B. TECH. PROJECT REPORT

On

Design and Analysis of Auto-Rickshaw Mufflers

BY

Vishnu Kumar Meena

DISCIPLINE OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Design and Analysis of Auto-Rickshaw Mufflers

PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of

BACHELOR OF TECHNOLOGY

in

MECHANICAL ENGINEERING

Submitted by:

Vishnu Kumar Meena
Discipline of Mechanical Engineering

Guided by:

Dr. Krishna Mohan Kumar

INDIAN INSTITUTE OF TECHNOLOGY INDORE
May 2022

<u>**CANDIDATE'S DECLARATION**</u>

I hereby declare that the project entitled **"Design and Analysis of Auto-Rickshaw Mufflers"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr. Krishna Mohan Kumar,** Assistant Professor, Discipline of Mechanical Engineering, IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Vishnu 26/05/2022

Vishnu Kumar Meena

180003064

<u>**CERTIFICATE by BTP Guide**</u>

It is certified that the above statement made by the students is correct to the best of my knowledge.

K. M. Kumar 26.05.2022

Dr. Krishna Mohan Kumar
Assistant Professor,
Department of Mechanical Engineering,
IIT Indore.

PREFACE

This project aims to get the best muffler design possible by analyzing auto rickshaw mufflers available presently in the market. The proposed methodology is divided into three major steps: 1. Mechanical Design, 2. Analysis, and 3. Improvements. For this, three old auto-rickshaw mufflers were selected from the scrap market. At first, these mufflers were cut to see the internal structure, then the measurement of dimensions were noted. Following to that, plane wave analysis and 3-D FEM analysis were carried out. The modification in one of the silencers were made to achieve the better attenuation characteristics in a low frequency region. Through this method, efforts have been made to present the proposed methodology, results and conclusions of the study in a lucid and comprehensible manner.

Vishnu Kumar Meena
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

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I wish to thank **Dr. Krishna Mohan Kumar** for their kind support and esteemed guidance.

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Vishnu Kumar Meena
B.Tech. IV Year
Discipline of Mechanical Engineering
IIT Indore

Abstract

In the cities and towns of India, high traffic is a big problem. Auto-rickshaw is an obvious choice for transportation in cities and towns. It can transport people and goods from any narrow street to the other street due to its small size and high steering ratio. The high steering ratio of auto-rickshaws makes it a better choice to move in high traffic hours. However, the noise radiation from such auto-rickshaws is not only the concern for other people on the roads or nearby houses, but also for the driver and passengers sitting because of the open passenger cabin which is partially covered with metal sheets and canvas. Therefore, the auto-rickshaws running on single cylinder engines need to have very efficient mufflers for the attenuation of unmuffled exhaust SPL. The automotive engines run on different crankshaft speeds and engine loads. Therefore, the muffler used in an auto-rickshaw need to have wideband insertion loss (IL) spectrum with good attenuation at low frequencies.

In this study, three old auto-rickshaw mufflers were taken from the scrap market. At first, these mufflers were cut to see the internal structure, then the measurement of dimensions were taken. After that, plane wave analysis and 3-D FEM analysis were carried out. The modification in one of the silencers were made to achieve the better attenuation characteristics in the low frequency region. Also, back pressure is calculated for all three mufflers, it should be too high.

Keywords: Auto-rickshaw mufflers, plane wave analysis, 3-D FEM, Insertion Loss

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Introduction

Urban air pollution is a severe problem across the globe, affecting the health of a huge amount of the worldwide population, particularly in developing countries. According to a recent World Health Organization (WHO) research on the Global Burden of Disease (GBD), it is one of the top 10 causes of mortality, accounting for 4.2 million premature deaths per year _(Kollambath). One of the primary sources of air quality degradation is traffic. The number of trips per day is increasing as a result of increased urbanisation and economic development. The access point of a signalised intersection is characterised by intense roadside development and intense traffic density, with no lane discipline, causing frequent interruption and congestion. These conditions result in higher traffic conflicts. Auto-rickshaws (three-wheeled vehicles) play a significant role in Indian traffic since they serve as an intermediary mode of public transportation. They bridge the gap between private car ownership and fixed-route and large-capacity public transportation networks in emerging cities. Because of their low initial and ongoing costs, auto-rickshaws are a popular means of private transportation.

In an automobile, exhaust gases are generated from the engine's combustion chamber and exhausted in the atmosphere. Internal combustion engine exhaust noise is one of the most significant pollutants in today's urban environment. A well-designed muffler, also known as a silencer, can effectively reduce this noise. After leaving the engine, exhaust gases pass through the exhaust manifold, catalytic converter, and muffler before exiting through the tailpipe. Today, a lot of designs are available, with the main variation being how they handle the number of gases released through the exhaust manifold. The additional static pressure produced on the engine by the muffler due to constraints in the flow of exhaust gases is known as Back Pressure. In general, an exhaust muffler must meet certain basic specifications, including proper insertion loss, low back pressure, and proper muffler sizing (which affects cost and accommodation), and durability to survive harsh conditions and extremely high temperatures and in the case of auto-rikshaw, we should also consider the space availability so ground clearance and centre of mass of the auto-rickshaw does not affect. As a result, various design considerations must be made to create an optimal muffler design. The muffler chamber design, exhaust gas flow constraints, and muffler material all affect muffler performance. One can design a very good muffler for noise attenuation, however, that may lead to very high backpressure which results to more pumping losses and ultimately high brake specific fuel consumption (BSFC). And, the high BSFC cannot cannot be tolerated for low fare transportation means like auto-rickshaw.

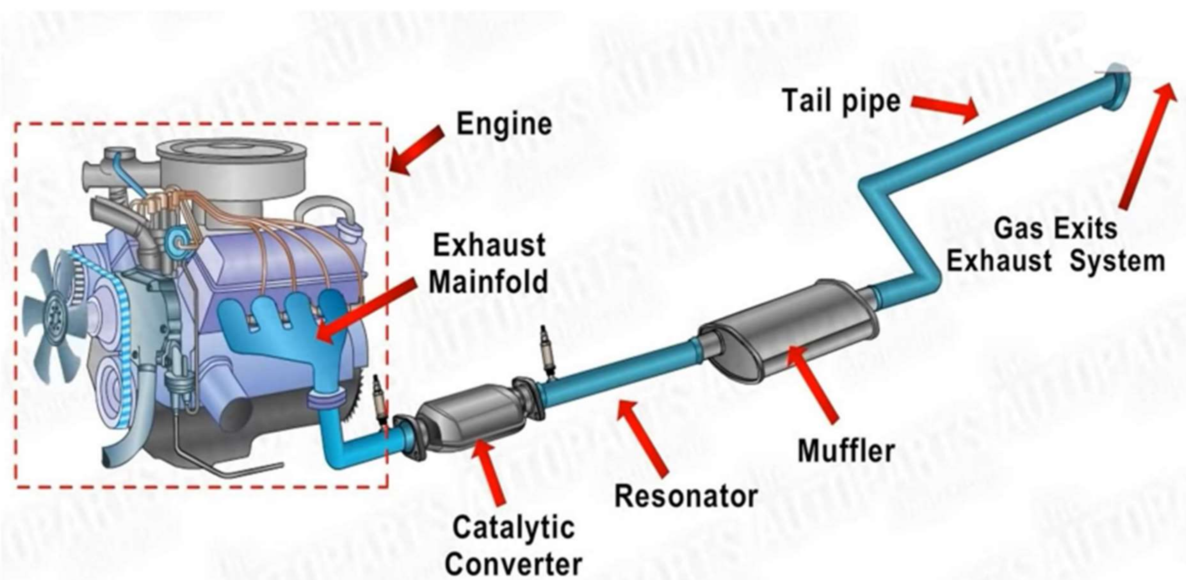

Figure 1 The exhaust system of an engine *(autoparts, n.d.)*

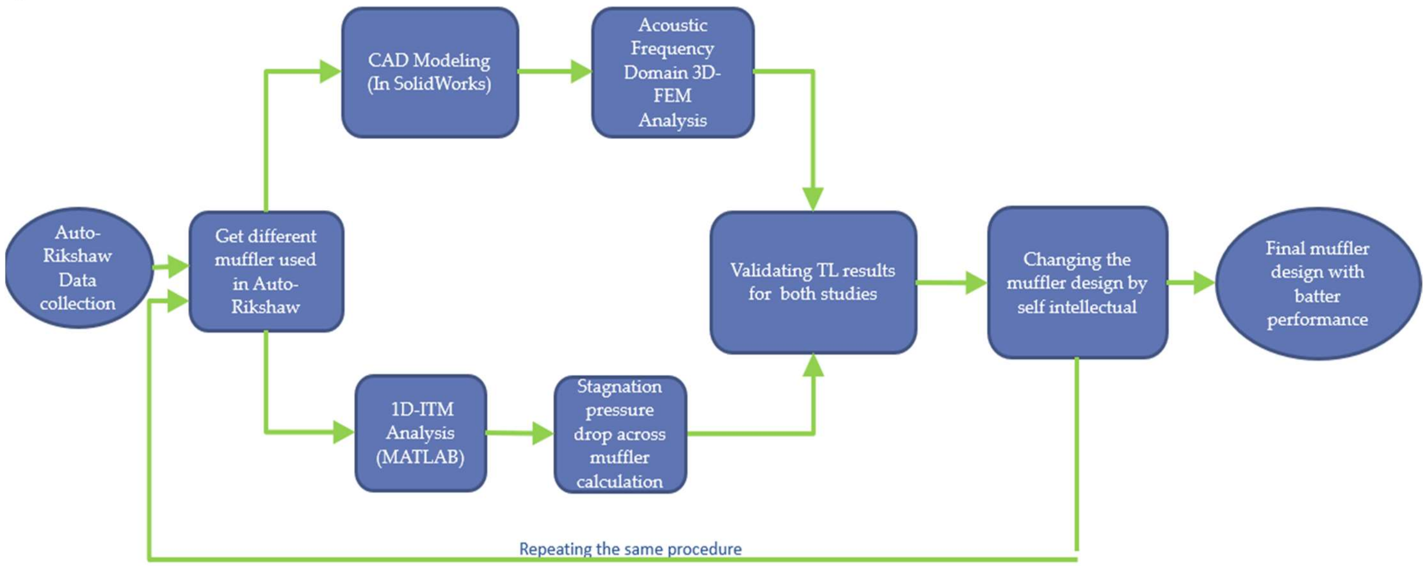

Figure 2 Flow chart of the process

1.1 Types of Mufflers

The exhaust gases from an internal-combustion engine are passed through a muffler, also known as a silencer, to reduce the engine's airborne noise.

1. **Dissipative(absorptive) silencer:** In these types of silencers fibrous and porous packing materials are used to absorb sound waves and reduce sound output. As sound waves travel through insulative materials, some of their energy is converted to heat energy, which is then diffused through the air.

