometry design of mufflers on its transmission loss. They numerically compared various types of mufflers such as chamber, turbo, reactive, and absorptive. The results indicated that muffler outperforms other types in terms of acoustic for a certain length. Pravin, and et.al. [21], designed six different models of reactive mufflers and numerically studied their transmission loss and how it changes by adding pores on inlet and outlet pipe in COMSOL software. They observed as the number of pores increases, sound transmission loss rises by 27% in single expansion chamber and 30% in double expansion chamber. They reasoned this occurs as a backpressure is generated by these pores. Another optimization study on mufflers' acoustic efficiency was carried out by Min-Chiu, and et.al. [22]. They designed a four-chamber with oval cross-section muffler which each sub-sections are connected with perforated tubes to each other. They then run simulations in COMSOL Multiphysics software and validated their results with experimentations. Moreover, a Genetic Algorithm (GA) and an Artificial Neural Network (ANN) was utilized to

establish a simplified objective function, making the optimization process simpler. The results confirmed that the lower-frequency noise can be mitigated if the oval curvature ratio (ratio of long axis to short axis) increases. Xu, and et.al. [23], carried out an acoustic-structure coupling simulation using modal superposition method to calculate the transmissions loss. The designed a diesel engine muffler with a rectangular cross section and optimized its geometry based on the initial TL results. The results indicated that stiffening the dominant mode shape at the maximum frequency point of coupling loss reduction improve the noise-reduction performance of the muffler.

Due to the limitation of spaces beneath the vehicles and the increase in environmental issues and noise pollution created by the large engine, the use of single-chamber mufflers has become obsolete and

2. Approach

Figure 1 illustrates the flowchart of the procedures for determining an optimum geometry. According to this flowchart, the study is mainly divided into three sections namely, modeling, numerical simulations, and data extraction. The present study aims to design a silencer with favorable dimensions and weight to tackle the issues mentioned above. In the first part, a geometry from a reference [6] is selected and its acoustic performance, say transmission loss, is obtained to validate the accuracy of the modeling and simulations conducted in this study.
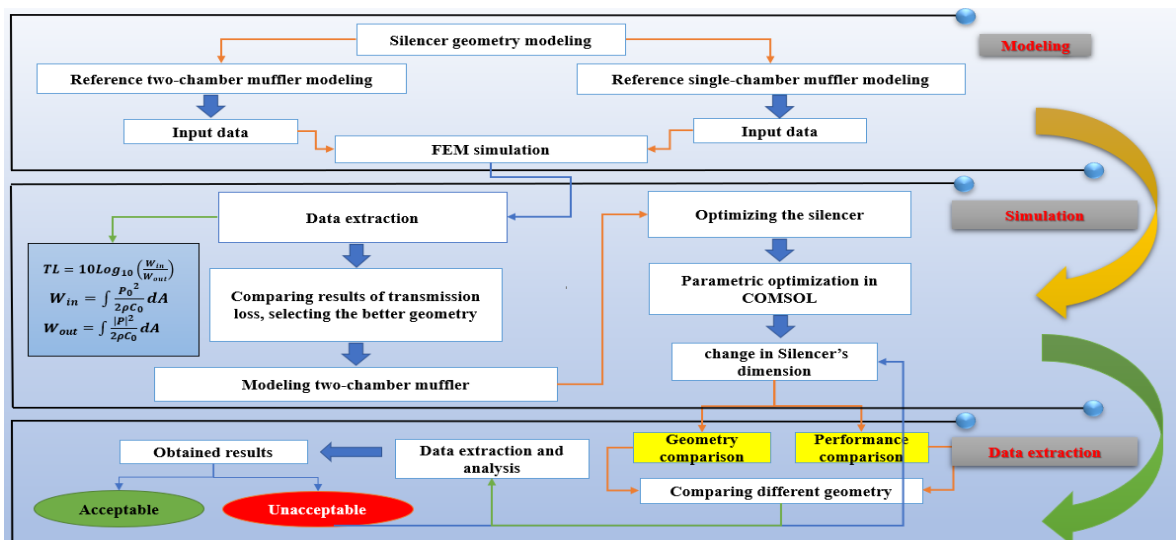

Figure 1: Study procedure flowchart

more studies have paid much attention to the design of double-chamber mufflers. Therefore, the aim of this study is to investigate the acoustic performance of double-chamber mufflers and optimized their efficiency by changing the geometry.

The remainder of the study is as follows; first, the flowchart of the study analysis is presented, the geometry of a reference model and two other new models are then designed, and the vibroacoustic analysis is performed in COMSOL Multiphysics software. After that, the acquired results are compared. Finally, the paper ends with a conclusion.

