



FEM Analysis and Optimization of Two Chamber Reactive Muffler by using Taguchi Method

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Abstract: In the present work, an attempt has been made to study the effect of various parameters such as different radius and lengths of various elements of muffler on the muffler's capacity of noise reduction (i.e. Transmission loss). The acoustic behavior of a circular two-chamber muffler is investigated in detail by: (1) the finite element method by using LMS Virtual. Lab10-SL 1 and effects of various parameters have been studied, such as (i) the presence of a rigid baffle in the chamber; (ii) the inner hole radius of the baffle; (iii) length and diameter of choke tube; (iv) the extended inlet/outlet and baffle ducts; Some of these effects are shown to modify the acoustic behavior drastically, suggesting potential means to improve the acoustic performance. (2) Validation by experimental work (two-load method).

Keywords: FEM, Two-load method, Transmission loss, Two-chamber muffler, Taguchi method, ANOVA.

I. Introduction

Accurate prediction of sound radiation characteristics from reactive muffler is of significant importance in automotive exhaust system design. The most commonly used parameter to evaluate the sound radiation characteristics of muffler is transmission loss (TL). 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 [1].

This study proposes an optimal design scheme to improve the muffler capacity of noise reduction of the exhaust system by Taguchi method. Performance of a muffler is measured by performance prediction software (LMS virtual Lab 10-SL 1).

In the first stage of a design, effect of extended inlet and outlet lengths along with baffle position and diameter of hole in it are selected as control factors. Then, L-9 table of orthogonal arrays is adopted to extract the effective main factors.

In the second stage of a design, effect of extended inlet and outlet lengths, baffle position along the axis, internal choke tube length and its diameter are selected as control factors. Then, L-27 table of orthogonal arrays is adopted to extract the effective main factors.

II. Taguchi method[2]

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 maximise 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.

III. Procedure for acoustic analysis

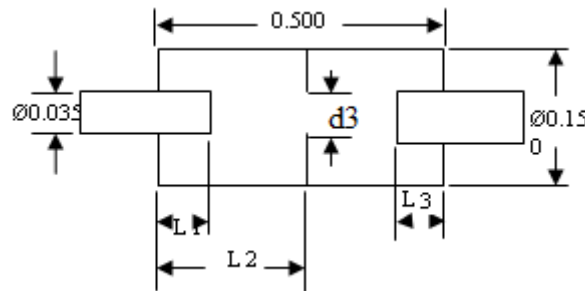
Basic procedure for analysis is started from CAD geometry. Muffler with given dimensions is modelled in Pro-E wildfire 4.0 and exported as neutral file format (.step). HyperMesh software is used for meshing solid models. .step files are imported in HyperMesh and mesh is generated. Meshed files are exported as Nastran bulk file format (.bdf) and then imported in SYSNOISE and harmonic acoustical FEM analysis is done.

IV. Acoustic analysis and optimisation of muffler

i. Two chamber muffler with baffle:

Effect of baffle on Transmission loss is analysed by inserting baffle in simple expansion chamber. Figure 1 shows configuration for the two chamber muffler with baffle. In initial stage of design of experimentation four factors are chosen for optimisation. Those are extended lengths of inlet and outlet (L_1 and L_3), axial position of baffle (L_2), and diameter of baffle hole (d_3).

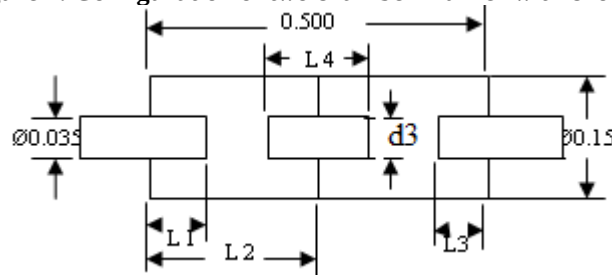
Figure 1: Configuration of two chamber muffler with baffle



ii. Two chamber muffler with choke tube:

Further, transmission loss was found to be increasing by inserting choke tube in baffle. Figure 2 shows the configuration for two chamber muffler with choke tube. Effect of choke tube length and diameter, length of extended inlet and outlet and baffle position is analysed and optimised by using Taguchi analysis.