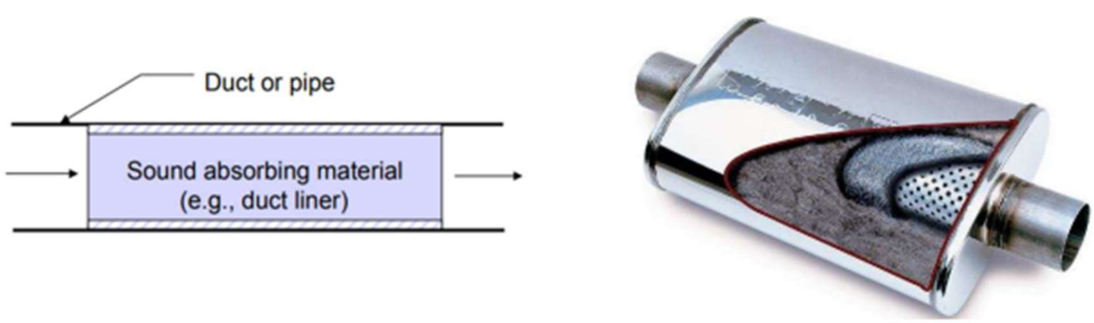

Figure 3 Absorptive Muffler (source 4wheelonline)

2. Reactive Mufflers: The Helmholtz principle governs the operation of the reactive muffler. The muffler reflects the pressure wave back to the noise source 180 degrees out of phase, cancelling it out through destructive interference.

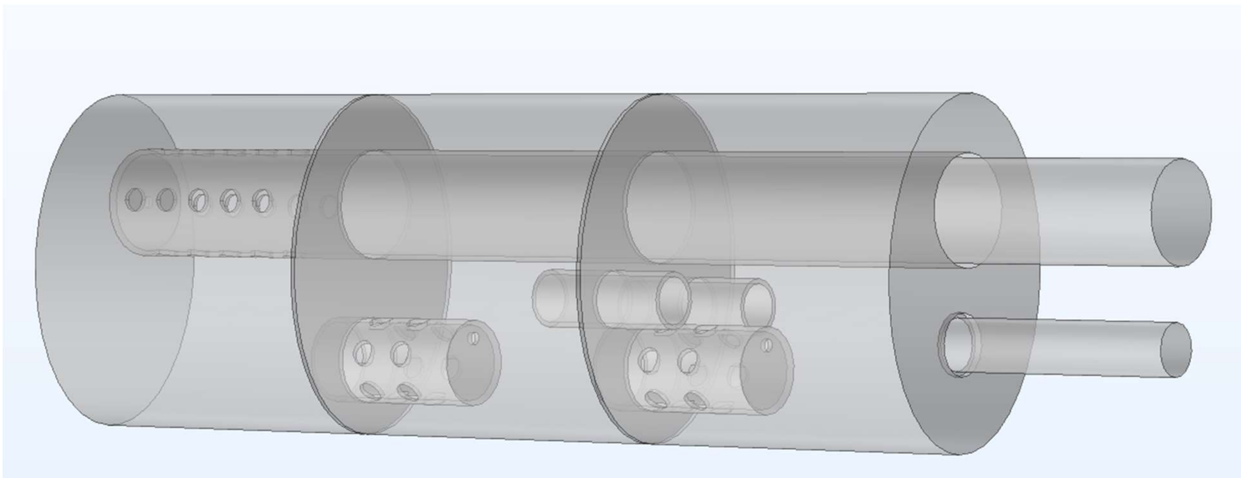

Figure 4 Reactive Mufflers

3. Combination of reactive and dissipative muffler: In this type of muffler the Sound is attenuated by reflection and "cancellation" of sound waves + absorption of sound.

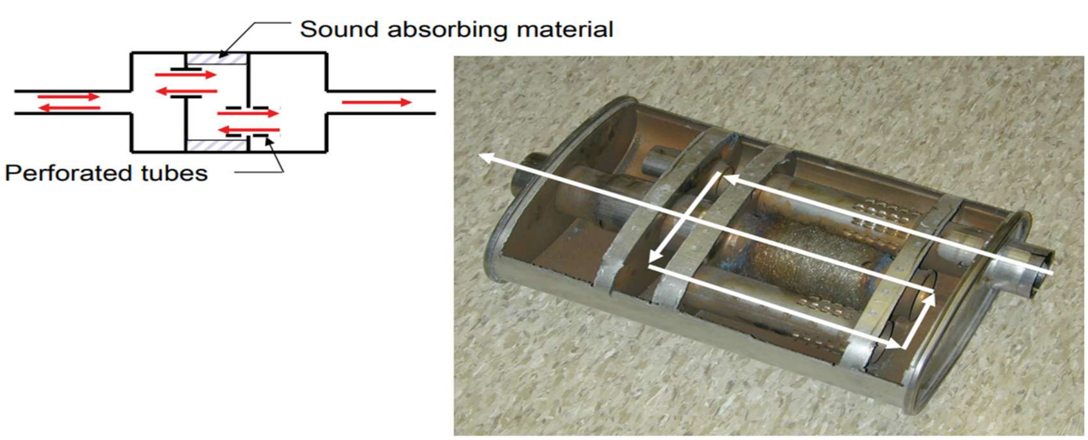

Figure 5 Combination of a reactive and dissipative muffler (source 4wheelonline)

5. **Heat recovery muffler:** The majority of the energy produced by the combustion of fuel in internal combustion engines, both reciprocating and gas turbines, is rejected as heat. At full load, a reciprocating engine, for example, turns approximately one-third of the available energy into productive work. The remaining two-thirds are lost as heat to the jacket water, exhaust gas, oil cooler, and radiation into the environment. Heat recovery can result in significant savings in installations where this heat can be put to good use. (H, 2014)

6. **Active silencer:** Active silencing or sound cancellation systems, which use detectors to detect noise in an exhaust pipe and a loudspeaker to reintroduce an inverted signal, have been created to minimize low-frequency noise. (H, 2014)

1.2 Objective

An auto-rikshaw engine creates noise above 100 dB (dsportmag.com, n.d.). Generally, a good silencer for automotive application has adequate insertion loss (in dBA) and low overall backpressure. So, the project aims to reduce the sound level of the auto-rickshaw silencer by doing some suitable modifications to the exciting silencer considering backpressure and space availability.

To analyse the performance of the auto-rickshaw muffler available in the market by using 1-D ITM (MATLAB) and 3D-FEM (COMSOL Multiphysics software).

Validation of simulation (3D-FEM) with numerically (1-D ITM).

Calculating Back Pressure by using Flow-Network Analysis method.

Based on the result making some suitable modifications in muffler design to get better performance.

Theory of Acoustic

1. **Sound Waves:** Sound is a pressure wave made up of alternating high and low air pressure pulses. When an exhaust valve opens unexpectedly, a burst of high-pressure gas enters the exhaust system, causing pulses. The gas molecules collide with the lower-pressure molecules in the pipe, forcing them to stack on top of one another. They pile up on the molecules a little further down the pipe, resulting in a low-pressure zone. As a result, the sound wave moves through the pipe faster than the actual gases. As these pressure pulses reach our ears, the eardrum vibrates back and forth, producing sound. The amplitude of the wave determines the volume of the sound. Higher amplitude sound waves move our eardrums more, resulting in a louder volume perception. It is possible to cancel the sound by creating a sound wave that is exactly opposite another wave resonance chamber within a muffler designed to reflect a sound wave that is 180 degrees out of phase with the engine noise. The reflected sound waves collide with the exhaust sound waves and cancel each other out, leaving the tailpipe with only low-level heat. When the engine's sound wave meets the resonance chamber wall, the muffler's resonance chamber reflects it. As a result, both destructive and constructive waves occur within the chamber, with only a small portion of the sound wave being released into the atmosphere. The length of the chamber is carefully calculated to accommodate the engine's typical sound pressure level.

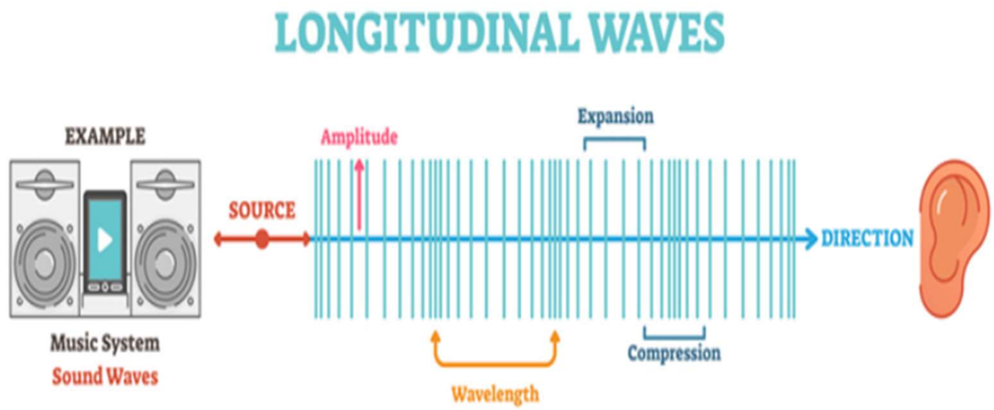

Figure 6 Sound Waves (source Pasco scientific)

2. **Back Pressure:** The mean exhaust pressure is the average pressure in the exhaust pipe during the exhaust stroke, while the ambient pressure is the pressure in the atmosphere. Backpressure is the difference between these two pressures.
   The greater the back pressure created by the exhaust system, the less net power available on the crankshaft, and thus the higher the specific fuel consumption. The amount of power lost varies under a variety of circumstances, but a decent thumb rule is that 25.4mm of mercury backpressure (3.39kpa) results in a 1.0 percent decrease in maximum engine power.

