Design and Analysis of Exhaust System for the Two Wheeler using FEA

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Abstract - *This work focuses on the exhaust mufflers for two wheeler vehicles. Study will include CFD analysis and Fluid structural interaction analysis to be performed on the current design of the exhaust muffler with boundary conditions as per engines. Design of the muffler will be generated according to requirements. Exhaust gas temperatures, Velocities and back pressure will be evaluated and verified through Finite Element Analysis package ANSYS. Also the modal analysis is performed to study the effect of geometric change on natural frequency of system. Actual testing will be performed by manufacturing modified exhaust muffler and test it on the two wheeler engine test rig for back pressure and noise.*

Key Words: Fluid Structural Interaction (FSI), Exhaust muffler Analysis.

I. INTRODUCTION

"Exhaust systems are developed to control emissions and to attenuate noise vibration and harshness to meet the regulatory requirements. The exhaust system components are manifold, close coupled and underbody catalytic converters, flexible bellow, muffler, resonator, connecting pipes, flanges, and tailpipe."
A well-designed exhaust system collects exhaust gases from engine cylinders and discharges them as quickly and silently as possible.

1.1 Problem Statement and Objective

Two wheeler exhaust system design and analysis using CFD and FEA tools is to be performed and actual testing is performed on the purchased or manufactured exhaust system for optimum back pressure. Study intends to compare the results of the actual testing of the exhaust system with the analysis performed by the software on the exhaust. Objectives of the project as follows:-

1. To design the exhaust system for the two wheeler vehicle.
2. To analyze the exhaust system model using CFD and FEA to find out performance parameters and structural performances.
3. To perform optimization of back pressure to find optimum back pressure
4. To manufacture the exhaust system as per optimization.
5. To test the performance of the exhaust system and compare the results with the analysis.
6. To validate the experimental results with FEA results

1.2 Methodology

- Performed background study on the exhaust systems.
- The exhaust system selected for engine according to flow requirements and structural loads on the system due to exhaust flow.
- Purchased the selected capacity engines exhaust system and measure the dimensions of the same for CAD model.
- Then the modeling of the exhaust system was done using CAD tool.

- The flow analysis was performed on the exhaust system model. To perform CFD analysis on the system at given velocity to calculate the pressure drop across the system.
- Performed parametric study of the CFD analysis to reduce the pressure drop across the system.
- From the results obtained through the FEA analysis, the parameter was changed in order to achieve optimum exhaust.
- Then an experimental analysis will be done on the optimized exhaust system.

1.3 Literature Review

Atul A. Patil, L.G. Navale and V.S. Patil presented their work, "Design, Analysis of Flow Characteristics of Exhaust System and Effect of Back Pressure on Engine Performance". They successfully designed the Exhaust system. Through CFD analysis, they studied the backpressures of various Exhaust diffuser systems. From the analysis they concluded that, the increase in inlet cone angle increases the pressure of the flow which leads to the reduction in the recirculation zones. [8]

Akshay Tajane, Mahesh Jadhav, Rumdeo Rathod and Vilas Elavande submitted a research paper on "Design and Testing of Automobile Exhaust System" The aim of this paper is to provide deeper understanding of the dynamics of automobile exhaust system to provide a basis for the improved design & development of computationally inexpensive theoretical system model. Modelling, simulation & experimental investigation of a typical exhaust system are performed to gain such an understanding & to evaluate modelling ideas. These models incorporate adjustable flexibility in their connection to the exhaust pipes & a procedure is developed for automatic updating of these parameters to obtain better correlation with experimental results. The agreement between the simulation results of the updated models & experimental results is very good, which confirms the usability of these models. The main objective of this project is to design exhaust system and to compare its performance with an existing system available. [10]

