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EVALUATING THE IMPACT OF STRUCTURE PARAMETERS ON THE ACOUSTIC PERFORMANCE OF AN EXHAUST MUFFLER WITH SHELLS

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Recently, environmental noise has arisen from various sources, such as those from exhaust mufflers of combustion engines found in cars, trucks, or power generators, which produce significant noise during their operation. Controlling the radiated noise from these mufflers is a major factor in improving acoustic comfort and minimizing the impact on the surrounding communities. Numerous research has been presented for this reason by modification of the internal structure of the exhaust muffler. The main objective of this work is to reduce the noise level emitted from exhaust mufflers. This can be achieved by adjusting structure parameters to attenuate the surrounding environment's radiated noise. Analysis of pressure-wave propagation has been done by building 3D models using COMSOL Multiphysics software. Different entities were conducted to investigate the influence of muffler shells and plate thicknesses on acoustic performance through the frequency domain to obtain better attenuation. SPL over a frequency band is presented, describing how the sound intensity varies at different frequencies within a given bandwidth. The results showed that increasing the muffler shell thickness improved the TL; this particularly causes a double value at a range above 1.2 kHz, where there are two distinct peaks at 1.3 kHz and 2.8 kHz. Additionally, it was found that increasing the muffler plate thickness reduces the TL whole range and moves the curve peak to higher frequencies.

This is because the pressure pulses that stimulate the shell plates would exert a more distinct influence on plates characterized by a reduced thickness, and the muffler structure thickness is correlated with its increased stiffness, resulting in an elevation of the frequency for this eigenmode

Keywords: exhaust mufflers, acoustics, noise control, combustion engines, sound transmission loss, SPL

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1. Introduction

Over time, noise, which is an undesired sound, has a significant negative impact on people's health. One of the important noise sources is that produced by the combustion engines of automobiles, which becomes a serious environmental problem. Thus, the noise control of these engines is always an important field of study since these engines have a rough operation of huge noise. Typically, during the combustion of hot exhaust gases, they exit through the exhaust system and into the outer air, producing the specific noise of the engine [1]. The pollution caused by emissions and noise is getting worse as the number of diesel engines grows quickly [2]. Noise reduction is important to keep hearing from getting worse; also, it can be a concern in some applications, such as power generation [3]. Exhaust mufflers play a crucial role in reducing the noise produced by these engines, and their acoustic performance is particularly important. Exhaust mufflers are mechanical devices that reduce engine noise before emission to the environment. However, for acoustical comfort, the radiated noise from any muffler should be considered sufficient. Noise characteristics can be significantly altered during the design and study of mufflers, and Transmission loss (TL) is a key muffler performance indicator.

For those, numerous techniques for designing and analyzing mufflers have been developed by researchers around the world to increase muffler performance, including methods, materials and structure [4]. Finding better techniques to develop and evaluate the effectiveness of their designs is crucial.

2. Literature review and problem statement

Recently, focusing on muffler geometry modification, the papers [5, 6] presented studies to predict an exhaust muffler's transmission noise and acoustical behavior. The transient acoustic characteristics at a commercial automotive muffler's tailpipe were analyzed using one-dimensional CFD and verified experimentally. Although, differences arise at high engine orders due to flow noise that was not incorporated in the study. Then, the model was developed with acceptable accuracy to meet the demand of time to market in the optimization design. In comparison, using a semi-analytical approach, a study of an elliptical chamber muffler with an end-inlet and side-outlet port is presented [7]. The acoustic performance of the muffler configurations is evaluated in terms of transmission loss (TL) in a range from 10 Hz to 3 kHz with a step size of 20 Hz. The results showed that the semi-analytical analysis of the effect of port angular and axial placement and chamber length on TL performance is faster. However, a step size of 20 Hz can be too large, leading to missing areas.

Furthermore, the paper [8] presented a numerical method investigation for estimating a muffler's acoustic transmission loss (TL). The method involves simulating in both frequency and time domains, addressing issues such as boundary layer meshing and solver selection. It has been demonstrated that the proposed numerical method can be used to estimate the acoustic TL of a muffler. The method has been verified by comparing estimated acoustic TL with experimental measurements. These can help designers with optimal mufflers for noise reduction in various applications.

The research [9] has proposed a detailed study to assess the influence of the heterogeneous properties on the acoustic attenuation performance of the muffler. The finite element method is used for modeling sound propagation in perforated dissipative mufflers with non-homogeneous properties. The results show that the spatial variations of the acoustic properties of the absorbent material have a significant impact on the acoustic attenuation performance of the muffler. The proposed finite element approach can be used to optimize the design of dissipative mufflers for better acoustic performance. The use of perforated liners is also utilized by multiple authors [10]. However, these works have not addressed the effect of lining thickness on the optimized results.

