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Selection of Appropriate Porous Material for Designing and Developing Hybrid Absorptive Muffler: A Wave 1-D Based Approach

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Abstract

In this study, glass wool and rock wool are used as sound-absorbing materials to assess the sound transmission loss (STL) of hybrid absorptive mufflers. Improving the muffler's acoustic performance and assessing how well these materials attenuate noise are the main goals. Rock wool, which offers greater thermal resistance and broader frequency absorption, is contrasted with glass wool, which is renowned for its lightweight construction and high-frequency absorption. Wave 1-D simulation is used for the design and analysis of hybrid absorptive mufflers in a variety of configurations, including as an empty muffler, a perforated pipe with a single baffle, and a double-baffle system. To comprehend changes in STL, the impact of baffle positioning at the center and at 125 mm from both ends is investigated. Once the ideal muffler design has been determined, experimental testing is carried out to confirm the STL gains made possible by absorptive materials. Through the modification of muffler chambers with baffle plates, the study emphasizes the contribution of glass wool and rock wool to the reduction of vehicle exhaust noise. The effectiveness of these materials in hybrid muffler designs is demonstrated by a comparison of the empirically and numerically simulated STL values. The results optimize material selection for maximum acoustic performance, which advances noise reduction tactics in exhaust systems.

Keywords: Hybrid muffler, transmission losses, noise reduction, wave-1 D, acoustics

INTRODUCTION AND LITERATURE SURVEY

Numerous sounds absorbing materials have been introduced for noise and vibration reduction in cars and industrial applications as a result of growing public concern towards noise pollution. These materials, which can be used alone or in combination with viscoelastic materials, can be found in vehicle linings, seats, under carpets, hollow interiors, etc. They include glass wool, rockwool, polymeric fibre materials, various types of foams, etc. To maximise acoustical properties or to satisfy structural design requirements, sound-absorbing materials are applied in multi-layered configurations. Engineering practise has demonstrated that properly designed multi-layered material treatments can effectively reduce the noise effects in terms of outcomes [1, 2, 24].

Most internal combustion engines have mufflers installed in their exhaust system, despite the fact that they are not intended to perform any primary exhaust functions. The muffler is built as acoustically soundproofing equipment with the purpose of acoustically quieting the engine's generated sound pressure. Mufflers, a crucial component of the engine exhaust system, are

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utilised to reduce noise transmissions brought on by exhaust gases. Muffler design is a sophisticated process that influences engine emissions, noise levels, and fuel efficiency. The two types of mufflers now-a-days utilised in the automotive industry, reactive and dissipative, both operate at a certain target frequency range [2, 25].

The desire for customer satisfaction should be taken into account from an environmental standpoint as the automotive sector has grown. As per the current scenario, the automotive design should be such that the comfort level and noise free condition must prevail. Active noise management and passive noise control are the two techniques available for minimising acoustic noise. By using supplementary sources, active noise control (ANC) introduces "anti-noise" waves. Through an electronic framework that applies a specific sign conforming computation for the particular scratch off plan, the auxiliary sources are connected. The management of acoustic noise by the use of barriers, enclosures, and mufflers to prevent the noise is known as passive noise control (PNC). Thus, the use of mufflers is intended to lessen noise by altering resistance by the insertion of tubes and baffles. They are primarily responsible for reducing exhaust noise. [1, 3, 26].

One part that reduces the noise produced by the exhaust of an internal combustion engine is a muffler. Mufflers are commonly utilized as part of the exhaust system of internal combustion engines to minimize exhaust noise. Motorized transportation is the most common source of noise that annoys individuals and is bad for their health. Cars have mufflers, which are essential noise control devices, to lessen the noise made by internal combustion engines. [4].

Numerous parameters can be used to characterize the acoustic performance of a muffler. These include noise reduction, insertion loss, and transmission loss. The difference in the muffler's sound pressure level is what reduces noise. Although it is easy to quantify, the noise reduction is not very helpful for designing mufflers. Despite being immensely useful to industry, the insertion loss is hard to quantify because it depends on the muffler design itself as well as the source and radiation impedances. [5, 27].

The outline of this research is to design and develop hybrid absorptive mufflers using different types of absorptive materials, perforated tubes, and varied types of chambers. This will be followed by testing with the aid of experimental set-up having the prime focus to reduce the transmission losses. The core essence of this research is to evaluate how well mufflers operate when employing diverse sound absorption materials and, -via- experimental validation while selecting the optimal absorption material for various industrial or automotive applications. Due to the fact that the use of hybrid mufflers has not been thoroughly investigated in comparison to the use of other types of mufflers. In this experiment, a hybrid absorptive muffler is developed employing wave 1-D analysis and experimentally validating its results in the designated laboratory. After experimental validation, single-baffle and double-baffle mufflers will be used inserting sound absorptive materials.

ENVIRONMENTAL IMPACT OF NOISE IN VARIOUS APPLICATION ZONES

Whether on land or in the ocean, noise pollution is perceived as a very serious threat to environmental sustainability. Noise pollution results in any unwanted or grating sound that has an effect on people's and other living things' health and wellbeing [6].

