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OPTIMIZATION OF EXHAUST SILENCER FOR WEIGHT AND SIZE BY USING NOISE SIMULATION FOR ACOUSTIC PERFORMANCE

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ABSTRACT

With ever-increasing competition in the car industry for launching fresh models every year, with lesser weights and costs, every system of the car is optimized for weights, without affecting the required performance of the car. One of the most important system of the car is the exhaust system, which attenuates the sound coming from engine to acceptable levels and meets BP (backpressure) requirement for engine performance. It is challenging to optimize the automotive silencer system for size and weight reduction with constraints of meeting the NVH performance, backpressure targets and without affecting the sound quality perception by the customer. This requires complete re-designing of the silencer, which is very complex.

In the present study, the silencer of the gasoline engine car is optimized by studying acoustic performance through noise simulation. For this the Transmission Loss (TL), which is attenuation characteristic of the silencer, was used for the analysis and comparisons. The baseline muffler was evaluated for TL & BP.Design iterations for silencers internals made and TL & BP predicted. The design proposal that matches the baseline silencer performance was chosen for making prototype and further experimental validation. The modified silencer was validated by actual measurement of TL and BP .Comparisons were made with predicted performance and concluded that modified silencer matches the baseline performance. This method can be also used during current design phases to reduce the design cycle time.

Key words- Exhaust, Muffler, Acoustics, Attenuation, BP (Back Pressure), IL (Insertion loss), NVH (Noise Vibration Harshness), TL (Transmission Loss)

I INTRODUCTION

Every year fresh models of cars are launched with reduced weights and improved performance by major car manufacturers in the industry. This is due to the ever-increasing competition and the struggle to survive in the market with your innovative products for the car manufacturers. The weight reduction and in turn, cost reduction is achieved by optimizing various aggregates of the car. One of the major component is the exhaust silencer. Its function is to reduce the noise of the car to the acceptable limits, meet regulatory requirements of pass-by noise and meet the requirements of the engine for BP (backpressure). To reduce the weight of the silencer, its design is optimized by studying the acoustic performance and comparing with baseline performance. The most important acoustic characteristics of the silencer are TL (Transmission Loss) and IL (insertion loss) .TL is the ratio of incident sound power to the transmitted power when the tail pipe end is terminated through anechoic chamber [1]. That is, there are no reflections of sound from the tail pipe. Insertion loss (IL) is the difference between radiated sound power with and without the silencer.IL is measured at some point away from the siencer.IL is difficult to calculate but easy to measure.TL is purely the property of the silencer and therefore chosen for evaluating the acoustic performance.TL is easy to calculate but difficult to measure.TL can be measured by test rig having tubes for upper and downstream sound wave flows [1].

In the present study gasoline, engine silencer was studied through TL for evaluating acoustic performance in comparison with existing silencer and BP predicted through analytical methods of calculations. In order to reduce the weight of the silencer, the current design of the silencer is optimized by changing the internals. Various design iterations for the internals of silencer made & compared with baseline muffler performance for TL & BP. The TL is predicted though the acoustic simulation software AVL Boost. The best option chosen for making prototype and experimental evaluation. The TL was measured and compared with predicted TL and that with baseline silencer performance. The BP was measured on test rig. Conclusion was made for matching the predicted and measured performance.

II LITERATURE REVIEW

Potente and Daniel [1] discussed the basic types of mufflers and their functional requirements for any application. They tested absorptive type of muffler for a formula SAE vehicle. Muffled and unmuffled engine was used to get required attenuation from muffled engine. L. J. Eriksson & P. T. Thawani have illustrated the close relationship between theory and practice for the exhaust system design [2]. Rahman, Sharmin, Hassan & Nur have covered design aspects of muffler for petrol engine. The performance characteristics, i.e. noise reduction capability of the muffler, have been tested and compared with that of the conventional muffler [3]. Shital Shah, Hatti & team have dealt with a practical approach to design, develop and test muffler particularly reactive muffler for exhaust system, which will give advantages over the conventional method with shorten product development cycle time and validation [4]. Jigar Chaudhary, has covered different types of mufflers and design of exhaust systems belonging to different engines [5]. Munjal, M. L.has covered actual design of practical exhaust and ventilation system, in his textbook [6]. Shubham Pal, Tejpreet Singh Golan & team have shown how resonator length affects insertion loss [7]. Don D. Davis, Jr., George M. Stokes, Dewey Moore, and George Stevens, Jr. In their report NACA, Report 1192, have covered applications of the theory to the design of engine exhaust muffler with charts [8]. Exhaust sound attenuation device and its method of use is covered under patent US8256569 B1 [9]. Muffler and silencer design aspects and sound absorption strategies available at world wide web [10,11].

