Design and Optimization of an Exhaustive Muffler and Experimentation to reduce Emission using Fly ash

Tanmay C. Agrawal, Abhijeet M. Malge

Abstract*: Exhaust gases from the combustion of the air-fuel mixture are reduced to non-harmful gases before releasing them into the atmosphere using a catalytic converter. Exhaust muffler or silencer are used to reduce noise and vibrations level due to the expansion of gases. In this research, a novel muffler is designed for 4-stroke, 125cc single-cylinder petrol engine and structural analysis are carried out for optimization using ANSYS Static Structural solver. The muffler is subjected to various pressure loads, acceleration loads, and load due to self-weight. Fatigue analysis is further carried out using stress-life approach and mean Soderberg theory of failures to determine Life, Damage, Safety factor, Biaxiality Indication, and Alternating equivalent stress under dynamic loading. Experimental analysis is carried out using an optimized muffler with fly ash as a catalyst to determine the reduction in emission. Structural analysis of the initial model was optimized by slight modification in design which reduced total deformation from 0.0379 mm to 0.0374 mm and equivalent stress from 52.878 Mpa to 50.969 Mpa. The safety factor was also increased from 1.6302 to 1.6902. Experimental results using Gas analyzer used for emission readings have shown a reduction in the emission of carbon monoxide and hydrocarbons by 21.06% and 23.07% respectively as compared to a standard muffler.

***Keywords*: Muffler, Dynamic loading, Optimization, Fly ash, Emission.**

I. INTRODUCTION

An exhaust system collects exhaust gases discharged through the valves from the cylinders and reduces harmful gases before releasing them into the atmosphere. Also, the air-fuel mixture in engines is subjected to higher temperatures these systems have to deal with extreme stresses as well. The stress results in the expansion of gases, producing noises which resemble a crack of explosion and needs to be treated as it may cause health problems such as hearing issues, headache, psychological strain, and mental fatigue. A muffler is engineered as an acoustic insulating device designed to reduce the loudness of the sound pressure created by the engine using the method of acoustic quieting [1]. The undesirable sound created due to combustion of exhaust gases and rapid operation of valves is in the form of pressure waves. Mufflers internal arrangement is made of baffles, inner pipes, perforations, and certain sound absorbing material to control pressure which results in controlling noise in form of pressure waves. In dealing with unwanted noises created due to the expansion of gases mufflers or silencers are used whereas a catalytic converter reduces harmful gases released due to the combustion of the air-fuel mixture in the engine. As per the current environmental scenario, there is a need to reduce the emission of these harmful gases released from the engine. Many researchers have worked on diesel engines as they have high emission rates. A mathematical model was developed of heat rejection in a storage device at the time of the catalytic process, during short time stops of vehicle thereby increasing its efficiency [2]. It was found that the vibrations are spread along the exhaust system after carrying out structural analysis of exhaust components, suggested use of Flex-couplings to reduce them [3]. Similar analysis has been carried out structural analysis on two different model of muffler and have found that perforated muffler gives better reduction in stress and deformation as compared to Non-Perforated [4]. Structural analysis on exhaust muffler was carried out and have found that with slight modification the total deformation, stress, strain can be reduced and the life of the muffler can be further increased [5].

An experimental analysis was carried out by supplying ammonia at a different rate to check for conversion efficiency of muffler in reducing NO_x at 75% loading condition and 0.6 kg/hr supply of ammonia [6]. The use of an alternative material as a catalyst and altered design has yielded results that an alternative material and cell structure modification can be productive [7]. Recently conducted experimental analysis using air-box to supply excess air, which increases the system efficiency and reduces back pressure on the engine [8]. Similarly, recent work by [9] has used a heating device before the catalytic converter, and observed an effective increase in the performance of the system. The effect of $Fecl_3$ with thermal barrier coating on the diesel engine, a significant increase in brake thermal efficiency and a decrease in brake specific fuel consumption was observed [10].

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One of the works carried out by [11] involved the use of Fly ash waste as a catalyst to reduce emission in a diesel engine. Fly ash contains about 42-53% silica, 22-30% alumina and 4-5% Fe [11], provides a low thermal expansion coefficient and can withstand high temperatures. They have also studied the effect of pressure, extra air supplied on the emission of gases. Reference [12] have studied the flow of gases through exhaust muffler and various engine parameters, resulting in a reduction of the emission values. Experimental study on effect of fluidised bed of silicon carbide on removal of particulate matter with air as medium was observed and significant results were obtained [14]. Similar studies were carried earlier on rotary fluidised bed of Si-C and centrifugal Fluidised chamber to reduce particulate matter in diesel engine [15, 16].