Sidharam Ambadas Basargi presented paper "Design and Development of Automobile Silencer for Effective Vibration Control" This paper postulates the first stage in the design analysis of an exhaust system. With the specified properties of the material, the exhaust system is modelled by using a conventional FEM package. This presents a computational approach for the lifetime assessment of structures. One of the main features of the work is the search for simplicity and robustness in all steps of the modelling, in order to match the proposed method with industrial constraints. The proposed method is composed of mechanical finite element computation. The results are compared with the reading taken on FFT analyser, so as to distinguish working frequency from natural frequency and avoid resonating condition.The validation of the silencer is done by physical prototype development. While the Silencer is made available in the physical form, the trials and testing would address the phase of validation.[2]

II. THEORETICAL ANALYSIS

1. Mass of air that the engine breaths in + mass of fuel = mass of exhaust gases
2. Volume of air the engine takes in = Displacement of the engine x rpm/2
3. To make calculations easy, assume perfect combustion, there aren't any by products and unburned fuel etc.
4. Intake system needs to flow 1.5 cfm per engine horsepower and your exhaust system needs to flow 2.2 cfm per engines horse power.

- Hero Splendor

Engine – Air cooled, 4 Stroke, Single Cylinder
BHP – 4 @ 8000 rpm
Torque @ 5000 rpm
Displacement – 97 cc
Top Speed – 37 mph
Several Assumptions made to design calculations:

1. Combustion will be stoichiometric and complete
2. Compression ratio
3. The engine is throttled (no variable valve timing)
4. Normal aspirate engine (no turbocharger)
5. Volumetric efficiency (the amount of air that makes it into cylinder during induction strokes) is 1.00

Engine is of displacement 97 cc = 0.097 litre
Intake volume of air = Engine displacement x rpm/2
Intake volume of air in engine = 388 litre/min

- That will approximately be the intake volume flow for an engine with the throttle wide open.
- Neglecting the addition of the fuel mass, the mass of the exhaust gas will be the same as the intake gas.

We choose the length of chamber,
1^{st} Chamber = 0.326 m
2^{nd} and 3^{rd} Chamber = 0.2165 m

Therefore total length of chamber,

$$L = l_1 + 2l_3$$
$$= 0.326 + 0.2165 + 0.2165$$
$$= 0.759\ m$$

Therefore Diameter of chamber,
D_1 = 91.44 mm = 92 mm

Total length of Chamber,
L = 759 mm

Baffle Pipes Design:

Diameter of pipes inside the baffles is so that the cross section area doesn't reduce. So,

Area of inlet pipe = Total Area of baffle pipe

$$\frac{\pi}{4} \times d^2 = \frac{\pi}{4} \times {d_1}^2$$
$$d_1 = 21.56\ mm$$

III. FINITE ELEMENT ANALYSIS

The solution of a general continuum problem by the finite element method always follows an orderly step-by-step process. With reference to static structural problems.

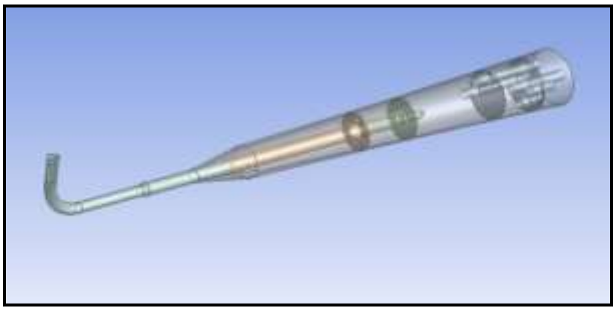

Fig-1: Two wheeler exhausts system

CAD model was created by measuring the actual model of exhaust system used for 100 cc SI engine of splendour. Model is shown in the figure above. SOLIDWORKS is used for modelling the exhaust. From design calculations velocity of 50 m/s is deduced and applied as a boundary condition to the inlet of the exhaust system. Temperature of the inlet gases to the exhaust system are assumed as 400 degree Celsius which is at the higher end of the 100 cc engine exhaust for SI engines. Outlet is applied with atmospheric pressure outlet boundary condition. All the part boundaries which are exposed to atmosphere are provided with heat convection rate of 200 W/m^2 K according to reference table of the convection heat transfer coefficients. 1 lakh 86 thousand nodes and 9 lakh elements are used to mesh the model of exhaust.