Moreover, in order to reduce exhaust noise, a study [11] is presented to investigate the possibility of finding the optimal design of a multi-cavity muffler model. Based on achieving the maximum overall acoustic Transmission Loss, the optimal configuration is selected numerically. Multiple chambers deal with attenuation at a wide frequency band. Quadratic quadrilateral elements mesh is used in model simulation. The model employed in the computation is experimentally and numerically validated. This technique of using cavities in mufflers is significant, but it requires additional space that can be used to design larger models. The importance of automotive noise pushed [12] to analyze the performance of different exhaust geometries. The model simulation was done on various factors; weight reduction was also considered secondary during structural analysis. The results revealed that adjusting the perforated hole width, tube diameter, and tube length had an influence on transmission loss. Finally, all of these settings reduced vehicle noise by nearly 10 dB, which may not be sufficient for the high level of emitted noise.

Although these studies provide a short overview of muffler structure and design for best attenuation, further research is still required to fully understand the liner's fundamental structural features and characteristics in mufflers with more proper resolution in the frequency domain. Thus, this study is presented with more details.

3. The aim and objectives of the study

The aim of the study is to improve the sound pressure level and sound transmission loss (TL) of exhaust mufflers. This will make it possible for mufflers to be a more ecologically friendly product.

To achieve this aim, the following objectives are accomplished:

– to build a three-dimensional muffler model using COMSOL Multiphysics software based on FEM;

– to investigate the acoustics performance and SPL of exhaust mufflers using various structure parameters;

– to analyze the influence of different structural factors (shell thickness, plate thickness) of the exhaust muffler on TL using the pressure acoustic frequency domain.

4. Materials and methods

4. 1. Object and hypothesis of the study

Muffler design has become more challenging as customers look for good exhaust sound quality. In designs, the structural parameter is the most influential factor on acoustic performance, including chamber length, width and tailpipe length. The main hypothesis of the study depends on the Sound Transmission Loss (TL), which is the main characteristic that can describe noise reduction in mufflers. TL is defined as the ratio in sound power level between the incident wave W_i stimulating the mufflers and the transmitted wave W_t to an anechoic termination, and it is independent of the source as per the following equation [13, 14]:

$$TL = 10\log\frac{w_i}{w_t}. \quad (1)$$

The present work assumes a muffler with a single intake and outtake, as shown in Fig. 1. The simulation model is done by using FEM analysis. Mufflers often have narrow inlets and outlets, so the acoustic wave travels mostly in a plane. The sound pressure p and particle velocity v at any point along the direction of wave propagation of the muffler (x) can be represented for harmonic response in the following (2), (3). The equations can be used to model the behavior of sound waves in various acoustic systems, such as mufflers or resonators [13, 15]:

$$p = \left(p_1 e^{-jkx} + p_2 e^{jkx}\right) e^{j\omega x}, \quad (2)$$

$$\upsilon = \frac{1}{\rho c}\left(p_1 e^{-jkx} - p_2 e^{jkx}\right), \quad (3)$$

where, k is the wave number, which is related to the wavelength (λ) and frequency (f) of the sound wave through the equation $k=2\pi/\lambda=2\pi f/c$, c is the speed of sound in the gas in the muffler in meters per second (m/s), ρ is the density of the gas in the muffler in kilograms per cubic meter (kg/m^3), p_1 and p_2 are complex amplitudes of the sound wave, which depend on the boundary conditions of the medium. Then, by making the assumption that the incident and reflected acoustic waves at the muffler inlet $x=0$, the sound pressure p and particle velocity v can be represented as the following equations:

$$p_{in} = p_1 + p_2, \quad (4)$$

$$\upsilon_{in} = \frac{1}{\rho c}\left(p_1 - p_2\right). \quad (5)$$

Similarly, p_3 and p_4 are the sound wave parameters for the muffler outlet located at $x=L$. Non-reflective boundary conditions are typically stated to end at the outlet, making p_4=0. Then, by substituting into (2), (3), the sound pressure *pout* and particle velocity υ_{out} can be represented as [13, 15]:

$$p_{out} = \left(p_3 e^{-jkx}\right) e^{j\omega x}, \quad (6)$$

$$\upsilon_{out} = \frac{1}{\rho c} p_3, \quad (7)$$

$$Z_{out} = \frac{p_{out}}{\upsilon_{out}}. \quad (8)$$

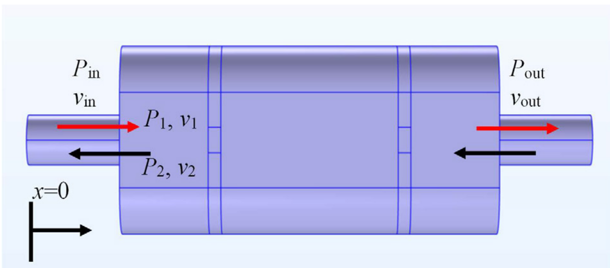


Fig. 1. Schematic diagram of the proposed shelled muffler

The inlet cross-sectional area of the muffler, denoted by the letter A_{in}, and the output cross-sectional area, denoted by the letter A_{out}, then the sound power W_{in} and W_{out} of plane wave at the muffler intake and outlet are computed using sound power (9) [13]:

