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Effect of Liner Layer Properties on Noise Transmission Loss in Absorptive Mufflers

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Abstract: The reduction of the emitted noise pollution from the exhaust system of engines is a real challenge for various industries. At this regard, mufflers have been used to reduce the transmitted noise from the engine of vehicles into the surrounding environment. Mufflers are designed to reflect the sound waves produced by the engine in such a way that they partially cancel themselves out. Noise transmission loss performance in muffler depends on its geometry. Therefore, maximization of noise transmission loss in mufflers using shape modification concept is an important research area. In this paper research, maximization of noise transmission in mufflers is studied and investigated. A model is developed to present the absorptive muffler. The muffler structure and its sound absorbing layer are modeled using shells elements. This model analyzes the muffler structure which has effects on the transmission loss (TL). The results are compared to a model without any absorbing layer. It indicates that the thickness and material type of absorbing layer have distinctive effects on the amount of noise transmission loss of muffler over a wide frequency range.

Keywords: Absorptive Muffler, Noise Transmission Loss, Sound Absorbing Material, Shell

1. Introduction

Mufflers are devices which attenuate the transmitted noise via them. They have designed to reduce the produced noise in their inlets by various methods, e.g. passive or active approaches. Actually, active mufflers are still not ready for mass production. Therefore, the attention of industry is focused on passive mufflers which use either reflection or absorption methods to reduce the energy of transmitted noise. Reactive mufflers can be mainly used for low frequency ranges while absorptive mufflers should be used for mid-range to high frequency ranges, i.e. more than 500 Hz, with little back pressure [1].

The reactive type muffler is usually restrictive and prevents even the good engine sounds from coming through, but does a good job of reducing noise. On the other hand, most absorptive type mufflers are less restrictive, but allow too much engine noise to come through. Regardless of the packing material, absorptive type mufflers tend to get noisier with age [2].

Mufflers have been developed over the last century based on electro- acoustic analogies and experimental trial and error. Many years ago Stewart used electro – acoustic analogies in deriving the basic theory and design of acoustic filters [3]. Later Davis et al. published results of a systematic study on mufflers [4]. They used travelling wave solutions of the one-dimensional wave equation and the assumption that the acoustic pressure and acoustic volume velocity are continuous at changes in cross sectional area.

An important step forward in the analysis of the acoustical performance of mufflers is the application of two- port network theory with use of four – pole parameters. Igarashi and his colleagues calculated the transmission characteristics of mufflers using equivalent electrical circuits [5].

Parrot later published results for the certain basic elements such as area expansions and contractions. Sreenath and Dr. Munjal gave expression for the attenuation of mufflers using the transfer matrix approach [6]. The expression they developed was based on the velocity ration concept. Later, Dr. Mujal modified this approach to include the convective effects due to flow [7]. Young and Crocker used the finite element method to predict four-pole parameters and then the transmission loss of complex shaped mufflers for the case of no flow [8].

A generalized scheme for analysis of multifarious commercially used mufflers was proposed by Panigrahi et al. [9]. They explained that the commercial automotive mufflers are often too complex to be broken into a cascade of one dimensional element with predetermined transfer matrices.

Boundary element analysis of packed silencers with protective cloth and embedded thin surfaces was presented by Wu et al. [10]. Bulk-reacting porous materials are often used as absorptive lining in packed silencers to reduce broadband noise. Modeling the entire silencer domain with a bulk-reacting material will inevitably involve two different acoustic media, air and the bulk-reacting material. A so-called direct mixed-body boundary element method (BEM) has recently been developed to model the two-medium problem in a single-domain fashion. They presented an extension of the direct mixed-body BEM to include protective cloth and embedded rigid surfaces.

The sound attenuation performance of micro-perforated panels (MPP) with adjoining air cavity was investigated for a plenum in Ref. [11]. The sound field inside of a plenum was compared for two cases. In the first case, the plenum was treated with an MPP and adjoining air cavity without any partitioning. For the second case, the adjoining air cavity was partitioned into a number of sub-cavities. The resulting sound pressure fields indicated that partitioning the adjoining air cavity increased the overall sound attenuation due to the MPP by approximately 4 dB.

Application of absorptive mufflers in automotive industry was investigated by Yasuda et al. [12]. The tail pipe noise from a commercial automotive muffler was studied experimentally and numerically under the condition of wide open throttle acceleration in the present research.