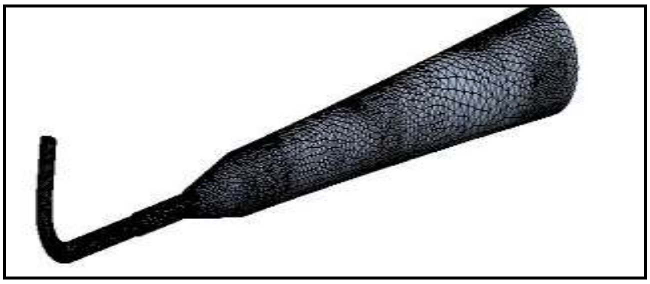

Fig-2: Meshed model for exhaust system

Basic flow analysis is to be performed on the exhaust system model. With inlet boundary condition is provided with inlet velocity and temperature, all the wall of the body exposed to the cooling air stream are provided with 200 convection heat transfer coefficient.

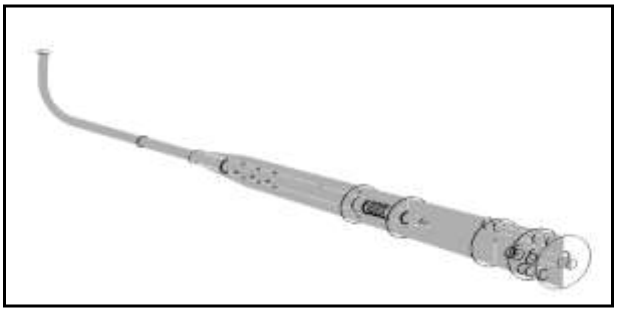

Fig-3: Sectional view of exhaust system

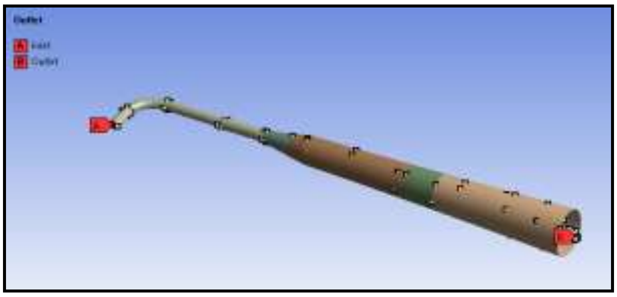

Fig-4: Boundary condition positions

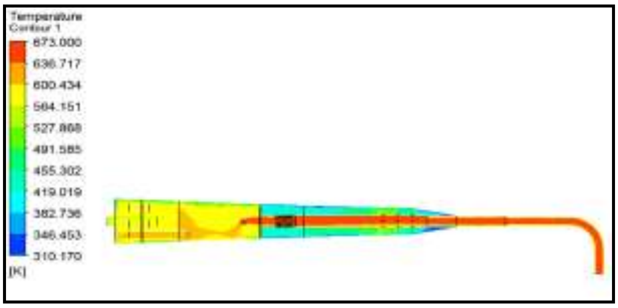

Fig-5: Temperature Plot of Exhaust system @ section

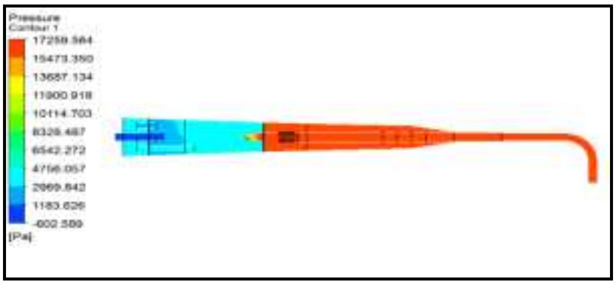

Fig-6: Pressure Plot @ section

Pressure drop across the exhaust system is that means there is almost 18.8 KPa pressure drop across the system. Mostly maximum permissible pressure drop allowed in the system