3. **Sound Intensity:** Sound energy passes through a unit area in 1 second.
   Faintest sound intensity for humans: $1.00 \times 10^{-12} (W/m^2)$
   Highest sound intensity for humans: 1.00 (W/m^2)

4. Acoustic Filter Performance Parameters

The performance of an acoustic filter (or muffler) is measured in terms of one of the following parameters:

1. Transmission loss, TL,
2. Insertion loss, IL
3. Level difference (LD), or noise reduction (NR).

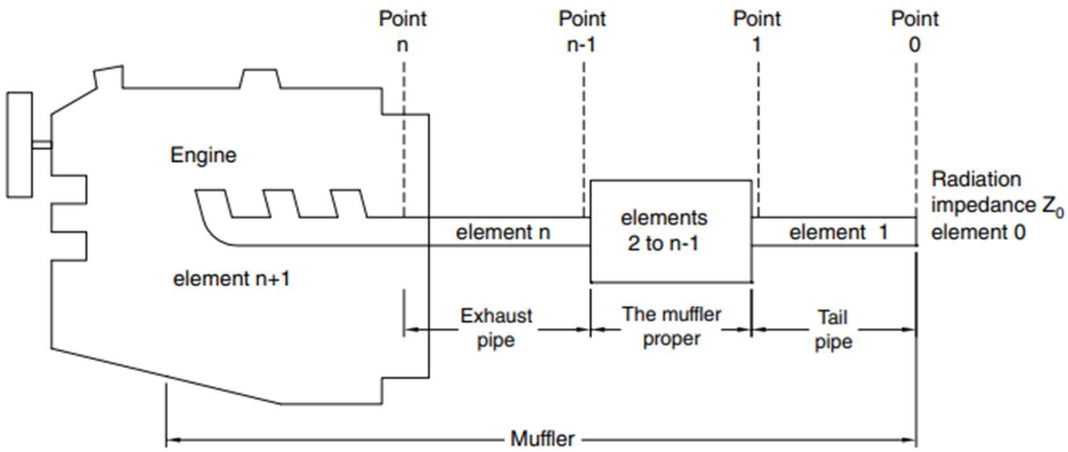

Figure 7 Engine exhaust system _*(Munjal M.)*

1. Transmission Loss (TL)

Transmission loss is independent of the source and assumes an anechoic downstream termination. It describes what is known as "the muffler proper's" performance. The difference in power levels incident on the muffler and those transferred downstream into an anechoic termination.

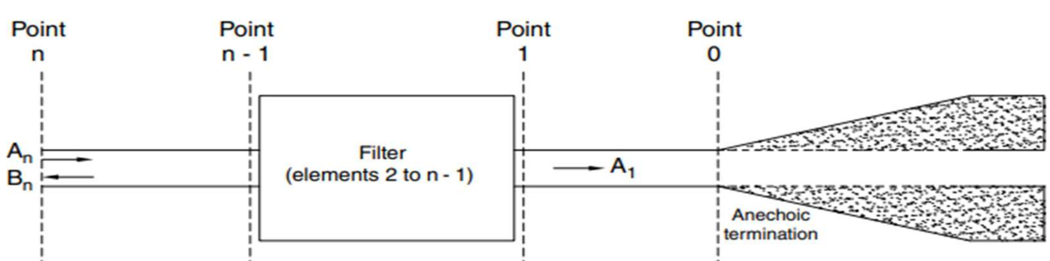

Figure 8 Transmission Loss _*(Munjal M.)*

TL = Lwi – Lwt.

Lwi = power level incident on muffler proper.

Lwt = power level transmitted downstream.

Anechoic termination: means there is an only incident wave there is no reflected wave.

Transmission Loss in Terms of the Four-Pole Parameters

$$TL = 20\log\left[\sqrt{\left(\frac{Y_1}{Y_n}\right)}\left|\frac{T_{11}+\frac{T_{12}}{Y_1}+T_{21}Y_n+\left(\frac{Y_n}{Y_1}\right)T_{22}}{2}\right|\right] \tag{3}$$

Here,

T_{11}, T_{12}, T_{21}, and T_{22} are the elements of the overall transfer matrix of a muffler.

Y_1 and Y_n are the characteristic impedance of the head and tailpipes.

2. Insertion Loss, IL

Insertion loss is the difference between the acoustic power radiated without and with the filter.

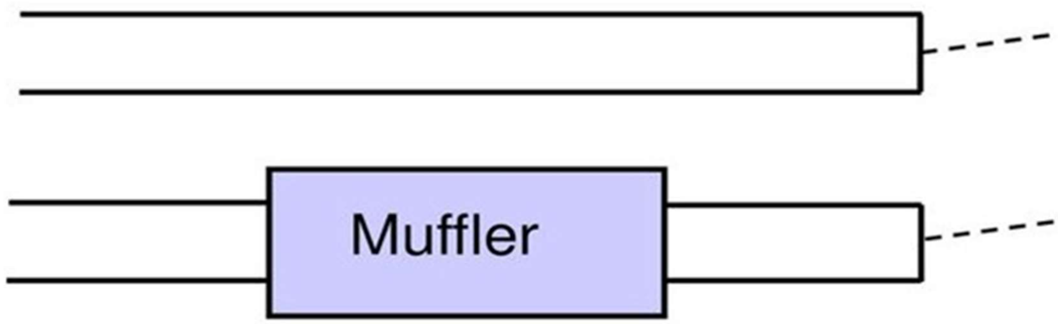

Figure 9 Insertion Loss

$$\text{IL} = \text{Lw1 - Lw2 (dB)}$$
$$= 10\log\left(\frac{W_1}{W_2}\right)(\text{dB}) \qquad (1)$$

Here, W1 = radiated acoustic power without any filter

W2 = radiated acoustic power with filter

Insertion Loss in terms of the four-pole parameters

$$\text{IL} = 20\log\left[\left(\frac{Y_1}{Y_n}\right)\left|\frac{T_{11}+\frac{T_{12}}{Y_1}+T_{21}Y_n+\left(\frac{Y_n}{Y_1}\right)T_{22}}{2}\right|\right] \qquad (2)$$

Here,

T_{11}, T_{12}, T_{21}, and T_{22} are the elements of the overall transfer matrix of a muffler.

Y_1 and Y_n are the characteristic impedance of the head and tailpipes.

3. Level difference (LD), or noise reduction (NR)

The difference in sound pressure levels at two randomly chosen points in the exhaust pipe and tailpipe is known as the level difference.

$$LD = 20 \log \left|\frac{p_n}{p_1}\right| \text{ (dB)} \quad (4)$$

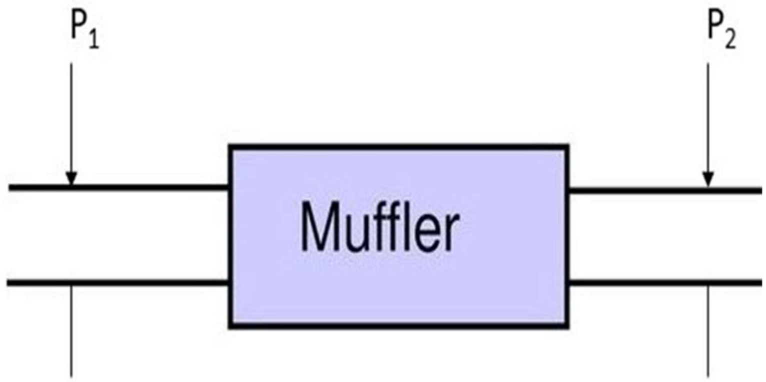

Figure 10 Level Difference

5. The Transfer Matrix Method

The transfer matrix relates the state variable on the two sides of the element.

$$\begin{bmatrix} p_r \\ v_r \end{bmatrix} = \begin{bmatrix} \text{A 2 } \times \text{2 transfer} \\ \text{matrix for the r}^{\text{th}} \text{ element} \end{bmatrix} \begin{bmatrix} p_{r-1} \\ v_{r-1} \end{bmatrix}$$

Here Pr and Vr are the upstream and Pr-1 and Vr-1 are the downstream variables

Transfer matrix of a uniform tube (distributed element)

$$\begin{bmatrix} \cos k_0 \, l_r & jY_r \sin k_0 l_r \\ j/Y_r \, sin \, k_0 l_r & cos \, k_0 \, l_r \end{bmatrix} \quad (5)$$

Transfer matrix of a Lumped in-line element

$$\begin{bmatrix} 1 & Z_1 \\ 0 & 1 \end{bmatrix} \quad (6)$$

Transfer matrix of a Lumped shunt element

$$\begin{bmatrix} 1 & 0 \\ 1/Z_r & 1 \end{bmatrix} \tag{7}$$

Sudden expansion and sudden contraction

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{8}$$

Here Z_r = acoustic impedance
k_0= wave number or propagation constant
Y_r = characteristic impedance

6. Mean flow Distribution and Back Pressure Estimation

Lumped flow resistance network uses an electrical circuit analogy with Kirchhoff's first law for the nodes or junctions and the second law for the closed loops.

Flow resistance R of the lumped element is defined as

$$R = \frac{\Delta p}{Q|Q|}, or\ R = \frac{\Delta p}{Q^2}, \tag{9}$$

Here

ΔP is the stagnation pressure drop across the element

Q is the volume flow rate passing through the element

Q is calculated as $\quad Q = \frac{\rho_a V_d N \eta_v}{120 \rho_{ex}}\left(1 + \frac{F}{A}\right) \qquad (10)$

Where ρ_a, V_d ,N, η_v, ρ_{ex} and F/A is the density of ambient air, the capacity of the cylinder, engine shaft speed in RPM, the volumetric efficiency of the cylinder, exhaust gas density, and fuel-air ratio, respectively.

Flow resistance at the open end

$$R_{open}=\varepsilon\frac{1}{2}\frac{\rho_0}{s^2} \tag{11}$$

Where S is the area of the cross-section of the duct and ε is 0.5 for an inlet and 1 for an outlet.

Flow resistance at holes

$$R_{holes} = \frac{\rho_0}{2C_d^2 s_{hole}^2} \tag{12}$$

Where C_d is the discharge coefficient, and S_{holes} is the total area of all the holes in the baffle.

7. Software used

a. SolidWorks: It is a solid modeling computer-aided design and computer-aided engineering application published by Dassault Systems. I have used it for CAD modeling of mufflers, it has a user-friendly interface end very easy to make a CAD model.