The main objective of this study to design and manufacture a muffler for a single cylinder petrol engine with fly ash disc as baffle plates to check for the reduction in emission of Hydrocarbons and Carbon monoxide experimentally. Structural analysis is carried on out under dynamic loading and fatigue analysis using the stress-life approach in order to optimize the designed model so that it can withstand various loads in extreme operating conditions.

II. MATERIAL AND METHODS

A. Design of Exhaust muffler

In order to design the muffler, the following parameters must be taken into consideration before proceeding;

- Type of Engine: The type of engine determines the overall length and body diameter of the muffler.
- Size of Muffler: The size of the muffler must be according to engine type as well as space constraints in the vehicle.
- Back Pressure: As the exhaust system causes obstruction in flow of gases it creates a back pressure on the engine which reduces its overall efficiency.
- Cost and weight: Cost and weight are also important factors while selecting the material type for the designed muffler.

In this case, the steps provided in the design data book for exhaust muffler by ASHRAE Technical Board 2.6. is used [17, 18]. For the research, the engine selected is 124.73 cc, 4-stroke, single cylinder SI engine (Honda engine) for which specifications are mentioned in Table 1(From Brochure [19]).

Table 1. Hero Honda Engine Specification

Parameter	Value
Type	Air Cooled, 4-stroke, SI engine
Cylinder Capacity	124.73 cc
Maximum Net Torque	10.30 @5500 rpm
Maximum Net Power	7.58 KW @7500 rpm
Bore	52.4 mm
Stroke	57.8 mm
Compression Ratio	9:2:1
Air Filter Type	Viscous paper Filter

To select the muffler grade insertion loss needs to be calculated and in order to do that consider, Unsilenced noise level (UNL) as 104 dBA at a distance of 1 m. Using the following equations, the value of Insertion loss (IL) is calculated [20];

$$L_p(X_r)_{UNL} = L_p(X_o) - 20 \log (X_r/X_o) \qquad (1)$$

$$\text{Insertion Loss (IL)} = UNL - ENC + 5 \qquad (2)$$

With reference to insertion values, muffler grade was selected as Residential. Further, chamber length and chamber diameter are calculated with the help of the equations mentioned in [20]. The solution obtained from the equations indicated that the length of the chamber should be less than 380 mm and more than 190 mm also, the diameter should be more than 80 mm but should not exceed 94 mm. A value for theoretical pressure drop is also calculated with exhaust flow rate and exhaust gas velocity for a given working condition of the engine. (In this case, full load condition is considered).

Based on the above analytical results, the range of overall length and diameter of the muffler are defined. Maximum exhaust gas velocity and pressure drop of the chamber without any obstruction are also obtained. Fig. 1, shows a cut section CAD model build on Creo Parametric 2.0 of the muffler which is within the specified dimensional limits, (Table 2).

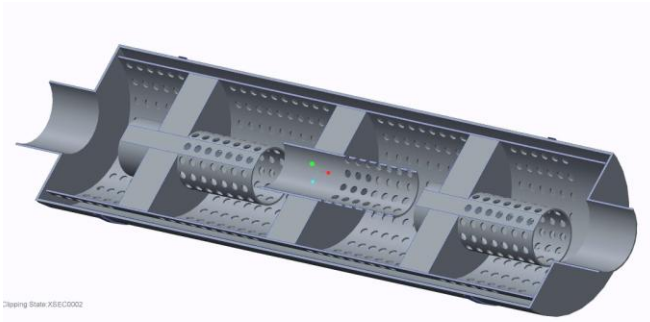

Fig. 1. Cut section of the Designed Model

Table 2. Dimensions of the Designed Model

Part	Quantity	Length/Diameter
Inner Pipe	3	90 mm (L)
Inner Pipe	2	80 mm (L)
Fly ash Disc	3	80 mm (D)
Upper Mesh	1	82 mm (D)
Outer Cover	1	94 mm (D)
Inlet Diameter	-	38.1 mm (D)
Outlet Diameter	-	20 mm (D)

Fig. 2, shows that the chamber is divided into four sections with three baffle plates made of Fly ash are fitted with pipes of one-inch diameter with holes along its length up to 50 mm. Fig. 3 shows that over these plates, a steel sheet with a net-like structure is welded, an absorptive material (glass wool) is used between the steel sheet and outer casing. A double expansion chamber offers better transmission loss as compared to a single expansion chamber [1]. Fig. 2 shows the internal arrangement of the muffler in which two pipes are fitted in first and last disc and a single pipe in the middle disc. Recently it was found, that this type of arrangement results in more reduction of exhaust gas pressure as compared to any other alignment [21].