The effect of liner for the acoustic energy absorption was studied by Herrin et al. [13]. They indicated that, if the dimensions of a silencer or muffler component are small compared to an acoustic wavelength, plane wave propagation can be assumed.

The proper use of plane wave models for muffler design was introduced by Herrin et al. [14]. In many industries, muffler and silencer design is primarily accomplished via trial and error. Prototypes were developed and tested, or numerical simulation (finite or boundary element analysis) was used to assess the performance.

In this paper, the effect of absorptive layer (liner) on the noise attenuation in muffler is investigated. At this regard, next sections will present the modeling, theory, calculations and results. Final conclusions and recommendations for the future work will also be presented at the last part of this work.

2. Helmholtz Equation

An absorptive muffler is shown in Figure 1. It uses absorption to reduce the sound energy. Sound waves are reduced as their energy converted into heat in the absorptive material. A typical absorptive muffler consists of a straight, circular and perforated pipe that is encased in a larger steel housing made from shell layers [15]. Between the perforated pipe and the casing is a layer of sound absorptive material that absorbs some of the pressure pulses.

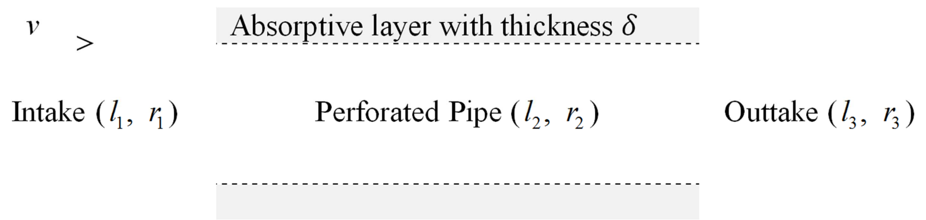

Figure 1. *An absorptive muffler.*

The equations that explain the propagation of sound in the fluid type mediums can be calculated from the equations of fluid flow. These equations are the fundamental equations of continuum mechanics which describes the conservation of mass, the conservation of momentum that is often referred as the Navier-Stokes equation and explain the energy conservation in a medium, and the equation of state that describes the relation between thermodynamic variables.

In most classical acoustic cases, the flow assumed lossless, viscous effects are neglected, and a linearized type of equation of state is used. Under these assumptions, the acoustic field can be described by one variable, i.e. pressure, and is governed by the wave equation as [16-18]

$$\frac{1}{\rho_0 c^2}\frac{\partial^2 p}{\partial t^2}+\nabla.\left(-\frac{1}{\rho_0}(\nabla p-q)\right)=Q \tag{1}$$

Where t is time in second, ρ_0 is the density of fluid in (kg/m^3), and q and Q are possible acoustic sources in (N/m^3). In the homogenous case, when there are no acoustic sources q and Q, one simple solution to Helmholtz equation is the plane wave as

$$p = P_0 e^{i(\omega t - k\cdot x)} \tag{2}$$

where P_0 is the wave amplitude and it is moving in the k direction with angular frequency ω and wave number $k=|k|$. In this paper, an absoptive muffler which has been shown in Fig. 1, is considered. It has a layer of absorptive material in its scilencer. This abroptive layer is named as liner. Several materials are used in the absorptive liner.

In the absorbing layer, the damping enters the equation 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 is the complex impedance.

For a highly porous material with a rigid skeleton, Delany and Bazley [19] presented a model which estimates these parameters as a function of frequency and flow resistivity by

$$k_c = k_a(1 + 0.098 \cdot (\rho_a f / R_f))^{-0.7} - i \cdot 0.189 \cdot (\rho_a f / R_f)^{-0.595}) \quad (3)$$

and

$$Z_c = Z_a(1 + 0.057 \cdot (\rho_a f / R_f))^{0.734} - i \cdot 0.087 \cdot (\rho_a f / R_f)^{-0.732}) \quad (4)$$

where R_f is the flow resistivity, and k_a and Z_a are the free-space wave number and impedance of air, respectively. For glass wool-like materials, Bies and Hansen [20] give an empirical correlation:

$$R_f = \frac{3.18 \cdot 10^{-19} \cdot \rho^{1.53}}{d^2} \quad (5)$$

where ρ is the material's apparent density and d is the mean fiber diameter. At the solid boundaries, which are the outer walls of the resonator chamber and the pipes, the model uses sound hard (wall) boundary conditions. The condition imposes that the normal velocity at the boundary is zero.

The boundary condition at the inlet involves a combination of an incoming imposed plane wave and an outgoing radiating plane wave.