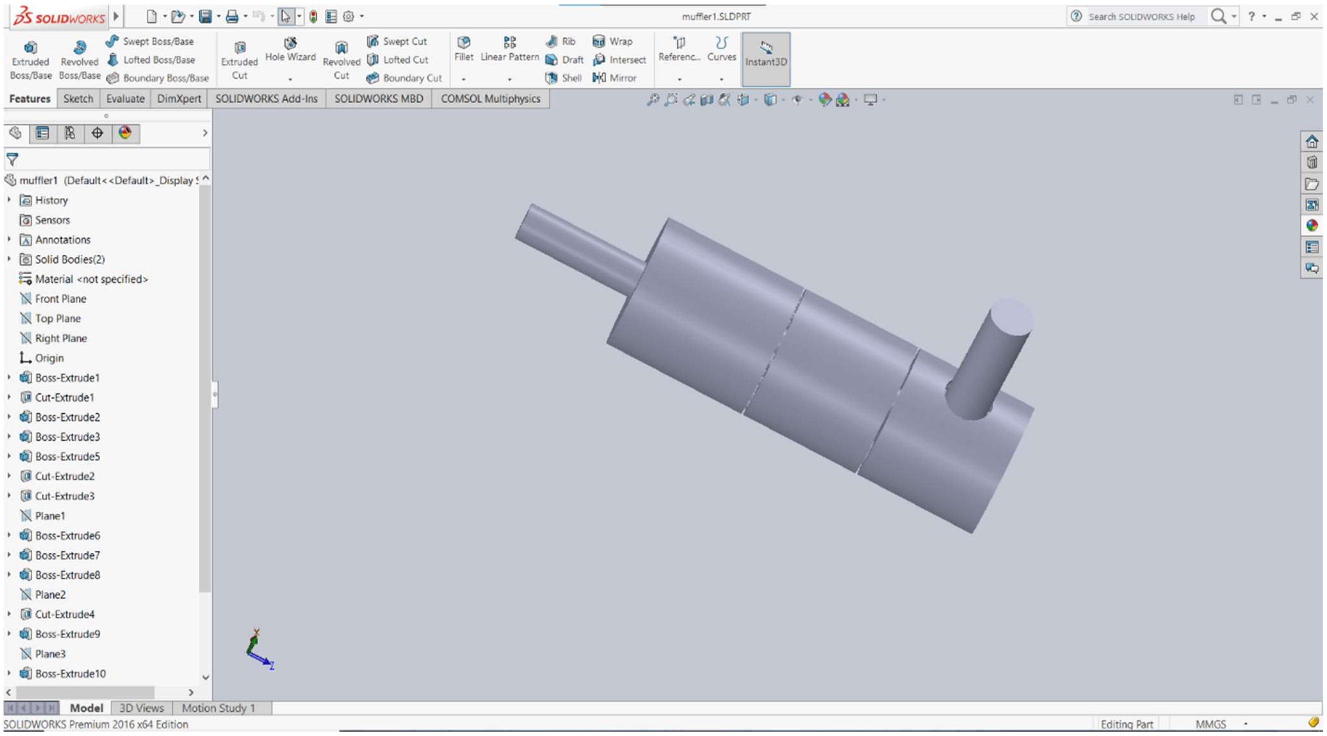

Figure 11SolidWorks Interface

b. COMSOL Multiphysics: COMSOL Multiphysics is a Multiphysics simulation and finite element analysis software that runs on any platform. It supports both traditional physics-based user interfaces and coupled partial differential equations systems. We can easily do more than study for the same model and we can import CAD files or can billed in COMSOL itself.

I have used it for Pressure Acoustics, Frequency Domain to find Acoustic Pressure, Sound Pressure Level variation in the muffler, and Transmission Loss Plot.

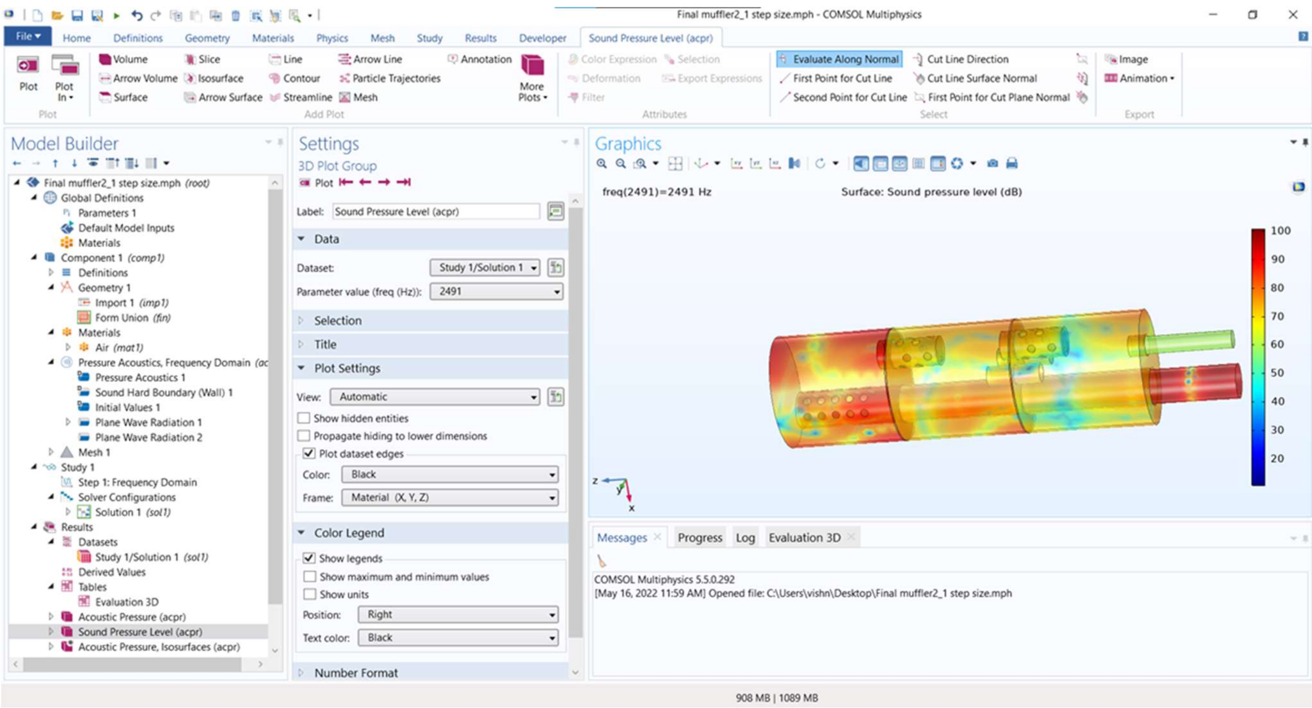

Figure 12COMSOL Multiphysics Interface

c. MATLAB: MathWorks developed MATLAB (matrix laboratory), a proprietary programming language and multi-paradigm numerical computing environment. MATLAB has various functions such as visualizing mathematical functions and data, matrix operations, connecting with other programming languages and designing user interfaces, and many more. we can successfully execute the mathematical model for 1D-ITM Analysis. This approach is quite rapid and highly useful for determining the influence of various settings. As a result, diagnosing issues is quite simple and quick. I have used it for 1D-ITM, Back-Pressure calculation, and plots.

Results and Discussion

Muffler 1: perforated side inlet end exit, one perforated baffle, and three chambers in a circular cross-section

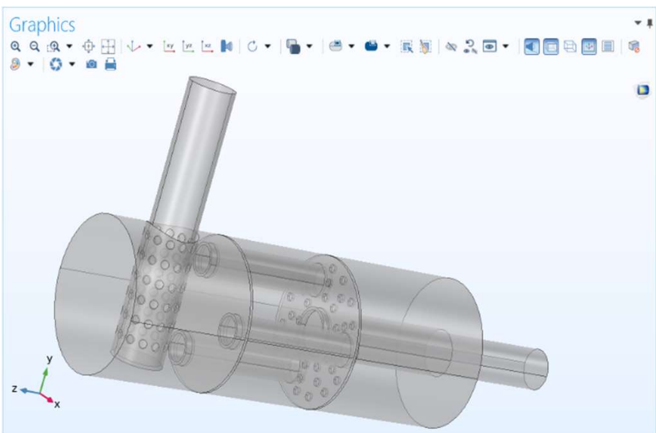

Figure 13Muffler 1 Acoustic Model

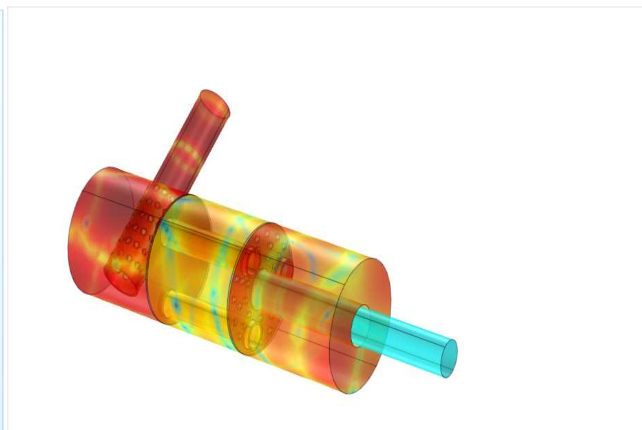

Figure 14 Muffler 1 Sound Pressure Level Distribution COMSOL

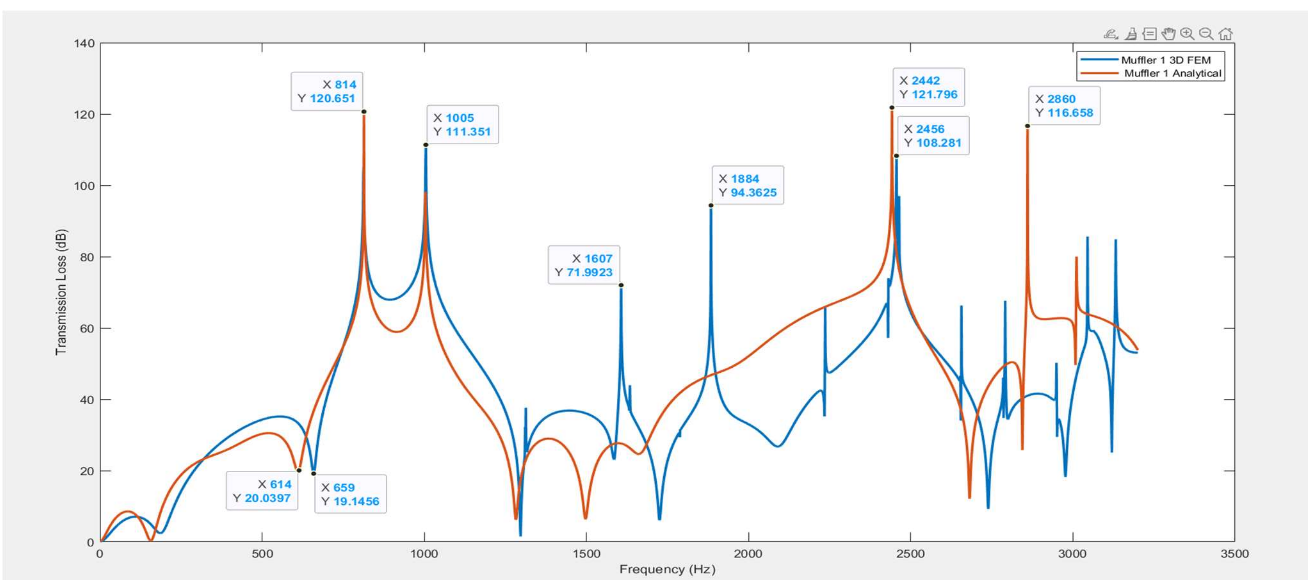

Figure 15 Transmission Loss Vs Frequency, combine plot for muffler 1 3D-FEM and Analytical without mean flow at 293.15K

A cut-off frequency of a circular tube is given as

$$f_{co} = \frac{1.84}{\pi}\frac{c_0}{D} = 0.5857 \quad \text{\_(Munjal M.)} \qquad (13)$$

It comes at around 1674 Hz, we can see from *Figure 15* that till the cut-off frequency both 1D-ITM and 3D-FEM are comparable after the cut-off of the plane wave condition will not be satisfied and the 1D-ITM plot will not be the same as 3D-FEM. So by this plot, we can validate our result, because from both methods result's are the same.