Not all sounds are subject to noise pollution. 'Noise exceeding 70 decibels (dB) is how the World Health Organisation (WHO) defines noise pollution. To be precise, noise starts to be bothersome over 75 decibels (dB) and harmful over 110 dB. Since getting a good night's sleep is impossible when ambient noise levels are higher than 27 dB at night, it is advisable that noise levels be kept below 67 (dB) during the day [7, 28].

According to Lee, C.M. and Wang, Y.S., Long-term noise exposure can have a number of negative health effects, including cognitive impairment in children, irritability, sleep disruption, negative effects on the cardiovascular and metabolic systems, and sleep disruption [12].

Table 1. Sound Levels for Different Application Zones.

S. N	Application areas	Range of sound level [in dB(A) L_{eq}*]	
		Range of sound level during daytime	*Range of sound level during night hours*
1	Industry-based Sector	72-76	69-73
2	Commercialized Sector	62-65	54-57
3	Inhabited Surroundings	64-66	44-46
4	Sound-Proof Region	48-50	39-41

Due to the prevailing condition of higher sound effects or noise levels, serious health concerns related to ischemic cardiac issues result in premature deaths [8].

The committee for eradicating the noise pollution was established by the central pollution control board. The following noise standards for ambient air and vehicles were suggested by this committee based on different aspects from the application perspectives shown in Table 1.

‘dB(A) Leq’ specifies in decibels on the scale A that corresponds to human hearing. The frequency weighting used to measure noise is denoted by "A" in ‘dB(A) L_{eq}’, which is equivalent to the human ear's frequency response characteristics [9].

WORKING PRINCIPLE OF HYBRID ABSORPTIVE MUFFLERS

Acoustics is the branch of science that examines the behaviour of sound. There are two different ways that sound waves can travel: spherical wave travel and plane wave travel. When the sound produced by an object goes solely in one direction, the It is claimed that the object is moving as a plane wave.

The wave travels in unique direction in muffler, pipelines, etc. When a sound wave comes from a source and travels in all directions, it is said to be propagating spherically [10, 29].

Put another way, when sound waves pass through the gaps between the densely packed, tiny-diameter fibres of the absorptive material, the resulting viscous friction releases the sound energy as tiny amounts of heat. A well-known example of a dissipative design is the absorptive muffler, which gets its ability to reduce noise from the straightforward observation that different types of fibrous packing materials effectively "absorbed" noise energy. [11, 24].

DESIGN PROCEDURE OF HYBRID ABSORPTIVE MUFFLERS

Different Losses in Muffler

Transmission loss

Transmission loss measures the effectiveness of muffler. Transmission loss is the outcome of a muffler preventing sound energy from passing through it. In anechoic conditions, transmission loss is the difference in sound intensity between incident waves passing through the muffler's inlet and waves passing through its exit. [13, 27].

Insertion loss

The difference between the sound pressure levels with and without the suppressor is known as the insertion loss. Impedance at the source, radiation impedance, and muffler design all affect insertion loss. Along with these other components.

Noise reduction

The difference between the SPLs at two points—one upstream and one downstream gives the measure of noise reduction losses. It does not require source impedance knowledge, similar to TL, and anechoic termination, similar to IL. As such, it will be easier to measure and compute, and it is now frequently employed for experimental validation of the predicted transmission characteristics for a given collection of elements.

Design Characteristics of Muffler

Muffler having baffle arrangement

By using a spot-welding technique, different types of baffle are inserted into the design compartments to for increasing the sound transmission loss. Less noise is generated due to exhaust gas travelling ample amount of distance when a baffle plate is used [14, 30].

Muffler having wave-control arrangement

Another form of muffler follows a particular kind of gas path. The repeating paths that the exhaust gases travel result in waves crests colliding with wave troughs. Theoretically, revoking waves result from two paths having length differences of half a wavelength.

Muffler having resonance-based arrangement

This type of muffler layout uses a pipe with an access port that passes through a number of Helmholtz resonators. The resonator in this pipe, which carries exhaust gases, regulates engine noise by filtering out its fundamental and higher harmonic frequencies.

Muffler using absorptive material

In this kind of muffler, Absorptive Material like steel wool or fibreglass are placed within a perforated tube. These materials have the effect of reducing the high-pressure fluctuation of the exhaust gases as they move through the chambers.

Muffler using integrated arrangement of resonance-based system and absorptive material

To additional lower the losses, a resonance cavity is added to a normal straight through absorber-type muffler at one end or in the middle. In some circumstances, a resonance chamber—a piece of independent machinery—is connected in series to the muffler [15, 26].

Characteristics Features of Noise Absorptive Material

The acoustic materials known as sound absorptive materials are utilised to dissipate the energy generated by acoustic sound waves. They diffuse the energy generated through the vehicle's outlet and also store some of the energy. According to the previous researches, using absorptive materials can significantly increase the transmission losses of a hybrid muffler [16, 29].