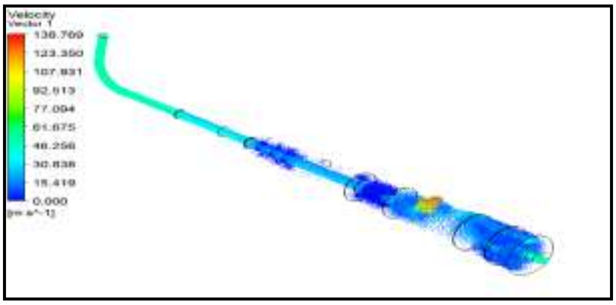

Fig-7: Velocity vector plot for Baseline flow analysis

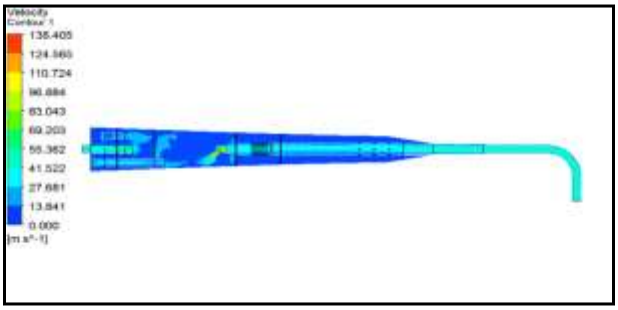

Fig-8: Velocity plot at the cross section

Above plots shows the information about the velocity, pressure and temperatures in the flow zone. Unit of the velocity used is m/s, temperature unit is Kelvin and pressure unit is Pascal.

Colour contour on the right hand side of all the plots show us the range of variable the colour represents, and colours in the plot gives us an idea about the values of the variables in the zone.

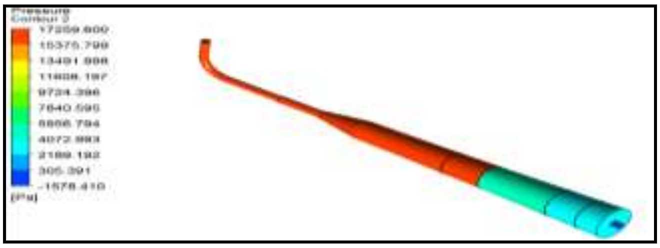

Fig-9: Pressure plot across system Baseline

Pressure drop across the system can, As there is 0 atm pressure boundary condition at outlet.
Total pressure drop = 17.3 KPa

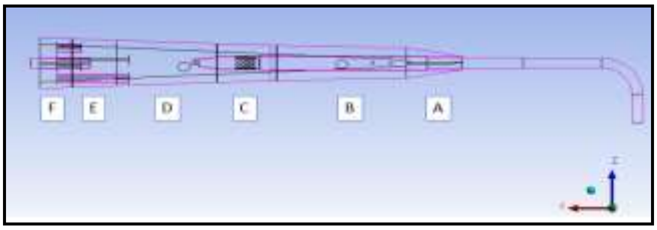

Fig-10: Wireframe diagram for iteration 1 side view

From inlet side, if the chambers are divided in 6 parts calling it A to F. Consideration for iteration 1 length of the chamber C is increased by 10 mm and analysis is done. Results are compared with the baseline.