P.S. Yadav, Muthukumar and team have shown how muffler performance can be predicted to optimize the muffler [12]. Nitin Chavan has shown how CFD approach is used in predicting the compressor muffler

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performance by using Transmission Loss [13]. Rahul at el.2014, used mathematical method using MATLAB was used to study the Transmission loss. It was concluded that the Transmission loss can be increased by adding pipe protrusion at inlet and outlet [14]. Thus, there has been a great deal of research and development in the area of predicting muffler performance [15:20].

Generally, mufflers are classified as dissipative and reflective type [21]. Dissipative mufflers convert exhaust sound energy into heat. The sound is absorbed by sound absorbing materials like glass fiber. Here pressure drop is less. Whereas reflective mufflers consist of numbers of chambers and tubes. The attenuation is good at lower frequencies but not good at higher frequencies. Also pressure drop is more due to baffles and flow reversals [22].

The most commonly used parameter to evaluate muffler sound radiation characteristics is the Transmission loss (TL) [23:30]. For the TL measurement in the presence of flow Hyunsu Kim,2011 [25] developed flow impedance tube setup using burst signals.TL can be predicted easily from the physical parameters of the muffler. Parrot et al,1973 [31] improved a standard transmission line theory for designing an expansion chamber muffler as an application to helicopter. Amiya and Mohanty, in 1993 [32] carried out experimental and numerical investigations for passive mufflers. Multi domain boundary element method (BEM) was used for modelling mufflers and predicting TL. Development of a formula for predicting transmission loss (TL) of a long rigid duct was conducted by Chen et al,1998 [23]. Yeh et al. 2003 [33] discussed the graphical analysis of optimal shape designs in order to improve the performance of the TL on a constrained single expansion chamber. Yeh et al,2004 [34] presented optimal design of a single chamber muffler with side inlet/outlet.

Investigation of the acoustic performance of a single pass perforated silencer through experimentally, analytically and BEM study of a hybrid concept was examined by Selamet et al.2003 [35]. Z. Tao and A. Seybert discussed two measurement methods that don’t require anechoic termination. The methods, two loads and two source, were demonstrated on two mufflers, simple and double expansion chamber [36]. A muffler containing perforated ducts in 3-D case for acoustic diffraction was evaluated by Besache et al,2006 [37]. Mufflers on the basis of transfer matrix method (TMM) were modelled by Mihai Bugaru and Ovidue Vasili,2007 [38]. They presented the methods of predicting TL by principles of TMM. Florent Masson et al,2008, carried out optimization of acoustic performance of the mufflers using micro perforated panels (MPP) for reducing cost [28]. Through experiments of random sound, Rahul Bansal,2005, investigated the acoustic performance of perforated chattered in a duct [39].

Jin Woo Lee and Yoon Young Kim,2009, optimized the partition layouts inside expansion chamber of a muffler. Formulation acoustical topology optimization problem was used by them to increase TL in the targeted frequencies[40].For optimizing muffler acoustic performance, for maximum TL at multiple frequencies ,Thomas and Hikkola,2010, made measurements to adjust reactive muffler components and optimize shape[41].TL was used to design and optimize acoustic performance of the muffler by Komkin,2010 [42].Shape optimization of multi-chamber plug-inlet mufflers with maximum back pressure was focussed by Min-Chie Chiu 2008 [43].Parametric shape optimization to evaluate appropriate size of extended inlet/outlet duct was used

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by Key Fonceca de Lima et al,2011 [44].Parametric studies to understand the effects of various parameters on cylindrically shaped muffler configurations were conducted by Maddali,2011 [45].

