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Acoustic Analysis of Reactive Muffler

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Abstract - **Mufflers are part of a vehicle's exhaust system and are located at the rear, bottom of the vehicle. A large burst of the burnt gases released from exhaust system has very powerful sound waves. Mufflers are used mainly to dissipate this loud sounds. This sound wave could be reduced by sound absorbing materials (Absorptive Muffler), or by expansion chamber (Reactive Muffler). In this project mufflers are designed with different expansion chamber and baffle profiles, and acoustic analysis were made for these mufflers. Then with respect to Transmission Loss graph the effective baffle profile or reactive muffler could be found.**

Transmission Loss (TL) is to be increased for the designed reactive mufflers. TL is increased by designing different shape of expansion chamber, baffle profile, creating resonance chamber, perforated pipes. Different CAD design were iterated, and the best model is converged and analyzed. The reports of the different reactive mufflers were compared to find the effective muffler for the greater Transmission Loss.

Keywords - Transmission Loss, Sound Pressure Level, Acoustic Pressure, Sound pressure waves.

1. INTRODUCTION

Mufflers are installed within the exhaust system of most internal combustion engines. The muffler is engineered as an acoustic device to reduce the loudness of the sound pressure created by the engine by acoustic quieting. The noise of the burning-hot exhaust gas exiting the engine at high speed is abated by a series of passages and chambers lined with roving fiberglass insulation and/or resonating chambers harmonically tuned to cause destructive interference, wherein opposite sound waves cancel each other out.

Some aftermarket mufflers claim to increase engine output and/or reduce fuel consumption by slightly reduced back pressure. This usually entails less noise reduction. On May 18, 1905, the state of Oregon passed a law that required vehicles to have a light, a muffler, and efficient brakes. The exhaust system varies by jurisdiction; in many developed countries such as the United States, Canada, and Australia, such modifications are highly regulated or strictly prohibited. Aftermarket mufflers usually alter the way a vehicle performs, due to back-pressure reduction.

Benchmarking

Design of a muffler has certain standards and it is followed by all the manufacturers. In this experiment a multi-cylinder Maruti - Suzuki Wagon-R engine and muffler is used for benchmarking. The obtained results are compared to the standard and being analyzed.

Wagon-R muffler Transmission Loss graph

Wagon-R muffler's TL is observed in figure 1

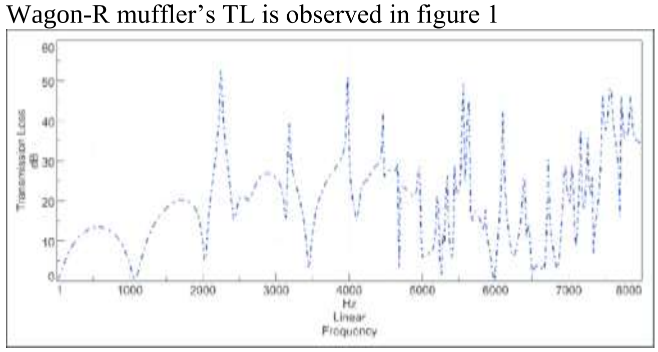

Figure 1
TL of Wagon R Muffler

Wagon-R Engine data
Bore diameter = 69.6mm
Stroke length = 82mm
No. Of Cylinder = 4
Speed (N) = 6800 rpm

Design

The muffler is designed using Creo parametric software and the shell dimensions of the muffler is common for all the three mufflers, only the internal profiles vary. Maruti - Suzuki WagonR muffler is being taken as reference muffler to compare with the proposed design of muffler with same engine exhaust parameters for better result.

Shell Volume of muffler

Bore diameter = 69.6mm
Stroke length = 82mm
Stroke volume (V_s) = cross-sectional area of cylinder * stroke
length
V_S = 3119000 mm^3
Exhaust gas volume (V_G) = Vs * (No. Cylinder / 2)
V_G = 632900 mm^3 / 2 revolution
Muffler volume = 25*V_S
Muffler volume = 7864000 mm^3

