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Optimization and Experimental Validation of Elliptical Reactive Muffler with Central Inlet Central Outlet

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***Abstract*- Exhaust noise from engines is one of component noise pollution to the environment. Exhaust systems are developed to attenuate noise meeting required db (a) levels and sound quality, emissions based on environment norms. Hence this has become an important area of research and development. Most of the advances in theory of acoustic filters and exhaust mufflers have been developed in last two decades.**

Mufflers are important part of engine system and commonly used in exhaust system to minimize sound transmissions caused by exhaust gases. Design of mufflers is a complex function that affects noise characteristics, emission and fuel efficiency of engine. Therefore muffler design becomes more and more important for noise reduction.

The objective of the paper is to propose a simple in construction, effective silencing device, which can achieve good results in minimizing the noise. The acoustic analysis is one of the methods which help to analyses the sound level at the tail pipe. This optimization revises acoustic analysis of muffler using Finite Element Analysis. The muffler is modeled in 'PRO E Wildfire 5.0 and 'COMSOL MULTIPHYSICS' is used for acoustic analysis. Effect of extrusion of inlet and outlet pipe inside the chamber and also the position of the extra inlet tube (i.e. divided inlet) to the chamber and then optimized this parameter to get the minimum sound pressure level (SPL) or maximum transmission loss (TL).

The effect of SPL on the walls of the muffler is not considered. The material of the muffler is also not considered. This optimized model of elliptical muffler is manufacture and then validate with the experimental analysis.

***Keywords*- Acoustics, elliptical muffler, optimization, sound pressure level (SPL)**

I. INTRODUCTION

Muffler is necessary component to reduce the noise level in the vehicle. Due to stringent norms for sound level at the tail pipe of exhaust, it is necessary to develop, design and optimized mufflers which full-fill that norms. Reactive muffler plays an important role as noise control element for reduction of automotive exhaust noise, fan noise, and other noise sources involving the flow of gases. Mufflers are typically arranged along the exhaust pipe as the part of the exhaust system of an internal combustion engine to reduce its noise. The expansion chambers with various cross section like Circular, Elliptical, Square & Rectangular are commonly use for noise attenuation. The degree of attenuation can also be improved with design optimization of inlet pipes, outlet pipes & baffle plates. Transmission loss is one of the most frequently used criteria of muffler performance because it can be predicted very easily from the known physical parameters of the muffler

There are a number of methods currently used to model and investigates the acoustic performance (TL) of mufflers including analytical methods such as the TMM, computational methods including the use of FEM & BEM & experimental measurement techniques .The use of finite element method (FEM) & the boundary element method (BEM) can aid in the prediction & design.

This study proposes an optimal design scheme to improve the muffler capacity of noise reduction of the exhaust system by FEM and Taguchi method. Performance of a muffler is measured by performance prediction software (COMSOL MULTIPHYSICS).

In the first stage of a design, effect of major diameter of elliptical chamber, extended inlet and outlet lengths as control factors. In the second stage of a design, along with the extended inlet and outlet optimized lengths, the location of the extra tube (i.e. divided) inlet to the elliptical chamber are selected as control factors. Then, L-9 table of orthogonal arrays is adopted to extract the effective main factors.

1.1 REQUIREMENTS OF MUFFLER

The properly designed muffler for any particular application should satisfy the often – conflicting demands of at least five criteria simultaneously

1. The acoustic criterion, which specifies the minimum noise reduction, required from the muffler as a function of frequency. The operating conditions must be known because large steady- flow velocities or large alternating velocities (high sound pressure levels) may alter its acoustic performance.
2. The aerodynamic criterion which specifies the maximum acceptable average pressure drop through the muffler at a given temperature and mass flow.
3. The geometrical criterion, which specifies the maximum allowable volume and restrictions on shape.
4. The mechanical criterion, which may specify materials from which it is durable and requires little maintains.
5. The economical criterion is vital in the market place.

1.2 TYPES OF MUFFLERS

The sole purpose of an automotive muffler is to reduce engine noise emission. Broadly there are two types of muffler:

1. Reflective/Reactive mufflers
2. Dissipative / Absorptive muffler
3. Combination muffler/silencer

1. Reflective/reactive mufflers:

These mufflers reflect acoustic waves by abrupt area expansions or changes of impedance. The noise reduction mechanism of reactive silencer is that the area discontinuity provides an impedance mismatch for the sound wave travelling along the pipe. The reactive silencers are more effective at lower frequencies than at high frequencies, and are most widely used to attenuate the exhaust noise of internal combustion engines.

2. Dissipative / Absorptive muffler:

These mufflers based on dissipation of acoustic energy into heat through viscous losses in fibrous materials or flow related (resistive) losses in perforated pipes. This type of muffler design uses only absorption of the sound wave to reduce the noise level without messing with the exhaust gas pressure. The sound produced by this type of muffler is much higher compared to the other type of mufflers. These mufflers produce much less restriction, but don't reduce the sound level as much as conventional mufflers.