An educational version of MAP software [21, 22] is used to calculate the noise transmission loss in absorptive muffle. The root mean square of calculated noise transmission loss (RMSL) in [dB] is considered as

$$RMSL = \sqrt{\frac{\int_{f_{\min}}^{f_{\max}} TL^2(f)\, df}{f_{\max} - f_{\min}}} \quad (6)$$

In a series of publication by Ranjbar et al. [23-37] the topic of design of complex structures. e.g. mufflers, and optimization of mechanical structures wee investigated. In the next sections, the results of simulations with MAP software are presented.

3. Model Description

Figure 2 shows the geometrical description of absorptive muffler when a full rotational symmetry around the centerline of model is considered. The radius of cylendrical inlet and outlet, i.e. r_1, is considered to be same. The radius of cylendrical scilencer part, i.e. r_2, is considered from the centerline to the beginning of absorbtive layer. The thickness of absorptive layer is δ.

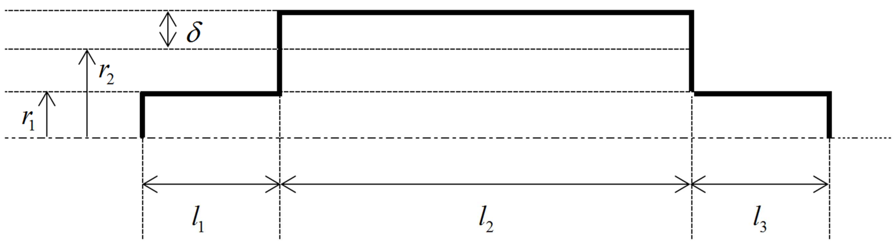

Figure 2. *Model of absorptive muffler considering rotational symmetry.*

Table 1. *Initial dimensions of specification of muffler.*

Muffler part name	Dimension value in [m]
Radius of inlet r_1	0.0254
Radius of outlet r_1	0.0254
Radius of silencer r_2	0.0762
Thickness of absorptive layer δ	0.0254
Length of inlet l_1	0.1524
Length of outlet l_2	0.1524
Length of silencer l_3	0.4572

The initial geometry and dimension values for the absorptive muffler is given in table 1. The radius of inlet and outlet is set to be 0.0254 m. The radius of scilencer is set to be 0.0762 m. The thickness of absoptive layer is considered as 0.0254 m. The lenghts of inlet, scilencer and outlet are considered to be 0.1524 m, 0.4572 m and 0.1524 m, respectively. If no liner is considered, then the radius of scilencer will be 0.1016 m.

Table 2. *Material specification of absorptive material.*

Parameter	Value
Fluid type	Air
Temperature in [$^\circ c$]	400
Fluid density in [g/cm^3]	0.0005
Fluid Mach number	0
Speed of sound in [*m/s*]	514.1
Density of Basalt wool in [g/cm^3]	2.7
Density of Polyester in [g/cm^3]	1.37
Density of Needle fiber in [g/cm^3]	0.18
Density of Cell foam in [g/cm^3]	0.3

Various material specifications for the absorptive muffler are described in table 2. Several types of absorptive materials as basalt wool, polyester, needle fiber and cell foam are considered.

The considered absorptive materials in this thesis are being commonly used as absorptive materials for producing absorptive mufflers. They absorb the energy of exhaust noise from the engine and convert it to heat. The main deficiency of such absorptive materials is environmental issues.

4. Simulation Results

An educational version of MAP software provided by the vibroacoustic consortium of university of Kentucky in USA is used for the simulation. MAP is the acronym for Muffler Analysis Program. It is a based on the direct mixed-body boundary element method (BEM) developed at the University of Kentucky [22].

MAP includes the four-pole method for evaluating the transmission loss (TL). The fundamental of four-pole methods and calculation of TL has been already discussed in the previous section. Hence, the one-dimensional wave theory is considered.

4.1. Transmission Loss of Muffler Without Absorptive Liner

At first, the transmission loss of muffler without any absorptive layer should be evaluated. At this regard, the same dimension of muffler as given in table 1 is considered.

Figure 3 shows that calculated transmission loss (TL) in decibel (dB) of such muffler over a wide frequency range from 0 to 4000 Hz. It indicates the TL is reduced after the frequency of 2000 Hz. The maximum TL peak is 23.1 dB at 2000 Hz. It represents that the muffler without absorptive liner cannot work good to attenuate the sound. Also, the RMSL is 10.7 dB over the wide frequency range.