The discs are made of fly ash with cement as a binding agent, which is a waste obtained from the boiler in a thermal power plant and is easily available at low cost. Fly ash is used directly without making any changes to the composition.

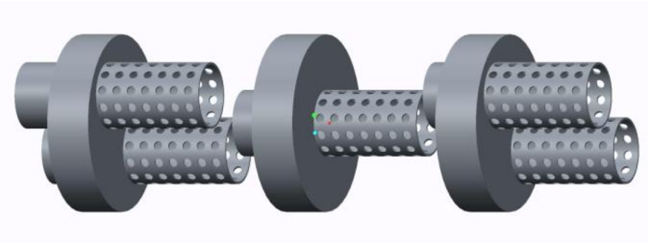

Fig. 2. Internal Arrangement of Exhaust Muffler

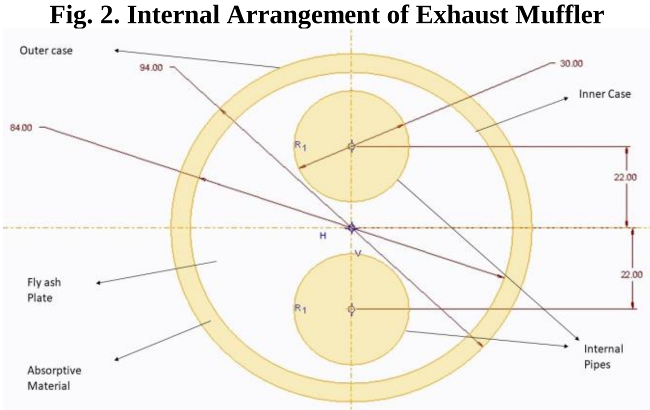

Fig. 3. Schematic Representation of Muffler (Side view)

B. Structural Analysis

For structural analysis of the model, ANSYS static structural solver is used with Steel SS2250 grade is selected for muffler geometry (Note: Properties of Material are mentioned in Table 3 obtained from Ansys software engineering material libraries). Structural analysis carried to check whether the selected design will be able to withstand the stresses expected and fatigue analysis gives the life of designed model subjected to different loads during operation. Two geometries (Model 1 and Model 2) with similar dimension but slight variation in thickness of the material is built in Creo Parametric 2.0. Fig. 4 shows, Fine Mesh with element size 2 mm is generated on both the models.

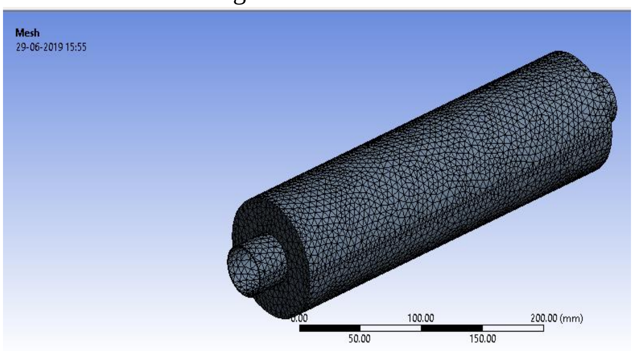

Fig. 4. Mesh generated on Designed geometry

Table 3. Material Properties of SS250

SS250 steel	
Density	7850 Kg/m^3
Coefficient of Thermal Expansion	1.2 x10^{-5}/C
Young's Modulus	2 x 10^5 Mpa
Poisson's Ratio	0.3
Bulk Modulus	1.67x 10^5 Mpa
Shear Modulus	7.692 x10^4 Mpa
Elongation Coefficient	0.23

- *Structural Analysis under dynamic loading:* For boundary conditions as shown in Fig. 5, two fix supports are provided at two ends, standard earth gravity for muffler's self-weight is taken as 9806.6 mm/s^2, and a point mass of 5 kg is applied remotely at a distance of 300 mm to compensate for the weight of other components in the exhaust system. Under dynamic loading an acceleration of 25011 mm/s^2 along negative X-direction is applied.