The two-cavity approach is used for experimental measurement of sound absorption materials. The effective expansion area of muffler decreases as an absorptive material is added, and this sound absorptive material absorbs pressure waves and barely reflects them. Fibres, glass wool, woven glass fibre, and other substances are some of the absorptive materials [17, 30].

METHODOLOGY

Methods adopted for Determination of Transmission Loss

There are various ways to assess transmission losses, but herein acoustic wave propagation and transfer matrix method (TMM) have been discussed which are the most prominent ones.

Acoustic wave propagation

The plane wave propagation model works when higher order modes can be disregarded and the acoustic pressure (p) and velocity (v) are expressed as the total of the left and right traveling waves wherever they appear in the pipe element. The impedance analogy can be used to connect the acoustic pressure p and velocity v at positions 1 (upside) and 2 (downside) in Figure 1 (x=0 and x=L, respectively).

$$p_1 = C_1 p_2 + C_2 v_2 \tag{1}$$

$$v_1 = C_3 C p_2 + C_4 v_2 \tag{2}$$

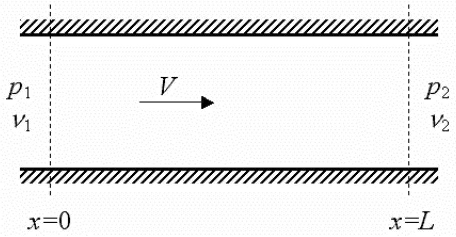

Figure 1. Propagation of plain waves in a straight pipe [18].

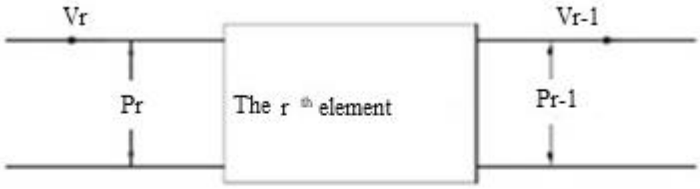

Figure 2. Schematic view of transfer matrix

In this acoustic model, the four-pole constants are commonly referred to as A, B, C, and D. They are complex frequency-dependent parameters that represent the pipe's acoustical characteristics [19]:

$C_1 = \exp(-jMk_c L) \cos k_cL$, $C_2 = j(\rho c / S) \exp(-jMk_c L)\sin k_cL$, $C_3 = j(S / \rho c) \exp(-jMkc L)\sin kcL$ and $C_4 = \exp(-jMkc L) \cos kc L$

where M=V/c represents the Mach number (M<0.2) for mean flow, c represents the sound speed (m/s), k_c=k/ (1-M^2) represents the wave number in convective condition (rad/m), k=ω/c represents the wave number in acoustic consdition (rad/m), ω represents the angular frequency (rad/s), ρ represents the fluid density (kg/m^3), and j represents the square root of -1.

Transfer matrix method

In the comparable circuit employing acoustic two state variables, mass velocity v and acoustic pressure p, the following matrix relation was developed to link state variables on the two sides of the element subscripted r shown in figure 2. [20, 24].

$$\begin{bmatrix} p_r \\ v_r \end{bmatrix} = \begin{bmatrix} A\ 2x2\ transfer\ matrix \\ for\ r\ ^{th} element \end{bmatrix} \begin{bmatrix} p_{r-1} \\ v_{r-1} \end{bmatrix} \tag{3}$$

[p_r v_r] is the vector specified at upstream point r and [p_{r-1} v_{r-1}] is the vector specified at downstream point. The matrix formation of r^{th} element is modelled as:

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{21} \end{bmatrix} \tag{4}$$

The values of $A_{11},\ A_{12}, A_{21}, A_{22}$ are computed as:

$$A_{11} = \left|\frac{p_r}{p_{r-1}}\right| v_{r-1=0}\ A_{12} = \left|\frac{p_r}{v_{r-1}}\right| p_{r-1=0}\ A_{21} = \left|\frac{v_r}{p_{r-1}}\right| v_{r-1=0}\ A_{22} = \left|\frac{v_r}{v_{r-1}}\right| p_{r-1=0}$$

Computation of Transmission Loss (TL) for Hybrid Absorptive Mufflers

The transmission loss is mathematically expressed as:

$$TL = 10\ log \frac{(incident\ energy)}{(transmitted\ energy)} \tag{5}$$

$$TL = 20\ log\frac{(p_{inc.})}{(p_{trans.})} + 10\ log\frac{(s_o)}{(s_i)} = 20\ log\frac{(p_1 + \rho c v_1)}{(2p_2)} + 10\ log\frac{(s_o)}{(s_i)} \quad (6)$$

There are numerous ways to determine muffler transmission losses which have been discussed accordingly.

Decomposition Method

For one-dimensional sound to travel via a duct, a standing wave emerges when there is a change in impedance at the muffler inlet. The sound pressure can be divided into incident and reflected waves in the form of spectra. Using the two-microphone approach and separating the waves according to decomposition theory is one of the approaches to decompose the wave. An anechoic termination at the outlet is required to obtain solely transmitted waves (with the exception of reflecting waves) in the tailpipe [21, 31, 32].