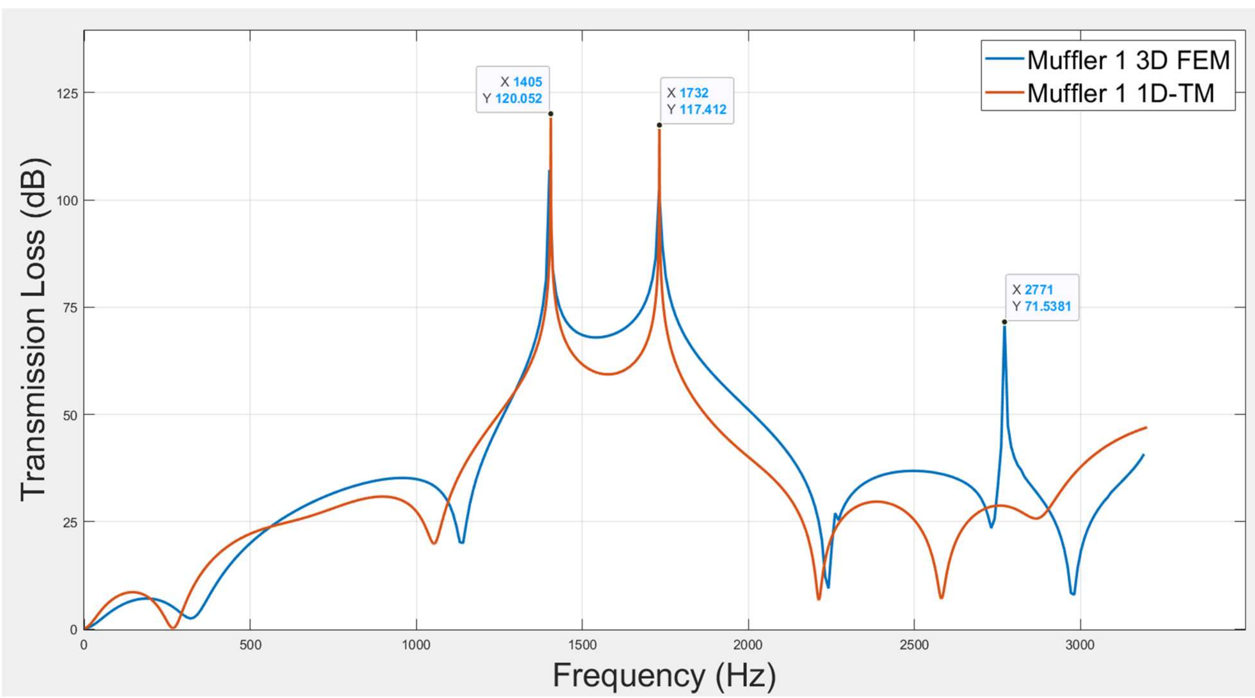

Figure 16 Transmission Loss Vs Frequency, Combine plot for muffler 1

In this plot, I have to check it with the mean flow at 873.15K and it follows the same trend. With mean flow, the graph shifts rightward because in the mean flow conditions at 873.15K sound speed will increase and a higher value of TL will occur at a higher frequency.

The first peak is shifted at 1405 Hz from 814 Hz due to the mean flow effect and the second one is at 1732 Hz from 1005 Hz.

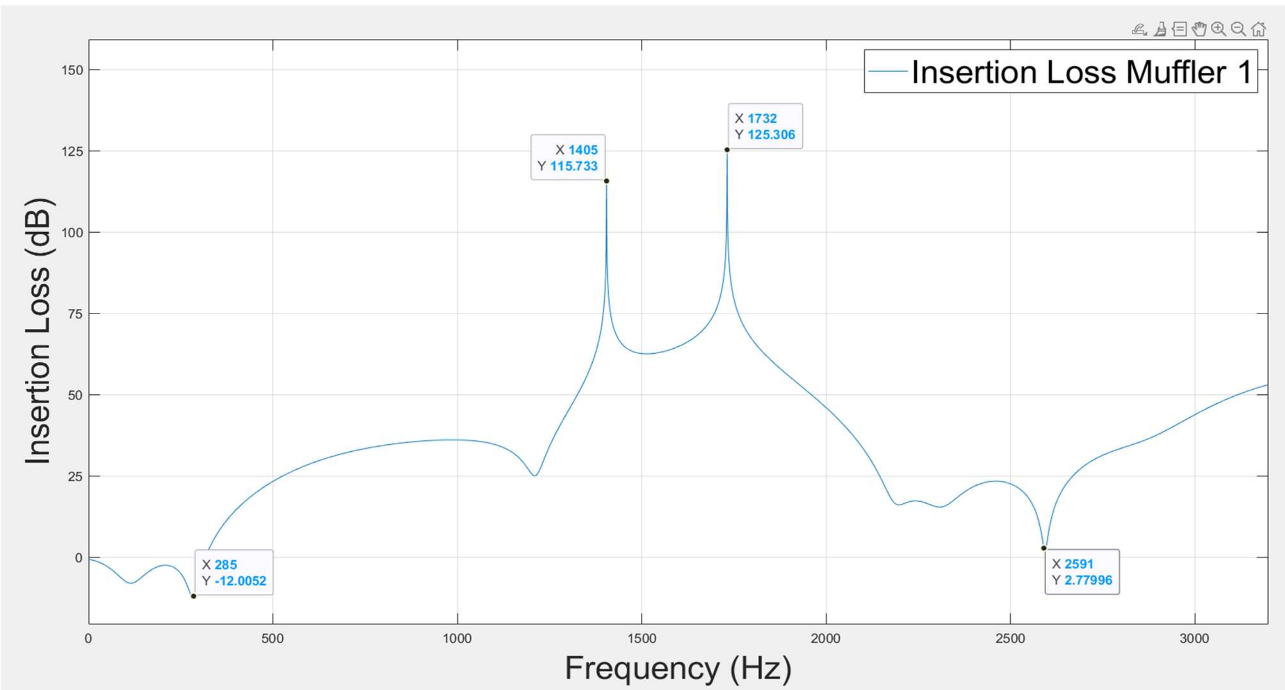

Figure 17 Insertion Loss vs Frequency for muffler 1 at 873.15k

The true performance of an acoustic filter is calculated by Insertion loss. *Figure 17* shows the IL vs f plot for muffler 1, at lower frequency rang IL comes negative which means that in this range muffler will produce more sound than the combustion engine exhaust sound.

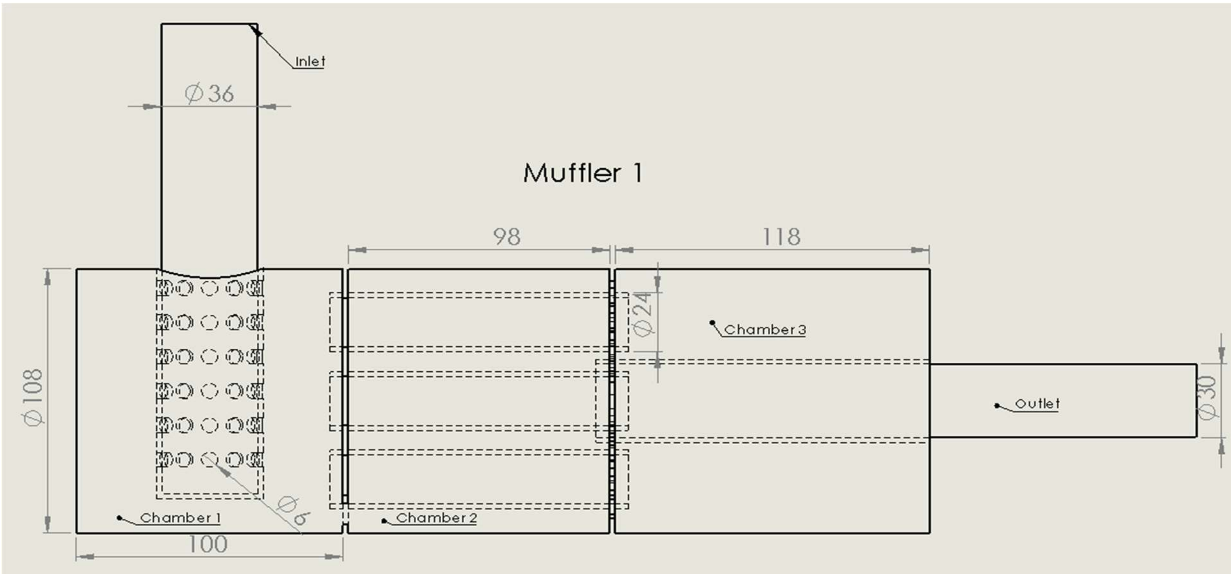

Figure 18 Muffler 1 CAD Drawing

Muffler 2: flow reversal end inlet end exit, with Three chambers elliptical muffler