3. Combination muffler/silencer

Some silencers combine both reactive and absorptive elements to extend the noise attenuation performance over a broader noise spectrum. Combination silencers are also widely used to reduce engine exhaust noise.

Reactive Mufflers are commonly used to reduce noise related with internal combustion engine exhausts, high pressure gas or steam vents, compressors and fans. Regulations for controlling noise pollution of automotive vehicles, mufflers are important part of engine system and commonly used in exhaust system to minimize noise caused by exhaust gases. Design of muffler is a complex function that affects the noise characteristics and fuel efficiency of the vehicle. Basically a muffler for an automobile is characterized by numerous parameters like Insertion Loss (IL), Transmission Loss (TL). The best used parameter to evaluate the sound radiation characteristics of muffler is transmission loss (TL). This is the one of the most frequently used criteria of muffler performance because it can be predicted very easily from the known physical parameters of the muffler.

II. LITERATURE REVIEW

The literature review is brief outline about the noise reduction technique using muffler and various methods available to predict the performance of the muffler of the exhaust system. The more focus of the research papers discussed here is on comparative study of the analytical and simulation methods to predict the acoustical performance of the muffler. In the following paragraph, some important points in this literature review are discussed related to the objectives of the project work.

A.Mimani, M.L.Munjal [1] have discussed the acoustical behavior of an elliptical chamber muffler having an end-inlet and side-Outlet port is analyzed semi-analytically. The acoustic performance of these configurations is evaluated in terms of transmission loss (TL). The analytical results thus obtained are compared with 3-D FEA carried on commercial software for certain muffler configurations.

A.Mimani, M.L.Munjal [2] has discussed acoustic analysis of the short elliptical chamber mufflers which are used often in the modern day automotive exhaust systems. The acoustic analysis of such short chamber mufflers is facilitated by considering a transverse plane wave propagation model along the major axis up to the low frequency limit. The transmission loss (TL) performance of the muffler configurations computed by this analytical approach agrees excellently with that computed by the Matrizant approach used earlier by the authors, thereby offering a faster and more elegant alternate method to analyze short elliptical muffler configurations.

Subhabrata Banerjee, Anthony M. Jacobi [03] have discussed a Green’s function solution method is implemented to study sound attenuation in single-inlet/double-outlet (SIDO) and double-inlet/ single-outlet (DISO) circular chamber mufflers. The mufflers are modeled as piston driven rigid circular chambers containing a stationary fluid. The pistons are assumed to perform simple harmonic motion with uniform velocities. Velocity potential in the chamber is derived as a superposition of three dimensional velocity potential due to each piston. Pressure field in the chamber is calculated from the velocity potential through conservation of linear momentum equation. Acoustic pressure acting on each piston is calculated by averaging over the surface of the piston. Transmission loss (TL) is evaluated from incident and transmitted acoustic energy. TL curves for various inlet/outlet orientations derived from this method is validated with results obtained from the literature. The effect of locations of inlet/outlet on TL is studied.

OvidiuVasile, NicoletaGillich and NeagoeLaurentiu [04] have discussed the pressure wave propagation in a muffler for an internal combustion engine in case of a lined muffler with rectangular cross section resonator chamber. The paper purpose is to show finite elements analysis of both inductive and resistive damping in pressure acoustics. The main output is the transmission loss for the frequency range 50 Hz–3000 Hz. This research paper helps to give a proper sequence of the acoustic analysis. It helps to define the boundary conditions. This gives idea to model a muffler with basic knowledge of it. This paper shows the results of sound pressure level with & without absorbing material. The results of this paper focused on transmission loss.

ZeynepParlar, Sengül Ari, RifatYilmaz, ErdemÖzdemir and ArdaKahraman.[05]have discussed the perforated reactive mufflers which have an effective damping capability are specifically used for this purpose. New designs should be analyzed with respect to both acoustics and back pressure. In this study, a reactive perforated muffler is investigated numerically and experimentally. For an acoustical analysis, the transmission loss which is independent of sound source of the present cross flow, the perforated muffler was analyzed by COMSOL. Back pressure was obtained based on the flow field analysis and was also compared with experimental results. Numerical results have an approximate error of 20% compared to experimental results. This paper helps to give idea to analyses the perforated mufflers. The boundary conditions, initial conditions and important results of acoustic analysis were studied from this paper. This paper helped me to model a perforated muffler with baffles. The meshing properties in this paper are as per the designer's considerations. At the end, the experimental results were compared with analysis.

Venkateshamb, Mayank Tiwari and M.L. Munjal [06] have discussed the transmission loss of a rectangular expansion chamber, the inlet and outlet of which are situated at arbitrary locations of the chamber, i.e., the side wall or the face of the chamber, are analyzed here based on the Green's Function of a rectangular cavity with homogeneous boundary conditions. The rectangular chamber Green's function is expressed in terms of a finite number of rigid rectangular cavity mode shapes. The inlet and outlet ports are modeled as uniform velocity pistons.. The results are verified against those in the literature where use has been made of modal expansions and also numerical models (FEM). The transfer matrix formulation for yielding wall rectangular chambers has been derived incorporating the structural–acoustic coupling. Parametric studies are conducted for different inlet and outlet configurations, and the various phenomena occurring in the TL curves that cannot be explained by the classical plane wave theory, are discussed.

