"USING THE TRANSFER MATRIX METHOD ANALYZING MUFFLER PERFORMANCE"

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ABSTRACT

Internal combustion engine is considered as a major source of noise pollution. And these engines are used for various purposes such as, in power plants, automobiles, locomotives, and in various manufacturing machineries. Engine created noise pollution becomes a vital concern when used in residential areas or areas where noise creates hazard. Generally, noise level of more than 80 dB is injurious for human being. Exhaust noise and the noise produced due to friction of various parts of the engine are the main sources of noise in an engine. The exhaust noise is the most dominant one and to reduce this noise, various kinds of mufflers are generally used. The construction and the working procedure of mufflers usually affects the level of exhausts noise reduction. Engine makers have been making mufflers for more than 100 years. As the name suggests, muffler serves the primary purpose as to reduce or muffle the noise emitted by the internal combustion engine. Technology for muffler has not changed very much over the past 100 years. The exhaust is passed through a series of chambers in reactive type mufflers or straight through a perforated pipe wrapped with sound damping material in an absorptive type muffler. Both types are having strengths and weaknesses. The reactive type muffler is generally restrictive and prevents even the good engine sounds from coming through, but it does a good job of reducing noise. On the other hand, most absorptive type mufflers are less restrictive, but allow too much engine noise to come through. Despite of the packing material, absorptive type mufflers tend to get noisier with time. [19]

Keywords: Analysis, investigation, validation, research, comparison

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I. INTRODUCTION

Now a days, automotive engineers have been experimenting with electronic noise suppression muffler. 180o out of phase sound pressure wave generated by an electronic device, cancel out a similar sound wave generated by the engine. This becomes an effective way of cancelling out noise without restricting the flow. But being costly it is currently impractical for most of today's engines. Nevertheless, out of phase sound wave cancellation is the best technology so far to control engine noise. Now-a-days, this 180o phase sound is created within the engine muffler by reflecting the out-going sound waves. This reflected sound is used to lessen the main noise. This procedure is called as reflective noise cancellation system. And with the use of a resonator sometimes does this. [19]

Engine Noise:

The cause of engine noise are the pulses released by the exhaust. As soon as expansion stroke of the engine comes near the end, the outlet valve opens and the remaining pressure in the cylinder discharges exhaust gases as a pulse into the exhaust system. These pulses are between 0.1 and 0.4 atmospheres in amplitude, with pulse duration between 2 and 5 milliseconds. The frequency spectrum is directly correlated with the pulse duration. The cut-off frequency lies between 200 and 500 Hz. Generally, engines produce noise of 100 to 130 dB depending on the size and the type of the engine. [19]

Muffler/ Silencer:

It is a device used to reduce the sound from systems such as combustion engines, compressors, air-conditioning systems etc. Muffler or silencer is connected to a noise source by a pipe or a duct system Muffler is a reactive system, while silencer is an absorptive or active system. Simple expansion chamber is one of the most basic types of silencing elements used in intake and exhaust system of the engine. A simple expansion chamber consists of inlet tube; expansion chamber and an outlet tube (see Figure 1.1)

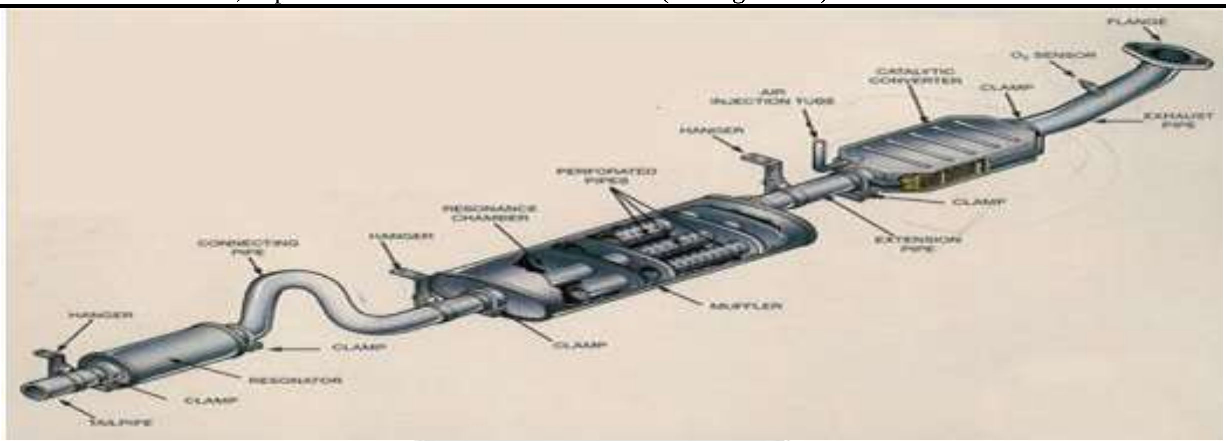

Fig-1.1: Exhaust Systems with its Components

In extended tube expansion chamber muffler the inlet tube is extended into the chamber.