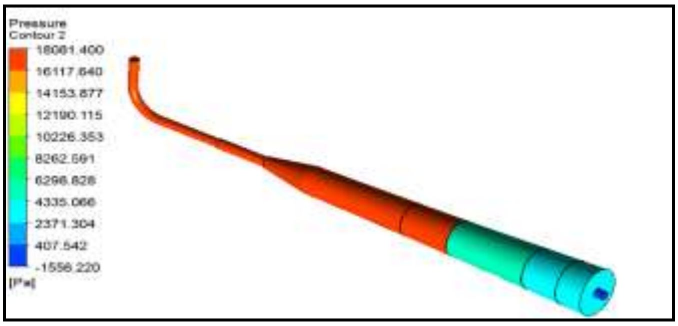

Fig-11: Pressure plot at Iteration 1

Pressure drop = 18.1 KPa
Pressure drop increased by 0.8 KPa.
So increasing the length of the air travel will increase the pressure drop as the resistance to the flow increases.

In Iteration 2 reduction of the lengths of the flow travel is tried. In iteration 2 the length of chamber C is reduced by 15 mm. And pressure plot is given below

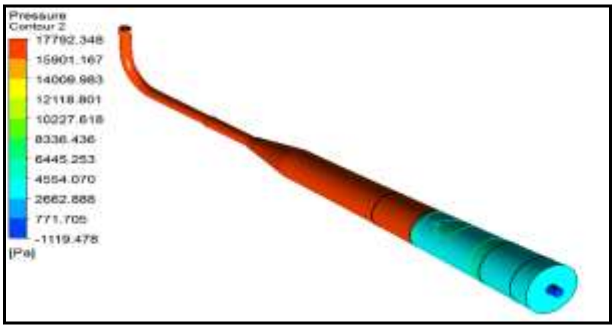

Fig-12: Pressure plot at Iteration 2

Pressure drop = 17.792 =17.8 KPa, as there is 0 gauge pressure or atmospheric pressure applied on the outlet. 17.8 KPa. Pressure drop is increased by 0.5 KPa in this iteration when compared with baseline.

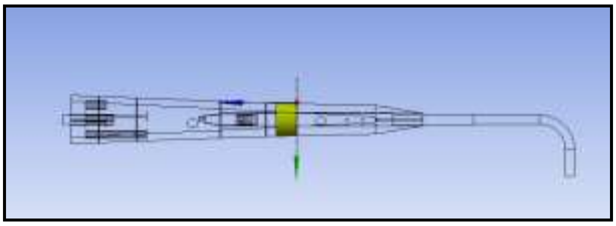

Fig-13: Iteration 3 design model

In Iteration 3 Chamber C length is reduced by 40 mm, and results for the same are observed.

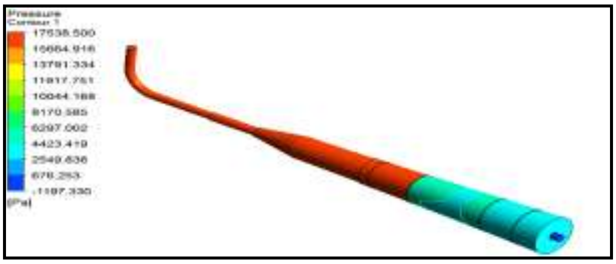

Fig-14: Pressure plot Iteration 3 model

Pressure Drop Increased by 0.2 KPa due to step in the geometry.
Step in the geometry is removed, and inlet pipe before entering the exhaust is reduced by 50 mm

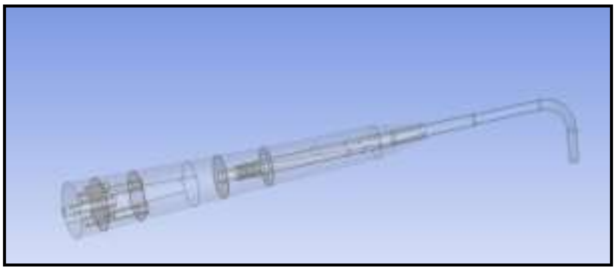

Fig-15: Iteration 4 Design model

In Iteration 4 design change pipe extruded and obstruction to flow in chamber D was removed and flow is directed directly in to the chamber D. This will reduce the resistance to the flow drastically and less effort will be required to force the gases out of the exhaust system. Fig.19 the wireframe diagram of the model.