M.L.Munjal [09] has discussed the various topics related to acoustics of ducts. It discusses the topic like propagation of waves in the ducts theory of acoustics filters, acoustic filter performance parameters, Helmholtz resonators, performance evaluation of ducts by using transfer matrix method etc. It also covers the various methods in order to predict the transmission loss of the ducts. This book also thoroughly discusses the finite element method for mufflers.

III. MODELING AND OPTIMIZATION OF ELLIPTICAL MUFFLER

Prediction of transmission loss virtually is an important analysis required for the development of muffler at an initial design stage. There are different software packages available in market for predicting the transmission loss. We have used COMSOL MULTIPHYSIS for Transmission loss measurements. COMSOL MULTIPHYSICS is an FEM/BEM based computational acoustics program that allows users to input a geometry,impose boundary conditions,select environment parameter,and solve the system of resulting equation in one ,two or three diamension.Onces the system has been solved,a host of post-processing options are available to detemine the various performance characteristics.

Basic procedure for analysis is started from CAD geometry. Muffler with given dimensions is modelled in Pro-E wildfire 5.0 and exported as neutral file format (.step/.igs). COMSOL MULTIPHYSIS it self used for meshing the solid models and then harmonic acoustical FEM analysis is done.

3.1 OPTIMIZATION PROBLEM #1

The dimensions and a schematic illustration of the first optimization case representing a muffler with a extended inlet and extened outlet duct are given in Fig. 5. Geometry of the muffler is determined by eight parameters, five of which are fixed, and three are varied to optimize the transmission loss. The fixed parameters are as follows.

- Diameter Inlet/outlet pipe(ID) =36mm
- Length of Inlet/outlet pipe =80mm
- Length of elliptical muffler(L) =300mm
- Minor diameter of elliptical muffler=150mm

The three design variables with their admissible ranges are as follows.

- Extended Inlet/Outlet pipe length(L1/L2)=(10-280mm)
- Major diameter of elliptical muffler =(200- 300mm)

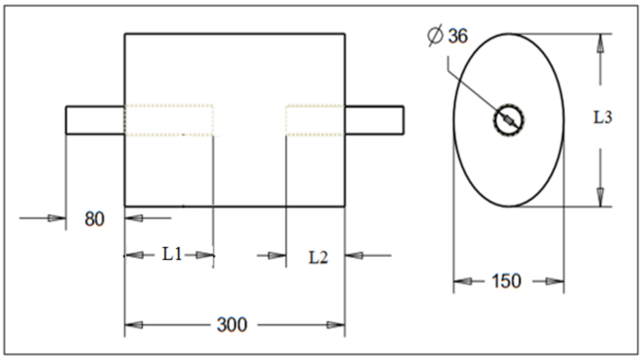

Fig.3.1.1:The diagram of a muffler component used in optimization problem #1.

In the first step length L2 is varies with the step of 10mm (L2=10mm) and L1 is also varies from 10mm up to 280mm and second step again L2 is varies with 10 i.e. (L2=20mm) and L1 varies again 10mm to 270mm and so on. After that all these models are save as the (.igs/.step) format and the exported to the COMSOL MULTIPHYSIC software for further acoustic analysis.

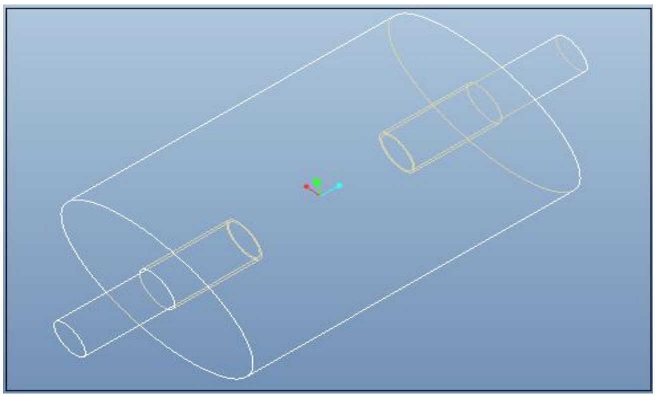

Fig.3.1.2:The Optimized CAD model of optimization problem #1

Figure shows the final optimized model of elliptical muffler with central extened inlet outlet.The optimized parameters are extended inlet pipe length(L1) is 80mm, extended outlet pipe length(L2) is 80mm and major diameter of the elliptical chamber(L3) is 225mm.