The transmission loss of a muffler can be formulated as follows [24]:

$$TL = 10Log_{10}\left(\frac{W_{in}}{W_{out}}\right) \quad (1)$$

$$W_{in} = \int \frac{P_0^{\,2}}{2\rho C_0} A \quad (2)$$

$$W_{out} = \int \frac{|P|^2}{2\rho C_0} dA \quad (3)$$

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Where W_{in}, W_{out}, are silencer's inlet/outlet acoustic power, respectively. The parameter P_0 is inlet pressure, ρ and C_0 are air density and speed of sound. Figure (2) depicts the designed mufflers in this study. Figure (2.a) is the model used in the reference, and Figure (2.b) is a single-chamber muffler designed to compare its transmission loss with a double-chamber silencer. After all consideration, the optimum design proposed in this study is designed and shown in Figure (2.c). Figure (2.d) represents the meshed muffler in the software. The mesh used has 59483 elements and equals to the shortest wavelength of $L_{min}/7.5$. The number of elements generated is adequate as we need to have 7.5 elements for a wavelength.

Table 2 and table 3 outline the models' geometry dimensions and simulation conditions, respectively.

Table 2: models' dimensions

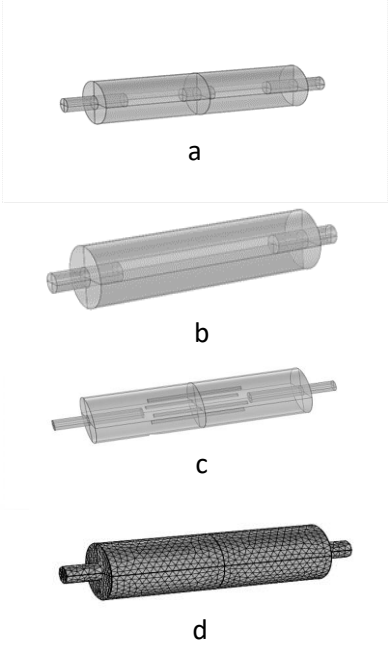| Parameter	Model (a)	Model (b)	Model (c)
Wall thickness	0.0009 m	0.0009 m	0.0009 m
Chamber length	0.5446 m	0.5446 m	0.4446 m
Input/output length	0.16 m	0.16 m	0.19 m
Tubes length between sub-chamber	0.08 m	-	0.116
Input/output diameter	0.0486 m	0.0486 m	0.04 m
Length of sub-Chamber	0.2823 m	-	0.2223 m
Chamber diameter	0.1532 m	0.1532 m	0.1332 m
Tube diameter between sub-chamber	0.04 m	-	0.01 m

Figure 2: Geometry modeling (a) used in the reference (b) single-chamber silencer (c) optimized double-chamber muffler (d) generated mesh in FEM simulation

Table 3: Simulation conditions

Parameter	Value
Frequency range (Hz)	0-3200
Temperature (K)	293.15
Input pressure (atm)	1
Speed of sound (m/s)	343.1

3. Results and discussions

In this section, the result obtained from numerical analysis is presented and discussed. Figure 3 shows a comparison between the transmission loss of a dual-chamber expansion muffler of the reference model and that of conducted in this paper as a validation. As it can be seen, in the range frequency range describe in table 3, there exist a well match between the results, meaning the current study's simulation produces the minimum error. Also, another simulation was conducted to investigate the acoustic performance of a dual-chamber expansion muffler and a single-chamber. As expected, the dual-chamber silencer out

performs the single-chamber in noise attenuation. As seen in figure (4), the noise is mitigated almost two times higher in dual-chamber muffler than that of in single-chamber silencer in the frequency of 950Hz, 1600Hz, and 2600Hz
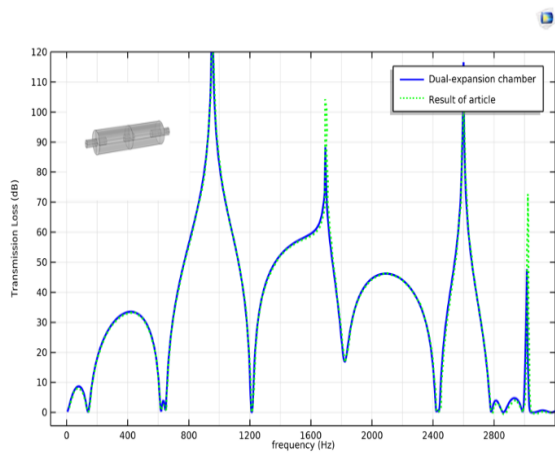
Figure 5: Optimized double-chamber muffler

Figure 6 shows a comparison between the transmission loss results of the optimized model and those of reference model. As shown in this figure, higher level of noise is attenuated with within the broader range of frequency. A 1500-Hz bandgap is seen in the results, indicating the efficiency of the proposed model in noise mitigation for a wide range of frequency. Furthermore, the transmission loss peaks have both increased by 20dB and shifted toward lower frequencies. According to the obtained results of transmission loss of single/double-chamber expansion muffler it is now clear that the double-chamber silencer with four designed tubes in the middle (the optimum model) has a better performance in terms of noise attenuation within the frequency range studied. Furthermore, this model is more cost-effective than others with less complexity in manufacturing them.