Figure 2: Configuration of two chamber muffler with choke tube



Selection of control parameters and levels:[3]

Selection of muffler parameters is on the basis of literature review by analysing the effect of parameters on the transmission loss. Levels of factors are also decided on the basis of literature review. Effect of extended inlet and outlet on TL is considerable.

Table 1: For Two Chamber Muffler with Baffle:

Level→	High	Medium	Low
Factors↓	1	0	-1
L_1 (m)	0.050	0.075	0.100
L_2 (m)	0.200	0.250	0.300
L_3 (m)	0.050	0.075	0.100
d_3 (m)	0.03	0.04	0.05

Table 2: For Two Chamber Muffler with choke tube:

Level→	High	Medium	Low
Factors↓	1	0	-1
L1(m)	0.050	0.075	0.100
L2(m)	0.200	0.250	0.300
L3(m)	0.050	0.075	0.100
L4(m)	0.100	0.125	0.150
d3(m)	0.03	0.04	0.05

Results and discussion:

Figure 3: Individual effect plot using Minitab[5]

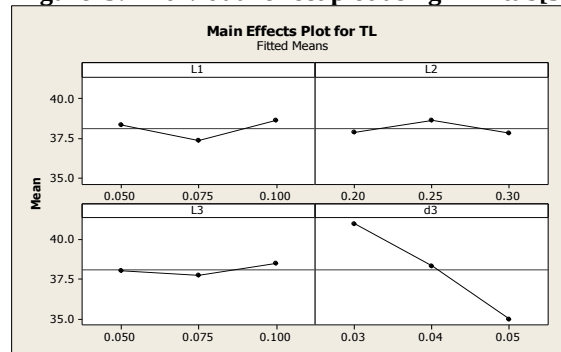


Figure 3 shows the effect of individual parameters of muffler with baffle on TL from L9 which is prepared from Table 1. As L1 and L3 increases TL value decreases but after middle value, TL increases, and for increase in L2 up to middle level TL increases but afterwards TL decreases. Increase in value of d3 there is decrease in TL value.

Figure 4: Individual effect plot

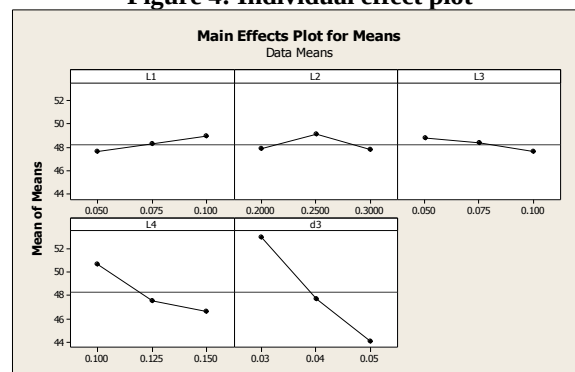


Figure 4 shows the effect of individual parameter of muffler with choke tube on TL which is prepared from L27 table. For increase in L1 there is increase in TL and for increase in L2 up to middle level TL increases but afterword's TL decreases. As L3 and L4 increases TL value decreases. Increase in value of d3 there is decrease in TL value for two chamber muffler with choke tube.

V. Taguchi analysis:

Taguchi analysis of SN ratio is used for single objective optimization of responses. In Taguchi method, SN ratio is used to measure the quality characteristics deviating from the desired value. The experimental values of various responses are transformed into signal to noise (SN) ratio. 'Higher the better' characteristics is used for the responses which are to be maximised. 'Lower the better' characteristic is used for the responses which are to be minimised.

The types of Signal to Noise (S/N) ratio are; 1. The-lower-the-better 2. The-nominal-the-better 3. The-larger-the-better. In our case the output is transmission loss. Hence in case of transmission loss, Larger-the-better characteristic is required.