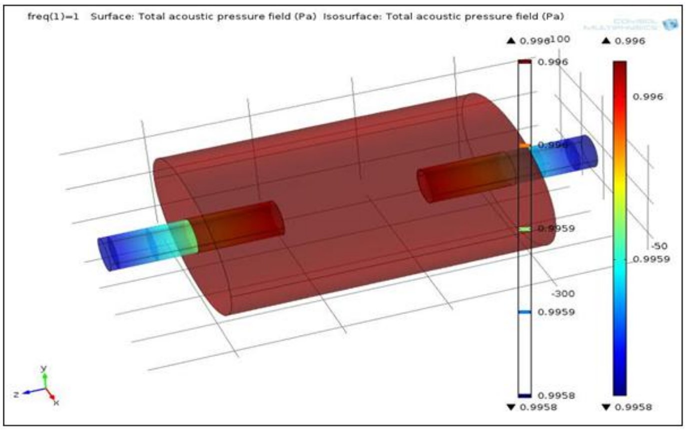

Fig.3.1.3:Optimized COMSOL model showing total acoustic pressrue field (Pa)

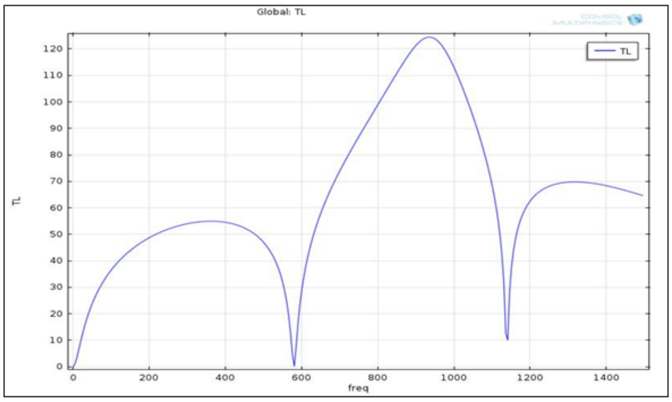

Fig.3.1.4:The transmission loss Vs frequency for the optimization case #1

Figure shows the transmission loss(TL) verses frequency plot for the first optimized model.Basically this optimization is to maximise the average transmission loss(Tl) in the frequency range 1-1500 Hz.The average optimized transmission loss for this model is **64.64 dB**.

3.2 Optimization problem #2

The second optimization test case represents a the provision of extra tube to flow chamber with above optimized parameter.

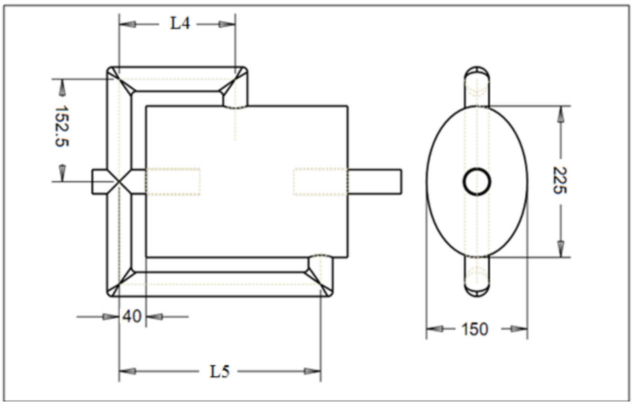

Fig.3.2.1:The diagram of a muffler component used in optimization problem #2.

The dimensions and a schematic illustration of the test case are given in Fig. 8. Geometry of the muffler is determined by 12 parameters, ten of which are fixed, and two are varied to optimize the transmission loss. The variable parameters are as follows.

- Location of the first tube =(L4)
- Location of the second tube =(L5)

In the first step the location of tube having length L5 is decided and then L4.The length L5 is varies with step of

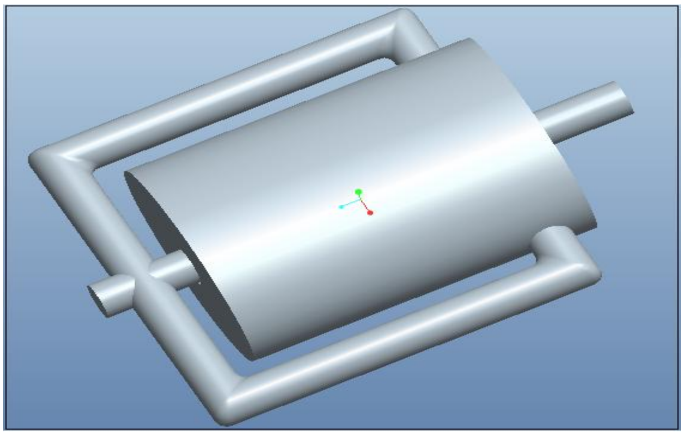

Fig.3.2.2:The Optimized CAD model

10mm from the front edege of the elliptical muffler up to total length of muffler.All these model modeled in CAD are then analyses in COMSOL MULTIPHYSIS for maximum transmission loss and similarally the length L4 is decided for the maximum transmission loss.