Reactive muffler 1

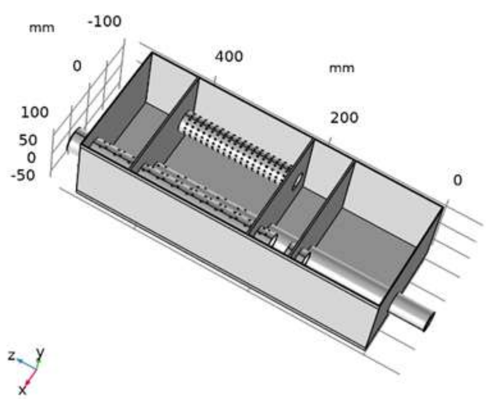

Figure 2
CAD model of muffler 1

The most critical component regarding back pressure of any commercial muffler is cross flow perforated tube in which the diameter of the perforated tube hole and porosity of the perforations are most critical. The perforated pipes are complex acoustic impedance and are evaluated using simple empirical relations. Perforated pipe forms an important acoustic element of muffler, which is tuned in line with the problematic frequencies. The diameter of the hole to be drilled / punched on the pipe is calculated by a thumb rule as given below:

Perforated diameter (Dp) = 1.29 / √N

N = Speed in rpm.
Porosity of pipe 1 = 3.6%
Porosity of pipe 2 = 7.36%
Porosity of plate = 4.78%
Porosity of pipe 3 = 1.28%

Reactive Muffler 2

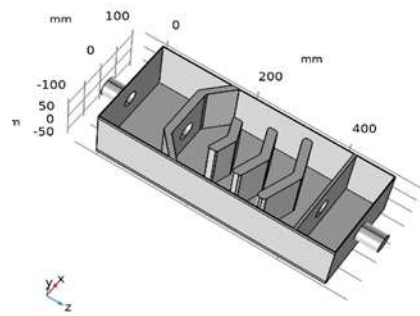

Figure 3
CAD model of muffler 2

The ‘V’ baffler plate profile acts a major component to reduce the sound pressure wave form the inlet observed in figure 3. The first chamber of the muffler has the inclined profile to deflect the sound pressure wave. The deflection of wave occurs at 43.09 degrees, the precise deflection would make destructive interference with other sound pressure wave. The first ‘V’ baffle is placed at 83.56mm from first chamber outlet with the thickness of 20mm. The ‘V’ profile has 140 degrees and sides with 45mm. All the edges are curved for the flow of sound waves the curved diameter is 7mm. The second ‘V’ baffle is placed at 50 mm from first baffle plate with 20mm thickness and angle of 140 degrees and sides with 65mm. The third ‘V’ baffle is placed at 50 mm from second baffle with 20mm thickness and 140 degrees inclined. The sides of the baffle with 85mm.

Reactive Muffler 3

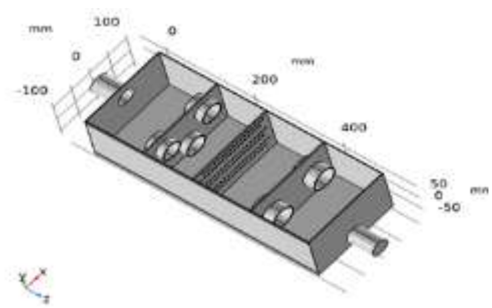

Figure 4
CAD model of muffler 3

Mechanical device designed to restrain or regulate the flow of a fluid, the emission of light or sound, or the distribution of sound. The rectangular baffle plate has the breadth 200mm and height 135mm, which is a projected loop sketch of the shell of muffler. The plate has the thickness of 3mm and it is perforated. The perforations take at six rows in the plate where the odd and even rows of perforations are offset.

ANALYSIS

The mufflers are analyzed in Finite element analysis software COMSOL MULTIPHYSICS. The mufflers are analyzed in pressure acoustics and frequency domain.

Acoustic parameters of muffler

The parameter used in the analysis of muffler is given in the table 3.1. The pressure p0 is assigned as 1 Pa for the analysis purpose but the actual pressure is 101325 Pa.

Table 1
Acoustic Parameters

Name	Expression	Value	Description
c	343[m/s]	343 m/s	Sound
p0	1[Pa]	1 Pa	Pressure

This parameter is common for all the muffler is analyzed.

VARIABLES OF MUFFLER

The variables used in the analysis of muffler is given in table 3.2. These are the formulas used to plot the transmission loss graph.