$$w = \frac{p^2 s}{\rho c}, \quad (9)$$

where *s* – cross-sectional area of the muffler in square meters (m^2). Finally, as demonstrated in (1), the equation for determining the muffler transmission loss is derived, which can be expressed as follows:

$$TL = 10\log\frac{w_i}{w_t} = 10\log\frac{p_1^2 A_{in}}{p_3^2 A_{out}}. \quad (10)$$

The final equation might produce the transmission loss (TL) that represents the results of attenuation that specify the analysis of damping as a function of frequency. The TL is commonly expressed in dB, or decibels.

4. 2. Three-Dimensional Models Built

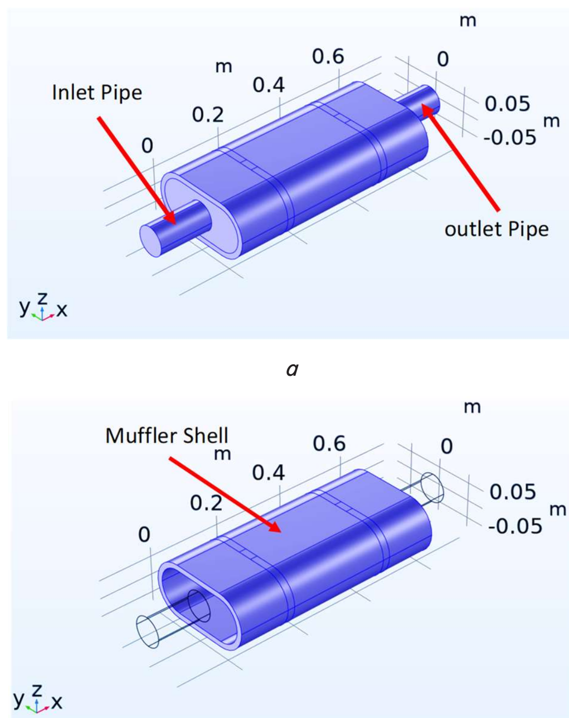
The first step is to create the geometry of the object being modeled. A three-dimensional model of an elliptical type of muffler has been built in COMSOL Multiphysics software (v6.0) to study and analyze the pressure-wave propagation for an internal combustion engine muffler. The model is based on the finite element method (FEM). Simulating a muffler involves modeling airflow, its interaction with the interior structure, and the acoustic waves it generates. The simulation is performed for typical and shelled muffler models in a specific frequency range. The schematic diagram of the muffler structure is shown in Fig. 2. The shell is the outermost layer of the muffler's primary volume. The design of the muffler and the parameter characteristics can be incorporated into the system; both play a role in the transmission loss.

For this study, during the implementation of the model, tubular pipes link the resonating chambers. Geometry features a single, identical radius and length of inlet and outlet. The muffler volume is kept constant, and the length of muffler *L* is 600 mm. The shell thickness *Lt* varies between (5–20) mm, and the plate thickness *Pt* varies between (1–2) mm. The values of the basic parameters listed in Table 1 include the muffler length, height, width, and others.

Table 1

Basic parameter values of the Muffler model

Basic parameters	Expression	Values, mm
Muffler length	L	600
Muffler height	H	150
Muffler width	*W*	300
Inlet and outlet length	*Lio*	150
Inlet and outlet radius	*Rio*	40
Liner thickness	*Lt*	5–20
Plate thickness	*Pt*	1–2



a

b

Fig. 2. A Three-dimensional model: *a* – muffler with shell; *b* – shell of muffler

Depending on the muffler application, the geometry parameters can be specified to analyze the TL results for the necessary frequency bandwidth.