The SN ratio for ‘Higher the better’ strategy is defined as

$$\eta = -10 \log [(1/n) * \sum (1/y_i^2)]$$

The SN ratio for ‘Lower the better’ strategy is defined as

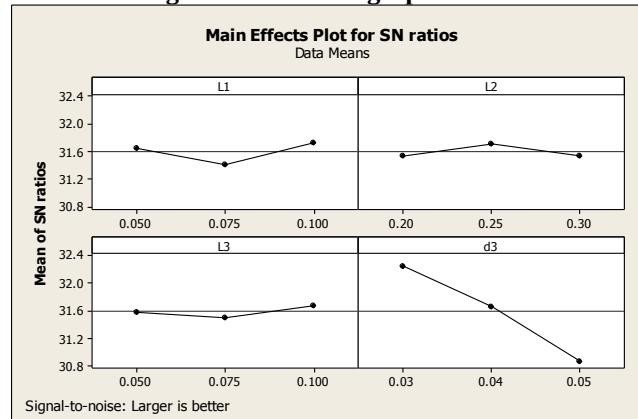
$$\eta = -10 \log [(1/n) * \sum (y_i^2)]$$

The SN ratio for ‘nominal-the-better’ strategy is defined as

$$\eta = 10 * \log ((y^2) / \sigma^2)$$

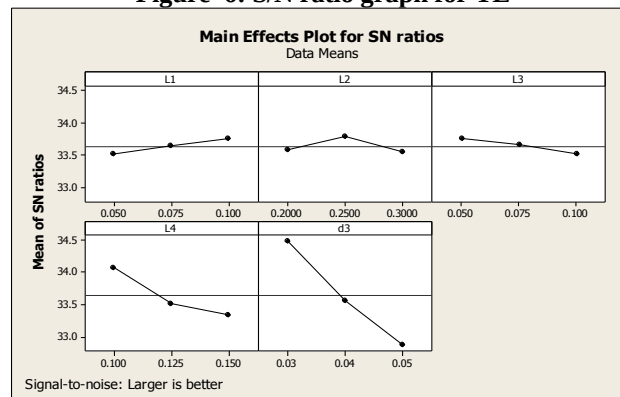
Where, η = resultant SN ratio, n = number of observations, y = respective response.

Figure 5: S/N ratio graph for TL.



From figure 5, the S/N graph for TL, the greater S/N ratio corresponds to the smaller variance of the output characteristic which is desirable. Maximum S/N ratio is for length L1 at level +1, while in case of length L2 it is at level 0. For length L3 it is at level +1 and diameter is at level -1. Thus it is clear that optimal process parameters for the TL are L1 at 0.100, L2 at 0.25, L3 at 0.100, and diameter at 0.03.

Figure 6: S/N ratio graph for TL



From figure 6, the S/N graph for TL, maximum S/N ratio is for length L1 at 0.100, while in case of length L2 it is at 0.25. For length L3 it is at 0.050 and length L4 is at 0.100 and diameter d3 at 0.03. Thus it is clear that optimal process parameters for the two chamber muffler with choke tube are L1 at 0.100, L2 at 0.25, L3 at 0.050, L4 at 0.100, d3 at 0.03.

Analysis of variance (ANOVA):

Table 7: Analysis of variance for TL using Adj. SS for test[8]:

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P	% contribution
L1	2	7.639	7.639	3.82	7.29	0.006	0.0161
L2	2	9.356	9.356	4.678	8.93	0.002	0.0197
L3	2	7.057	7.057	3.528	6.74	0.008	0.0149
L4	2	80.479	80.479	40.24	76.83	0	0.1699
d3	2	360.67	360.67	180.33	344.3	0	0.7615
Error	16	8.38	8.38	0.524			
Total	26	473.58					

S=0.723699 R-Sq=98.23% R-Sq(adj)=97.12%

As seen from ANOVA table % contribution of factors L1, L2, and L3 are negligible compared to other two factors (i.e. L4 and d3).

Regression analysis:

To determine the best suited equation connecting response with input variables regression technique has been used. Regression coefficient is the measure to indicate how far the established relationship is valid to ensure the values of dependent variable, using the values of independent variables for which readings are not available in the range of minimum and maximum value of independent variables. ANOVA table is used to check the significance of the regression model. The exponential equation established for TL is as follows:

For Two Chamber Muffler with Baffle:

$$TL = 37.9988 * L1^{0.001793} * L2^{0.00015} * L3^{0.00237} * d3^{-0.03451}$$

R square value comes out to be 0.914376 for TL, therefore relationship established is acceptable.