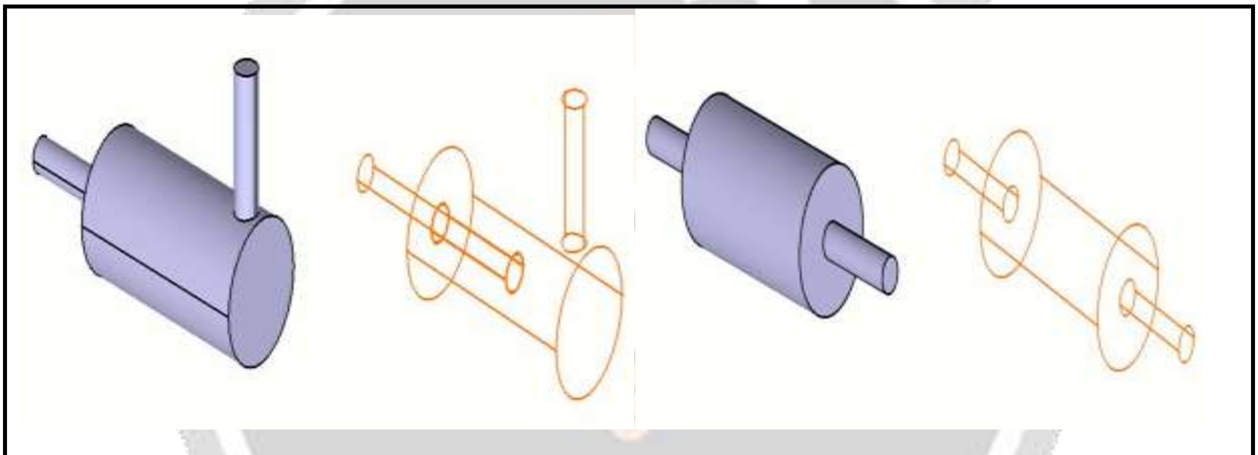

Fig-1.2: Extended inlet expansion chamber & Simple expansion chamber

II. LITERATURE REVIEW

A number of researchers have worked on design, analysis and experimental investigations of mufflers since the I.C. engine came into existence.

Masson et al. [7], worked on optimize the acoustic performance of low cost, simple geometry mufflers by using micro-perforated panels (MPP) in their expansion chambers. In this, the Transmission Loss (TL) given by the computational model is compared with the laboratory measurements, both for the mufflers which contains the micro-perforated panels and with muffler without micro-perforated panels. The easy computing transfer matrix approach is used for optimization calculation. Then, the Boundary Element Method (BEM) is used in order to compare the evaluation of the Transmission Loss. To detect the real effect of resonator absorbers based on micro-perforated panels in the expansion chambers different configurations have been tested. It is shown that their presence increases the Transmission Loss at certain frequencies if their parameters are well chosen, but their dissipative effect is negligible when occurs at a reactive effect resonance.

The two-dimensional (2D) axisymmetric analytical approach investigated in detail the acoustic behavior of perforated dissipative circular mufflers with empty extended inlet/outlet, that matches the acoustic pressure and velocity across the geometrical discontinuities, and the finite element method(FEM) presented by Denia et al. [6]. To evaluate the axial wave number in the fibrous material and the central perforated pipe the complex characteristic impedance, wave number, and perforation impedance are taken into account. For the muffler sections two different analytical procedures are presented that allow the computation of the modal wave coefficients. Benchmarking against FE calculations exhibited an excellent agreement. For further validation both the approaches are also compared with experimental work.

For acoustic analysis of perforated pipe muffler components a new method based on the Matrizant theory is developed which is put forward by Dokumaci [5]. The analysis is presented in a generality encompassing any number of parallel pipes that communicate along a common length. The utility and potential of the method is demonstrated on a plug muffler and a reverse flow muffler.

To predict the acoustic performance of multiple pass silencers with perforated tube sections a time domain computational approach is applied which is performed by Dickey et al. [10]. It shows that the non-linear, one-dimensional method may readily include temporal and spatial variations in sound pressure level, orifice flow velocities, and mean duct flow, all above can affect the local orifice behavior of perforated tube elements, and therefore it can affect overall noise reduction characteristics. For the limiting case of low sound pressure levels and zero mean flow, the transmission loss of two anechoically terminated multiple pass muffler configurations is determined computationally and experimentally. Comparisons between the numerical results and experimental data is done to correlate well for frequencies where the one-dimensional assumption is justified.

Selamet et al. [2] investigated in detail the acoustic behavior of circular dual chamber muffler with the help of two dimensional axis-symmetric analytical approach, FEM and with the help of experimental work. Comparison of FEM and experimental results are consistent with the analytical approach. Several effects like presence of rigid baffle, inner radius of baffle, position of baffle and extended inlet/outlet and baffler duct are been studied. These effects are shown to modify the acoustic behavior drastically.

For commercial automotive exhaust system, advancements in the analysis and design of complex mufflers incorporating 3D or high order mode effects which have long been anticipated by Sahasrabudhe et al. [1]. In this work the analysis of reactive expansion chamber mufflers of simple and extended tube type is presented. It is found that the suitable positioning of the inlet and outlet tubes helps to lessen the effect of certain higher order modes.

The effect of length on the acoustic attenuation (TL) performance of concentric expansion chambers done by Selamet et al. [3]. In this study, it has been shown analytically, computationally, and experimentally that how the propagation of multidimensional waves in expansion chambers is dependent on the length of the chamber, as well as on the expansion ratio and on frequency.

In determining the acoustic response for different configurations of simple expansion chamber mufflers Computational Fluid Dynamics (CFD) is well suited and thus Middelberg et al. [8] has used to evaluate the performance of simple muffler design used CFD. A simple expansion chamber, an expansion chamber with a central baffle and an expansion chamber with an extended inlet-outlet are the three muffler types which were studied. Middelberg et al. used Fluent 6.1 CFD package to generate a two dimensional axisymmetric model. Long inlet and outlet pipes models are used to minimize the effect of reflected waves on the monitoring points when subject to acoustic perturbation. As it has been previously shown to be 14 times the length of the expansion chamber as the the optimum length of the inlet-outlet pipe. The CFD results for the transmission loss were compared to previously publish experimental results. The acoustic numerical results obtained with the help of CFD shows good agreement with the published experimental results. CFD analysis was further carried out on the three muffler configurations in the presence of mean flow. To evaluate both the mean flow and acoustic performance of an expansion chamber muffler, it was concluded that computational fluid dynamics can be used successfully with various modifications which includes baffles and extended inlet-outlet pipes.