Table 2
Variables of muffler

Name	Expression	Unit	Description
w_in	intop1(p0^2/(2*acpr.rho*acpr.c))	W	Inlet Power
w_out	intop2(p*conj(p)/(2*acpr.rho*acpr.c))	W	Outlet Power
Tl	10*log10(w_in/w_out)		Transmission Loss

Table 3
Expressions for muffler

Name	Expression	Unit	Description
acpr.rho	material.rho	kg/m³	Density
acpr.c	material.c	m/s	Speed of sound

Exhaust gas properties

Exhaust gas density can be calculated by considering pressure (p0) as 101325 Pa, gas constant (R) as 287 J/Kg-K and temperature of exhaust gas as 953K

$\rho = p0/RT = 101325/(287*953) = 0.37$ kg/m^3

Reactive Muffler 1

The plane wave radiation is selected at the inlet of the muffler 1 as intop1 which is an integrating coupling operator which couples the source with expression. Incident pressure is selected for the intop1. Then the next plane wave radiation is selected at the outlet of the muffler 1

Table 4
Incident Pressure field of muffler 1

Description	Value
Pressure field type	Plane wave
Pressure amplitude	p0
Speed of sound	From material
Wave direction, x component	-acpr.nx
Wave direction, y component	-acpr.ny
Wave direction, z component	-acpr.nz
Phase	0

Meshing

The final step for the analysis process is meshing the meshing size and statictics can be referred in the table. The meshing size is fine with the maximum element size of 47.6 mm and minimum element size of 5.95 mm. Mesh size and the meshed model is observed in the table 5 and figure 5.

Table 5
Mesh size of muffler 1

Description	Value
Maximum element size	47.6
Minimum element size	5.95
Curvature factor	0.5
Resolution of narrow regions	0.6
Maximum element growth rate	1.45
Predefined size	Fine

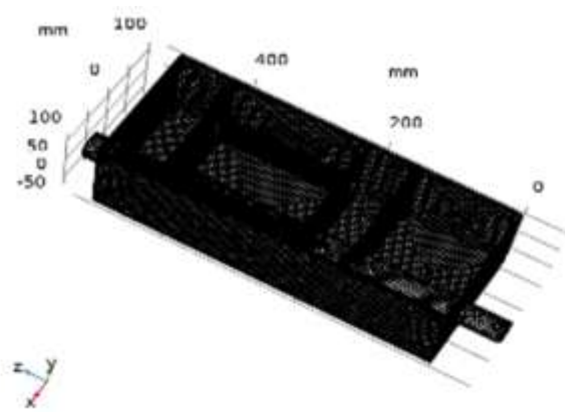

Figure 5
Meshed muffler1

Reactive Muffler 2

The plane wave radiation is selected at the inlet of the muffler 2 as intop1 which is an integrating coupling operator which couples the source with expression. Incident pressure is selected for the intop1. Then the next plane wave radiation is selected at the outlet of the muffler 2

Table 6
Incident pressure field of muffler 2

Description	Value
Pressure field type	Plane wave
Pressure amplitude	p0
Speed of sound	From material
Wave direction, x component	-acpr.nx
Wave direction, y component	-acpr.ny
Wave direction, z component	-acpr.nz
Phase	0

Meshing

The final step for the analysis process is meshing the meshing size and statictics can be referred in the table. The meshing size is fine with the maximum element size of 48.1 mm and minimum element size of 6.02 mm. Mesh size and the meshed model is observed in the table 7 and figure 6.

Table 7
Mesh size of muffler 2

Description	Value
Maximum element size	49.6
Minimum element size	6.2
Curvature factor	0.5
Resolution of narrow regions	0.6
Maximum element growth rate	1.45
Predefined size	Fine

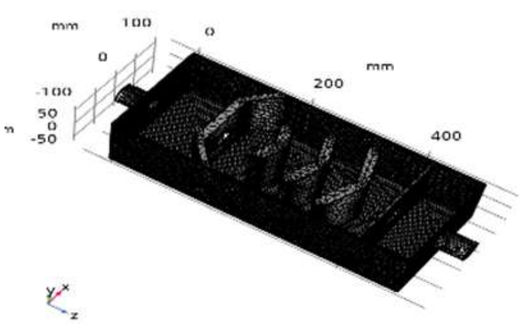

Figure 6
Meshed muffler 2

Reactive Muffler 3

The plane wave radiation is selected at the inlet of the muffler 3 as intop1 which is an integrating coupling operator which couples the source with expression. Incident pressure is selected for the intop1. Then the next plane wave radiation is selected at the outlet of the muffler 3.