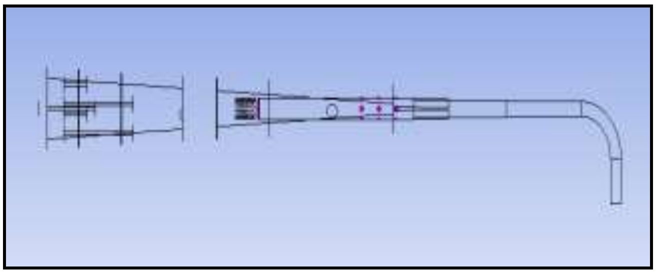

Fig-16: Iteration 4 design wireframe model

Fig-17: Iteration 4 pressure drop contour

Above figure shows pressure plot for Iteration 4 geometry. Only removing the obstruction and small geometrical changes like minimizing the length of inlet of exhaust pipe which reduce the pressure drop across the system drastically. Removing the portion in front in the chamber D results in pressure drop across the system as 4.9 KPa that is 12.4 KPa pressure drop reduction from the original system. Now according to this design, changes will be made in the fabrication model and system will be analyzed for the exhaust gas constituents as well as pressure drop in practical applications. Final iteration other result plots are shown in the images below.

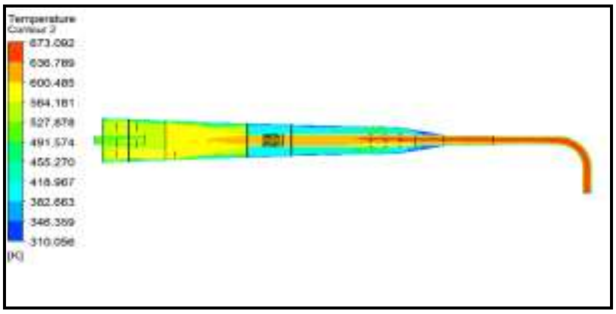

Fig-18: Temperature Plot of Iteration 4 design

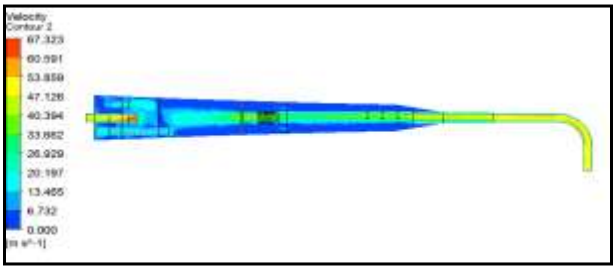

Fig-19: Iteration 4 velocity plot @ cross section

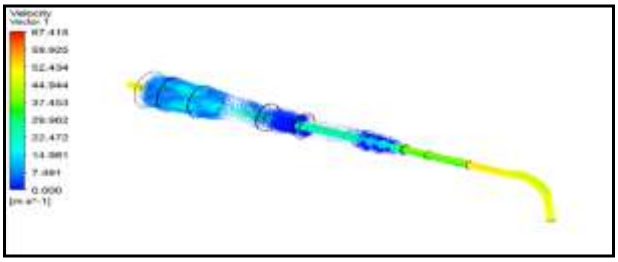

Fig-20: Velocity vector plot at Iteration 4 Design

After iterative study of the pressure drop across the system it is important to study the effect of geometric changes on the natural frequencies of the system if any. For the purpose of finding out if there is any resonance issue developed due to changes made. Shell model is created for the structural analysis purpose thickness plot for the same is shown below. Shell 181 element type is by default used by the workbench for meshing. Modal analysis module is used. Thickness is provided as a property to the shell surface models extracted from solid model.