Fully automatic 3D analysis tool for expansion chamber mufflers has been developed by Srinivasan et al. [12]. The results obtained by fully automatic 3D analysis tool are compared with analytical and experimental results for simple as well as extended-tube expansion chambers, with an offset or without an offset.

Work done on exhaust noise, legislation targets, customer expectations and cost reduction by Anderson which shows importance for design optimization of the exhaust systems. To use three dimensional linear pressure acoustics and to calculate the transfer matrix of the muffler is one of the solution. For calculating either the insertion loss or transmission loss of a muffler the transfer matrix is the basis. The 3D simulations in Comsol of different muffler configurations are verified by measurements in a flow acoustic test rig with the help of two-source method.

According to Datchanamourty [4] as modelling the actual geometry of the perforated tubes with holes is very expensive, perforated tubes are usually modelled by the transfer impedance approach due to the enormity of the boundary elements required. Required detailed modelling of the perforated tubes has become very possible as the sub-structuring technique is developing, which greatly helps to reduce the number of elements. In this thesis of Datchanamourty, mufflers with perforated tubes are analyzed by modelling the actual geometry and with the help of locations of holes on the perforated tubes. To model the mufflers the Direct-mixed-body boundary element method with sub-structuring is used. The mufflers of various geometry containing perforated tubes with holes of different sizes and porosity are tested. Analyses obtained results are compared with the empirical formula results and experimental results. A preliminary kind of investigation on the detailed modelling of flow-through catalytic converters is also conducted.

According to S.Bilawchuk [17] it is postulated that the use of the finite element method and the boundary element method to help to analyses in acoustical engineering design is increasing rapidly day by day. For designing purpose of acoustical silencer systems, the traditional, 4-pole and 3-point method used in conjunction with the FEM and the BEM, can be a powerful tools. The Boundary Element Method is quite slow when compared to the FEM. Thus it should, only be used when the modelling requires its flexibility, such as for insertion loss predictions due to the interior/exterior coupling required. Also, it is seen by the fundamental differences between the 4-pole method and 3-point method that each one is better suited according to certain specific design applications.

Despite of being, as accurate as the other two methods, the traditional method, is time consuming and more difficult to implement due to the two separate geometry's required due to the plane wave assumptions and inlet and outlet boundary conditions. The 4-pole method is mostly suited when the cascade of muffler elements is used. For continuity between adjacent sections the method produces the 4-pole parameters necessary. It is seen that, it is quite slower than the 3-point method and therefore for multiple runs or optimization it is not recommended. There is a modified 4-pole method that has been seen to be just as fast as the 3-point method, but the problem is that the code required for this method, was not possible to implement using SYSNOISE.

On the other hand, the 3-point method, is as accurate as and as easier to use. The 3-point method is faster than the traditional method and 4-pole methods and adjusts itself very well for repeated computational runs for optimization. It does not produce the 4-pole parameters and, as such, the section being evaluated, it cannot be inter-linked with other sections. All of the sections have to be created as the one large section and then meshed and evaluated, in order to perform such an evaluation. Therefore, the 3-point method, is a great tool for evaluation purpose of the response of modifying individual parameters such as baffle spacing, absorptive material properties, overall silencer length and width, and effects of multiple small chambers.

III. ACOUSTIC ANALYSIS OF MUFFLER

Considering only one-dimensional models, the two types of simulation models may be distinguished as

1. **Linear Acoustic models:** This is based on the hypothesis of small pressure perturbations within the ducts, and
2. **Non-linear gas dynamics models:** This describes the propagation of finite amplitude wave motion in the ducts.

Linear acoustic models are frequency domain techniques, which for instance use the four-pole transfer matrix method to calculate the transmission loss of mufflers. On the other hand, non-linear gas dynamic models are able to simulate the full wave motion in the whole engine intake and exhaust system and are based on time domain techniques.

There are a number of methods currently used to model and investigate the performance of mufflers. They Include:

3.1 Analytical Method:-

Analytical methods are well suited for determining the acoustic response of different configurations of simple expansion chamber mufflers but not for mufflers with complex geometries.

Following empirical formula is used to find out the transmission loss of single chamber muffler.

$$TL = 10\log_{10}\left[1+\frac{1}{4}\left[(M)-\left(\frac{1}{M}\right)\right]^2 \sin^2(KL)\right] \tag{3.1}$$

An expansion chamber has a predictable transmission loss curve having maxima at,

$$f = \frac{nc}{4L} \tag{3.2}$$

Where n = 1, 2, 3….

3.2 Experimental Method:-

Experimental method requires set-up of an experiment and manufacturing a prototype muffler. As shown in figures two microphones were connected upstream while two were connected downstream. The Microphones are used to convert acoustic signal into electrical signal [12]. The microphone output is given to "Data Acquisition System" which processes it and gives it to computer. At downstream end of muffler, the noise signal is terminated anechoically so that no reflection of pressure wave takes place. The output of data acquisition system is given to computer, which gives Transmission loss for various frequencies.