For Two Chamber Muffler with choke tube:

$$TL = 48.0606 * L1^{0.005874} * L2^{-0.00085} * L3^{-0.00592} * L4^{-0.01809} * d3^{-0.03995}$$

R square value comes out to be 0.942145 for TL, therefore relationship established is acceptable.

VI. Experimental validation

Models which got highest TL by S/N ratio analysis are experimentally validated by using two-load method^[3]. Experiments are conducted for simple expansion chamber muffler, two-chamber muffler with baffle and for two chamber muffler with choke tube.

Experimental setup and procedure [6]:

Figure 7: Schematic Diagram of Experimental Setup with Its Components

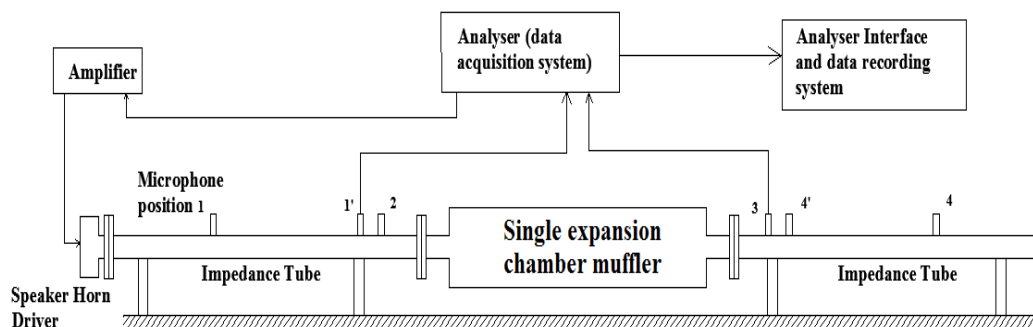


Figure 7 shows the schematic diagram of experimental setup for two load method [7] to measure transmission loss of muffler. It consists of a noise generation system, noise propagation system and noise measurement system.

Figure 8 shows actual experimental setup with its different components. The TL is measured by transfer function method. System consists of following components.

1. Noise source with amplifier:

Noise source is speaker which is used to generate noise in system. Sound source used is of high power to produce at least 120 dB of noise. It is attached with amplifier whose function is to increase and adjust the sound level.

2. Impedance tube:

Impedance tube is a rigid tube through which sound propagates and reflects from test sample which results in creation of standing waves in it. Main purpose of it is providing guidance to sound wave as required for plane wave propagation. It has measuring locations at specific distances from test sample where the acoustic pressure is measured. We are measuring incident power and reflected power; hence we use two tubes, one at inlet and one at outlet.

3. Data acquisition system:

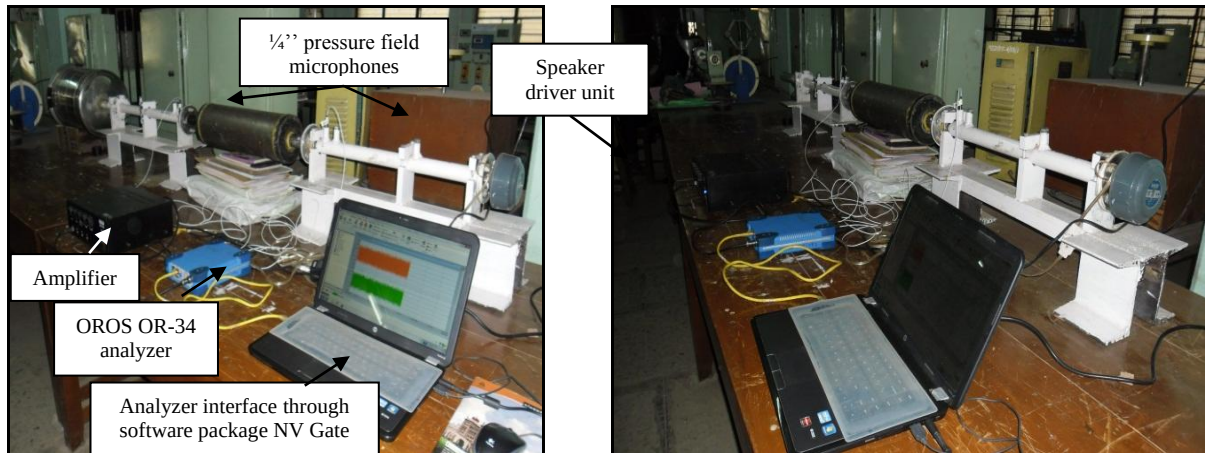
The data acquisition system used is a four channel FFT analyser with an interface for the control and setting of analyser. It collects the pressure data from microphones and feed it to data recording storage system. It also has