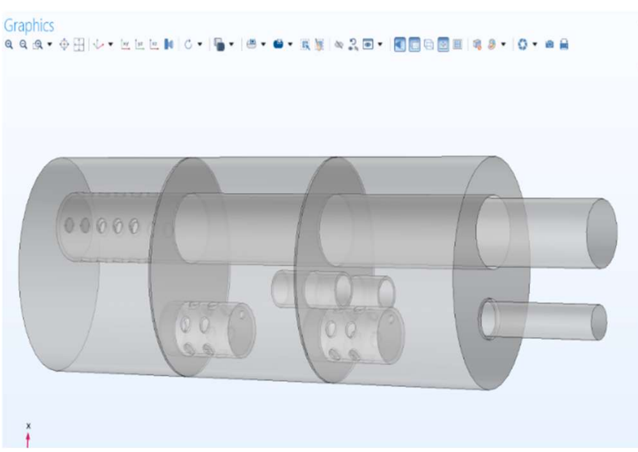

Figure 20 Muffler 2 Acoustic Model

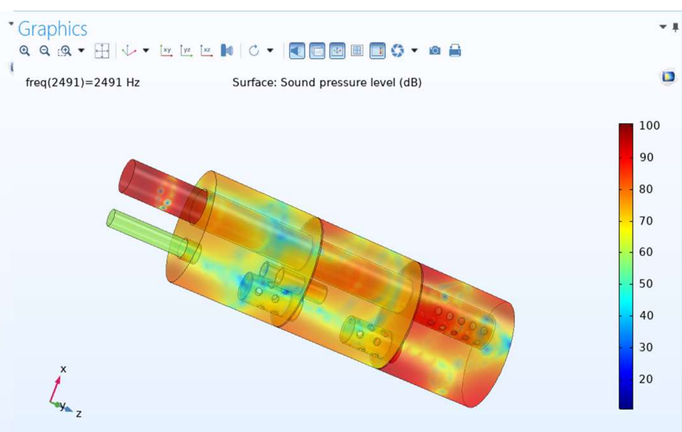

Figure 19 Muffler 2 Sound Pressure Level Distribution COMSOL

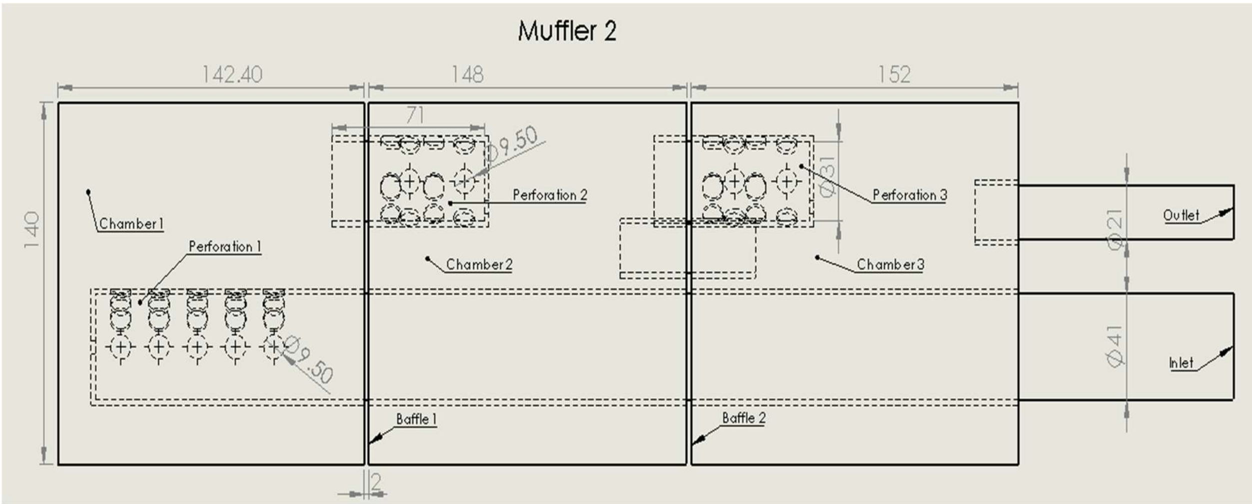

Figure 22 Muffler 2 CAD Drawing

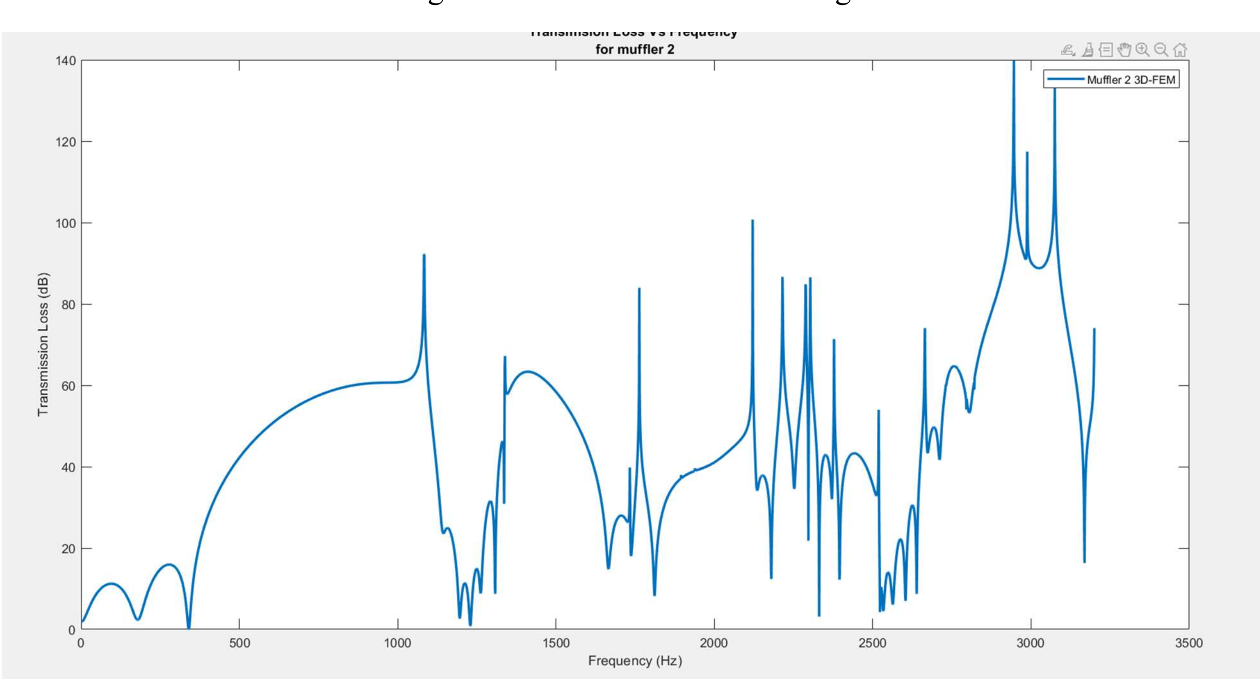

Figure 21 Muffler 2 Transmission Loss Vs Frequency Plot 3D-FEM at 293.15K

The cut-off frequency of the muffler 2 is 1443 Hz and the first peak is around 1000 Hz. This muffler does not perform well in starting without mean flow we can see in *Figure 22*.

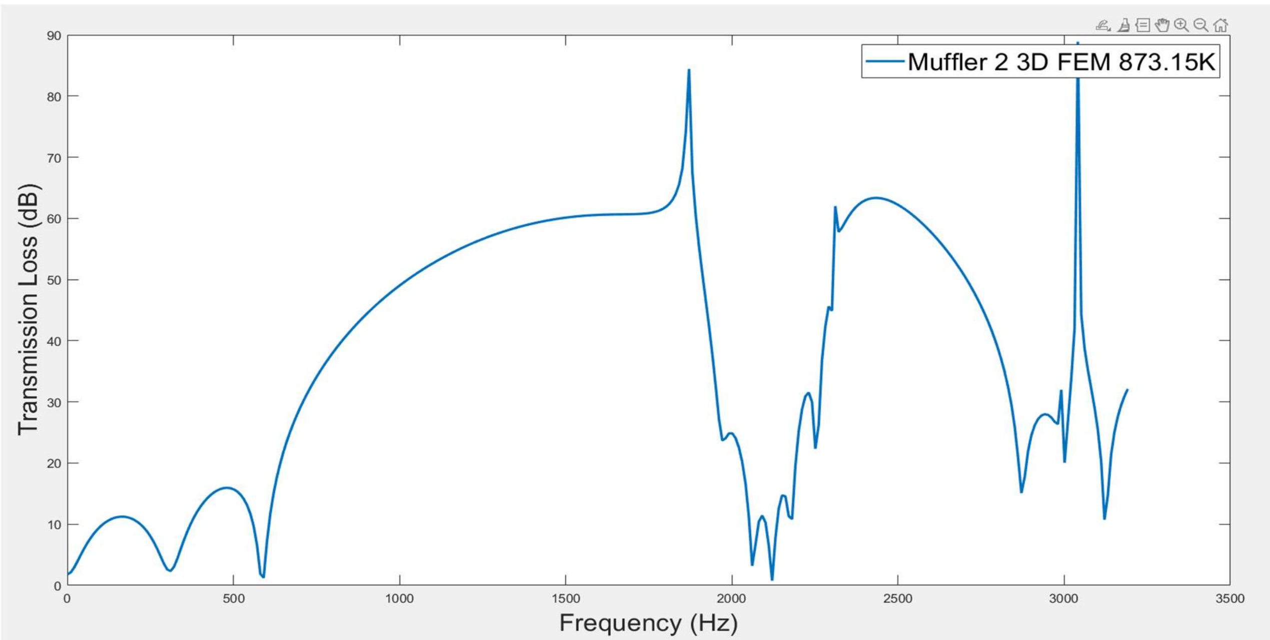

Figure 23 Muffler 2 Transmission Loss Vs Frequency Plot 3D-FEM at 873.15K

We can see in *Figure 23* that with the mean flow the peaks shift toward the right (at a higher frequency).

To get the best performance from muffler 2 we should shift the higher transmission loss value at a lower frequency.