4. 3. Boundary conditions

The acoustic simulation calculation process for the model shown in Fig. 2 is solved under specific assumptions of boundary conditions in COMSOL Multiphysics software. In order to precisely simulate the behavior of the system, appropriate boundary conditions must be defined. Firstly, after the model geometry is constructed, it must next be submerged in the fluid medium. The fluid medium for the acoustic transmission wave was set to be air to simulate the acoustic domain. Its properties were added to the material data in the COMSOL material section. The characteristics of air at a temperature of 20 °C are utilized as a density of 1.2 kg/m^3, specific heat of 1,007 J/kg·K, and thermal conductivity of 0.0215 W/m·K. The dynamic viscosity is 1.825*10^{-5} kg/m·s. All walls are made from a steel material with a characteristic of (E=210 GPa, ν=0.3, ρ=7,800 kg/m^3, η=0.02, and t=1 mm). After that, in the physics section for both the inlet and exit surfaces, a plane wave boundary condition is applied, with an incident pressure of 1 Pa applied at the inlet. For simplifications adopted in the work, the gas in the muffler is ideal, and there is no energy loss in the process of sound propagation. All interior and exterior walls are considered sound-hard barriers. The condition imposes that the normal velocity at the boundary is zero and a no-slip condition of the fluid [16]. During the acoustic analysis, a radiation boundary condition is applied to the silencer's inlet and outlet sections. Furthermore, the sound speed is assumed to be 343 m/s, and for sound absorption materials, poroacoustic material attributes are applied based on the material employed.

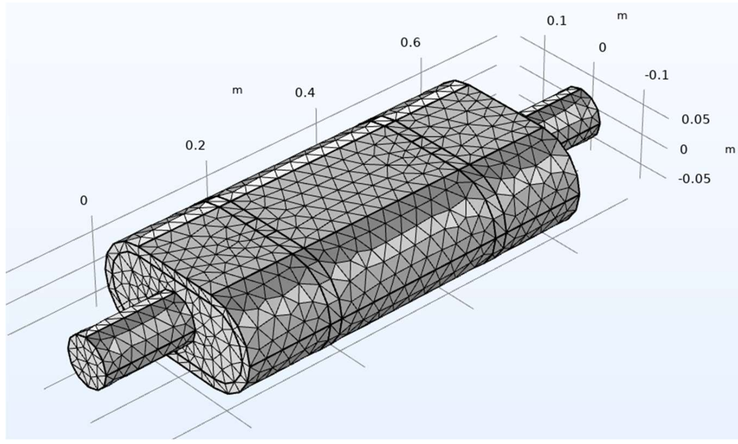


Fig. 3. Meshed geometry of an exhaust muffler with shell

This discretization rule of this mesh configuration is used for each FEM analysis of muffler models to guarantee the modeling accuracy for all frequencies of interest.

4. 4. Meshing

The mesh is an essential component of the FEM; it can be defined as the discretization of a continuous problem domain into a finite set of smaller, interconnected subdomains, known as finite elements, allowing for the formulation of differential equations to be solved on each element. The solution on each element is then combined to obtain the solution for the entire domain. Since mesh size and shape of the elements can significantly impact the accuracy and computational efficiency of the FEM solution, and poor quality meshes can lead to inaccurate results, thus adequate meshing setup is crucial.

As the intricate design and various configurations of the exhaust silencer, which includes intake and exhaust pipes, using a hexahedral structure for meshing poses an inaccurate process, which makes it easy to make the interface error. This prevents muffler TL simulation. Thus, a tetrahedral mesh may provide precise calculations [13]. This study used a user-controlled mesh by employing an unstructured tetrahedral – Taylor Hood-like type to mesh the muffler. According to the Nyquist criteria, a repeated waveform can be successfully reconstructed if the sampling frequency is larger than twice the greatest frequency to be sampled. This could be clear that at least two mesh elements per wavelength [17, 18]. Eight elements per wavelength are applied here in this study to provide accurate results for Finite Element Analysis, as shown in Fig. 3. The wavelength calculation is expressed as the following equation:

$$\lambda = \frac{c}{f_m}, \qquad (11)$$

where λ – wavelength of sound, c – speed of sound equal to 343 m/sec, and f_m – maximum frequency, which is assumed to be equal to 2,500 Hz:

$$\lambda = \frac{343}{2{,}500} = 0.1372. \qquad (11)$$

Therefore, the maximum element size is to be as follows:

$$\frac{\lambda}{8} = 0.01715 \text{ m}. \qquad (12)$$

5. Results of simulation analysis of exhaust muffler

5. 1. Validation of the 3D Model

Fig. 4 depicts the simulation results of the noise level for the exhaust muffler model shown in Fig. 2. A comparison of two muffler cases is presented, with no shells and with shells as shown in Fig. 4, *a*, *b*. The presence of shells in the muffler results in a notable increase in resonant peaks variation, particularly in the 2.1 kHz to 2.4 kHz range, compared to mufflers without shells.