Figure 3.2.2 shows the optimized CAD model of second optimization problem with optimized parameters as the location of the first tube having length(L4)=280mm from the inlet of elliptical muffler and the location of the second having the tube length(L5)=280 from the inlet of elliptical muffler.

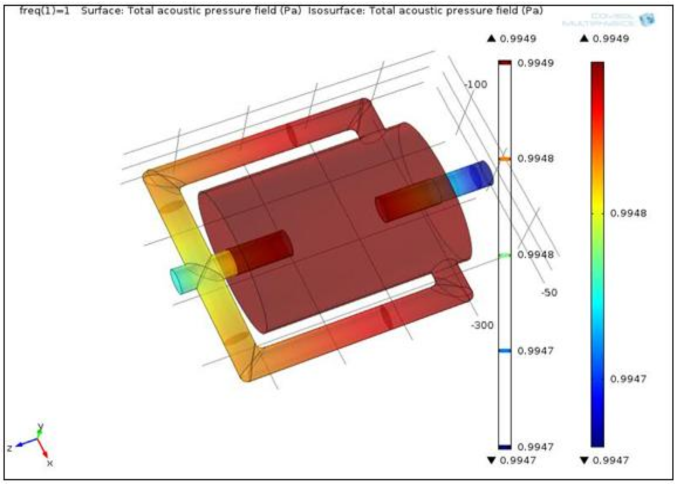

Fig.3.2.3:Optimized COMSOL model showing total acoustic pressrue field (Pa)

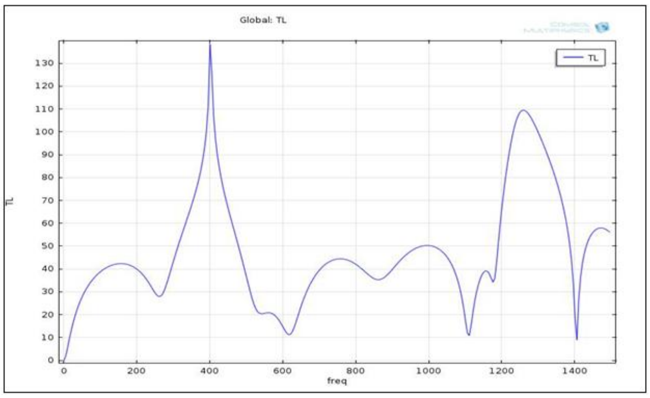

Fig.3.2.4:The transmission loss versus frequency for the optimization case #2

The above figure shows the graph of transmission loss Vs frequency. Basically the aim of this optimization is to maximize the transmission loss in the frequency range of 1-300 Hz. The average transmission loss for the second optimization case in the frequency ranges 1-300 Hz is **33 dB** and in 1-1500 Hz is **47.56 dB.**

For the final optimization or to find the best combination of the above optimized parameters of central inlet central outlet elliptical muffler the Taguchi Method is used.

IV.TAGUCHI METHOD

The Taguchi method is a powerful tool for the design of high quality systems. It provides a simple, efficient and systematic approach to optimize designs for performance, quality, and cost. The methodology is valuable when the design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the settings of design parameters and reduce the sensitivity of the system. Taguchi recommends the use of the Signal to Noise (S/N) ratio to measure the quality characteristics deviating from the desired values. The main principle of measuring quality is to minimize the variability in the products performance in response to Noise factors while maximizing the variability in response to Signal factors. Noise factors are those that are not under control of the operator of a product and the Signal factors are those that are set or controlled by the operator of the product to make use of its intended functions. Therefore, the goal of quality improvement effort can be given as to maximize the Signal to Noise (S/N) ratio for the product. Usually there are three types of quality characteristics in the analysis of the S/N ratio, i.e. the lower-the-better, the-higher-the-better, and the- nominal-the-better. Here higher-the-better is used to maximize transmission loss. The S/N ratio for each level of process parameter is computed based on the S/N analysis. Regardless of the category of the quality characteristic a greater S/N ratio corresponds to better quality characteristics. In our case the output is transmission loss. Hence in case of transmission loss, Larger-the- better characteristic is required

Taguchi proposed a standard 8-step procedure for applying his method for optimizing any process,

8-Steps in Taguchi Methodology:

1. The main function, side effects, and failure mode
2. Identify the *noise* factors, testing conditions, and quality characteristics
3. Identify the objective function to be optimized
4. Identify the control factors and their levels
5. Select the orthogonal array matrix experiment
6. Conduct the matrix experiment
7. Analyze the data; predict the optimum levels and performance
8. Perform the verification experiment and plan the future action.

Treatment Condition	A	B	C	D	Response
1	1	1	1	1	Y_{1111}
2	1	2	2	2	Y_{1222}
3	1	3	3	3	Y_{1333}
4	2	1	2	3	Y_{2123}
5	2	2	3	1	Y_{2231}
6	2	3	1	2	Y_{2312}
7	3	1	3	2	Y_{3132}
8	3	2	1	3	Y_{3213}
9	3	3	2	1	Y_{3321}

Table4.1:L9 Table of Taguchi Method

The 9 in the designation L9 represents the number of rows, which is also the number of treatment conditions (TC) and the degree of freedom. Across the top of orthogonal array is the maximum number of factors that can be used, which in our case are four. The levels are designated by 1 and 2. If more levels occur in the array, then 3, 4, 5, etc., are used. Other schemes such as -, 0, and + can be used.