Wang in 2013, evaluated the acoustic performance of the mufflers with combined effects of flow rate, temperature and thermal viscous effects, to calculate the transmission loss [29]. Rahul at el.2014, studied the TL of muffler using MATLAB and concluded that finite element modal analysis method has certain significance on the vibration characteristics of the muffler [14].

III TYPES OF SILENCERS AND MUFFLER DESIGN THEORY

The purpose of the automotive exhaust muffler is to reduce the noise of the engine. Noise is defined as the unwanted sound [1]. Sound is a pressure wave formed by pulsation of alternating, high pressure & low pressure air. When exhaust valve of engine opens, high pressure gases are poured into the exhaust system. This creates high pressure waves. These high pressure pulses are the sound we hear. As the engine rpm increases, pressure fluctuations increase & the emitted sound is of high frequency.

The automotive muffler has to allow passage of the exhaust gases while restricting the transmissions of the sound. Mufflers used to attenuate the undesired noise can be of three types- reactive, dissipative and combination of reactive & dissipative.

The reactive or reflective mufflers use the phenomenon of destructive interference to reduce noise. A reactive muffler, as shown in Figure 1, generally consists of a series of resonating and expansion chambers that are designed to reduce the sound pressure level at certain frequencies. The inlet and outlet tubes are generally offset and have perforations that allow sound pulses to scatter out in numerous directions inside a chamber resulting in destructive interference [2].

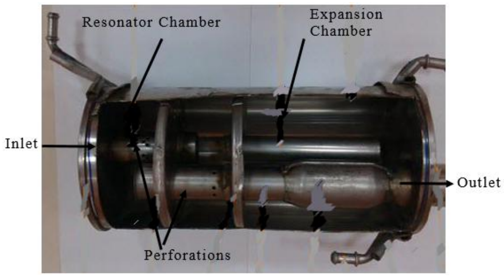

Fig. 1 Reactive Muffler

An absorptive or dissipative muffler, as shown in Figure 2, uses absorption to reduce sound energy. Sound waves are reduced as their energy is converted into heat in the absorptive material. [1,2] A typical absorptive muffler consists of a straight, circular and perforated pipe that is encased in a larger steel housing. Between the perforated pipe and the casing is a layer of sound absorptive material that absorbs some of the pressure pulses.

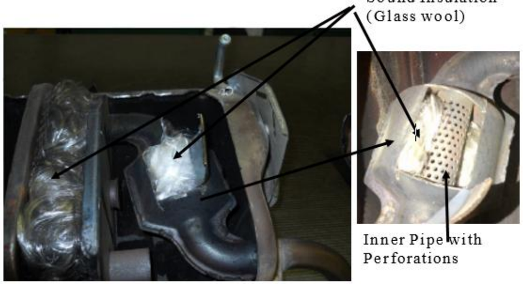

Fig. 2 Absorptive Muffler

Absorptive mufflers create less backpressure then reactive mufflers, however they do not reduce noise as well. Generally reactive mufflers use resonating chambers that target specific frequencies to control noise whereas an absorptive silencer reduces noise considerably over the entire spectrum and more so at higher frequencies.

It is good practice to design a muffler to work best in the frequency range where the engine has the highest sound energy. In practice the sound spectrum of an engine exhaust is continually changing, as it is dependent on the engine speed that is continually varying when the car is being driven. There is always more than one way to design a muffler for a specific application, however if the designed muffler is practical and achieves the required noise reduction and meets all functional requirements then the designer has succeeded.