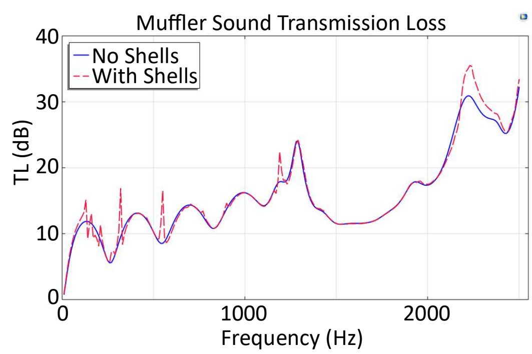


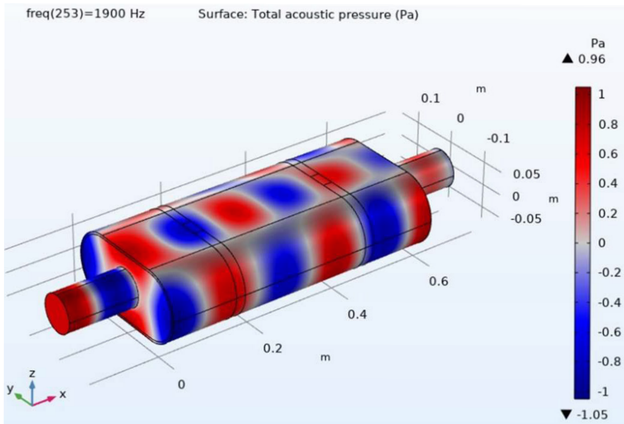
Fig. 4. A comparison of two cases of mufflers, with no shells and with shells

For accurate results, the model is verified with a reference manual [17] with a good agreement.

5. 2. Acoustics performance

Recently, researchers have conducted several studies to investigate the acoustics performance of exhaust mufflers. In this work, to evaluate the muffler parameters' effect on its acoustic performance, different entities for gauging are presented and discussed. One of the important parameters is the shell thickness (known as a lining thickness) and the thickness of the muffler's plate and how these affect its performance. These can be done using acoustic-structure interaction models.

A parameterized study is performed using the same muffler model. Various muffler shell and plate thicknesses are performed to observe their effects on total acoustic pressure and SPL results. It starts with a muffler shell at a base thickness of 5 mm, then increases to 20 mm. Fig. 5 visualizes the effect of varied shell thickness on the muffler's total acoustic pressure field distribution in a three-dimensional representation, which refers to the sum of the static pressure and the fluctuating pressure of the acoustic wave at a particular point in space.



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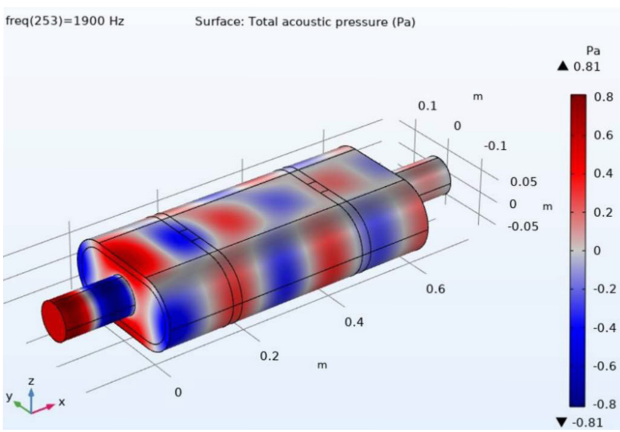

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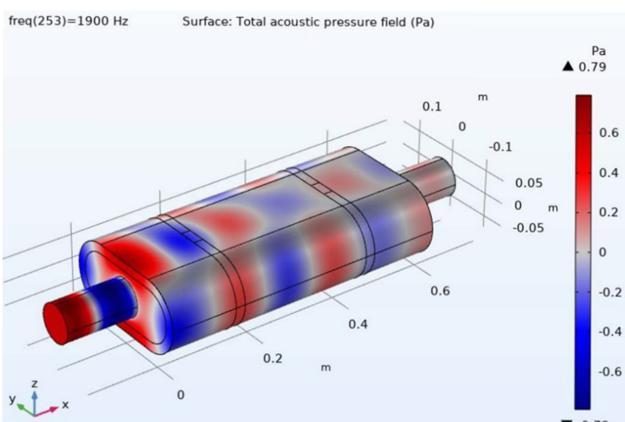
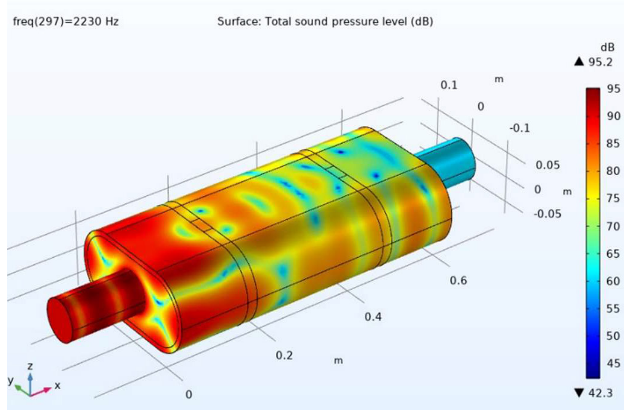


c

Fig. 5. Total acoustic pressure of a muffler with shell for varied shell thickness: *a* – *Lt*=5 mm; *b* – *Lt*=15 mm; *c* – *Lt*=20 mm

In Fig. 6, the graph plots the SPL over a frequency band that provides a representation of how the sound intensity varies at different frequencies within a given bandwidth. Three shell thicknesses are presented in order to comprehend their capabilities for noise reduction of the muffler.