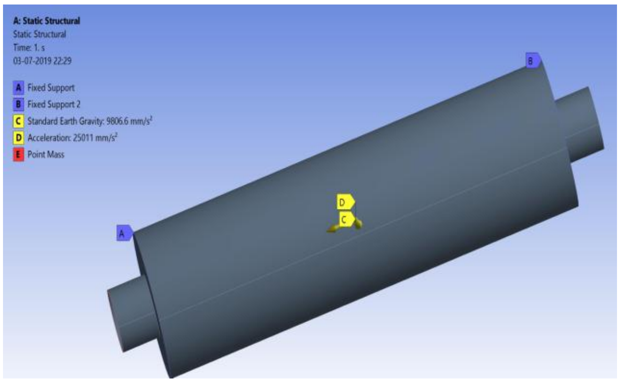

Fig. 5. Boundary Conditions for Structural Analysis

- *Fatigue Analysis:* The type of loading selected was constant amplitude fully reversed load and method used was Stress life approach. Soderberg theory which uses material properties to account for mean stresses is applied to yield more accurate results.

C. Experimentation

- *Setup:* Performance of fly ash disc which acts as a catalyst in muffler in the exhaust system is carried out by connecting it to a Hero Honda Splendor of type (125cc, 4-stroke, and single cylinder) manufactured in India after 16 years of operation (Model 2003). This complete component that is the engine and muffler after connecting to a combustion gas Analyzer (Pollution Under Control-PUC) as shown in schematic Figure 6, which gives the Carbon monoxide and hydrocarbon emission readings. In a Diesel engine, five readings of emission are taken and their average constitutes the Final reading. Whereas in a petrol engine, only one reading is enough in Finalizing the result. The only difference between petrol and diesel engine is that while taking the reading accelerator is not pressed in a petrol engine.

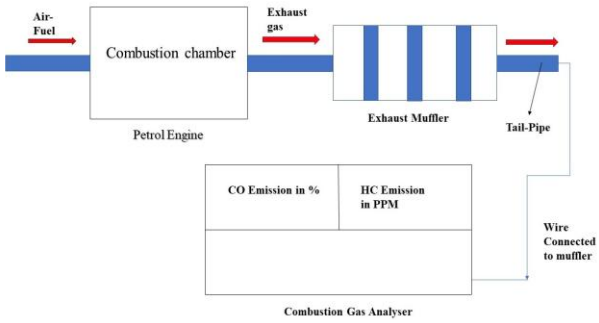

Fig. 6. Schematic Representation of Experimental Setup

- *Analysis and Method:* The experiment is carried out only once to get the reading for CO and HC emission. Taking the emission readings with muffler and without muffler attached to the system and cross-checking of these values are within the government standards for two-wheeler vehicles in India. Calculating the percentage difference between the two values of CO and HC gives the percentage amount of reduction in emission.

III. RESULT AND DISCUSSION

A. Structural Analysis

Structural analysis to calculate total deformation, Equivalent stress, and Fatigue Analysis using stress life approach have been done on Ansys 18.2. This analysis gives the effect of dynamic loading on the designed muffler in order to optimize the design thereby reducing deformation, stresses and increasing the overall life of the design.

- *Structural Analysis of Model 1 under dynamic loading:* Following results were plotted for total deformation and equivalent stress as shown in Fig. 7 and Fig. 8 respectively.