4.1 ANALYSIS USING TAGUCHI METHOD:

The transmission loss (TL) values used in this Taguchi analysis are the average transmission loss value in the frequency range of 1-1500 Hz. The four variable parameters are used for the analysis or optimizations of the transmission loss (TL) by using Taguchi Method are as follows

1. Length of inlet pipe extended in elliptical chamber(L1)
2. Length of outlet pipe extended in elliptical chamber (L2)
3. Location of the tube provided to the elliptical chamber (L3)
4. Length of major diameter of the elliptical chamber(L4)

Trial	L1	L2	L3	L4	TL
1111	75	75	255	220	47.96
1222	75	80	260	225	50.05
1333	75	85	265	230	49.34
2123	80	75	260	230	47.82
2231	80	80	265	220	45.07
2312	80	85	255	225	43.82
3132	85	75	265	225	44.61
3213	85	80	255	230	43.07
3321	85	85	260	220	42.04

Table 4.1:L9 Table for frequency ranges

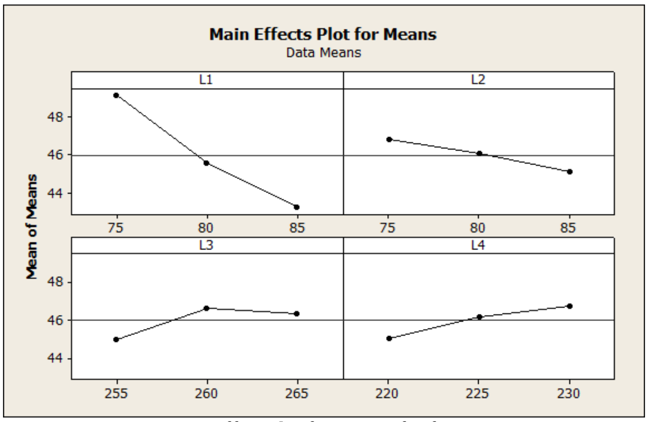

Fig.4.1.1: Main Effect plot for Means for frequency ranges

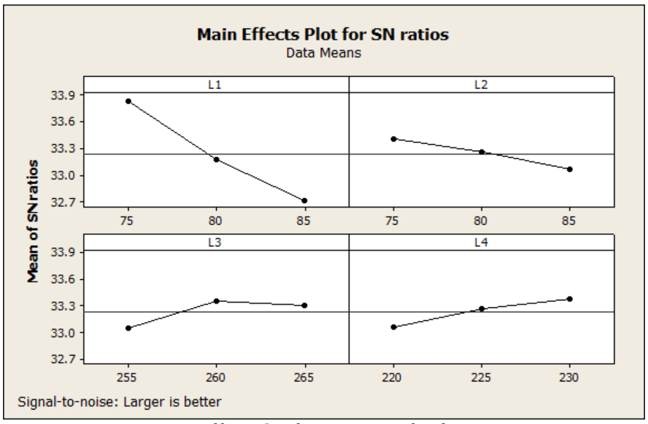

Fig4.1.2: Main Effect plot for SN ratios for frequency ranges

For present work 'Larger the Best 'condition was used. This is because the best transmission loss is one with higher value which gives lower sound level. Thus (S/N) ratio of this TL needs to be maximum. From the above graph the maximum transmission loss value for L1 occurs at L80, L2 occurs at L85, L3 occurs at L155 and L4 occurs at L230 positions. The final optimized parameters for central inlet central outlet elliptical muffler are as follow

1. The length of extended inlet pipe(L1)=75mm
2. The length of extended outlet pipe(L2)=75mm
3. The location of the tube to elliptical chamber (L3)=260mm(from inlet)
4. The major diameter of the elliptical chamber (L4) =230mm