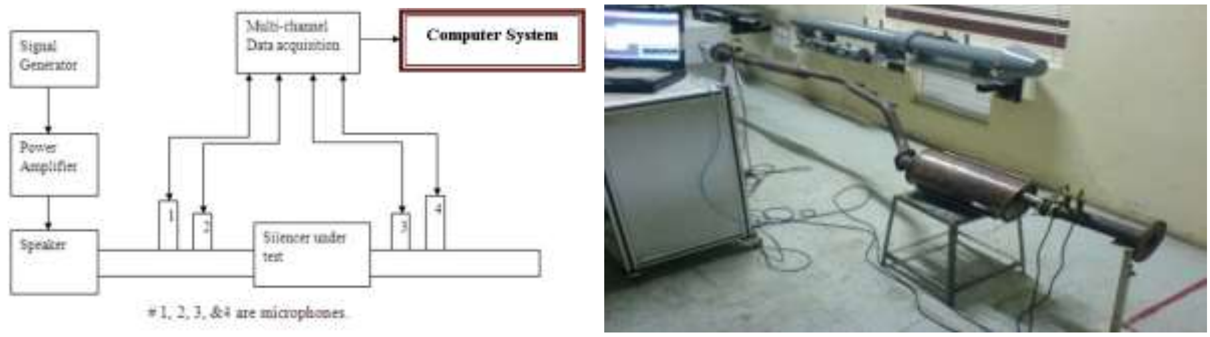

Fig. 3.2.1 Experimental Setup line diagram for Transmission Loss Evaluation & Experimental Set Up for Transmission Loss Evaluation

3.3 Computational Modelling (FEM/BEM):-

With the ever-increasing computational speed and storage capacity of computers, the use of the finite element method (FEM) and the boundary element method (BEM) in design is growing rapidly. One area that lends itself very well to these methods is the design of silencer systems for noise control. There is much work that has been done for smaller systems such as those used in automobiles and small engines, however, the design of much larger systems (such as the parallel baffle type used for gas turbines and other large industrial machines) is still largely guesswork and empirical extensions of previous results. Due to the large size, difficulties in testing and high costs of these silencer systems, the ability to accurately predict the performance before construction and commissioning would be very beneficial. To properly predict the performance of a silencer system, many factors need to be involved in the calculation. Geometrical concerns, absorptive material characteristics, flow effects (turbulence), break out noise, self-generated noise, and source impedance all need to be included in the design calculations of insertion loss (IL).

IV. ANALYSIS OF SIMPLE EXPANSION CHAMBER

SYSNOISE is an FEM/BEM based computational acoustics program that allows users to input a geometry, impose boundary conditions, select environmental parameters, and solve the system of resulting equations in one, two or three dimensions. Once the system has been solved, a host of post-processing options are available to determine the various performance characteristics. Using command line code, it was possible to perform the calculations for all three methods, utilizing both FEM and BEM, and in both two and three dimensions.

Principle Steps of Finite Element Application:-

- Model Definition:
  - Model Type
  - Meshes
  - Materials & Properties
  - Field Point Mesh
  - BC: source, vibrating panels
- Use of FEM solvers
- FEM applications
- Post processing

Principle Steps of Boundary Element Application:-

- Model Definition
  - Meshes
  - Model Type
  - Acoustic Properties
  - BC: source, vibrating panels
  - Advanced Boundary Conditions
- Use of BEM solvers
- BEM applications
- Post processing.

4.1 Geometry of Simple Expansion Chamber:-

The three-dimensional simple expansion chamber muffler is modelled in the CATIA V5R17. The muffler is subjected to a harmonic input velocity and boundary conditions were set. The acoustic performance of the muffler is then obtained using the transmission loss equation. Following Fig. shows the 3-D geometry of simple expansion chamber using CATIA V5R17.

Single Expansion Chamber:-

The transmission loss of simple expansion chamber whose dimensions are (d1=d2=50 mm D=150 mm L=250 mm) is investigated by using,

(1) Computational method by FEM and BEM.

(2) Analytical method.

Computational Method (FEM and BEM)

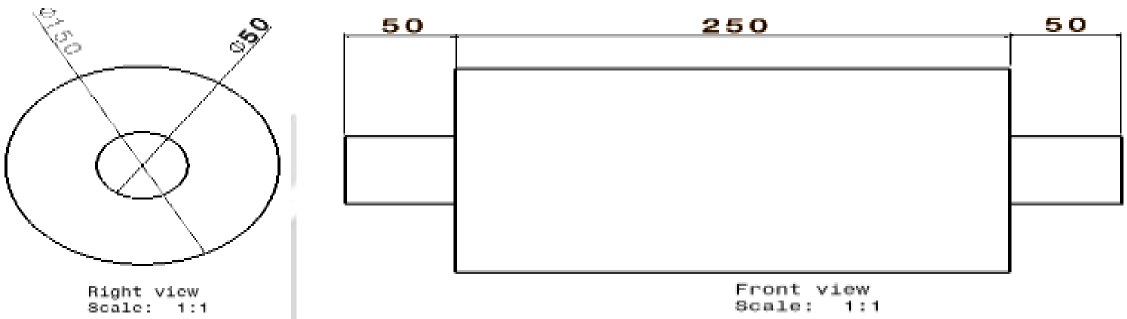

Fig. 4.1 Geometry of simple expansion chamber (All dimension in mm)

4.2 Building the Finite Element Model and Boundary Element Model: -

Fig.5.3.2-1(a) show the FEM mesh created for the geometry as used by SYSNOISE. Fig.5.3.2-2(b) is an example of a BEM mesh where each dot represents a node while the lines in between the dots represent elements. The model used for the study was not shown because the large numbers of elements appear as a single outline when printed on paper; therefore a much simpler model is illustrated.