Table 8
Incident Pressure field of muffler 3

Description	Value
Pressure field type	Plane wave
Pressure amplitude	p0
Speed of sound	From material
Wave direction, x component	-acpr.nx
Wave direction, y component	-acpr.ny
Wave direction, z component	-acpr.nz
Phase	0

Meshing

The final step for the analysis process is meshing the meshing size and statictics can be referred in the table. The meshing size is fine with the maximum element size of 49.6 mm and minimum element size of 6.2 mm. Mesh size and the meshed model is observed in the table 9 and figure 7.

Table 9
Mesh size of muffler 2

Description	Value
Maximum element size	48.1
Minimum element size	6.02
Curvature factor	0.5
Resolution of narrow regions	0.6
Maximum element growth rate	1.45
Predefined size	Fine

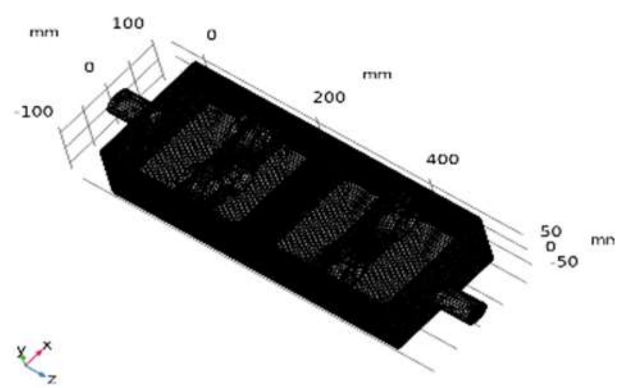

Figure 7
Meshed muffler 3

RESULTS AND DISCUSSION

Acoustic Pressure (Acpr)

Acoustic pressures generated in a fluid that is in contact with a structure influence its vibrational behavior. In the majority of cases of mechanical systems operating in atmospheric air, the effect is small because the impedance of the structures greatly exceeds that of the air, even at structural resonance frequencies where the impedance is minimal. The acoustic fields and streaming in a confined fluid depend strongly on the viscous boundary layer forming near the wall. The width of this layer is typically much smaller than the bulk length scale set by the geometry or the acoustic wavelength, which makes direct numerical simulations challenging.

Acoustic Pressure of Muffler 1

The reactive muffler 1 acoustic pressure is calculated at the frequency of 1451 Hz observed in figure 8. Exhaust gat at inlet of muffler with atmospheric pressure and at the velocity of sound 343 m/s. The pressure in intensity varies throughout the muffler. And the variation is observed. The gauge pressure is considered for this analysis. The maximum pressure of 0.33 Pa gauge pressure is identified i.e.- 1.33 absolute Pressure. And the minimum pressure of 0.3 negative gauge pressure is observed at the wall of the muffler and at some perforations. The lowest pressure is 0.7 absolute pressure which is less than atmospheric pressure.

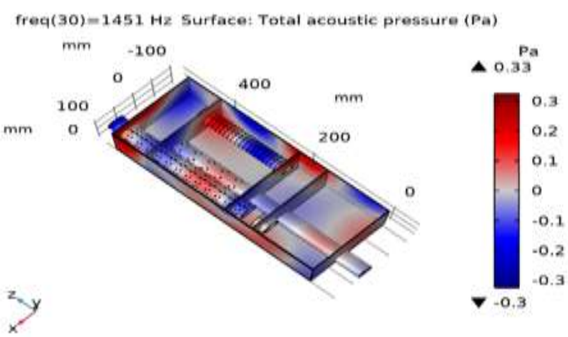

Figure 8
Acpr of muffler 1

Acoustic Pressure of Muffler 2

The reactive muffler 2 acoustic pressure is calculated at the frequency of 951 Hz observed in figure 9. Exhaust gat at inlet of muffler with atmospheric pressure and at the velocity of sound 343 m/s. The pressure in intensity varies throughout the muffler. The maximum gauge pressure of 1.45 is observed at the inlet of the muffler, i.e.- 2.45 absolute pressure. Then the pressure is decreased gradually from the inlet to outlet. From the second chamber the pressure is approximately maintained at the atmospheric pressure. The minimum pressure of 0.93 negative gauge pressure is observed at the first chamber of muffler due to sudden expansion. The inlet has 0.07 absolute pressure which is approximately at the stage of vacuum.