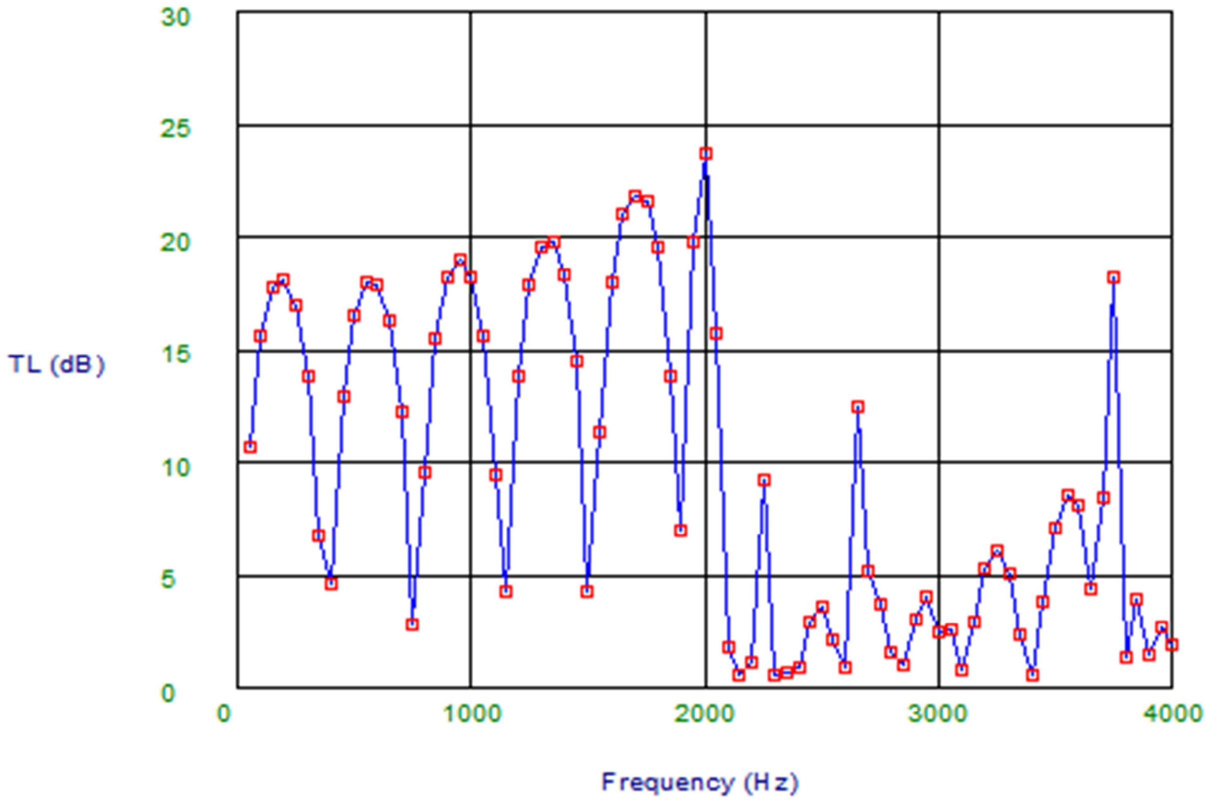

Figure 3. *Transmission loss of muffler without liner, same dimension as given in table 1 but with silencer radius of 0.1016 m.*

4.2. Transmission Loss of Muffler with Absorptive Liner

In this part, the transmission loss of muffler with absorptive layer with the geometry shown in figure 2 is presented. Figure 4 shows the TL for the case when Needle fiber is considered for the absorptive layer. The highest peak of TL curve in this case is 47.1 dB has appeared at the frequency of 2720 Hz. Here the RMSL value is 27.5 dB which is 16 dB more than the original case without absorptive layer. So, it shows significantly the effect of adding absorptive layer to muffler, especially for the high frequency ranges more than 2000 Hz.