Two-load Method

There are four microphones used in the two-load approach. To identify both the progressive and reflecting waves, two microphones are placed in the piping leading into and leading out of the system. Using Equation 7, transmission losses can be computed when the 4-pole muffler specifications have been determined using this method. Equation 3 demonstrates that there must be two loading conditions because there are only two equations connecting the state variables and only two unknown (2-pole) parameters. A stiff termination, like a steel plate, is typically used to close the outlet tube after leaving the termination exposed to the atmosphere [22].

$$TL = 20\ log_{10}\left(\left| \frac{1}{2}\left[A + \frac{B}{(\rho_0 c)} + (\rho_0 c)\ C + D\right] \right| \right) + 10\ log_{10}\frac{(s_o)}{(s_i)} \quad (7)$$

Two source Method

The previously mentioned two-location approach has been enriched further, advancing to the two source-location method. For the second setup, the source is relocated using this approach from the inlet to the output location. The terminations need not have to be identical or anechoic due to the two varied testing setups. However, in most of the cases, the prime focus is to reduce the background noise that is being measured.

This method was used throughout this entire research since it is the most accurate and steady measurement available. When mass flow was added, this method gained another advantage because air was free to exit the tailpipe. If the outlet was shut off, this would not be feasible for the two-load setup [23, 28].

Wave 1-D Approach Aid in Designing and Optimizing Muffler Performance

In this work Wave 1-D evaluated the muffler's acoustic behaviour for transmission loss by simulating the one-dimensional sound wave propagation using the Wave 1-D program. It is a crucial metric for assessing how well a muffler reduces noise. It calculates the difference between the incident and transmitted sound waves' sound power levels after passing through a muffler. Transmission loss is only a feature of the muffler itself and is unaffected by the source or termination conditions.

Selection of Materials

The selection of porous material significantly impacts the thermal and mechanical durability of the muffler. Here we compare our work for two materials namely Glass Fibre and Rock Wool as Porous materials this consist high thermal resistance which can withstand with high elevated temperatures at muffler, which is essential for maintaining structural integrity under high exhaust temperatures. Mechanically, the material must exhibit sufficient strength and fatigue resistance to endure the vibrational stresses and pressure fluctuations encountered during operation. The choice of material thus directly affects the longevity and reliability of the muffler. The table 2 represents the thermal and mechanical durability for both the materials.

Table 2. Comparison of glass fiber and rock wool material property

Property	Glass fiber	Rock wool
Sound Absorption	Excellent at mid to high frequencies	Excellent at low to mid frequencies
Transmission Loss	Good across a wide frequency range	Superior at low frequencies
Thermal Resistance	Up to 230°C	Up to 600°C
Mechanical Durability	Less durable, flexible	Highly durable, rigid

Geometry and Arrangement of Porous Materials

The geometry and arrangement of porous materials are critical factors in determining the muffler's noise reduction capacity. The geometry influences the surface area available for sound absorption, while the arrangement affects the flow path (by using Baffle plate, extended pipe, resonator etc.) and interaction of sound waves with the porous material here we used namely two porous materials Glass Fibre and Rock Wool. The Optimized geometry and strategic arrangement can enhance the dissipation of acoustic energy, leading to improved noise attenuation. Proper design ensures that the sound waves are effectively absorbed and converted into heat, thereby maximizing the muffler's noise reduction performance.

EXPERIMENTAL VALIDATION OF HYBRID ABSORPTIVE MUFFLER

This experimental setup enclosed with hybrid absorptive muffler consist of other components attached to it which are two microphones, a speaker of AU-60 capacity and a defined load. This set up is further connected to amplifier, sound analyser and a software gadget. The experiment is executed at frequencies between 50 and 3000 Hz. To cover the appropriate frequency range, the measurements are divided into two halves at two places, 1-1' and 4-4' (Figure 3). For measuring pressure in the frequency range of 50 to 400 Hz, the requisite sites 1-2-3-4 are utilised, while locations 1'-2-3-4' are used for measuring pressure in the frequency range of 400 to 3000 Hz.

A circular muffler that comprises of a coaxially positioned internal perforated tube and an exterior cylindrical tube. Circular flanges installed on the internal tube cover the two ends of the exterior cylindrical chamber. The test setup includes the perforated pipe with internal diameter of 35 mm, while the expansion chamber is 500 mm long and 130 mm in diameter. Glass fibre and rock wool have been chosen as the two materials for the performance of sound transmission loss. As depicted, it is now filled with various packing densities, including 60 kg/m^3, 80 kg/m^3, and 100 kg/m^3 in Figure 4.