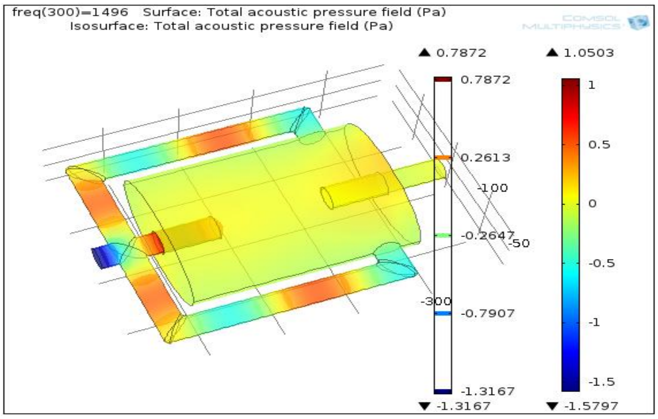

Fig4.1.3: Optimized COMSOL model showing acoustic pressure

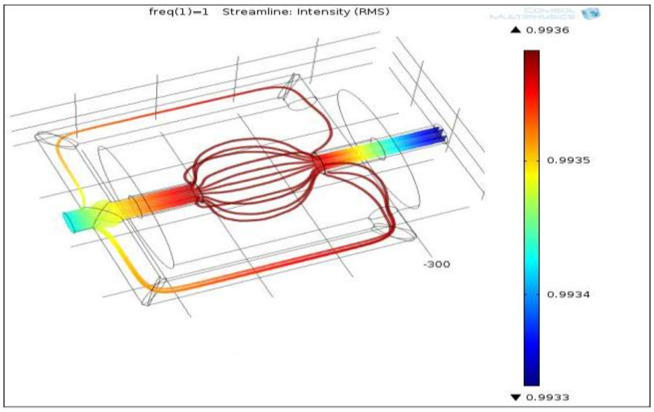

Fig.4.1.4: Optimized COMSOL Model showing Intensity Streamline (RMS)

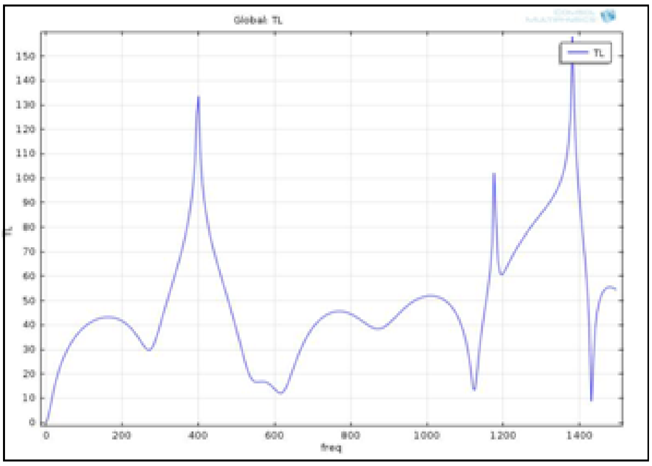

Fig.4.1.5: Graph for optimized model TL Vs Frequency

The above figure shows the graph of transmission loss Vs frequency. Basically the aim of this optimization is to maximize the transmission loss in the frequency range of 1-300 Hz and to maximize the average transmission loss (TL) in the range of 1-1500 Hz. The average transmission loss for the final optimized case with Taguchi Method in the frequency ranges 1-300 Hz is **33.80 dB** and in 1-1500 Hz is **49.43 dB.**

V.EXPERIMENTAL VALIDATION

Models which got highest TL by Taguchi analysis are experimentally validated by using two-load method. Experiments are conducted for simple expansion chamber muffler, elliptical chamber muffler with extended inlet and extended outlet with extra tube to chamber.

5.1 EXPERIMENTAL SETUP [8, 10]:

A schematic diagram of experimental set-up for calculating TL of simple expansion muffler is shown in Figure1.It consists of a noise generation system, noise propagation system and noise measurement system. The TL is measured by transfer function method. The set-up has the following main components.

- Impedance tube
- Data acquisition system
- Noise source with amplifier
- Sound pressure measuring microphones

Impedance tube is a rigid tube through which sound propagates and reflects from test sample which results in creation of standing waves in it. It has measuring locations (1, 1', 2, 3, 4 and 4') at specific distances from test sample where the acoustic pressure is measured. A sound source device is connected at one end of impedance tube and test muffler at the other end. As we are interested in incident and transmitted wave, two impedance tubes are used on either side of the muffler. The main purpose served by impedance tube is providing guidance to sound wave as required for plane wave propagation. The data acquisition system used is a four channel FFT analyzer (OROS OR34, 4Channel) with an interface for the control and setting of analyzer. A Fourier transformer converts time signal data into frequency signal data and vice versa; an FFT rapidly computes such transformations. As a result, FFT is widely used for many applications in engineering and science.

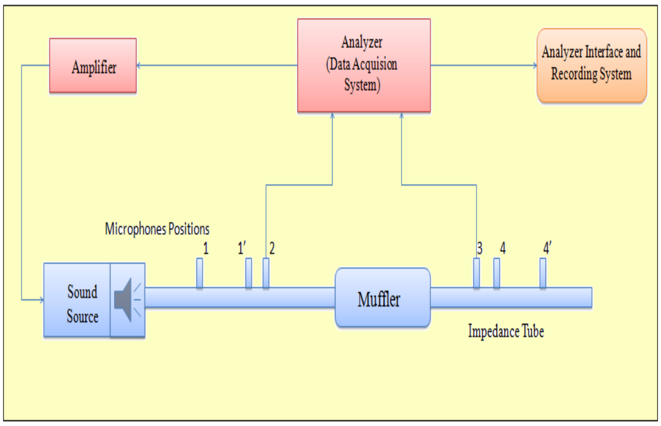

Fig.5.1: Experimental Set Up with its Components

Figure 5.1 shows OROS, 4 channel, compact, real time multi analyzer along with required instruments and accessories. OR34 is the synthesis of the ultimate 3 series technology, that integrates the best of noise and vibration analysis technology in an ultra mobile instrument. It is low weight, portable and robust instrument which can be used with laptop for intensive use.