There are several parameters which describe the acoustical performance of a muffler. [12] These include noise Reduction (NR), Insertion Loss (IL), Attenuation (ATT), and the Transmission Loss (TL). Noise Reduction is the sound pressure level difference across the muffler. It is an easily measurable parameter but difficult to calculate and a property which is not reliable for muffler design since it depends on the termination and the muffler. The Insertion loss is the sound pressure level difference at a point usually outside the system, without and with the muffler present. Insertion loss is not only dependent on the muffler but also on the source impedance and the radiation impedance. Because of this insertion loss is easy to measure and difficult to calculate, however insertion loss is the most relevant measure to describe the muffler performance. For TL, since it is difficult to realize a fully anechoic termination (at low frequencies) TL is difficult to measure but easy to calculate. Attenuation is the difference in the sound power incident and the transmitted through the muffler but the termination need not be anechoic.

The most common approach for measuring the transmission loss of a muffler is to determine the incident power by decomposition theory and the transmitted power by the plane wave approximation assuming an anechoic termination [36]. Unfortunately, it is difficult to construct a fully anechoic termination.

IV ITERATIONS FOR MUFFLER DESIGN BASED ON NOISE SIMULATION

The TL is given by $TL = 10 \log_{10} (Wi / Wt)$,

Where Wi is incident sound power and Wt is the transmitted sound power. The decomposition method requires anechoic termination whereas for two source and two load method does not require anechoic chamber for termination and are easy to measure TL.

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Design iterations are made for reducing the weight and volume of the baseline mufflers through noise simulation. Refer fig.3 for baseline and the required muffler.

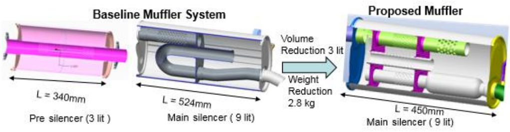

Fig.3 Baseline and Proposed Muffler

The baseline muffler system including pre silencer and mail silencer is modelled in AVL Boost 1d software and simulated TL is as shown in fig.4

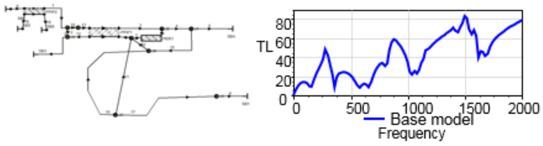

Fig.4 AVL Boost 1d model & TL simulation of Baseline muffler

Various design iterations done for the design of internals of the muffler to meet the baseline TL performance are as shown in below fig.5 and fig.6

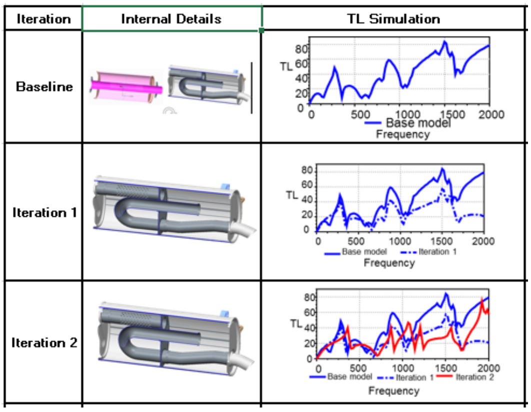

Fig.5 Comparison of Design iteration 1 and 2 with baseline muffler system

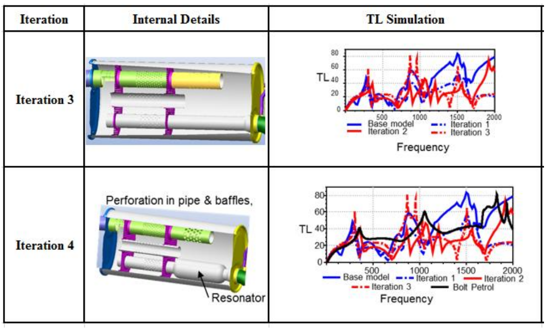

Fig.6 Simulation of Design iteration 3 and 4

Iteration 1 was chosen by just deleting the pre silencer from baseline muffler. As can be seen from the simulation results, the iteration 1 results not matching the target TL of bassline muffler. Therefore 2nd iteration was made by reducing the length of the baseline muffler from 524 to 475mm. But simulation results of TL, did

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not match with the bassline muffler TL.Therefore 3rd iteration was made with new internals. However, simulation results of this proposals also not match with baseline muffler. Therefore went for the 4th iteration of completely new internals. The TL simulation results of this proposals match with the baseline muffler. Therefore this design was taken forward for the actual manufacture of prototype.