Figure 3. Experimental setup for hybrid absorptive muffler to determine transmission loss under the condition of loading

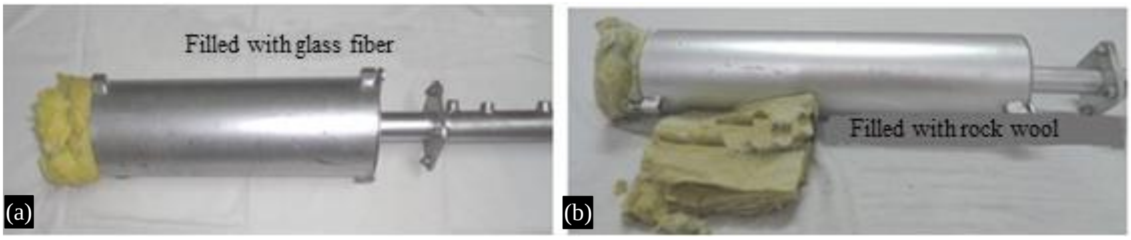

Figure 4. Unfilled muffler compartment consisting (a) Glass wool (b) Rock wool

Figure 5 and figure 6 highlights the comparative analysis of sound transmission loss for Glass wool and Rock wool material at same packing density based on experimental validation and wave 1-D analysis. Wave 1-D analysis can be also simulated incorporating alternate design criterion.

WAVE 1-D ANALYSIS FOR HYBRID ABSORPTIVE MUFFLER

A circular muffler with dimension of 500 mm in length and 130 mm in diameter and having tail pipe of length 130 mm and diameter 35 mm is designed in wave 1-D *as* shown in Figure 7.

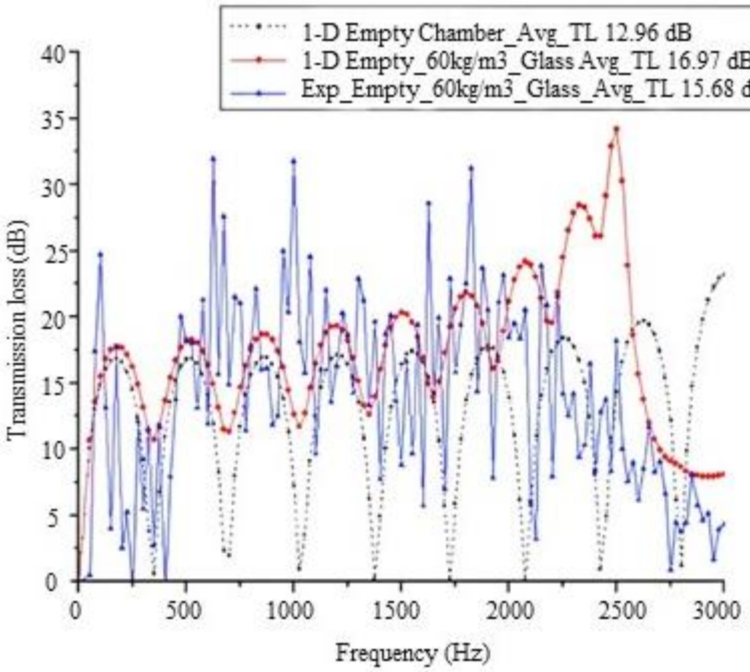

Figure 5. Comparative analysis for glass wool material with constant packing density.

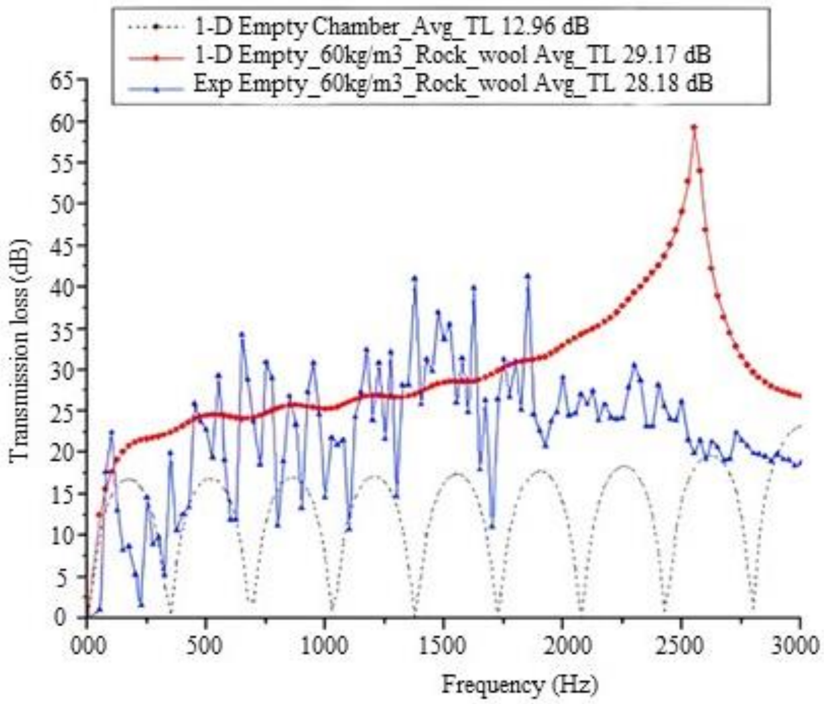

Figure 6. Comparative analysis for rock wool material with constant packing density.