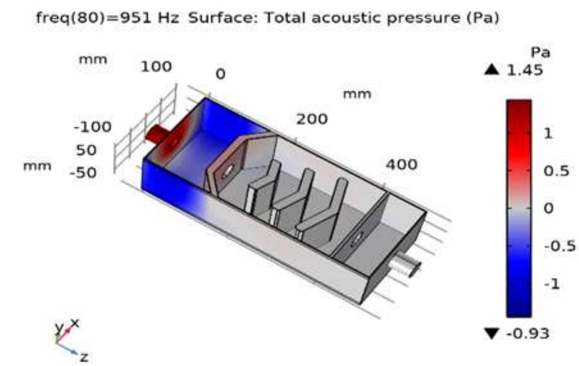

Figure 9
Acpr of muffler 2

Acoustic Pressure of Muffler 3

The reactive muffler 3 acoustic pressure is calculated at the frequency of 951 Hz observed in figure 10. Exhaust gat at inlet of muffler with atmospheric pressure and at the velocity of sound 343 m/s. The pressure in intensity varies throughout the muffler. The maximum gauge pressure of 1.24 is observed at the inlet wall of muffler, inlet pipe of muffler and inlet baffle and baffle tubes. From second chamber to the outlet of muffler pipe the pressure is approximately maintained at atmospheric pressure. The second chamber perforated baffle plate experience less pressure than the first chamber. The minimum pressure of 0.83 negative gauge pressure is observed at the first chamber of muffler due to sudden expansion

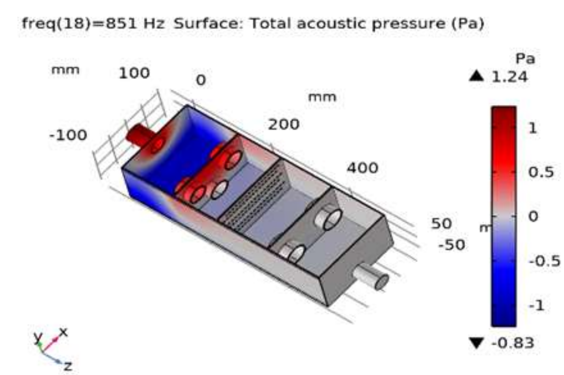

Figure 10
Acpr of muffler 3

Comparison of acoustic pressure
The three different reactive muffler has different acoustic pressure. The back pressure is considered as a factor for comparing the mufflers.
Back pressure of muffler 1: 0.3 negative gauge pressure
Back pressure of muffler 2: 0.93 negative gauge pressure
Back pressure of muffler 3: 0.83 negative gauge pressure

Sound Pressure Level (SPL)

The sound pressure level is the most commonly used indicator of the acoustic wave strength. It correlates well with human perception of loudness and is measured easily with relatively inexpensive instrumentation. Sound pressure levels are also measured on a logarithmic scale but unit decibel 2 × 10−5 N/m2. There is another advantage in using the decibel scale. Because the ear is sensitive to noise in a logarithmic fashion, the decibel scale more nearly represents how we respond to a noise. The term 'sound pressure' may be proceeded by other noise measurement terms such as instantaneous, maximum, and peak. The proper notations for sound pressure level using this reference are LP (re 20 μPa).

SPL of Muffler 1

The SPL is calculated at the frequency 1451 Hz. The SPL is observed below in the units of decibel dB observed in figure 11.

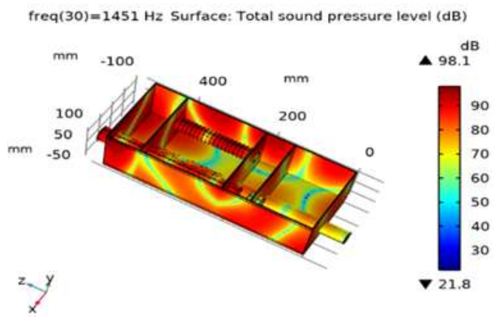

Figure 11
SPL of muffler 1

The sound pressure level of reactive muffler 1 is observed. The maximum of 98.1 dB sound pressure is measured. The walls are subjected to more sound pressure waves and the impact of waves is observed. The Helmholtz – Chamber and the outlet pipe of muffler experience lesser sound waves compared to first and second expansion chamber. The minimum of 21.8 dB is measured at the small portions of wall and at the perforated pipes.

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SPL of Muffler 2

The SPL is calculated at the frequency 951 Hz. The SPL is observed below in the units of decibel dB observed in figure 12.