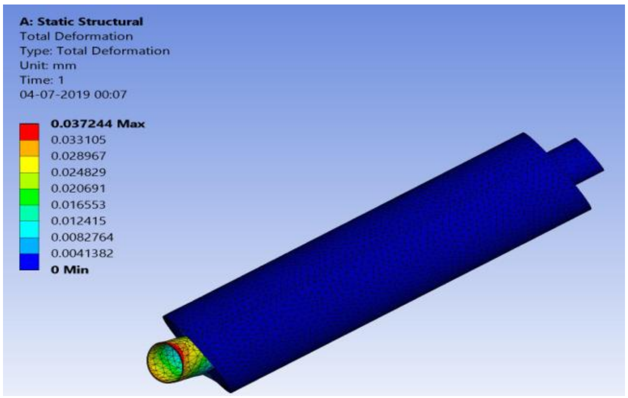

Fig. 7. Total Deformation

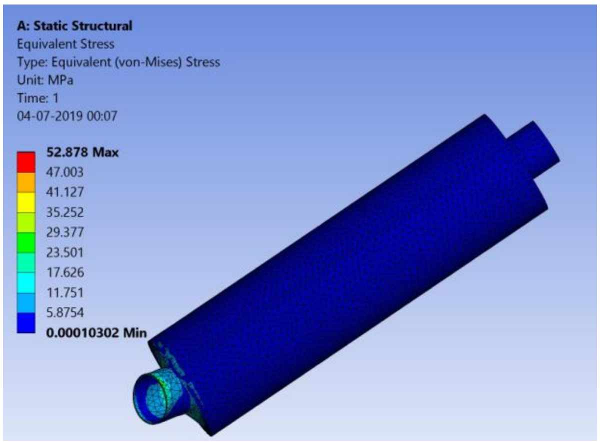

Fig. 8. Equivalent Stress (Von-Misses)

Structural Analysis results for model 1 under dynamic loading are as follows;

Table 4. Structural Analysis results for Model 1

Equivalent (Von-misses) stress: Maximum: 52.878 Mpa Location: Outer Case near the inlet area Minimum: 1.0 x10^{-4} Mpa Location: Internal Pipe 4	Total deformation: Maximum: 0.037244 mm Location: Outer case near the inlet area Minimum: 0.00 mm Location: Outer case

- *Fatigue Analysis for Model 1:* Following results were plotted for fatigue analysis of Model 1 as shown in figures below;