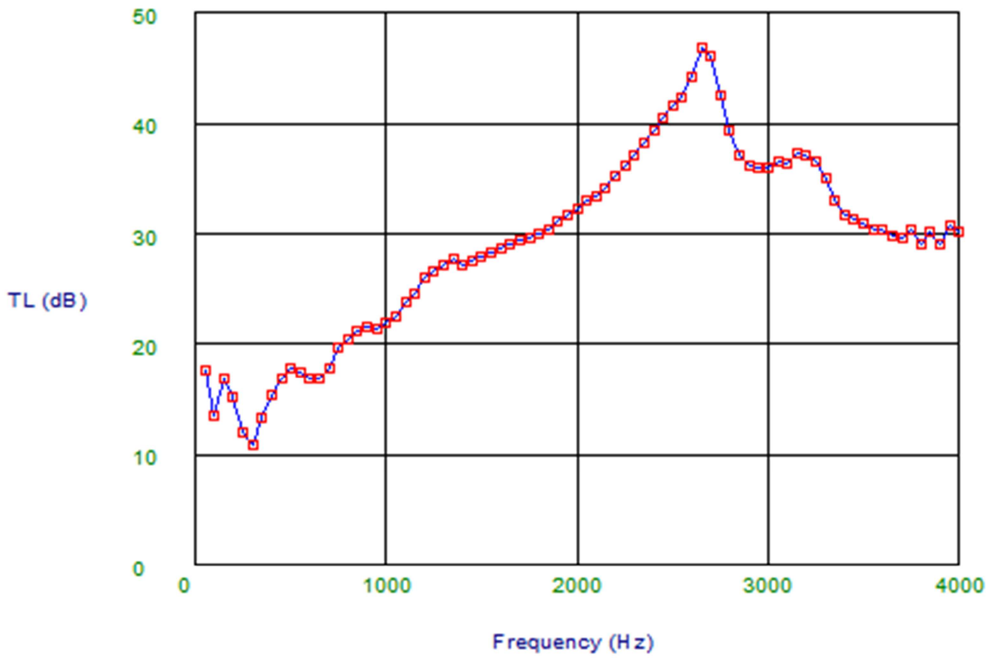

Figure 4. *Transmission loss of muffler with Needle fiber absorptive layer around silencer.*

Figure 5 shows the TL for the case when Polyester is considered for the absorptive layer. The highest peak of TL curve in this case is 62.6 dB has appeared at the frequency of 2290 Hz. Here the RMSL value is 31.6 dB which is 20.9 dB more than the original case without absorptive layer. So, it shows significantly the effect of adding denser absorptive layer to muffler, especially for the mid-frequency range.

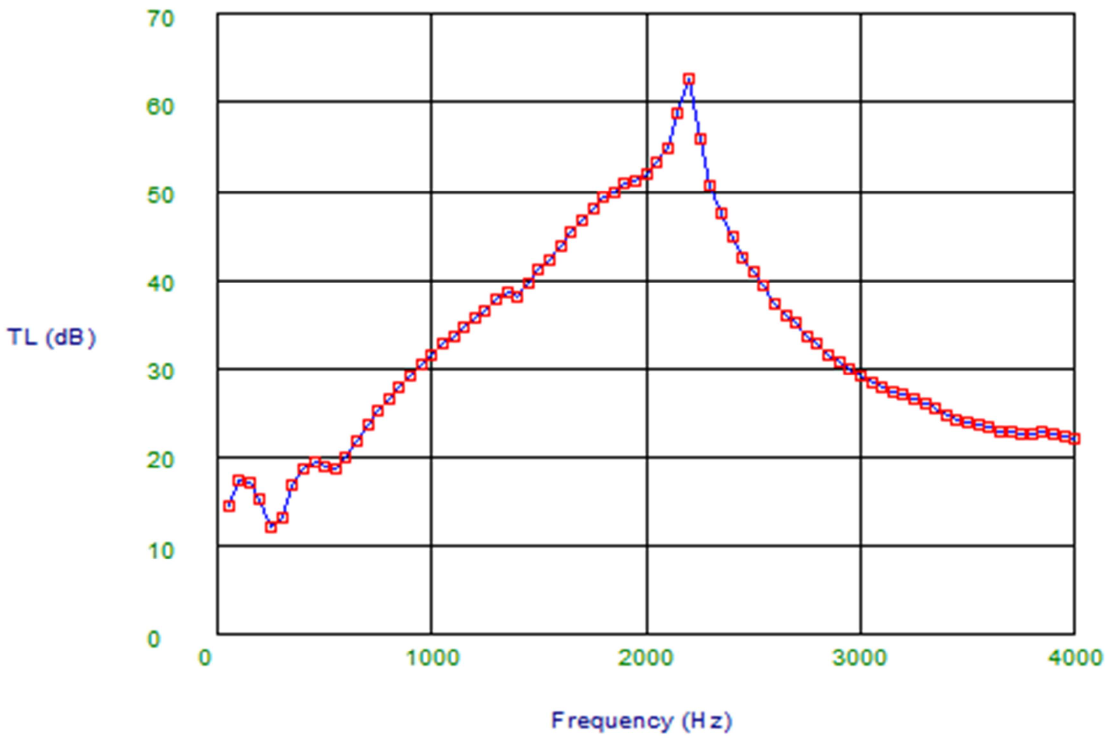

Figure 5. *Transmission loss of muffler with Polyester absorptive layer around silencer.*