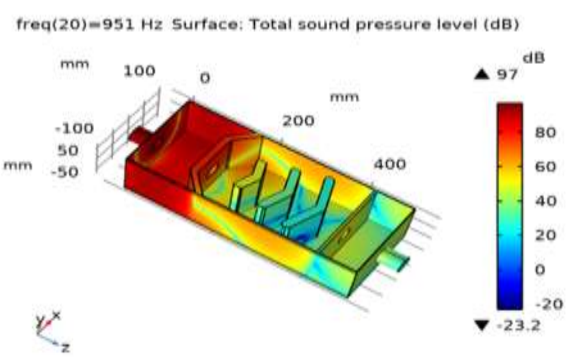

Figure 12
SPL of muffler 2

The Sound pressure level for muffler 2 is observed, maximum of 97 dB is measured. The first chamber has the most of the high sound pressure waves. Due to sudden expansion from inlet of the muffler and sudden contraction to the second chamber of muffler, most to sound waves hit the walls and reflected waves cancelled the other sound waves. The second chamber has ‘V’ shaped baffle plate which block the sound waves. At the 3rd ‘V’ baffle plate it is observed less sound pressure wave. Minimum of -23.2 dB (Since decibel is not a unit) is measured in the reactive muffler 2

SPL of Muffler 3

The SPL is calculated at the frequency 851 Hz. The SPL is observed below in the units of decibel dB observed in figure 13.

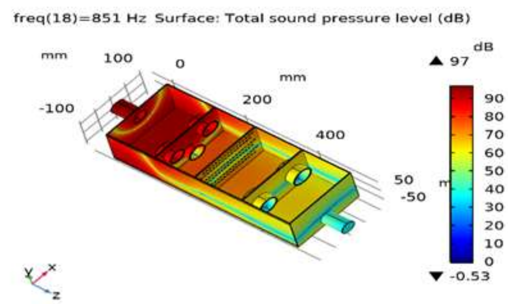

Figure 13
SPL of muffler 3

The sound pressure level of muffler 3 is observed. Maximum of 90 dB is measured, most of the high sound pressure waves are hit the walls and reflected sound wave cancelled other sound waves. The impact of the high sound pressure waves observed at the first two chambers. The perforated baffle plate at the end of the second chamber experience lesser sound pressure. The 2nd set of perforations in the perforated baffle plate reduce the sound pressure waves. Minimum of -0.53 dB (Since decibel is not a unit) is measured.

Transmission Loss (TL) graph

In the transmission of a signal from one point to another, the decrease in the power level, such as the optical, electronic, acoustic power level, that occurs (a) within a component, (b) from the output of one component to the input of another component, or (c) from one point to another in a propagation medium. Transmission loss usually is expressed in dB. The number of dB of transmission loss is given by the relation $10 \cdot \log_{10}(P_o/P_i)$ where p_o/p_i is the ratio of the output power at one point to the input power at the other point, such as the output power divided by the input power of a transmission line component, such as a connector, a splice, or a transformer. In passive elements, the transmission loss will be expressed as a negative number and labelled as a loss because P_o/P_i is less than unity, i.e., less than one (1).
There will always be a transmission loss when only passive elements are between the points of measure. Should there be active elements and the ratio of P_o/P_i. The TL graph is plotted by frequency and decibel. Frequency in the X – axis

and transmission loss in decibel in the Y – axis. The graph show decibel lost at the particular frequency in the muffler. The trend of the graph is used to find the relation between frequency and insertion loss (transmission loss) of the muffler. It is expected that the graph should be with increasing peak for the better transmission loss in the muffler.

Transmission Loss graph of Muffler 1

The sound transmission loss graph for the muffler 1 is observed in figure 14.

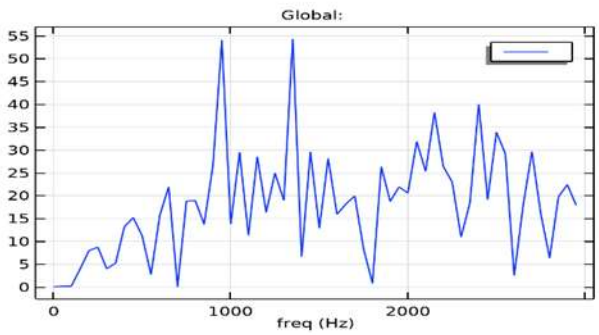

Figure 14
TL of muffler 1

Maximum transmission loss of 55 dB is achieved at approximately two particular frequency 951 Hz and 1451 Hz. When the incoming sound pressure wave has the frequency 951 Hz and 1451 Hz the maximum sound transmission loss is achieved. The average transmission loss of 37.8 dB for the frequency range 1 to 3000 Hz is achieved in this muffler. The valley point records lowest transmission loss at 1951, 801 Hz, this is due to the reflected sound wave from the walls, pipes, plate, chambers instead of destructive interference it would have formed constructive interference which make the waves stronger.