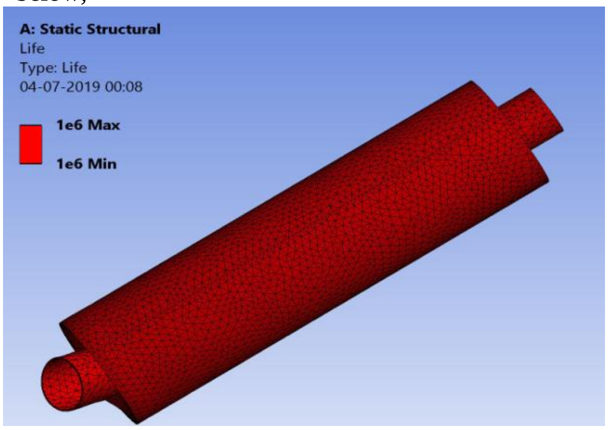

Fig. 9. Life

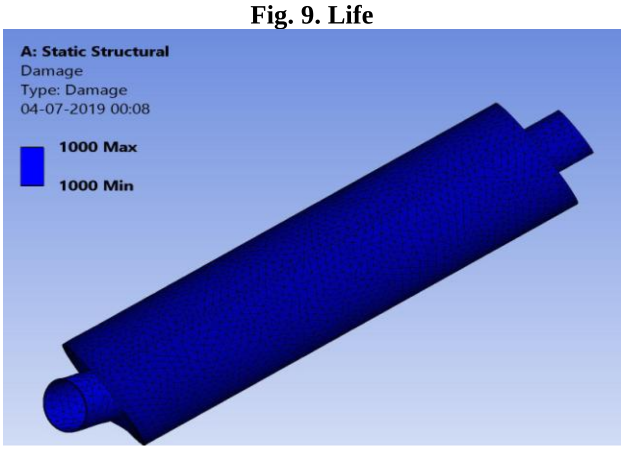

Fig. 10. Damage

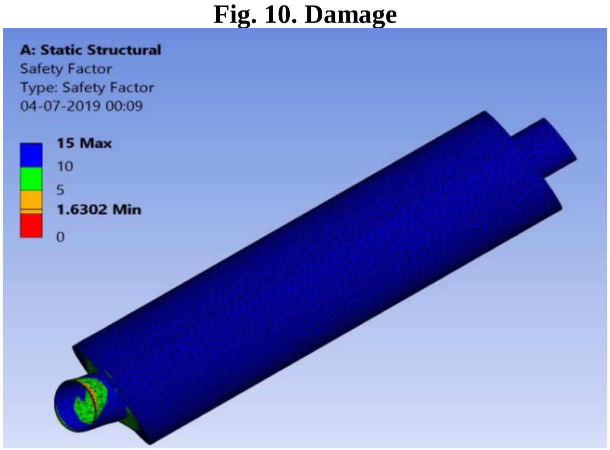

Fig. 11. Safety Factor

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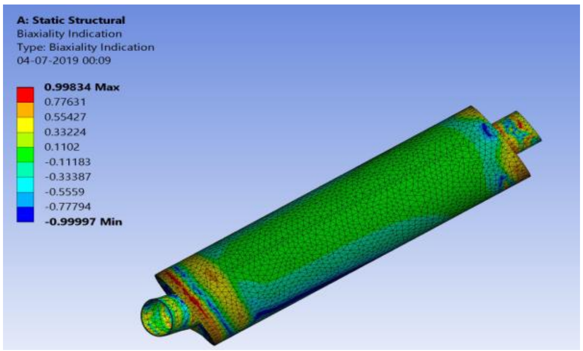

Fig. 12. Biaxiality Indication

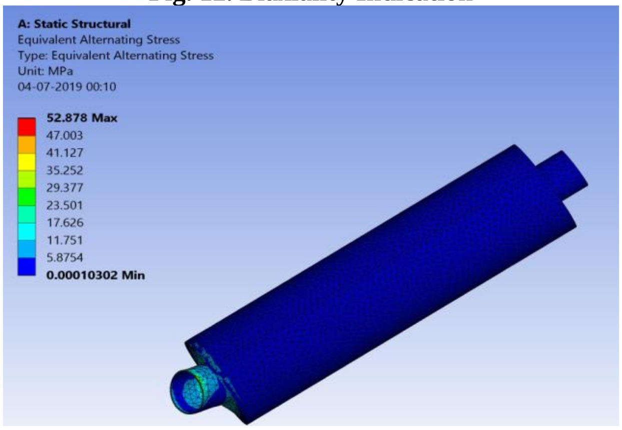

Fig. 13. Equivalent Alternating Stress

Fatigue Analysis results for Model 1 are as follows;

Table 5. Fatigue Analysis results of Model 1

Parameter	Maximum value	Minimum Value	Location
Life		1.0×10^6 Cycles	Baffle 1
Damage	1000 cycles		Baffle 1
Safety		1.6302	Outer case
Biaxiality Indication	0.938	-0.999	Baffle 3 (Max) Baffle 2 (Min)
Alternating Stress	52.878 Mpa	1.0×10^{-3} Mpa	Outer case (Max) Inner Mesh (Min)

Table 4 shows, the total deformation and equivalent stresses maximum and minimum values and their location where they occur. The maximum deformation near the inlet area as shown in Figure 7 indicates the designed muffler will deform a maximum of 0.037244 mm and minimum of 0.00 mm whereas maximum equivalent stress is 52.878 Mpa on the outer case of the muffler where the deformation is maximum. Table 5 shows, fatigue analysis for Model 1 and it can be seen that the life of muffler is 1.0×10^6 cycles under loading with minimum safety factor of 1.6302. Biaxiality indication maximum and minimum values indicate pure shear and pure biaxial state respectively. Although the deformation values and the stresses on the Model are within the specified limits, some slight modification are carried to build a Second model and perform structural analysis to compare the results of both the models.

- *Structural Analysis of Model 2 under dynamic loading:* Following results were plotted for total deformation and equivalent stress as shown in Fig. 14 and Fig. 15 respectively.

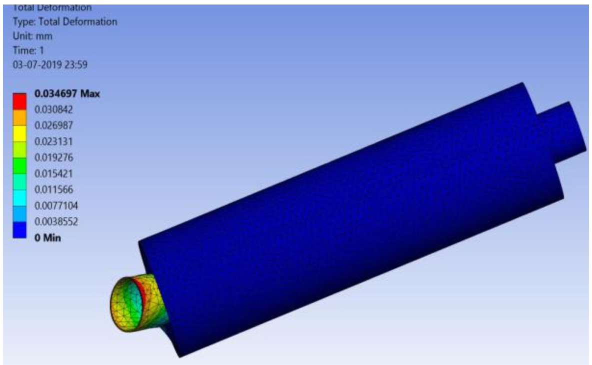

Fig. 14. Total Deformation

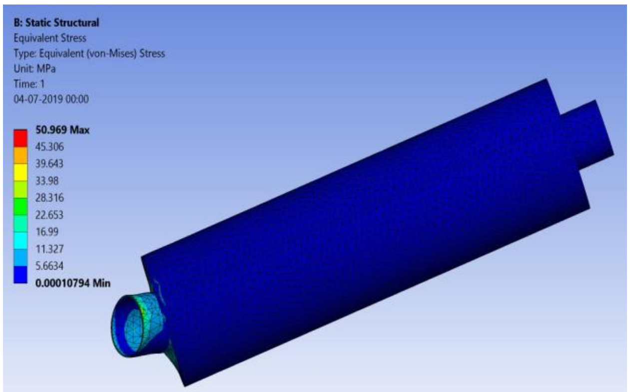

Fig. 15. Equivalent Stress (Von-Misses)