a single output channel which is fed to speaker through analyser. A random noise signal is generated in the same analyser and directed to the speaker via amplifier.

4. Sound pressure measuring microphones:

Pressure field microphones (make PCB) are used for measurement. The two microphones are sufficient as transfer function method is used. Transfer function is evaluated for each set of reading.

Figure 8: Experimental setup with and without load



The experiment is performed for frequency range of 50 to 3400 Hz. The measurements are taken in two slots with two locations 1-1' and 4-4' as shown in figure 7 respectively to cover desired frequency range. 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 400-3400 Hz. The first set of readings is taken for no load condition (figure 8) 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 H_{31} , H_{32} and H_{34} with respective locations. All other locations except locations where microphones are inserted are sealed with pins 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.

VII. Comparison of Experimental and FEM Results

I Two chamber muffler with baffle:

Two-chamber muffler with baffle is analysed by using L9 OA in SYSNOISE and by S/N ratio model shown in figure 9 found out as optimum model 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 43.97dB and by FEM 41.0989 dB. Figure 10 shows the comparison between experimental TL curve and FEM TL curve and it matches very well in the entire frequency range.

Figure 9: Optimum configuration of two chamber muffler with baffle.

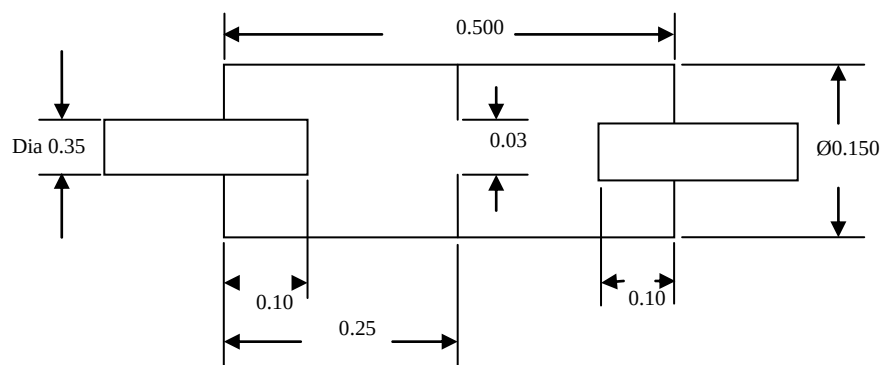
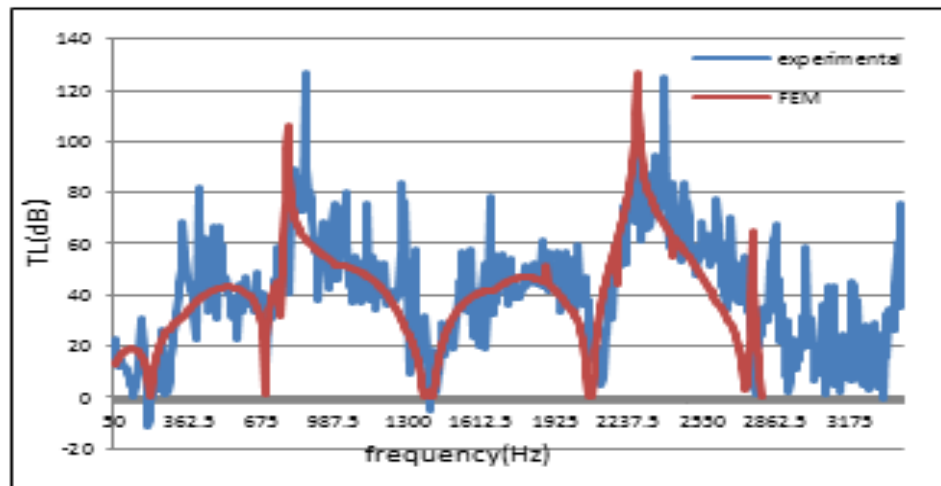


Figure 10: Comparison of experimental and FEM TL curve of Two chamber muffler with baffle.