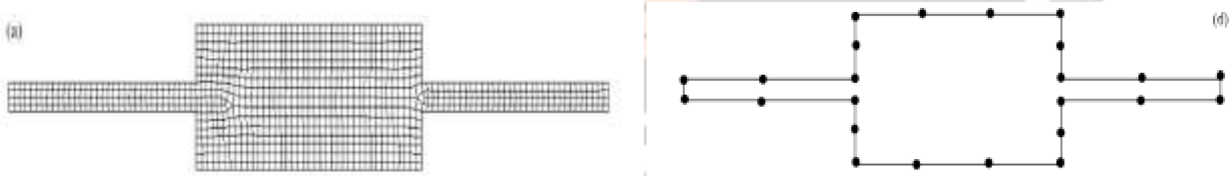

Fig.4.2 (a) Finite Element Mesh for Simple Expansion chamber & (b) Boundary Element Mesh for Simple Expansion chamber

4.2 Boundary Conditions: -

To calculate the acoustic performance of the muffler using the transmission loss equation, two boundary condition cases need to be satisfied as per TMM. In SYSNOISE boundary conditions apply at inlet and outlet. At inlet we apply velocity in m/s and at outlet impedance in kg-s/m2.Transmission losses are indirectly calculated via the calculation of the transfer matrix coefficients. Calculation requires two runs with different BC.

METHOD 1:-

1. Boundary condition U1=1 , U0=0
   Calculate P0 and P1
   Calculate T11 and T21
2. Boundary Condition U1=1 , P0=0
3. Calculate P1 and U0

METHOD 2:-

In SYSNOISE transmission losses calculated in one step by applying following boundary condition.

1) Impose boundary conditions U1=1 , Z0=0
2) Calculate P0 and P1
3) Calculate TL from given formula

Advantage – Shorter calculation time

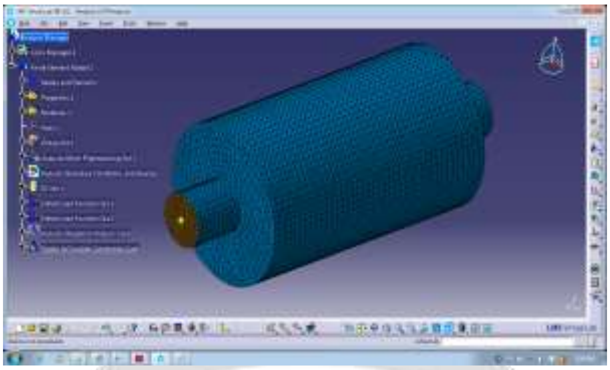

Fig.4.2 View of model after apply of Boundary Condition in SYSNOISE

4.3 Post Processing:-

The acoustic performance of the muffler is calculated using the transmission loss given by equation (4.1 and 4.2) from Chapter 4. The terms of the equation A11, A12, A21, A22 are complex. The resulting pressures are imaginary and the velocities are real. From evaluating each term, the following expressions can be obtained:

$$A_{11} = \frac{P_{inlet}}{P_{outlet}} = \frac{0+A_j}{0+B_j} = \frac{A}{B} \quad \text{(Real)} \quad (4.10a)$$

$$A_{12} = \frac{P_{inlet}}{U_{outlet}} = \frac{0+A_j}{B+0_j} = \frac{(0+A_j)(B-0_j)}{(B+0_j)(B-0_j)} = j\frac{A}{B} \quad \text{(Imaginary)} \quad (4.10b)$$

$$A_{21} = \frac{U_{inlet}}{P_{outlet}} = \frac{A+0_j}{0+B_j} = \frac{(A+0_j)(0-B_j)}{(0+B_j)(0-B_j)} = -j\frac{A}{B} \quad \text{(Imaginary)} \quad (4.10c)$$

$$A_{22} = \frac{U_{inlet}}{U_{outlet}} = \frac{A+0_j}{B+0_j} = \frac{A}{B} \quad \text{(Real)} \quad (4.10d)$$

$$A_{11} = \frac{(P_o \times U_o) + (P_i \times U_i)}{(P_i \times U_o) + (P_o \times U_i)} \quad \text{(Real)} \quad (4.11a)$$

5
$$A_{12} = \frac{P_i^{\,2} - P_o^{\,2}}{(P_i \times U_o) + (P_o \times U_i)} \quad \text{(Imaginary)} \quad (4.12b)$$

$$A_{21} = \frac{U_i^{\,2} - U_o^{\,2}}{(P_i \times U_o) + (P_o \times U_i)} \quad \text{(Imaginary)} \quad (4.13c)$$

$$A_{22} = \frac{(P_o \times U_o) + (P_i \times U_i)}{(P_i \times U_o) + (P_o \times U_i)} \quad \text{(Real)} \quad (4.14d)$$

The post-processing (POST1) command is used to extract these terms from the results for both boundary condition cases. For the first boundary condition results, where $U_{outlet} = 0$, A11 and A21 terms are calculated. Similarly for the second case where $P_{outlet} = 0$, A12 and A22 terms are calculated.

$$TL = 20\log_{10}\left[\frac{1}{2}\left(\left|A_{11} + \frac{A_{12}}{\rho c} + A_{21} * \rho c + A_{22}\right|\right)\right] \quad (4.15)$$

This transmission loss is calculated for every 5 Hz from 1 Hz to 3000 Hz. The Fig. graph shows the transmission loss verses frequency.