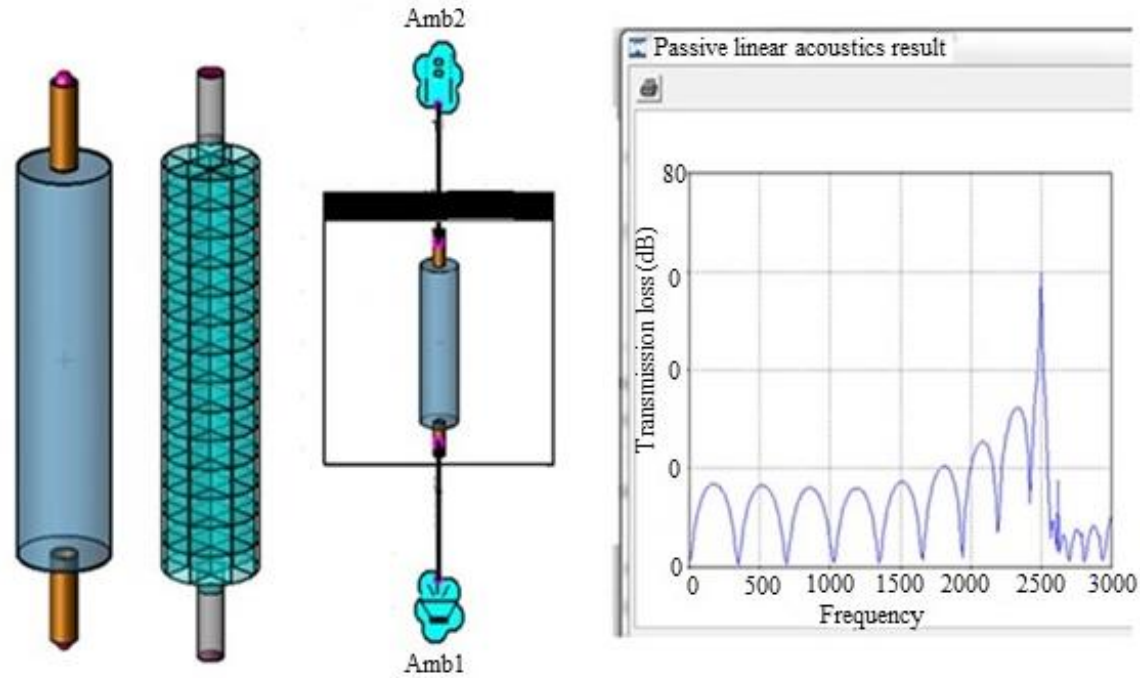

Figure 7. Muffler with non-perforated arrangement.

After performing the 1-D analysis, It was discovered that the loss in sound transmission is 12.5 dB. Further in this muffler, a perforated tube is inserted and at flow percentage of 10, the transmission loss is increasing having the value of 14.8 dB.

RESULTS AND DISCUSSION

The transmission losses have followed an increasing trend having the numeric values as 16.1dB, 17dB, 15dB and again 15 dB for these values of flow percentage – 12.5, 15,17.5 and 20 respectively as indicated in the Figure 8.

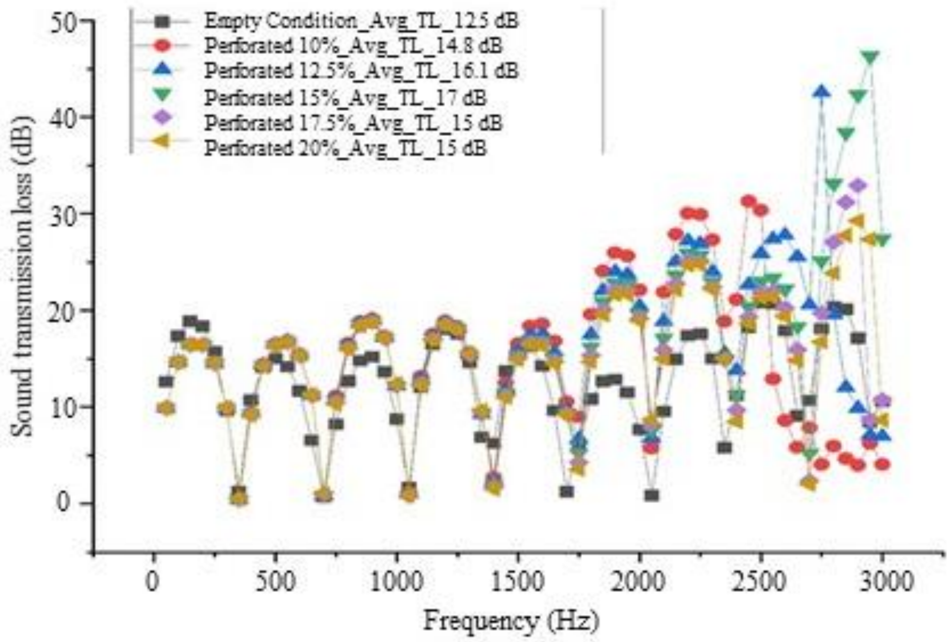

Figure 8. Variation in transmission loss employing perforated arrangement.

