Design and Analysis of a Expansion Chamber Mufflers

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Abstract
Internal combustion engines are fitted with exhaust muffler to attenuate the pressure pulsation generated during combustion process. Effective prediction of sound pressure loss of hot gases as it flows through the muffler greatly helps in the design of mufflers. An attempt has been made here to predict the transmission loss through modal analysis, followed by acoustic analysis using finite element analysis technique for three different configurations of mufflers under different fixing conditions. It was found that three-chamber muffler provides higher attenuation of sound pressure compare to one and two chamber mufflers. And, fixing the muffler at the center enhances sound pressure attenuation.
Key Words: Muffler, sound, transmission loss

1. Introduction
Sound is the result of pressure variations, or oscillations, in an elastic medium (e.g., air, water, solids), generated by a vibrating surface, or turbulent fluid flow. Exhaust noise (unwanted sound) of internal combustion engines is known to be the biggest pollutant of the present-day urban environment. Hence they are typically equipped with exhaust muffler to attenuate the pressure pulsation generated during combustion process. Among dissipative and reflective type of mufflers [1,2], reflective type muffler is mostly preferred in all internal combustion chambers. A reflective muffler consists of a number of tubular elements of different transverse dimensions joined together so as to cause impedance mismatch at every junction. This results in reflection of a substantial part of the incident acoustic energy back to the source. A well designed muffler is one which ensures adequate insertion loss, reduces back pressure, small in size, durable, maintains effective performance for a long period of time, ability to arrest spark and produces less flow generated noise within the muffler element. Acoustic performance of a muffler may be ascertained from parameters such as insertion loss, noise reduction and transmission loss. Different muffler configurations have been analyzed through various techniques (3, 4, 5) and it was found that Finite Element Analysis (FEA) technique offers the best solution [3, 4]. In this paper, simple expansion chambers of fixed length are modeled as fluid structure interaction problem and a 3-D finite element analysis was carried out. The resulting acoustic attenuation expressed in terms of transmission loss has been compared with the data available in the literature
(3, 4]. Performance of a muffler is measured by predicting transmission loss for free-free and fixed conditions of the muffler.

1.1 Acoustic wave equation
The muffler analysis was carried out by treating it as a acoustical fluid structure interaction problem. Therefore, the structural dynamics equation is considered along with Navier-stokes equations of fluid momentum and the flow continuity equation. The discretized structural dynamics equation can be formulated using the structural elements. The fluid momentum (Navier – Stokes) and continuity equations are simplified to get the acoustic wave equation:

$$\frac{1}{c^2}\frac{\partial^2 P}{\delta t^2} - \nabla^2 P = 0$$

Where, c = speed of sound, ρ = sound density, P = acoustic pressure, t = time.

1.2 Methodology
Mode shapes and corresponding frequencies were obtained for three, free-free end configurations and two fixed configurations of the muffler through harmonic analysis module of FEA software. Harmonic analysis was carried out over a range of 0 Hz to 2000 Hz since most of the noise is limited to firing frequency and its few harmonics. Subsequently acoustic analysis was carried out to compute the transmission loss for a unit pressure input. Performance of the muffler is ascertained by analyzing and comparing the transmission loss for various configurations and is presented in the following sections.

1.3 Finite Element Analysis
1.3.1 Free-Free Ends
Three configuration of the muffler considered is a) single expansion chamber muffler b) two chamber muffler and c) three chamber muffler, as shown in figures 1, 2 and 3. They are considered to be free at ends for one set of analysis Subsequently, the single chamber muffler is analysed by considering it to be fixed at both ends and fixed at the center. Figure 4 shows the schematic model of the single chamber muffler. Sonic velocity and density is given to acoustic elements as material property. Young,s modulus, Poision's ratio and density are given to structural elements. Unit pressure is applied at the entry of the muffler. Harmonic analysis was carried out for the frequency range 0 Hz to 2000 Hz. Transmission loss is computed by taking the pressure values at the entry and exit of the muffler using the expression:

$$TL = 20\log 10\frac{p_i}{p_t} + 10\log 10\frac{S_i}{S_o}$$

s_i and s_0 are muffler inlet and outlet tube area and are equal in this case. Graph of transmission loss versus frequency is plotted for 0 Hz to 2000 Hz.