Figure 6 shows the TL for the case when Basalt wool is considered for the absorptive layer. The highest peak of TL curve in this case is 71.5 dB has appeared at the frequency of 2570 Hz. Here the RMSL value is 38.4 dB which is 27.9 dB more than the original case without absorptive layer. So, it shows significantly the effect of adding denser absorptive layer to muffler, especially for the mid-frequency range. This indicates that denser absorptive layer is absorbing more energy from the fluid stream inside the muffler. However, it causes to add the weight of muffler.

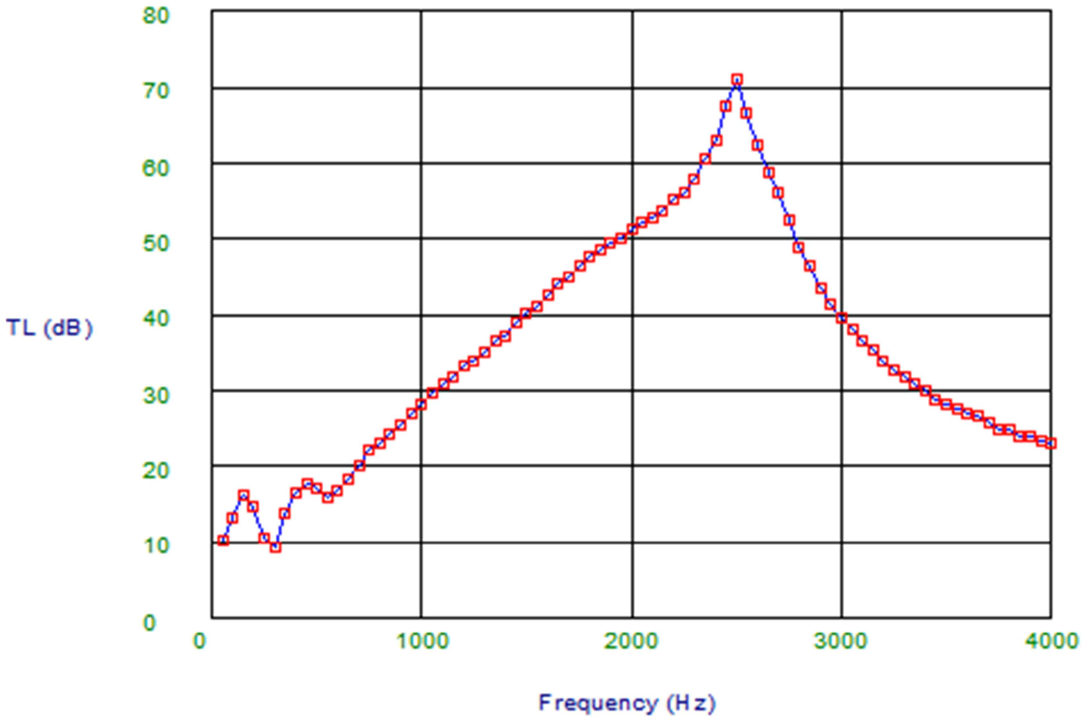

Figure 6. *Transmission loss of muffler with Basalt wool absorptive layer around silencer.*

Figure 7 shows the TL for the case when Cell foam is considered for the absorptive layer. The highest peak of TL curve in this case is 55.4 dB has appeared at the frequency of 2430 Hz. Here the RMSL value is 30.4 dB which is 19.9 dB more than the original case without absorptive layer. So, it shows significantly the effect of adding denser absorptive layer to muffler, especially for the mid-frequency range. This indicates that denser absorptive layer is absorbing more energy from the fluid stream inside the muffler. However, it causes to add the weight of muffler.