Transmission Loss graph of Muffler 2

The sound transmission loss graph of muffler 2 is observed in figure 15.

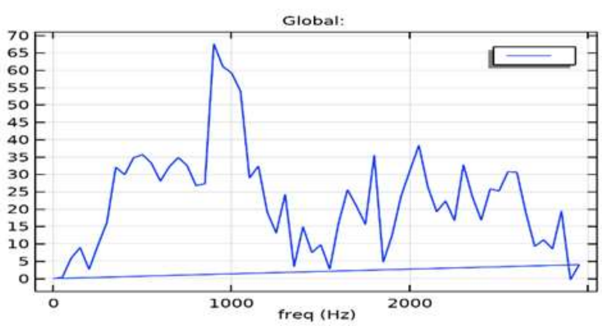

Figure 15
TL of muffler 2

The graph has varying trend as the frequency increase. From 1 to 1500 Hz the transmission loss of the muffler is better than from 1500 to 3000 Hz. The first half has average TL of 45.7 dB and the second half has average TL of 32.3 dB. Maximum transmission loss of 67.5 dB is achieved at the frequency 951 Hz. So, when the inlet sound pressure wave has the frequency 951 Hz maximum transmission loss is achieved. The average TL of this graph is 45.6 dB for the frequency range 1 to 3000 Hz is achieved in this muffler. The valley point records lowest at the frequency at 1500 Hz. This is due to constructive interference by the reflected sound pressure wave.

Transmission Loss graph of Muffler 3

The sound transmission loss graph of muffler 3 is observed in figure 16.

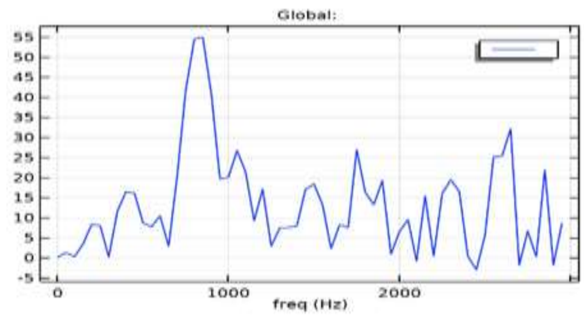

Figure 16
TL muffler3

The graph trend is varying with more peaks and valley. There is a valley point immediately after every peak point. Maximum transmission loss of 55 dB is achieved at the frequency of 851 Hz. When the incoming sound pressure level is 851 Hz the maximum transmission loss of 55 dB is achieved. The valley points are increasing as the frequency increase after 2000 Hz. This graph has the average transmission loss of 27.8 Hz.

CONCLUSION

Three reactive mufflers were designed and analyzed for better transmission loss than the benchmarked Wagon-R muffler. From the three reactive muffler 2 shows better result in acoustic pressure, sound pressure level, transmission loss analysis. So, the Reactive Muffler 2 is compared with benchmarked Wagon-R muffler. The average transmission loss of benchmarked Wagon-R muffler is 35.6 dB. But the designed Reactive Muffler 2 has average transmission loss of 45.6 dB. The transmission loss graph of reactive muffler 2 has maximum transmission loss at two different frequency. The acoustic pressure of the benchmarked Wagon-R muffler has the minimum pressure of 0.03 negative gauge pressure. But the designed Reactive Muffler 2 has the minimum pressure of 0.93 negative gauge pressure.

The design of the Reactive Muffler 2 has simpler geometry than the benchmarked Wagon-R muffler. The sound pressure level of the designed Reactive Muffler 2 has high intensity sound pressure wave only at the first chamber. But the benchmarked Wagon-R muffler has high intensity sound pressure wave at many places like chamber, pipes. Based on the acoustic analysis of the designed muffler. Muffler 2 has better results. And the results were also better than benchmarked Wagon-R muffler

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