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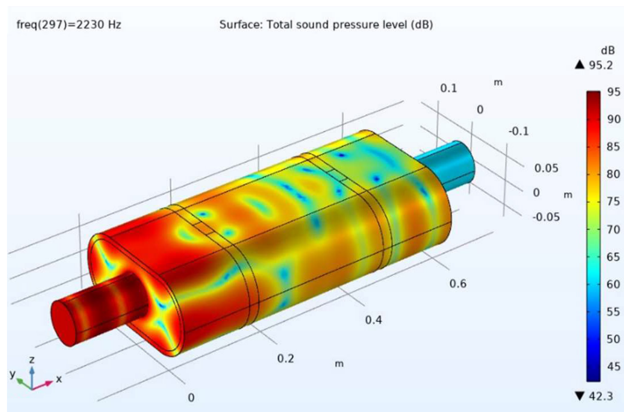

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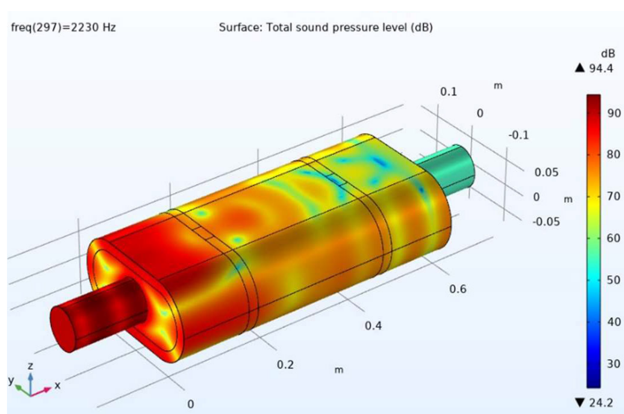

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Fig. 6. Sound Pressure level of a muffler with shell for varied shell thickness: *a* – *Lt*=5 mm, *b* – *Lt*=15 mm, *c* – *Lt*=20 mm

5. 3. Results of analysis of acoustic frequency domain

Previous studies showed that transmission loss (TL) serves as the primary acoustic performance measure for mufflers. It has been observed that a higher TL value corresponds to a better noise reduction capacity of the muffler [19]. The main objective is to obtain the maximum sound transmission loss for the muffler according to structure parameters. This section presents the sound pressure level (SPL) and transmission loss (TL) for the 0 to 2.5 kHz frequency range.

The muffler shell thickness could impact the TL of an exhaust muffler particularly in the range above 1.2 kHz, which is more than double with distinct peaks at 1.3 kHz and 2.8 kHz. As shown in Fig. 7, decreasing the shell thickness could generally reduce the overall TL.

The second parameter to investigate is the shell plate thickness of the muffler. Here in this section, different thicknesses are performed to involve the acoustic performance. Fig. 8 depicts the comparison of TL curves along with the case for 1mm to 2 mm shell thickness. Multiple peaks of TL are observed for the curve of 1 mm thickness compared to other curves. The 1 mm curve shows three distinct peaks lying between 100 Hz and 600 Hz; however, one peak can be observed for the 1.5 mm curve and a small peak for the 2 mm curve.

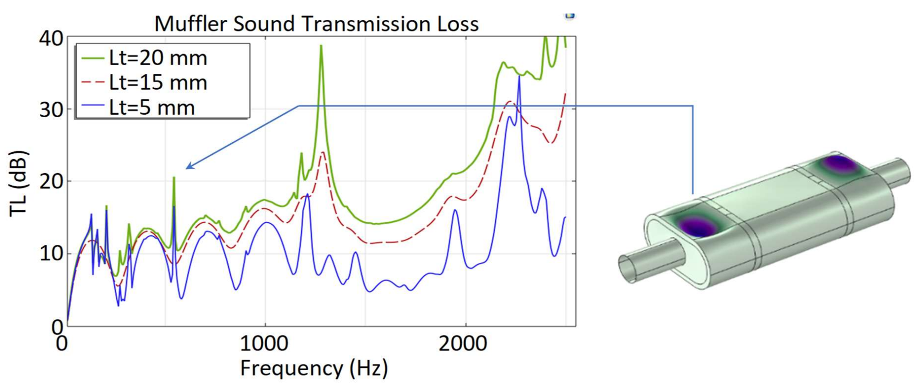

Fig. 7. Sound transmission loss of a muffler with varied shell thickness (*Lt*)