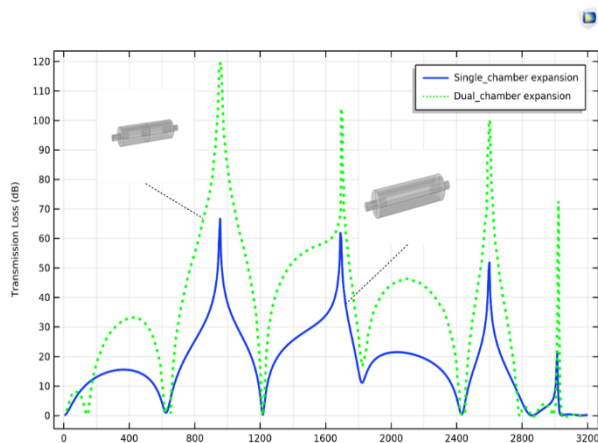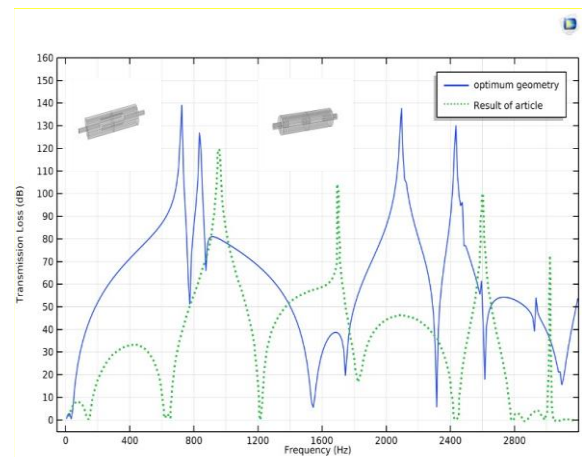**Figure 3:** Transmission loss comparison between reference and current study

Figure 4: Transmission loss comparison between single/double chamber

In order to improve further the acoustic performance of dual-chamber silencers, a software built-in parametric optimization was conducted. After all consideration and optimizations, a dual-chamber expansion muffler with four tubes which connect the sub-chambers. The designed muffler is presented in figure 5.

Figure 6: Optimized muffler and reference model Transmission loss comparison

Table 4 summarizes the potential improvement by using the enhanced model. In order to have a better understanding of the designed model in this study and the traditional models in the market, a comparison is made between these types of mufflers tabulated in table 5.

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Table 4: Summary of improvements introduced by using optimized design

Parameter		Conventional	Improved	Difference
Volume		$۱۰۴۰۷ \, cm^3$	$۶۱۹۵ \, cm^3$	40% volume reduction
Weight	**0.9 mm thickness (one layer)**	1.51 Kg	1.13 Kg	**25 % weight reduction**
	0.9 mm thickness (two layer)	3 Kg	2.26 Kg	
	2 mm thickness (one layer)	2.91 Kg	2.31 Kg	**25 % weight reduction**
	2 mm thickness (two layer)	5.83 Kg	4.63 Kg	

Table 5: Comparison between optimum and traditional silencer in market

Vehicle type	Parameter	Silencer Type 1	Silencer Type 3	Improved muffler (2mm thickness layer)
206	Chamber length	740 mm	800 mm	44.46 mm
	Chamber diameter	240 mm	240 mm	13.32 mm
	Weight	6 kg	6.8 kg	4.63 kg
	Cost	35 $	42$	-
	Difference with improved model	22.76 %	31.85 %	-
Renult-type L	Chamber length	780 mm	1000 mm	44.46 mm
	Chamber diameter	180 mm	200 mm	13.32 mm
	Weight	7.1 kg	8 kg	4.63 kg
	Cost	52 $	46 $	-
	Difference with improved model	34.733 %	42.07 %	-

4.Conclusions

The present study aims to optimize a double-chamber expansion muffler so as to maximize the noise cancellation of the exhaust system as well as reduce its weight. Using COMSOL Multiphysics software, several vibroacoustic simulations were conducted to determine mufflers' transmission loss. In order to ensure that the modeling has the minimum error, a double-chamber muffler was selected from a reference paper and their data was regenerated. The obtained results showed that there is a good match between the reference's results and this study's. Moreover, A single-chamber muffler was designed and its acoustic performance was investigated compared to a double-chamber silencer. As expected, the double-chamber muffler was far better in noise reduction than the single-chamber muffler in the frequency range discussed above. To observer a further enhancement in the muffler acoustic efficiency, a parametric study was conducted using Grid Optimization, which is a built-in method in the software. After all consideration and optimization, the acquired results of the optimized silencer demonstrated the it is capable of reducing the noise in low-frequency range. More specifically, we observed a 78-dB peak in transmission loss results withing the 0-500 Hz frequency. Weight reduction, which leads to lower fuel consumption, was another merit of using the optimized model. It was found that the weight of the exhaust system can be reduced up to 25%.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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