The back pressure prediction for the above iterations was done based on analytical calculations methods and the comparisons are shown in the table 1.

Table 1 – Back Pressures of various muffler proposals from analytical methods of calculations

Sr.No.	Muffler Configuration	Back Pressure (mbar) calculated Target-250 mbar
1	Baseline	242.2
2	Iteration1	235.2
3	Iteration2	229.1
4	Iteration3	374.1
5	Iteration4	286.5

Back pressure prediction of the above proposals was made through analytical calculations methods and are as shown in table 1. For iteration 3 and 4 proposal mufflers, BP is more than targeted value. Considering correlation factor between predicted and actual measured BP, it was decided to go ahead with actual measurements.

V EXPERIMENTAL VALIDATION

The schematic flow diagram and the experimental set up for measuring TL is as shown in the fig.7 and fig 8. [36]. The experimental setup consists of a speaker connected to the silencer at one end. The speaker excites the silencer cavity using a random noise generator. Two microphones were placed at the upstream and downstream tubes of the silencer.

A multi-channel data acquisition system was used to acquire the acoustic transfer functions between the two microphones. The transfer functions were further processed to obtain the four pole parameters, which leads to the TL of silencer [36].

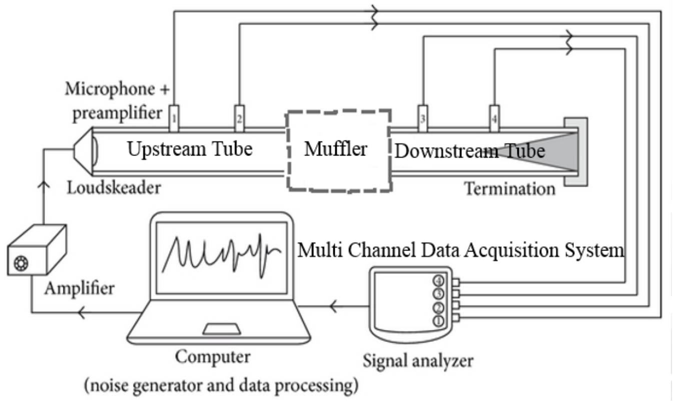

Fig.7 Schematic of the Experimental Set-up for measuring TL

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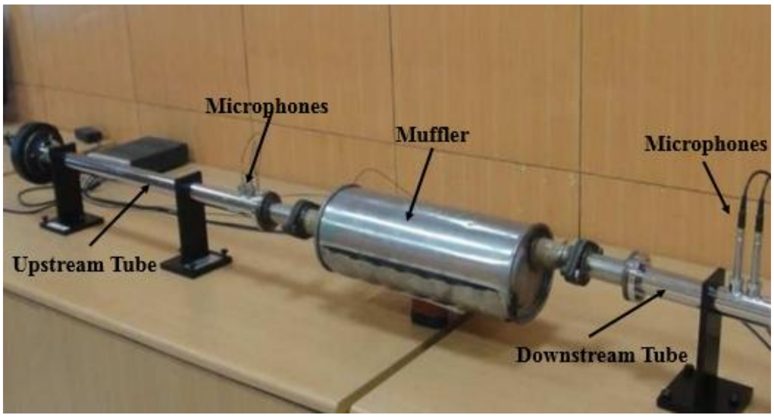

Fig.8 Experimental Set-up for TL measurement

The results of measured TL & simulated TL for iteration4 are shown in fig.9 and match fairly over wide range of frequencies.