Muffler 3: flow reversal end inlet end exit four-chamber

Elliptical muffler

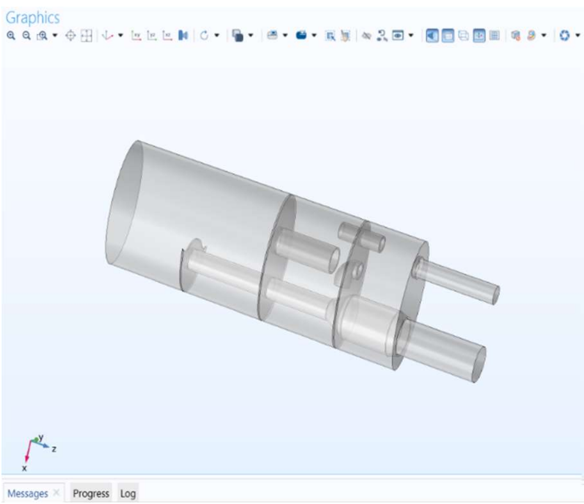

Figure 25 Muffler 3 Acoustic Model

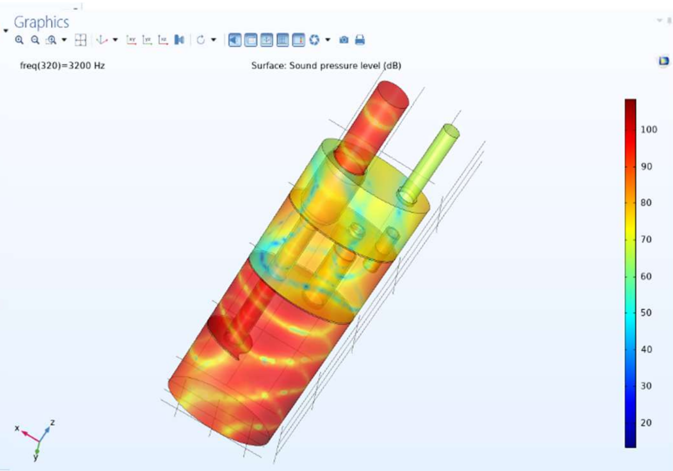

Figure 26 Muffler 3 Sound Pressure Level Distribution COMSOL

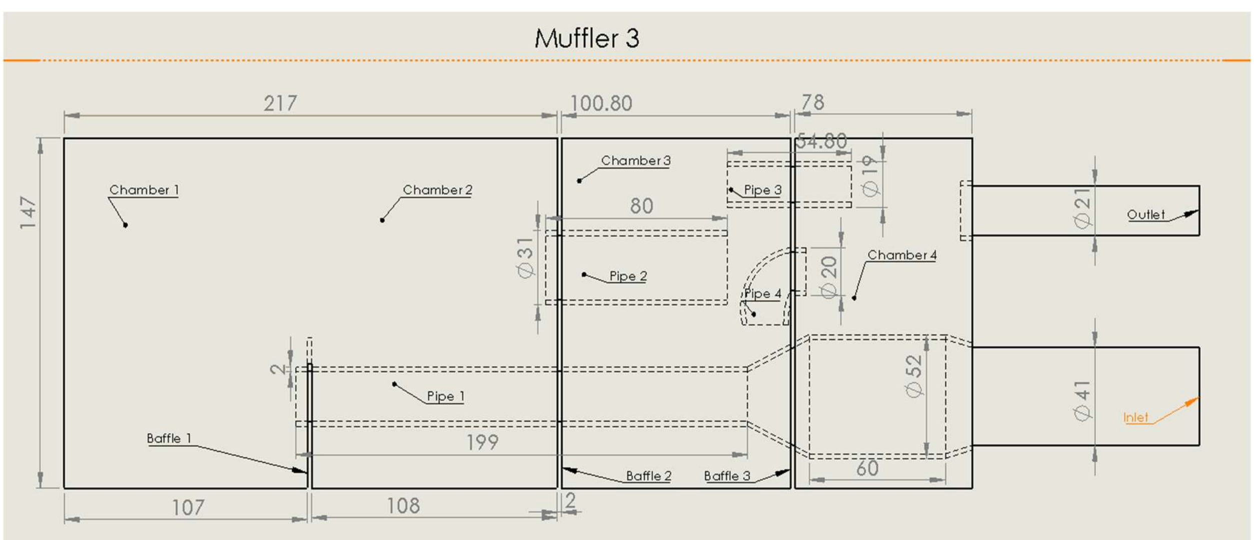

Figure 24 Muffler 3 CAD Drawing

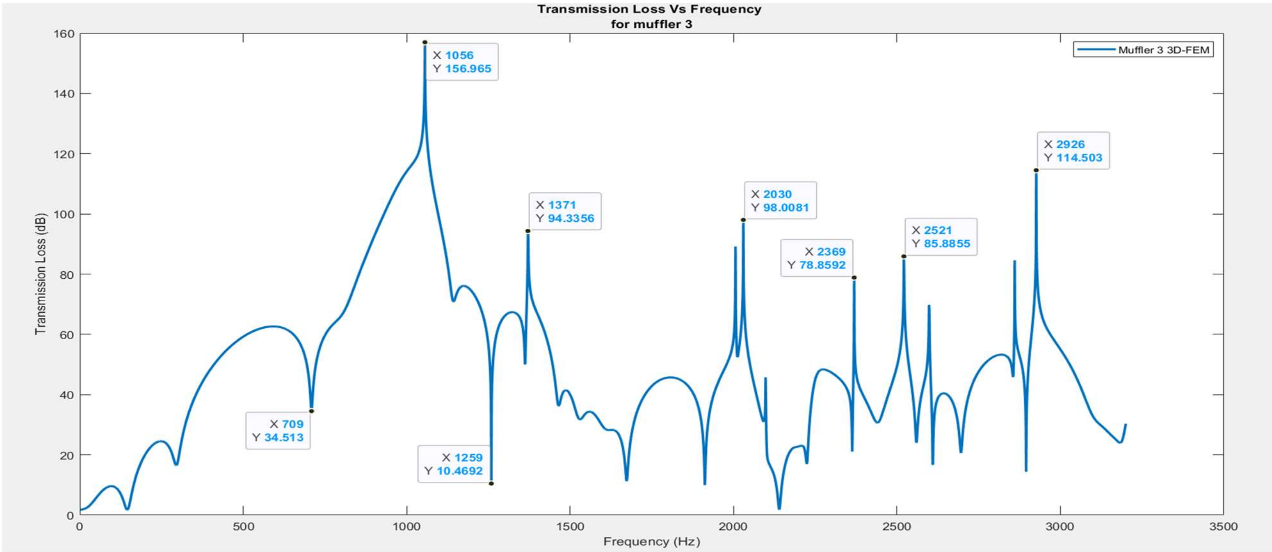

Figure 27 Muffler 3 Transmission Loss Vs Frequency Plot 3D-FEM at 293.15K

The cut-off frequency of the muffler 3 is 1367 Hz and the first peak is at 1056 Hz. This muffler does not perform well in starting we can see in *Figure 27*. If we ignore the starting part then this muffler performed well.

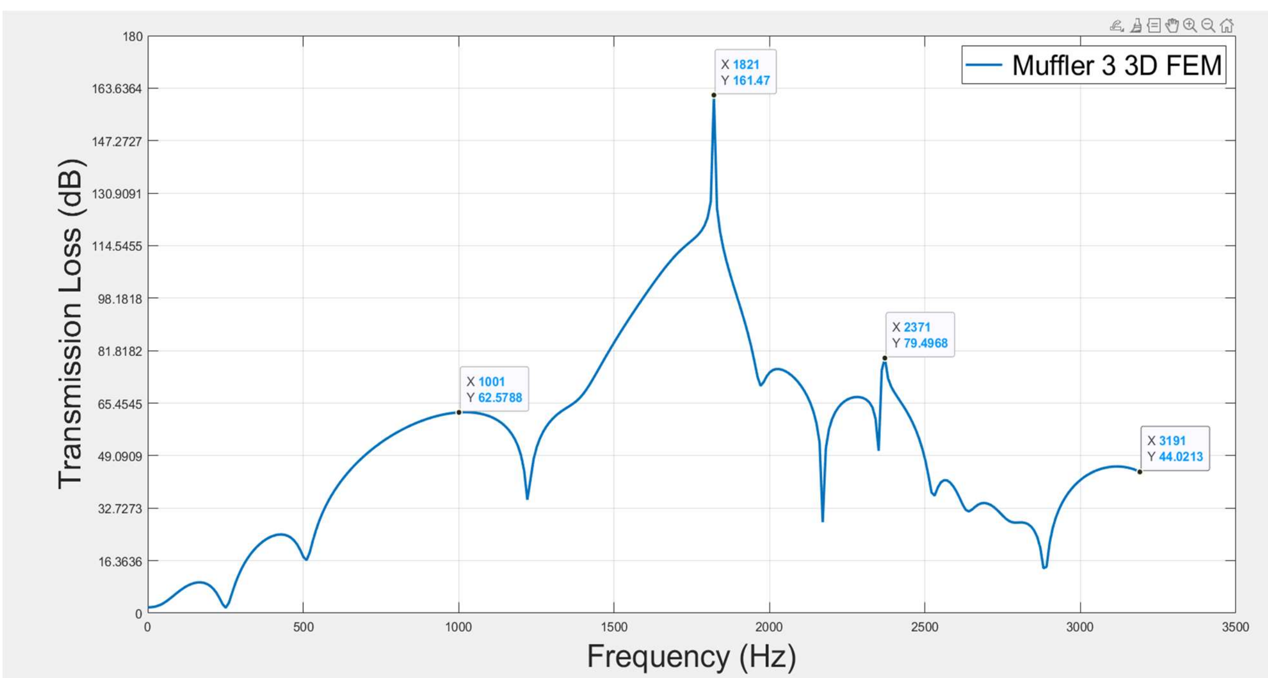

Figure 28 Muffler 3 Transmission Loss Vs Frequency Plot 3D-FEM at 873.1K

We can see in *Figure 28* that with the mean flow the peaks shift toward the right (at a higher frequency) at 1821 Hz from 1056 Hz.
To get the best performance from muffler 2 we should shift the higher transmission loss value at a lower frequency, especially to get higher TL in the range of 0-500 Hz.

Comparison between all three mufflers

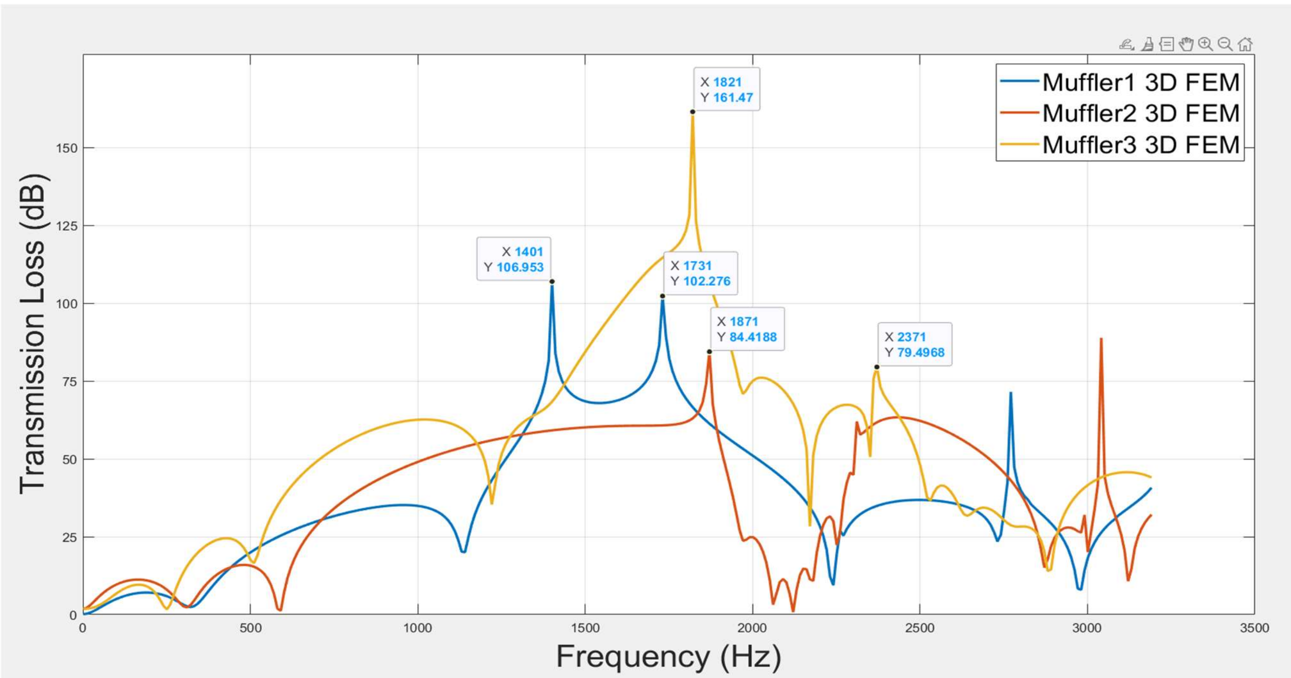

Figure 29 Combine mufflers 1, 2, and 3 3D-FEM Plot at 873.15K

In fig 29 we can see that all three mufflers have low TL at starting, but in terms of overall performance muffler, 3 is good.