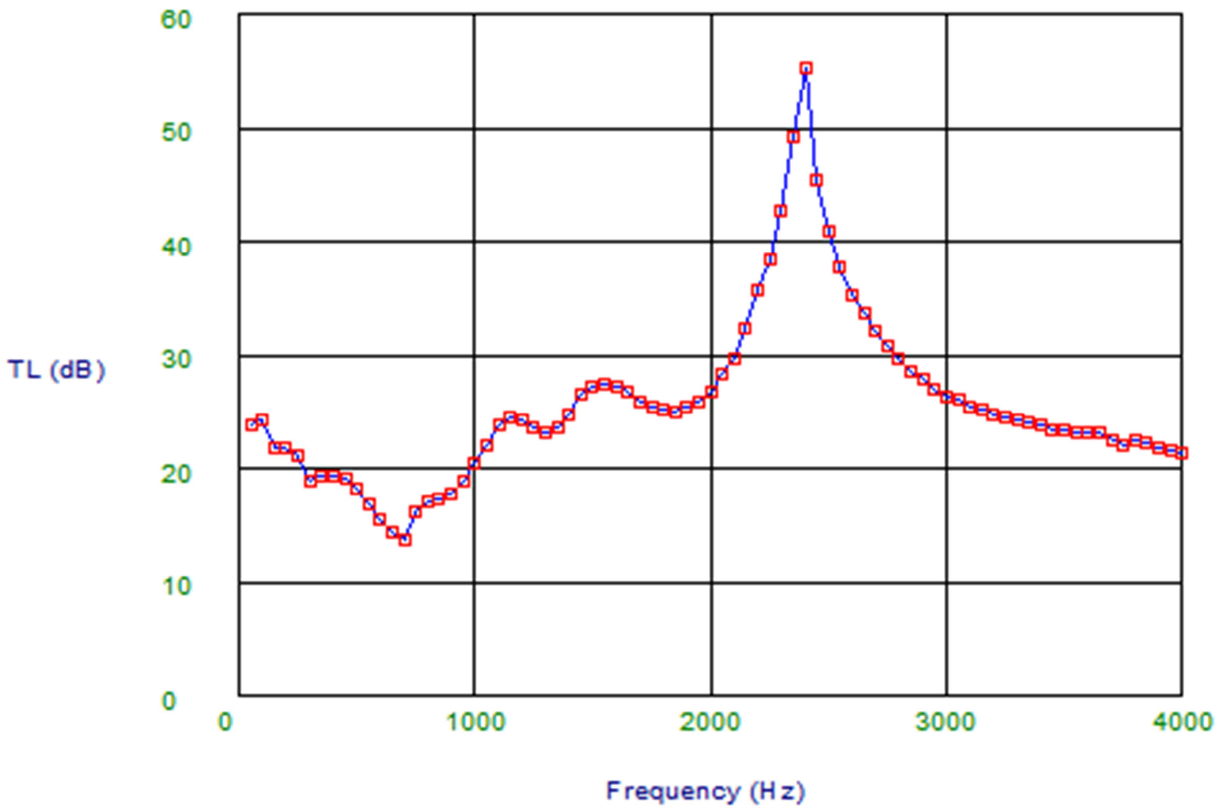

Figure 7. *Transmission loss of muffler with Cell foam absorptive layer around silencer.*

In figure 8, a comparative study on the effect of various materials for absorptive layer is presented. In fact, it is a summary of previous cases. As it is shown, the muffler with no absorptive layer has the lowest level of sound transmission loss. The situation even gets worse for the frequencies more than 2000 Hz. However, if absorptive layer is being added the structure of muffler, then the value of TL and RMSL is increasing. Moreover, it is understandable that with using denser absorbing materials as liner around the silencer, the value of noise transmission loss both over the wide frequency range and at picks are increased.

A sensitivity analysis is done in this section to understand the effect of various thickness layers for absorbing liner of muffler. Also, various geometries for the structure of muffler is considered to have more general understanding about the effect the geometry on the level of noise transmission loss in an absorptive muffler.

Table 3 shows the effect of glass wool liner thickness δ on TL and RMSL of absorptive muffler. The density of glass wool is considered to be 0.48 g/m^3. Seven various cases are considered. In all cases, the geometry of muffler has not been changed; only the thickness of absorbing layer is modified. It indicates that with increment of liner thickness, the level of noise transmission loss is increased.