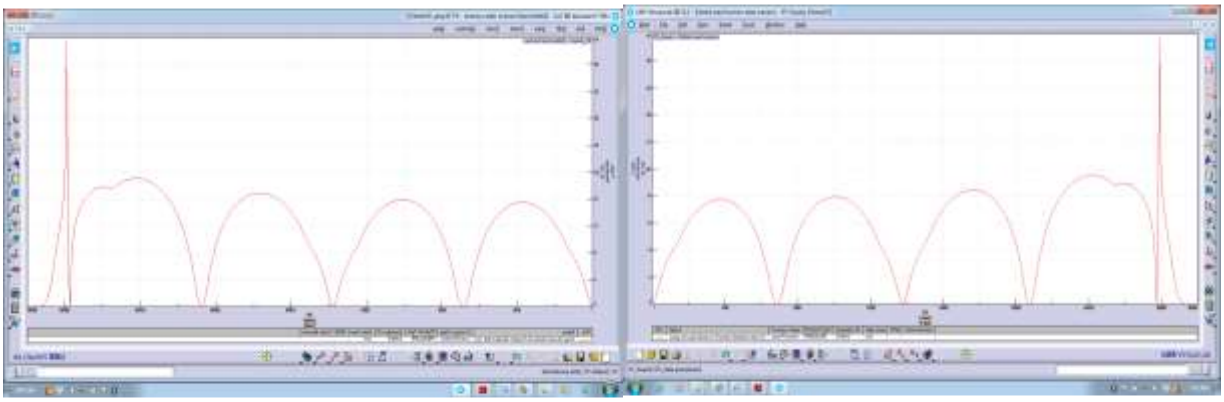

Fig.4.3 TL of simple expansion chamber muffler by FEM & TL of simple expansion chamber muffler by BEM

V. RESULTS AND DISCUSSIONS

The objective of this study is to investigate the acoustic behaviour of simple expansion chamber with perforated tubes and baffles.

A) Simple Expansion Chamber:-

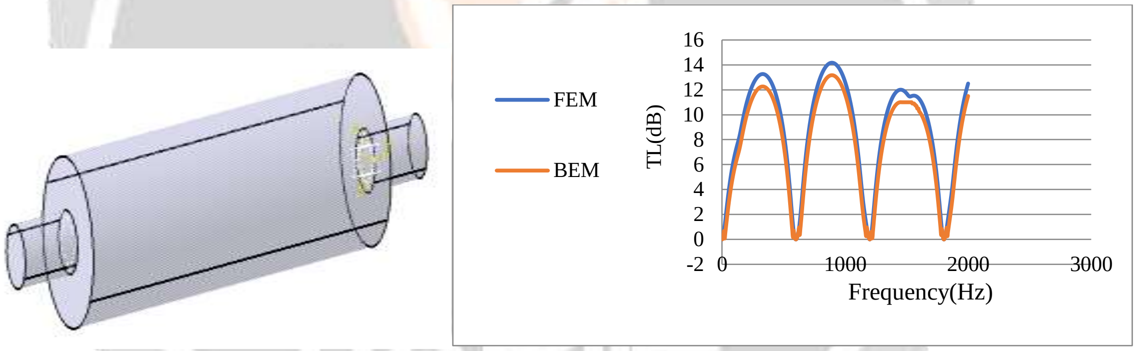

Fig.3.1 3-D View of Simple Expansion Chamber Comparison of Simple expansion chamber by FE and BE Method

B) Muffler with 2 baffles, 6 pipes and one pipe at center supported by baffle:-

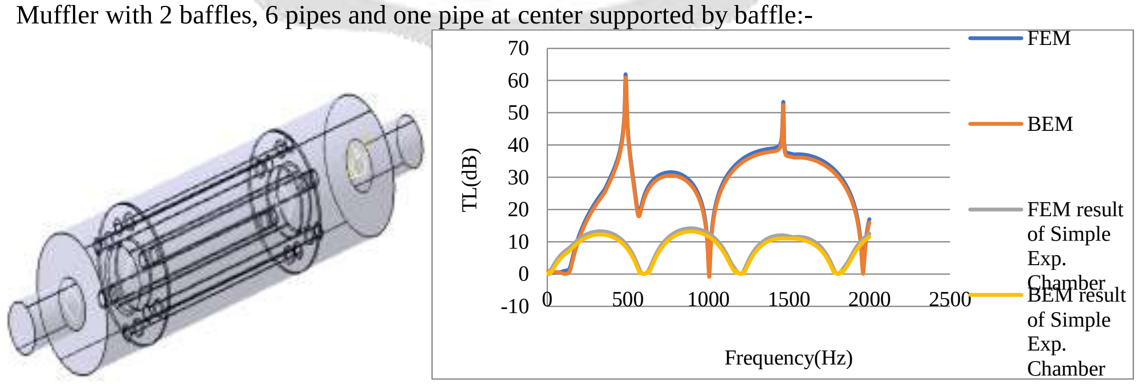

Fig.3.2 3-D view of muffler Comparison of model with simple expansion chamber

From the result of modified model it is concluded that if we used number of restriction in expansion chamber then Transmission loss will higher than the simple expansion chamber.

C) Extended inlet and outlet pipe with 2 baffle, 6 pipe and 1 pipe centrally supported by baffle:-

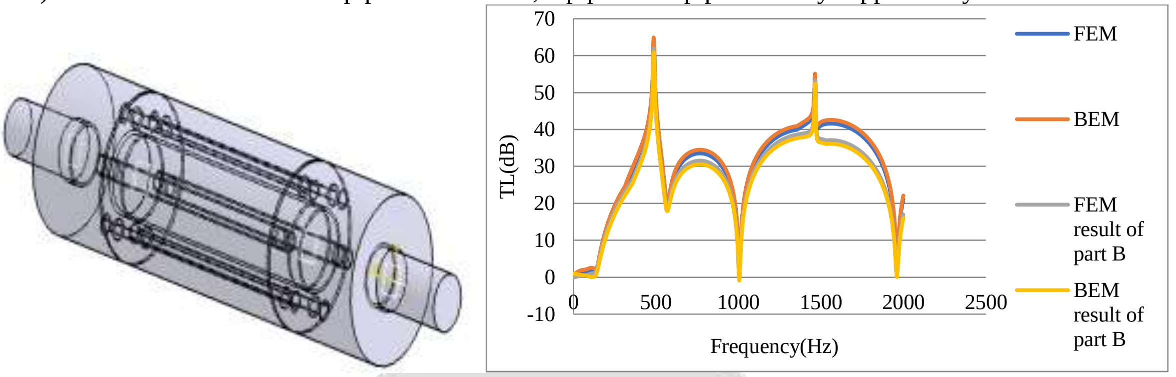

Fig.3.3 3-D View of modified muffler &Comparison between part B

D) Extended inlet and outlet pipe with 2 baffle, 6 pipe and 1 perforated pipe centrally supported by baffle