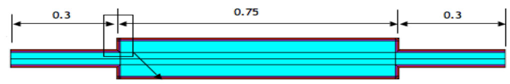


Figure 1

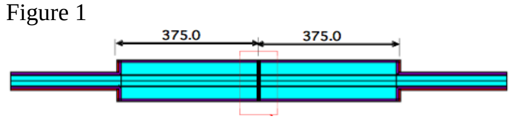


Figure 2

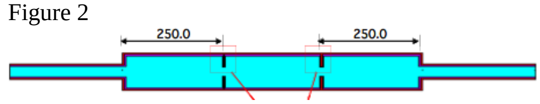


Figure 3

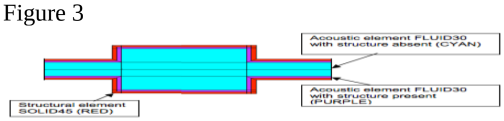


Figure 4

Modal analysis were carried out on all configurations of the muffler using Block Lancozos method for free-free ends and fixed conditions of the muffler to find its natural frequencies between 100 Hz to 2000 Hz. Acoustic analysis was carried out to compute the transmission loss.

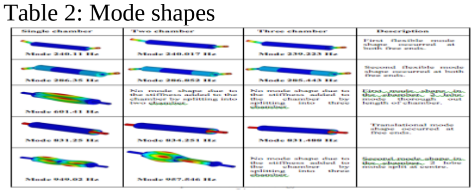
Result and discussion

Table 1 shows natural frequencies obtained from the modal analysis for the three muffler configurations. Table 2 and Table 3 present comparison of mode shapes for the natural frequencies presented in table 1. Figure 5a, b and c shows the plots of transmission loss versus frequency for the three muffler configurations. Plots indicate that transmission loss is a function of natural frequency and the loss is minimum when natural frequency of the muffler matches with the frequency of sound of engine exhaust. Further, the transmission loss versus frequency confirm to the fact that most of the noise in the engine exhaust is limited to the firing frequency and its first few harmonics. Transmission loss is about 26 dB, 34 dB and 45 dB for single, two and three chambers respectively tally with the available literature [3. 4]. The fact that higher natural frequencies occur inside the chamber and the lower natural frequencies at the free ends, strengthen the need for proper design of muffler. Number of natural frequencies has reduced for two and three chamber mufflers. The transmission loss curve appears to be high and broad at higher frequencies for two-chamber muffler and is broad at multiple frequencies for three-chamber muffler.

Table 1: Natural frequencies

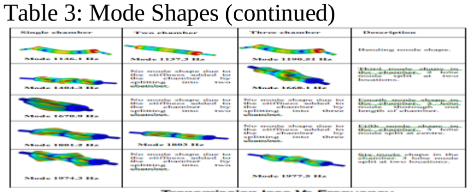
Single chamber	Two chamber	Three chamber
Frequency (Hz)	Frequency (Hz)	Frequency (Hz)
240.11	240.02	239.22
286.35	286.85	285.44
601.41		
831.25	834.25	831.49
949.02	957.55	
1146.1	1137.3	1190.51
1404.3		
1670.9		1672.1
1801.2	1803.7	
1974.3		1977.5

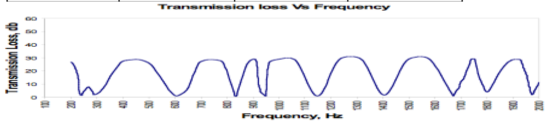
Table 2: Mode shapes



Single chamber	Two chamber	Three chamber	Description
Mode 240.11 Hz	Mode 240.017 Hz	Mode 239.223 Hz	First flexible mode shape occurred at both free ends.
Mode 286.35 Hz	Mode 286.852 Hz	Mode 285.443 Hz	Second flexible mode shape occurred at both free ends.
Mode 601.41 Hz	No mode shape due to the stiffness added to the chamber by splitting into two chamber.	No mode shape due to the stiffness added to the chamber by splitting into three chamber.	First mode shape in the chamber. 3 lobe mode thorough out length of chamber.
Mode 831.25 Hz	Mode 834.251 Hz	Mode 831.488 Hz	Translational mode shape occurred at free ends.
Mode 949.02 Hz	Mode 957.546 Hz	No mode shape due to the stiffness added to the chamber by splitting into three chamber.	Second mode shape in the chamber. 2 lobe mode split at centre.

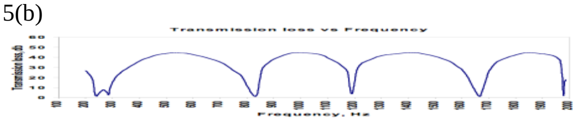
Table 3: Mode Shapes (continued)





5(a)

5(b)



5(c)

Figure 5a, b and c: Plots of transmission loss versus frequency for single, two and three chamber mufflers respectively.