II Two chamber muffler with choke tube:

Two-chamber muffler with choke tube is analysed by using L27 OA in SYSNOISE and model shown in figure 11 found out as optimum model by using S/N ratio 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 54.89dB and by FEM is 56.6491. Figure 12 shows the comparison between experimental TL curve and FEM TL curve and it seems to be very similar in nature.

Figure 11: Optimum configuration of two chamber muffler with choke tube.

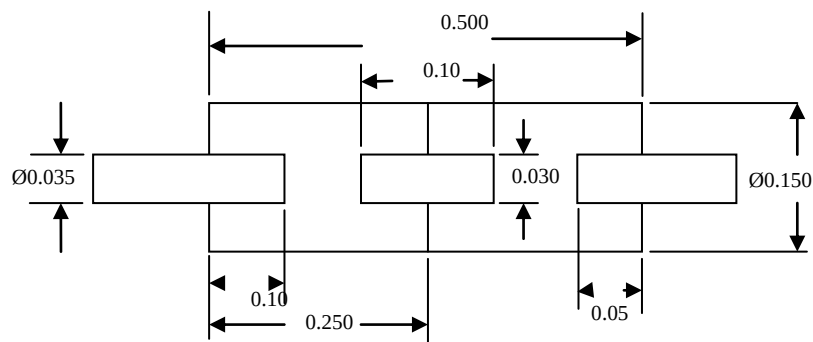
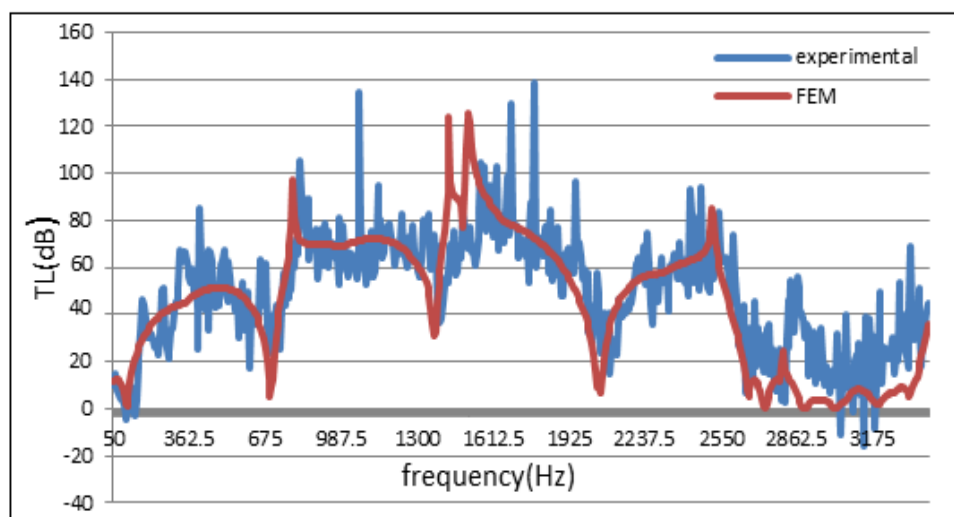


Figure 12: Comparison of experimental and FEM TL curve of two chamber muffler with baffle and choke tube.



VIII. Conclusions

Comparison of all models by using FEM analysis shows that there is good agreement between experimental and FEM results. Analysis of two chamber muffler with baffle shows that baffle 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 choke tube in two chamber muffler with baffle, TL increases compared to muffler without choke tube. L27 Taguchi OA is used to find out optimum configuration of muffler. Analysis of variance is done to find out most significant factors, which have an effect on TL. By ANOVA it is clear that, choke tube diameter has most effect (76.15%) on TL, and choke tube length also has an effect (16.99%) on TL.

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