Table 6. Structural Analysis results of Model 2

Equivalent (Von-misses) stress: Maximum: 50.969 Mpa Location: Outer Case near the inlet area Minimum: 1.0×10^{-4} Mpa Location: Outlet pipe	Total deformation: Maximum: 0.034967 mm Location: Outer case near the inlet area Minimum: 0.00 mm Location: Outer case

- *Fatigue Analysis for Model 2:* Following results were plotted for fatigue analysis of model 1 as shown in figures below;

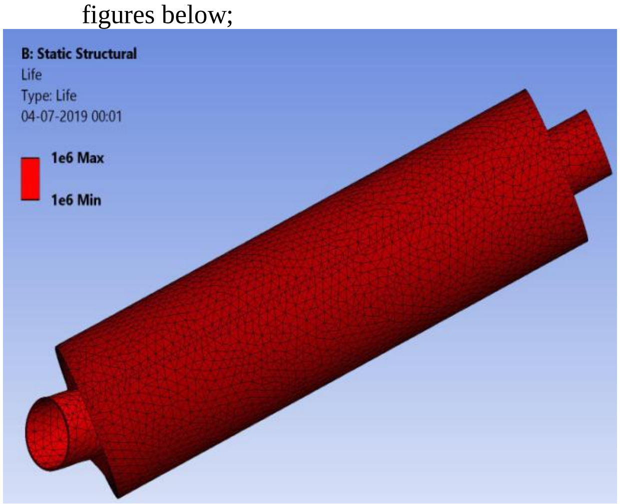

Fig. 16. Life

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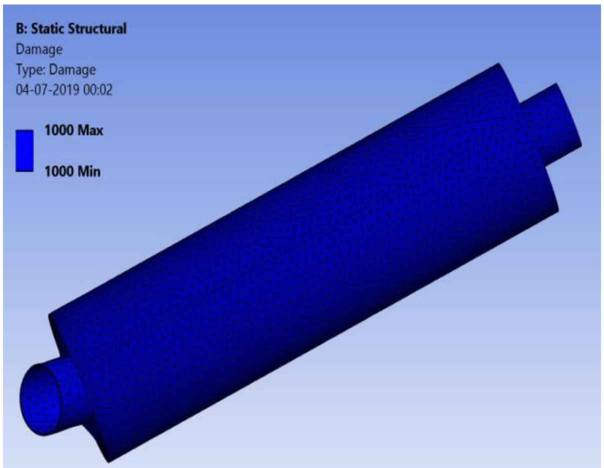