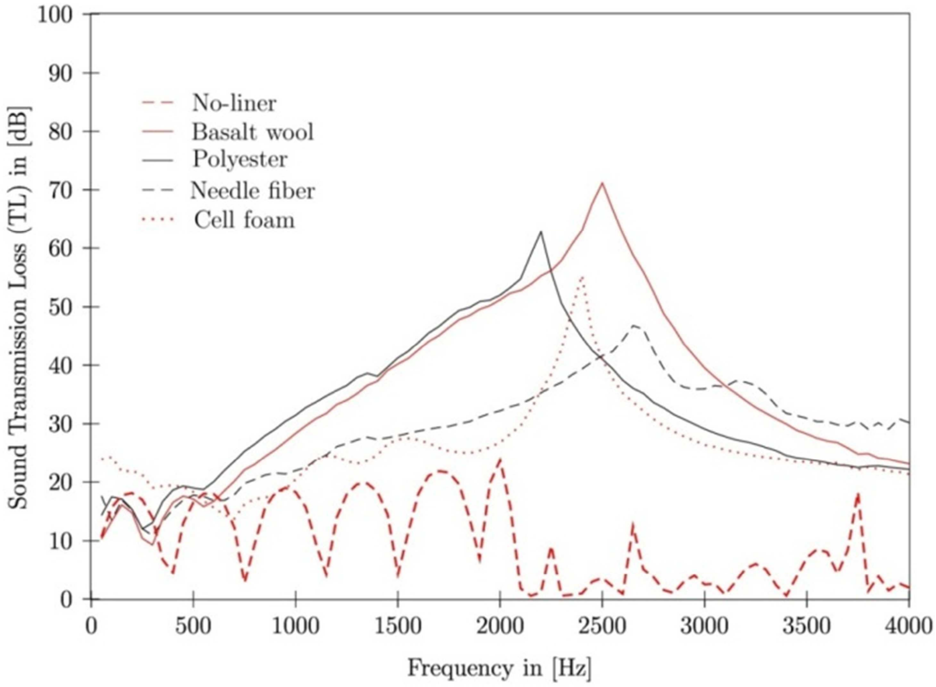

Figure 8. *Summary of sound transmission loss for various absorbing materials of liner in absorptive muffler.*

Table 3. *Effect of glass wool liner thickness δ on TL and RMSL of absorptive muffler.*

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Inlet and outlet lengths l_1, l_3 (m)	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Inlet and outlet radius r_1 (m)	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Silencer length l_2 (m)	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Silencer radius r_2 (m)	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Liner thickness δ in (m)	0.0	0.005	0.01	0.015	0.02	0.03	0.04
Maximum TL (dB) at frequency (Hz)	22.6 (1225)	16.5 (1201)	16.1 (1201)	23.8 (1270)	39.1 (1280)	31.8 (1269)	30.2 (1230)
RMSL (dB)	6.4	6.8	7.3	9.7	14.2	16.5	19.1

5. Conclusions and Future Works

Typically, the greater the ratio of packing surface area to flow area, the greater is attenuation capability of the silencer. Many different packing materials can be used in absorptive silencers and are chosen for use based on varying absorptive performance, price, temperature and corrosion characteristics. Also, the effect of the thickness of absorptive material and spacing play an important role in sound attenuation. The attenuation increases sharply at high frequencies as the spacing is narrowed. Better performance at lower frequency is obtained as the thickness of the absorbing material is increased. In order to attenuate high frequency noise, a metal tube surrounded by acoustical-quality glass wool inside the muffler outer containment shell has been used here. The sides of the tube are perforated that permit sound waves impinge on the absorbing materials. Also, the density of absorptive materials plays an important role in the level of transmission loss. In fact denser absorptive materials can increase the TL more than the absorptive materials with lower density. The structural mode shapes in mufflers made from thin shell are very close acoustic mode shapes. Therefore, it indicates that full fluid-structure interaction should be considered.

Generally, absorptive mufflers produce better performance for the maximization of noise transmission loss at high frequencies. This matter is clearly shown in this thesis. Moreover, with increment of thickness of absorptive layer in muffler, the value of TL at higher frequencies and even RMSL over the whole frequency range are increased. However, usage of denser absorptive materials will result to heavier structure for the muffler. Furthermore, it will cause to reduce the natural frequencies of structure of muffler; hence resonance in muffler can be more seen.

For the future work, it is recommended to consider full fluid-structure coupling between the structure and acoustic medium. However, it increases the duration of calculation and complexity of problem. More environmental friendly absorptive materials should be considered for the reduction of air pollution impact of absorptive mufflers. Novel shapes of absorptive muffler with well-designed absorptive layer shapes should be considered.

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