From the perforated design analysis, it was found that the optimum design condition for considered dimension of muffler is at perforated flow percentage of 10 where sound transmission loss was maximum with17 dB. Further in this optimum design a baffle was inserted in the centre with change in perforation and it was found that there was no change or increase in value of transmission losses as shown in Figure 9.

While using double baffle arrangement, at 10% flow, the sound transmission loss has slightly got incremented to 17.2 dB but at 5% flow, the sound transmission loss has increased somehow more to 19.8 dB which has made this arrangement in non-operation mode because of back pressure inside the muffler chamber that can also damage the engine as highlighted in Figure 9.

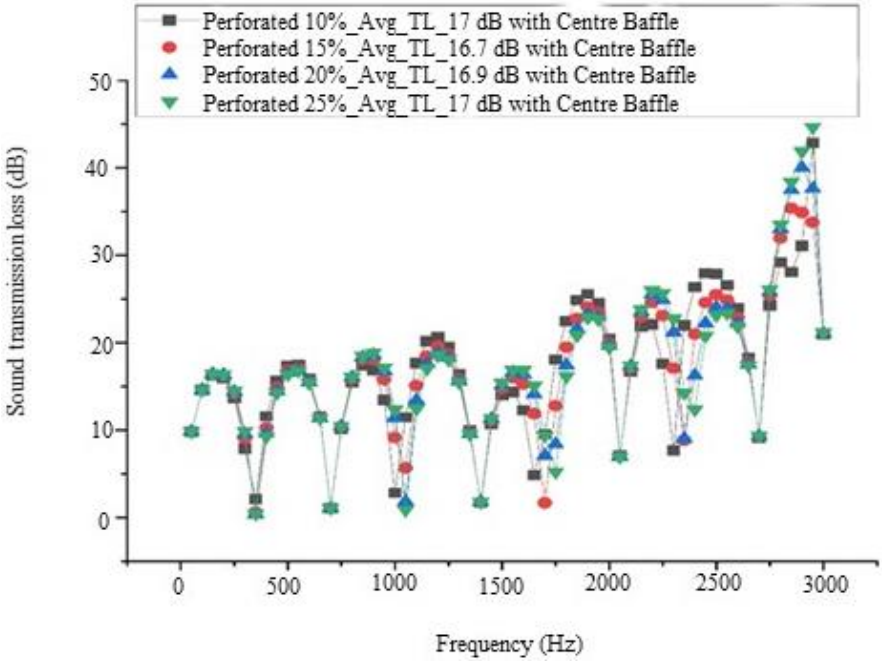

Figure 9. Variation in transmission loss employing centrally placed baffle arrangement.

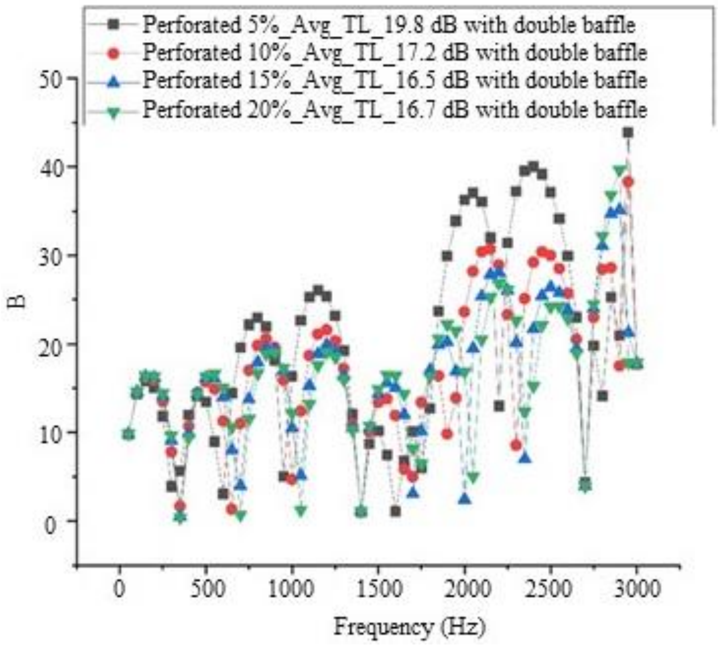

Figure 10. Variation in transmission loss employing double baffle arrangement.