Fig. 17. Damage

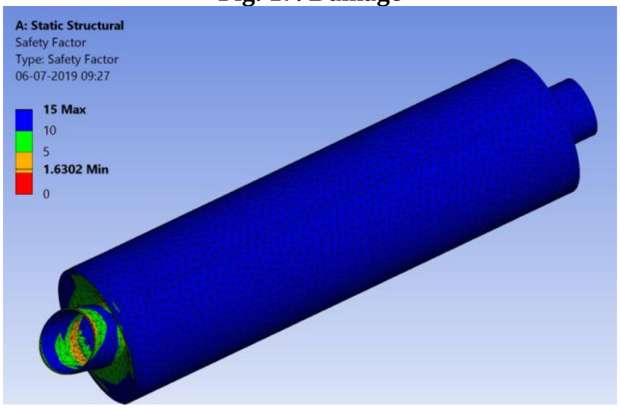

Fig. 18. Safety Factor

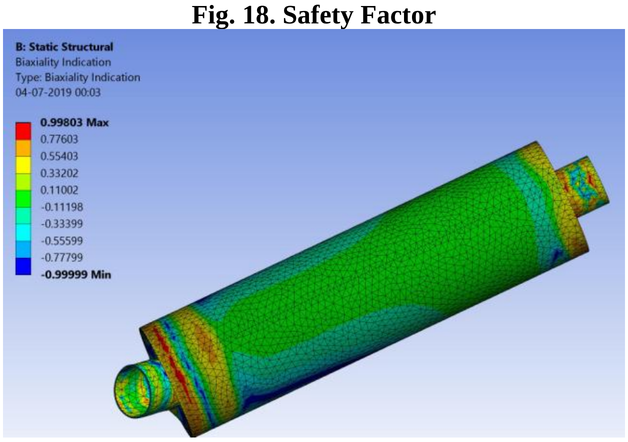

Fig. 19. Biaxiality Indication

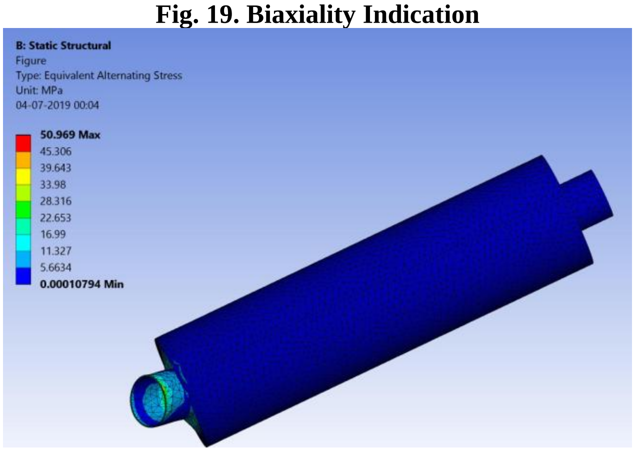

Fig. 20. Equivalent Alternating Stress

Table 7. Fatigue Analysis results of Model 2

Parameter	Maximum value	Minimum Value	Location
Life		$1.0x10^6$ Cycles	Baffle 1
Damage	1000 cycles		Baffle 1
Safety		1.6902	Outer case
Biaxiality Indication	0.938	-0.999	Baffle 3 (Max) Baffle 2 (Min)
Alternating Stress	50.969 Mpa	$1.0x10^{-3}$ Mpa	Outer case (Max) Inner Mesh (Min)

On comparing the results obtained for both the Model 1 and Model 2, it is clearly evident that with slight modification in model 1 have reduced the total deformation to 0.0349 mm from 0.0372 mm. The Equivalent stress of the silencer are 52.878 Mpa which decreases to 50.969 Mpa after modification in Model 2. The safety factor in the silencer increases from 1.6302 to 1.6902. The results confirm that model 2 is slightly better than model 1 and can be manufactured to carry out further experimental analysis.

B. Experimental Analysis on Model 2

In a petrol engine, only one reading is enough in finalizing the result of the emission of Carbon monoxide and Hydrocarbon. On combustion gas analyzer readings are taken in which one emission reading is with muffler and one without muffler attached to the system. The experimental values obtained for the emission of CO and HC in Table 8.

Table 8. Experimental results

Type	**CO emission in %**	**HC emission in ppm**
Without Muffler	2.9	2600
With Muffler	2.3	2000

The government emission standards for the vehicles in India for two-wheeler, four-stroke engines manufactured after 2000, has to be less 3.5% for CO and 4500 ppm for HC emission. The results obtained are within the limits when the muffler with fly ash catalyst is used there is a decrease in emission of CO and HC by 21.06% and 23.07% respectively.

IV. CONCLUSION

In this research, a muffler design on Creo Parametric 2.0 was built successfully on which structural analysis and fatigue analysis was carried out using Ansys Static Structural solver under dynamic loading conditions. Slight modification in the initial designed model to optimize the exhaust muffler was carried out with same boundary condition applied. It can be seen that Model 2 was slightly better as compared to initially designed model and which was further manufactured for experimental analysis. However, increasing the thickness of material will increase the weight of the muffler so there is a limit up-to which modification in the geometry of the muffler is possible. The experimental results were obtained using combustion gas analyzer for CO and HC emission readings. There was an increase in efficiency of CO and HC emission by 21.06% and 23.07%. The results are quite significant when compared to experimental analysis carried on diesel engine with increased content of alumina and silica in Fly ash by [11].

Fly ash as a catalyst in exhaust muffler is effective in reducing the emission of CO and HC from both diesel and petrol engine. Fly ash can be activated to increase its content and obtain more reduction in emission. The use of fly ash waste from the power plants in two-wheeler seems to be relevant as compared to the high-cost catalyst used in 4-wheeler engines and can be turned to large scale production

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