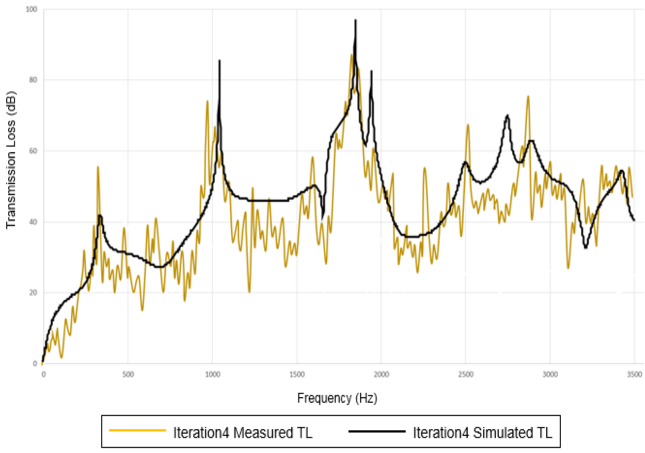

Fig.9 Comparison of simulated Vs measured TL of iteration4 muffler

Finally the measured TL of baseline muffler and iteration4 muffler is compared and shown in fig 10.This is also in line with baseline muffler.

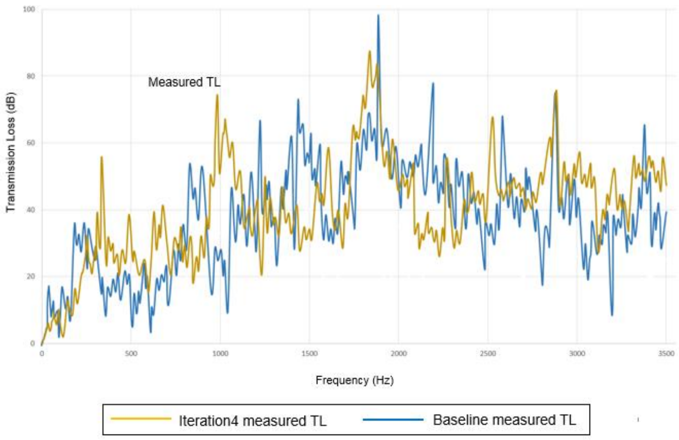

Fig.10 Comparison of measured TL of baseline and iteration4 muffler

Back pressure confirmation is done by actually measuring the BP on engine test bed. The results are shown in table 2 below.

Table 2-Comparision of BP predicted & measured

Sr.No.	Muffler Configuration	Back Pressure (mbar) calculated Targte-250 mbar	Measured BP mbar
1	Baseline	242.2	299.0
5	Iteration4	286.5	258.0

The measured BP is within the specified limit and the measured TL & simulated TL is in line with the baseline muffler. The volume and weight reduction achieved with the proposed muffler is as shown in the table3.

Table 3 – Size, volume and weight comparisons of bassline & proposed muffler.

Sr.No.	Item	Units	Baseline Muffler	Reduced Size Muffler	Difference	Remarks
1	Length	mm	524	450	74	Length reduction
2	Volume	Litres	14	9	5	Volume reduction
3	Weight	kg	13.8	11	2.8	Weight reduction of 2.8 kg
4	Back Pressure calculated	mbar	299	258	41	Target is 250 mbar

Thus with this process, muffler size is reduced by 5 liters along with weight reduction of 2.8 kg without affecting the NVH performance of the car.

VI CONCLUSIONS

This methodology of matching the acoustic performance of the muffler, by comparing Transmission Loss (TL), helps component manufacturers as well as OEMs of cars to reduce the size, weight and cost of the exhaust system, without affecting performance parameters of the car like NVH, backpressure and power. In the current study, the size of the muffler was reduced by 5 litres & weight was reduced by 2.8 kg, without affecting original performance of the car. It was concluded that the current work on the optimization of muffler noise, using attenuation behaviour through transmission loss, was quite desirable and more research needed to be done for complete optimization.

VII SCOPE OF THE FUTURE WORK

The same methodology can be used for reducing the design cycle time of the muffler designs of any new car. The method could be used for optimization of current designs of mufflers on the car to get the weight and cost reduction benefit.

DEFINITIONS / ABBREVIATIONS

BP – Back Pressure. The extra static pressure exerted by the silencer on the engine through its restriction to the flow of gases.

IL-Insertion Loss

NVH- Noise Vibration and Harshness

TL- Transmission Loss

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