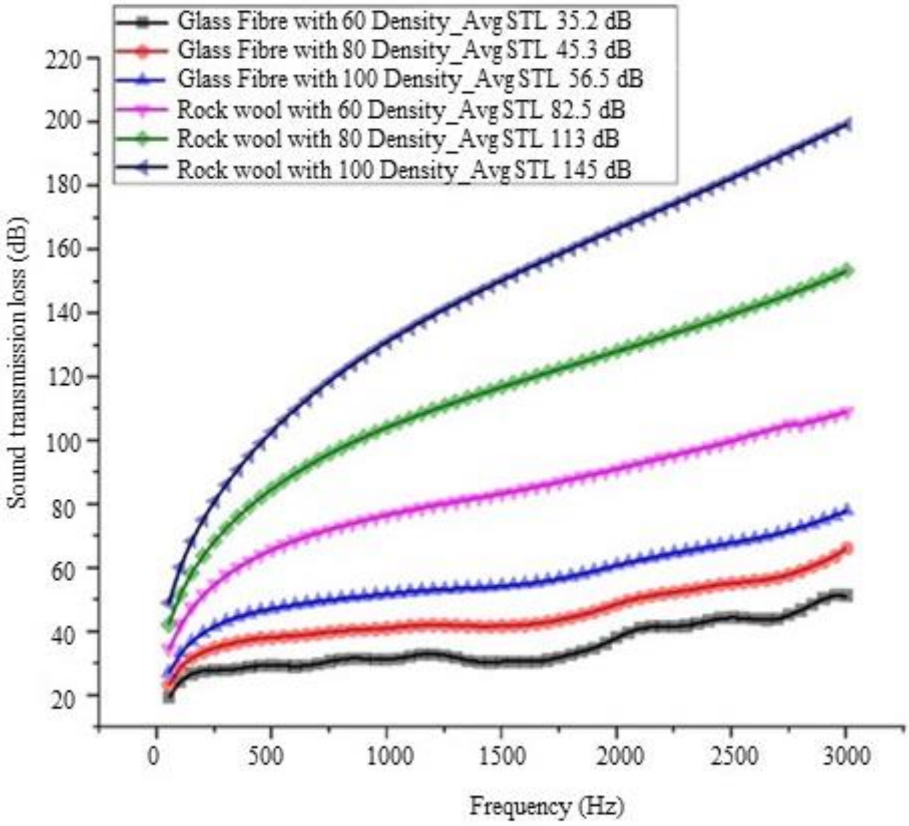

Figure 11. Variation in transmission loss for double baffle arrangement using different materials at different densities (kg/m^3)

The muffler finally selected after performing the 1-D wave analysis was found to be the muffler with double baffle arrangement having 10% flow and sound transmission loss 17.2 dB shown in figure 10. The further analysis had to be performed employing two different types of absorptive materials – glass fibre and rock-wool to measure the transmission losses at different density levels shown in Figure 11.

While filling with two different types of absorptive materials – glass fibre and rock wool at different packing density levels. At 60 kg/m^3 packing density level, for glass fibre, the numeric value for sound transmission loss was found to be 35.2 dB. Similarly, at 80 kg/m^3 and 100 kg/m^3 packing density the sound transmission losses have increased to 45.3 dB and 56.5 dB respectively. In contrast to this, for rock wool at 60 kg/m^3 packing density level, the transmission loss was computed as 82.5 dB. Similarly, at 80 kg/m^3 and 100 kg/m^3 packing the sound transmission losses have incremented to 113 dB and 145 dB respectively.

CONCLUSIONS

As the density level increases, the sound transmission has an increasing trend in its numeric value. While comparing between two different types of materials, glass fibre and rock wool during filling in the muffler chamber, rock wool has better characteristics in conformance to improved transmission loss than glass fibre. In order to estimate the transmission losses for a muffler with optimal design being created, wave 1-D analysis was performed.

Initially, absorptive materials such as glass wool and rockwool were used to measure sound transmission loss for the hybrid absorptive muffler. Rockwool, as the absorptive material, was found to produce the highest transmission loss. For the frequencies ranging in between 50Hz and 3000 Hz, the transmission losses were determined inserting sound absorptive materials in the hybrid absorptive muffler.

For rock wool, the maximum average sound transmission loss at 60 kg/m^3 density of 82.5 decibels was noted, at 80 kg/m^3 and at 100 kg/m^3 it was 113 dB and 145 dB respectively. The experimental setup incorporated in this research for hybrid absorptive muffler was used to corroborate these findings, and it revealed that the sound transmission loss for reactive muffler was found to be 12.96 dB experimentally and when the same mufflers were designed with same dimensions in wave 1-D the transmission loss were found to be 12.5 dB as indicated in Figure 7.

Future Directions of Research

In order to reduce the sound of a muffler, one of the greatest noise-reducing devices would be this hybrid absorptive muffler with rockwool as the absorptive material. This study strengthened the argument that rockwool is among the best sound absorptive materials for the applicability in hybrid absorptive mufflers. Incorporating novel theory for numerical analysis of the hybrid absorptive muffler employing a 3D time domain numerical technique can be visualized as a new research effort. This research can be advanced inserting few other absorptive materials like polyester, melamine, powertex, and using other glass fibres while comparing these materials addressing their applicability to reduce the sound impact during the usage of hybrid absorptive muffler.

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