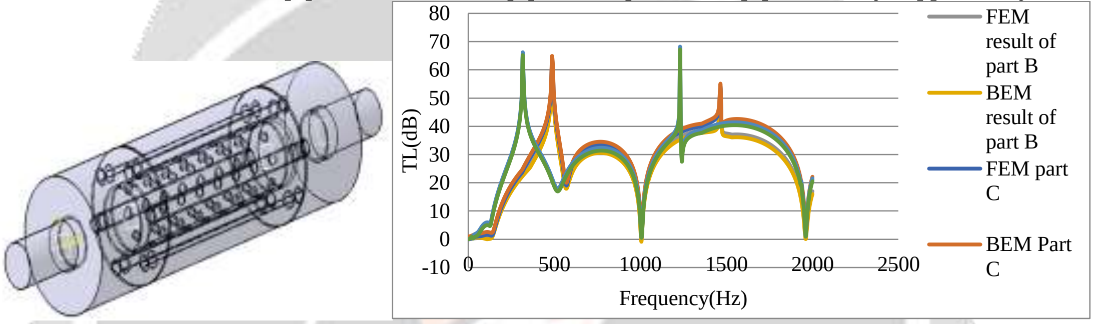

Fig.3.4 3-D view of muffler Comparison between part B, Part C and Part D

E) Simple expansion chamber with perforated tube with 3 different diameter hole:-

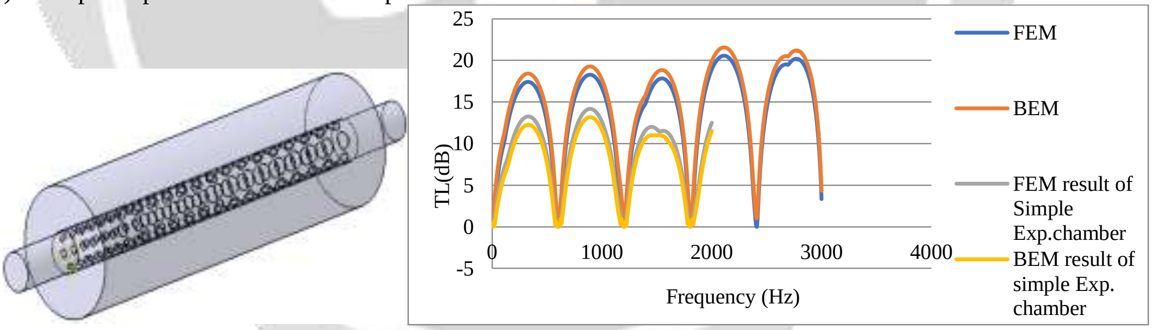

Fig. 3.5 3-D view of muffler comparison with simple expansion chamber.

F) Single expansion chamber with radius of baffle hole:-

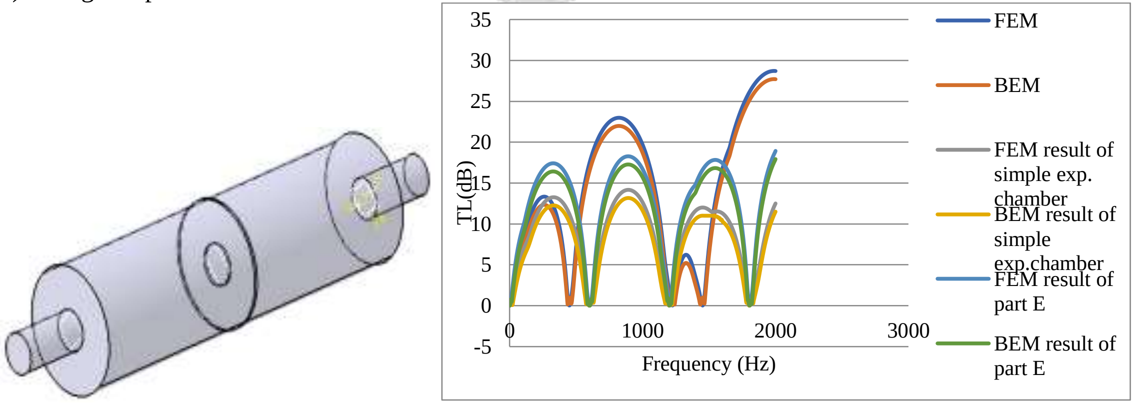

Fig.3.6 3-D View of single expansion chamber with radius of baffle hole. & comparison with part A and part E