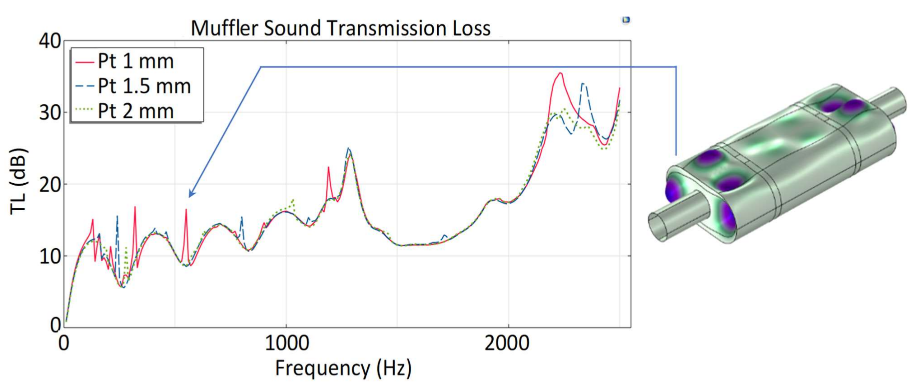

Fig. 8. Sound transmission loss of a muffler with varied shell plate thickness (*Pt*)

The subsequent notable peak observed in all three curves is situated at the frequency range of 2.2 kHz to 2.4 kHz. As the shell thickness increases from 1 mm to 1.5 mm, the position of the peak shifts to the right. This is because the thickness of the muffler structure is correlated with its increased stiffness, resulting in an elevation of the frequency for this particular eigenmode.

6. Discussion of acoustic analysis results

This research was carried out on a simplified model of exhaust mufflers of combustion engines. The analysis of the proposed 3D model has been utilized on total acoustic pressure, SPL and TL with variation of structure parameters using FEM.

Generally, in order to explain the obtained results shown in Fig. 7, it can be observed that the muffler model with a shell thickness of 20 mm has better transmission loss with higher peaks, particularly in the range of up to 1 kHz. In other words, decreasing the shell thickness could reduce the overall TL. This is due to the fact that a thicker lining provides further insulation, which improves dissipation and reduces the sound energy generated by exhaust gases.

Furthermore, Fig. 8 depicts the comparison of TL curves along with the case for 1mm to 2 mm shell thickness. Multiple peaks of TL are observed for the curve of 1 mm thickness compared to other curves. The 1 mm curve shows three distinct peaks lying between 100 Hz and 600 Hz; however, one peak can be observed for the 1.5 mm curve and a small peak for the 2 mm curve. This outcome is anticipated, as the pressure pulses that stimulate the shell plates would exert a more pronounced influence on plates characterized by a reduced thickness. The second note for all three cases is the presence of resonant acoustic mode between 1.3 kHz and 1,850 kHz, as shown by the sharp decline in all three curves at this frequency.

These outcomes of the presented muffler models could help engineers try more designs in the inner structural optimization of the muffler.

This study of the exhaust muffler is limited to a range of shell thickness and plate thickness that was mentioned before. The research can be developed into a three-dimensional model of a muffler with multiple shell materials that can be implemented and experimentally verified in future work.

7. Conclusions

1. The analysis of the combustion engine muffler's acoustic performance is presented in this work. COMSOL Multiphysics software based on the finite element method has been used to build a three-dimensional model of conventional and shelled mufflers. The presence of shells in the muffler results in a notable increase in resonant peaks variation, particularly in the 2.1 kHz to 2.4 kHz range, compared to mufflers without shells.

2. The results of an investigation of the simulation are implemented under specific assumptions of boundary conditions in a frequency range of up to 2.5 kHz. Different entities were conducted to study the influence of shell thickness and muffler plate thickness on the total acoustic pressure field and SPL distribution.

3. Analysis of the TL showed that the increase in shell thickness has been observed to produce improved TL, particularly at higher frequencies. Additionally, it was found that increasing the plate thickness had the opposite effect of what was expected, reducing the TL, and moving the peak of