5.2 EXPERIMENTAL PROCEDURE

Experimentation for pressure measurement mainly consists of analyzer setting and data processing for TL calculation. The experiment is performed for frequency range of 1 to 1500 Hz. The measurements are taken in two slots with two locations 1-1' and 4-4' (refer Figure 1) respectively to cover desired frequency range [8]. The locations 1-2-3-4 are used for measuring pressure in frequency range 50-400 Hz, while the locations 1'-2-3-4' are used for measuring pressure in frequency range of 400-1500 Hz. The first set of readings is taken for no load condition with both frequency ranges and same procedure is repeated for with load condition. Two microphones are used for measurement, which are sufficient for measurement of transfer function between sound pressures measured at two locations. One microphone is placed at location 3 and other placed at location 1, 2 and 4 respectively to get transfer function H31, H32 and H34 with respective locations. All other locations except locations where microphones are inserted are sealed with plugs to avoid sound leakage. The sound leakage is tested and wax is used to seal these leaks. The obtained transfer functions are then directly used in four-pole element calculations to get TL.

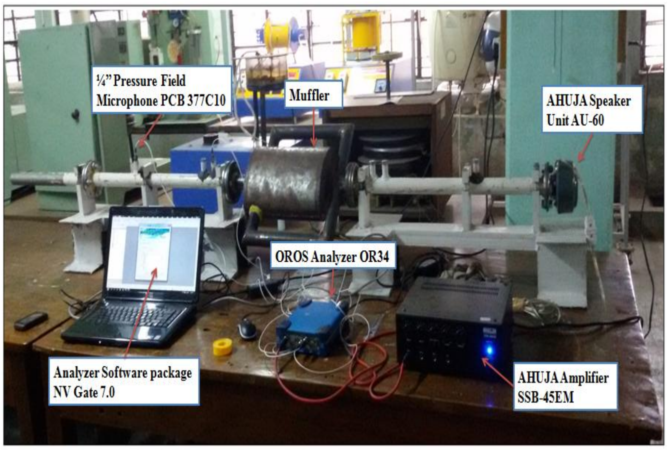

Fig.5.2.1: Experimental Setup Without load Condition

Fig.5.2.2: Experimental Setup With load Condition

VI.RESULTS AND DISCUSSION

The elliptical chamber muffler with extended inlet, extended outlet and extra tube (i.e. divided inlet) to chamber is analyzed by using FEM (COMSOL MULTIPHYSIS) and model shown in figure 4.1.3 found out as optimum model by using Taguchi analysis which gives high transmission loss among others. This model is manufactured and experiment was conducted on it to calculate average transmission loss. The average transmission loss obtained by experiment is 43.89 dB and by FEM is 49.43 dB.Figure 6.1 shows the comparison between experimental TL curve and FEM TL curve and it is seems to be very similar in nature.

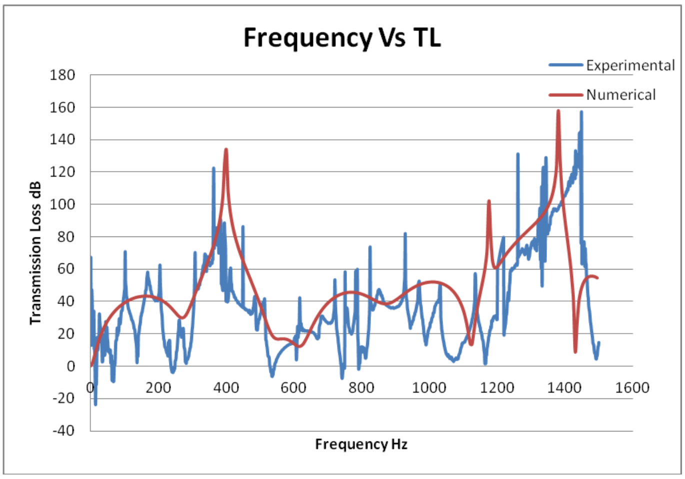

FIG.6.1.Comparision of Frequency Vs Transmission loss for FEM and Experimental

VII.CONCLUSIONS

Comparison of model by using FEM analysis shows that there is good agreement between experimental and FEM results. Analysis of elliptical chamber muffler with extended inlet extended outlet shows that extension of inlet and outlet had a considerable effect on TL. L9 Taguchi OA is used to analyze the muffler. S/N ratio analysis gives optimum value of dimensions of muffler which gives maximum transmission loss. After inserting extra divided inlet tube in elliptical chamber muffler with extended inlet outlet, TL increases compared to muffler without tube in the initial frequency range (1-400Hz).and also the average TL increases in the range 1-1500Hz.

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