G) Simple expansion chamber with rad. of the baffle hole and perforated tube:-

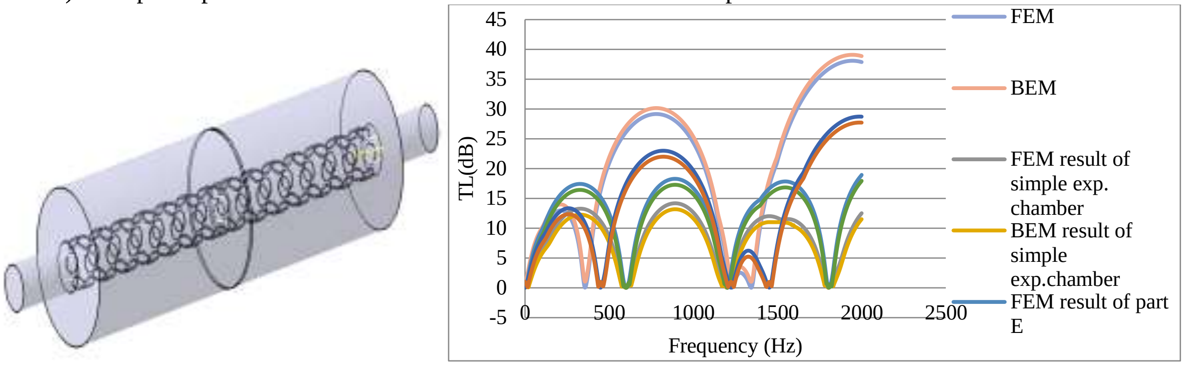

Fig.3.7 3-D view of simple exp. chamber with radius of the baffler hole and perforated tube. Comparison with part A, part E and part F

H) Extended inlet and outlet with perforated tube and baffle:-

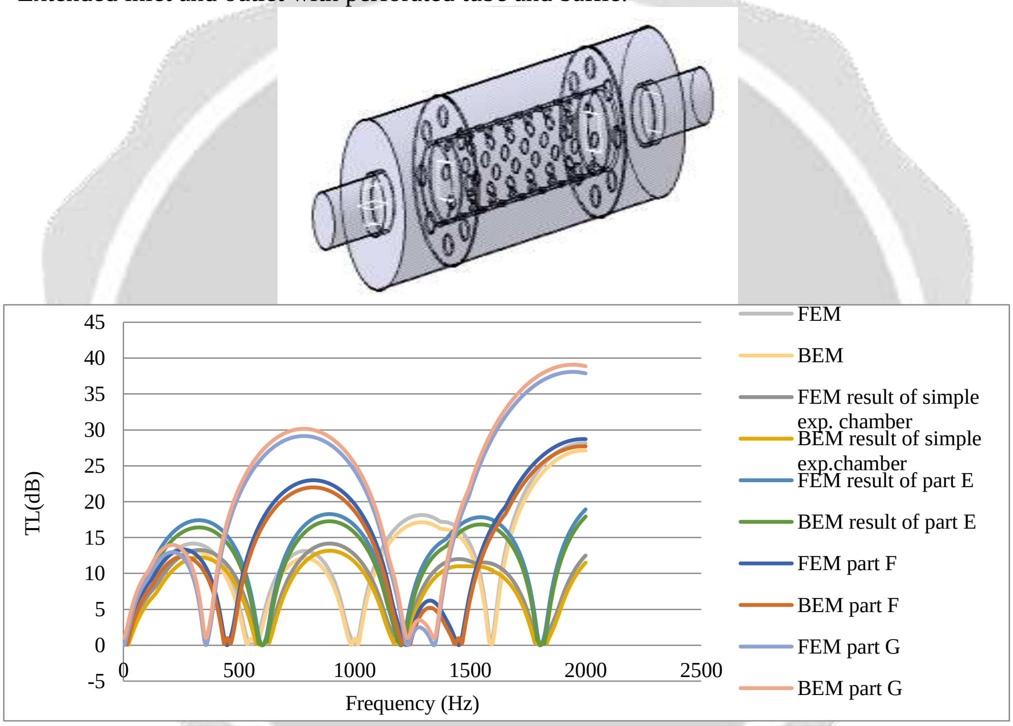

Fig.3.8 3-D view of the muffler & comparison with part A, part E, Part F, and Part

In this result I have compared nearly 5 type of muffler by keeping same dimension but changed the internal design of expansion chamber. From that result it is concluded that for perforate tube with constant diameter of hole and baffle (part G) have high transmission loss. In the above muffler I have used perforated tube with perforated baffle and extended inlet and outlet but transmission loss for that muffler is less.

VI. CONCLUSION

1. The acoustic performance in terms of TL of reactive simple expansion chamber with various lengths of expansion chamber and baffle investigated computationally. The computational (FEM and BEM) result shows good agreement with experimental published results.
2. It shows how the transfer matrix may be extracted using the complex wave amplitudes at two specific points on the inlet side and outlet side, while running only a single simulation at multiple frequencies.
3. The presence of a cantered baffle leads to an acoustic attenuation that exhibits pairs of domes. The first dome of each pair is smaller in amplitude and frequency bandwidth than the second one. When the baffle whole diameter is reduced, the amplitude and frequency bandwidth of the second dome of each pair become larger for constant porosity and constant number of holes.

4. No frequency limitations, short setup time, and easy redesign are among the advantages of using 3D pressure acoustic simulation without making prototype model. The FEA has the particular advantage of being able to model any complicated shape to study the muffler performance and effect of higher order modes.

VII. FUTURE SCOPE

1. For reducing computation time and storage, perforated tubes were modelled by using sub-structuring technique to facilitate the modelling of the complex perforate pattern. SYSNOISE may be used to predict the acoustic performance of mufflers with the inclusion of mean flow. Investigate the effect of backpressure on the engine due to the perforated pipes and baffles in the muffler.

2. This study can be extended to mufflers with absorptive lining can be modelled; modifications should be made to the current model, to examine the acoustic performance of mufflers with more complex geometries can also be considered. Investigate whether this method useful for analysis of catalytic converter that consists of the micro perforated panels.

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