the curve to the right to higher frequencies. This is because the pressure pulses that stimulate the shell plates would exert a more pronounced influence on plates characterized by a reduced thickness, and the thickness of the muffler structure is correlated with its increased stiffness, resulting in an elevation of the frequency for this eigenmode.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Zhong, W., Pachiannan, T., Li, Z., Qian, Y., Zhang, Y., Wang, Q. et al. (2019). Combustion and emission characteristics of gasoline/hydrogenated catalytic biodiesel blends in gasoline compression ignition engines under different loads of double injection strategies. Applied Energy, 251, 113296. doi: https://doi.org/10.1016/j.apenergy.2019.05.099
2. Xia, Q., Wang, K., Han, Z., Tian, W. (2019). A comparative study of combustion and emission characteristics of butanol isomers on a diesel engine with dual fuel butanol isomers/diesel compound combustion. Fuel, 254, 115581. doi: https://doi.org/10.1016/j.fuel.2019.05.164
3. Ashok Reddy, K. (2017). A Critical Review on Acoustic Methods & Materials of a Muffler. Materials Today: Proceedings, 4 (8), 7313–7334. doi: https://doi.org/10.1016/j.matpr.2017.07.061
4. Yasuda, T., Wu, C., Nakagawa, N., Nagamura, K. (2010). Predictions and experimental studies of the tail pipe noise of an automotive muffler using a one dimensional CFD model. Applied Acoustics, 71 (8), 701–707. doi: https://doi.org/10.1016/j.apacoust.2010.03.001
5. Mimani, A., Munjal, M. L. (2012). 3-D acoustic analysis of elliptical chamber mufflers having an end-inlet and a side-outlet: An impedance matrix approach. Wave Motion, 49 (2), 271–295. doi: https://doi.org/10.1016/j.wavemoti.2011.11.001
6. Mimani, A., Munjal, M. L. (2011). Transverse plane wave analysis of short elliptical chamber mufflers: An analytical approach. Journal of Sound and Vibration, 330 (7), 1472–1489. doi: https://doi.org/10.1016/j.jsv.2010.09.035
7. Jena, D. P., Panigrahi, S. N. (2017). Numerically estimating acoustic transmission loss of a reactive muffler with and without mean flow. Measurement, 109, 168–186. doi: https://doi.org/10.1016/j.measurement.2017.05.065
8. Antebas, A. G., Denia, F. D., Pedrosa, A. M., Fuenmayor, F. J. (2013). A finite element approach for the acoustic modeling of perforated dissipative mufflers with non-homogeneous properties. Mathematical and Computer Modelling, 57 (7-8), 1970–1978. doi: https://doi.org/10.1016/j.mcm.2012.01.021
9. Hacham, W. S., Hiji, F. S. (2020). Impact of using Double Layers Perforated Liners on the Acoustic Treatments of the Combustor Systems. Al-Khwarizmi Engineering Journal, 16 (4), 19–26. doi: https://doi.org/10.22153/kej.2020.10.002
10. Ouédraogo, B., Maréchal, R., Ville, J.-M., Perrey-Debain, E. (2016). Broadband noise reduction by circular multi-cavity mufflers operating in multimodal propagation conditions. Applied Acoustics, 107, 19–26. doi: https://doi.org/10.1016/j.apacoust.2016.02.001
11. Kashikar, A., Suryawanshi, R., Sonone, N., Thorat, R., Savant, S. (2021). Development of muffler design and its validation. Applied Acoustics, 180, 108132. doi: https://doi.org/10.1016/j.apacoust.2021.108132
12. Fu, J., Xu, M., Zheng, W., Zhang, Z., He, Y. (2021). Effects of structural parameters on transmission loss of diesel engine muffler and analysis of prominent structural parameters. Applied Acoustics, 173, 107686. doi: https://doi.org/10.1016/j.apacoust.2020.107686
13. Rafique, F., Hui Wu, J., Rui Liu, C., Ma, F. (2022). Transmission Loss analysis of a simple expansion chamber muffler with extended inlet and outlet combined with inhomogeneous micro-perforated panel (iMPP). Applied Acoustics, 194, 108808. doi: https://doi.org/10.1016/j.apacoust.2022.108808
14. Kalita, U., Singh, M. (2023). Acoustic performance analysis of muffler by varying sound absorption materials. Materials Today: Proceedings. doi: https://doi.org/10.1016/j.matpr.2023.02.272
15. Fu, J., Zheng, W., Xu, M., Wang, W., Huang, Y. (2021). Study on the influence of structure factors of diesel engine exhaust purification muffler on transmission loss in different frequency bands. Applied Acoustics, 180, 108147. doi: https://doi.org/10.1016/j.apacoust.2021.108147
16. COMSOL Multiphysics Reference Manual. Available at: https://doc.comsol.com/5.5/doc/com.comsol.help.comsol/COMSOL_ReferenceManual.pdf
17. Prasad, A., Thiagarajan, R. C. (2015). Acoustic Performance Design of Automotive Muffler. Excerpt from the Proceedings of the 2015 COMSOL Conference in Pune. Available at: https://www.researchgate.net/publication/350063080_Acoustic_Performance_Design_of_Automotive_Muffler
18. Kalita, U., Singh, M. (2023). Optimization of reactive muffler through pressure acoustic analysis and Taguchi approach. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45 (2). doi: https://doi.org/10.1007/s40430-023-04023-1