1.3.2 Fixed at ends and at center

Finite element analysis is carried out by considering only the single expansion chamber muffler for two fixed conditions: (a) Fixed at ends (b) Fixed at center. The result is then compared with the result of free-free end muffler.

Table 4 show the natural frequencies obtained from the modal analysis and table 5 shows the corresponding mode shapes and their comparison. Figure 6a, b and c shows transmission loss versus frequency plots for the single expansion chamber under free-free conditions, fixed at ends and fixed at the center respectively.

Table 4: Natural frequencies

Single chamber	
Mode no	Frequency (Hz)
1	213.697
2	368.033
3	601.41
4	949.02
5	1167.4
6	1404.3
7	1670.9
8	1801.2
9	1974.3

Mode no.	Frequency (Hz)
1	220.8
2	664.2
3	830.8
4	1188
5	1200
6	1823

Table 5: Comparison of mode shapes

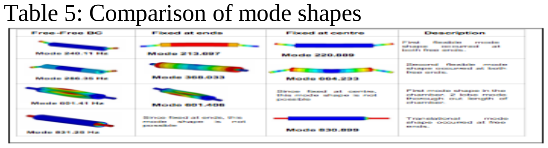
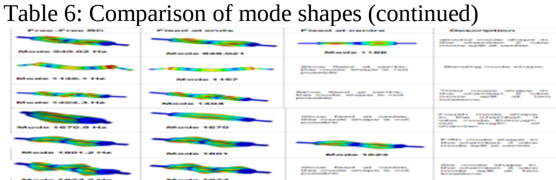


Table 6: Comparison of mode shapes (continued)



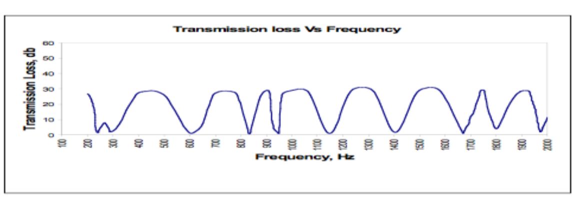


Figure 6a. Plot of transmission loss Vs. natural frequency for free-free end condition.

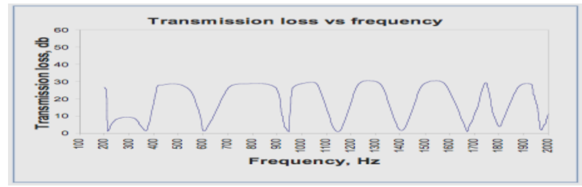


Figure 6b. Plot transmission loss Vs. natural frequency for fixed end condition.

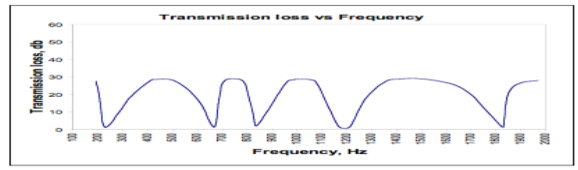


Figure 6c. Plot of transmission loss Vs. natural frequency fixed at center.

Result and discussion

Fixing the muffler at both the ends results in avoiding of only one mode that too at lower frequency range. Since all the higher natural frequencies are occurring in the cylinder region, there is not much difference in the results between free-free ends and fixed at ends. However, fixing at the center avoids five mode shapes when compared to free-free ends. Fixing at center will give better transmission loss compare to free - free and fixed at ends. Trend of transmission loss for a central supported single chamber muffler is almost similar to that of the two-chamber cylinder (Figure 5b). Fixing at center is likely to produce high stress at higher natural frequencies.

1.4 Conclusion

The method adopted to predict the attenuation characteristics of the muffler predicts that transmission loss is minimum at resonance. Further, the fact that muffler is an acoustic filter and its performance varies with frequency is well confirmed. And, the transmission loss increases with the increase in number of chambers and the loss is uniform
at all peak frequencies and occurs over reasonably wide range of frequencies indicating that effective attenuation take place over a wide range of frequencies making the three chamber configuration better among the three muffler configuration and the method adopted appears to provide an easy and effective means of predicting attenuation characteristics of the mufflers. Since fixing at the center shows transmission loss almost similar to that of the two-cylinder muffler. Further investigation on mufflers of different types (like, mufflers with extended tubes, plug type, perforated type, offset inlet and outlets etc) and of different length is required, to arrive at an optimum configuration.

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