Modification in muffler 1

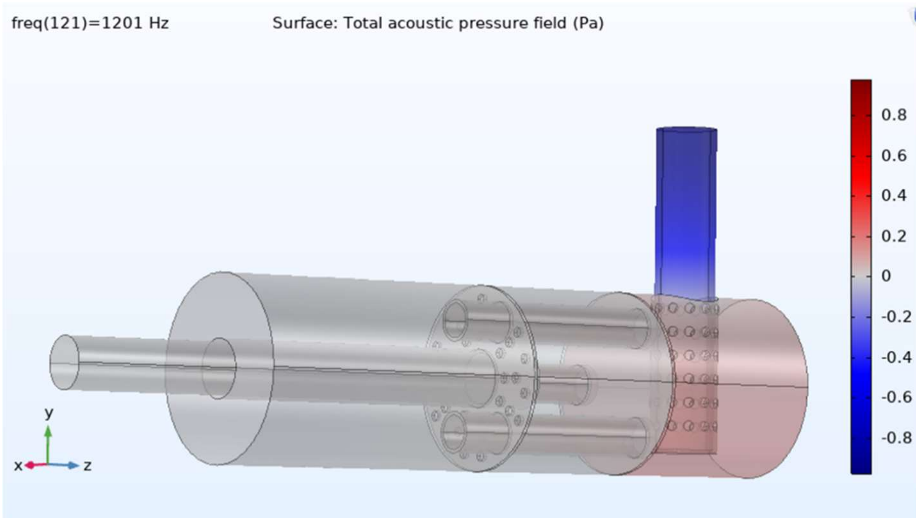

Figure 30 Modified muffler 1 3D Acoustic Model

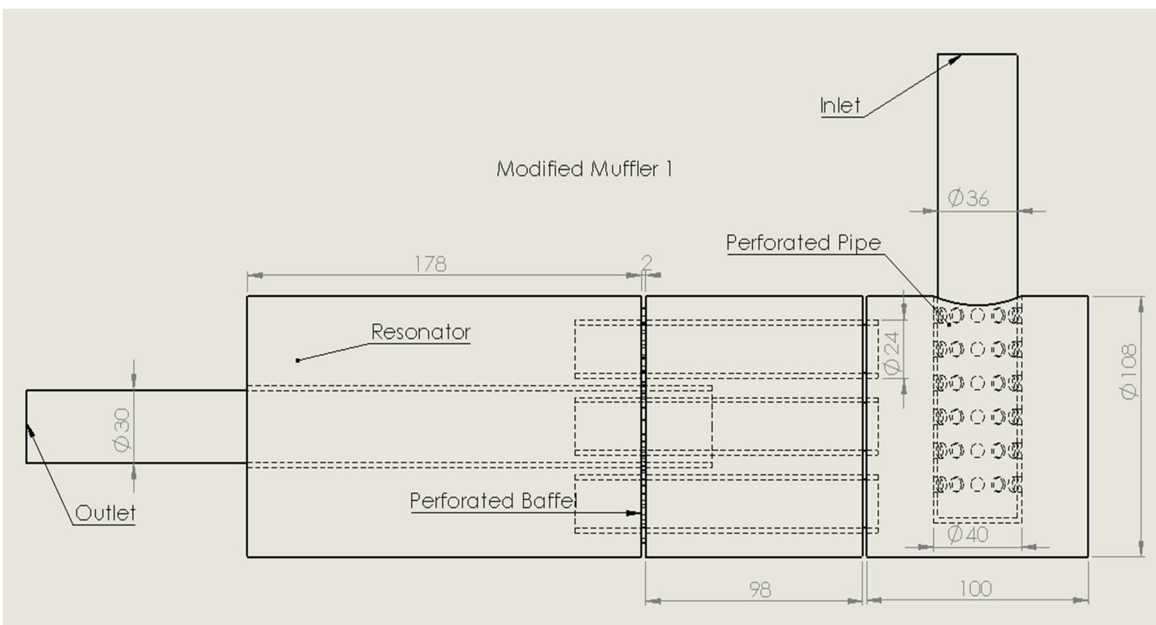

Figure 31 Modified muffler 1 CAD Drawing

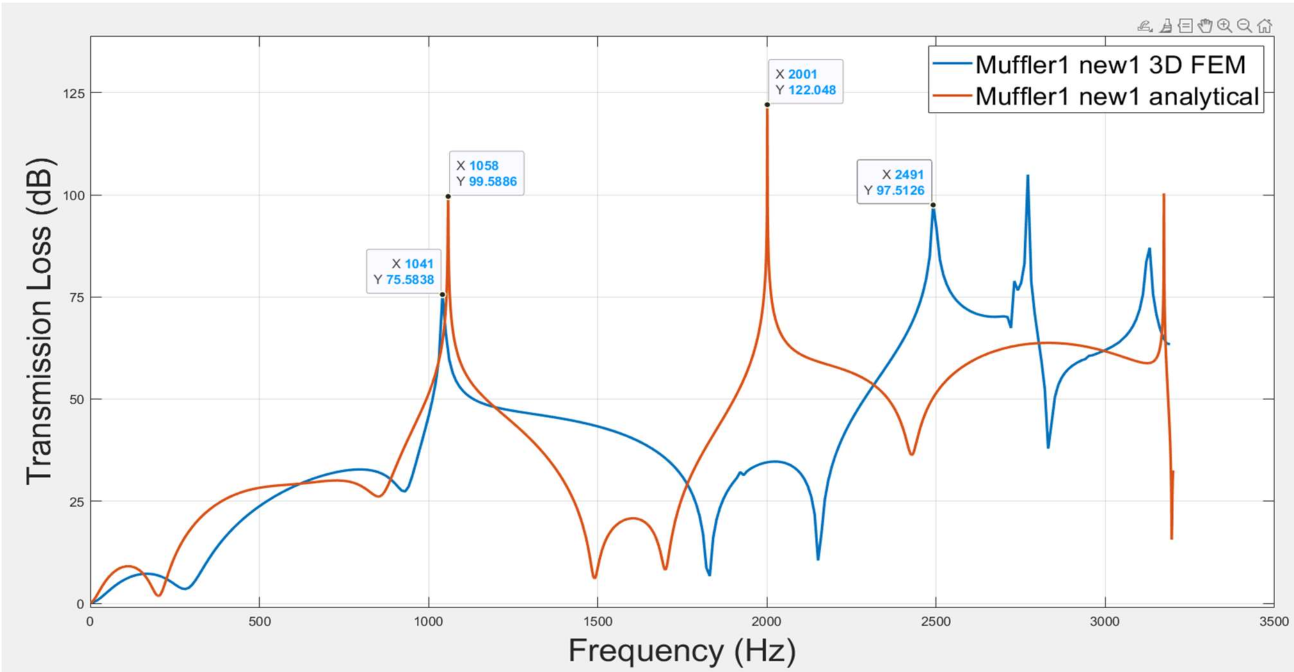

Figure 32 Transmission Loss Vs Frequency, Combine plot for modified muffler 1 3D-FEM and Analytical at 873.15K

In *Figure 32* we can see that both 3D-Fem and Analytical plots follow the same trend till the cut-off frequency and the first peak is at 1050 Hz. In this design

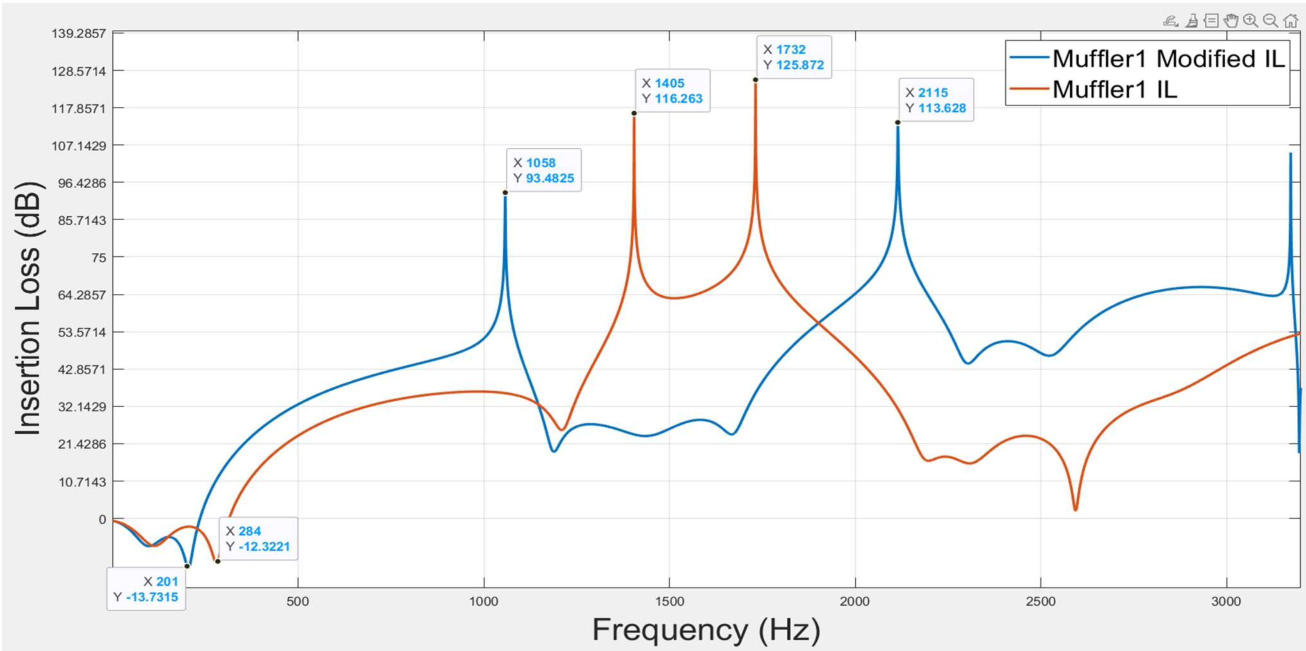

Figure 33 Insertion Loss Vs Frequency, Combine plot for modified muffler 1 and muffler 1 3D-FEM at 873.15K

In this *Figure 33* we can see that modified muffler 1 has better performance compare to original one, because it has higher IL at lower frequency.

Stagnation pressure drop across muffler calculation

For a Bajaj Maxima C auto-rikshaw model

Engine Displacement(cc) = 470.5 cc

Maximum net power = 6.74kw@4500rpm

Volume flow rate at the muffler inlet = 0.0591 m^2/s

By mean flow lumped resistance network theory

Stagnation pressure drop across muffler 1 (ΔP1) = 4.20kpa

Stagnation pressure drop across muffler 2 (ΔP2) = 3.58kpa

Stagnation pressure drop across muffler 3 (ΔP3) = 10.52kpa

Conclusions

After analyzing all three mufflers, I found that they do not cover all frequency ranges. We can get better performance from these silencers by modifying their design.

1. By designing a quarter-wave resonator.
2. Using perforated baffles and pipes.
3. We can use perforated interacting pipes to get better performance.
4. In muffler 1 modified design I tried to shift the higher TL at the lower frequency ranges to get better performance at low speed.
5. While modifying the muffler configuration, we should consider that the stagnation pressure drop across the muffler is not too high.

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