Fig shows the meshed model of the meshing model meshed with size of 1 mm and number of elements used to model it are 191769 and node are 191398. Modal analysis is performed to find first 6 non-zero frequencies of the free free modal analysis

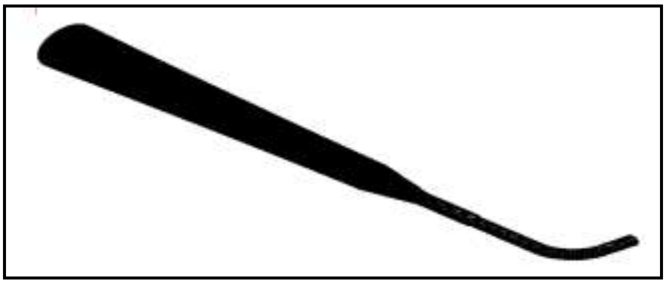

Fig-21: Meshing of the structural model

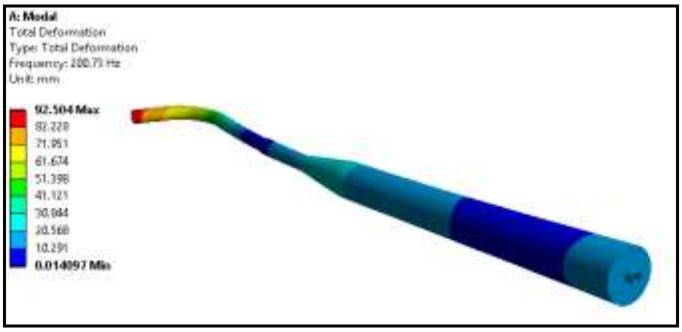

Fig-22: First frequency mode shape plot @ 200.73 Hz

First non zero modal frequency of the model in free modal analysis is found to be 200.73 Hz in FEA analysis for baseline.

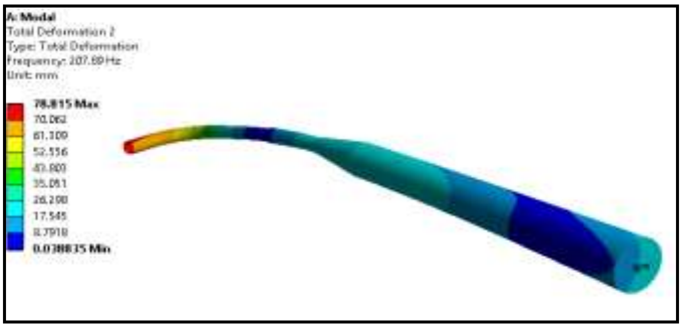

Fig-23: Second frequency mode shape plot @ 207.89 Hz

Second non zero modal frequency of the model in free modal analysis is found to be 207.89 Hz in FEA analysis for baseline.

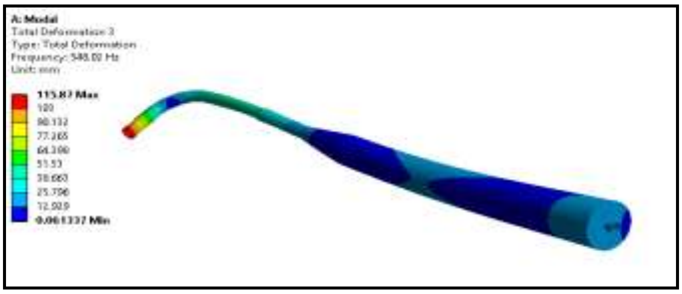

Fig-24: Third frequency mode shape plot @ 548.02 Hz

Third non-zero modal frequency of the model in free modal analysis is found to be 548.02 Hz in FEA analysis for baseline.After performing modal analysis on the system baseline model, model changes of the iteration 4 are performed on the baseline geometry to simulate modal analysis for the final iteration. After performing changes same modal analysis is ran for the iteration 4 modal and changes in the natural frequencies and mode shapes are observed if any. Structural model changes in the final iteration model and baseline model are shown in the image below.

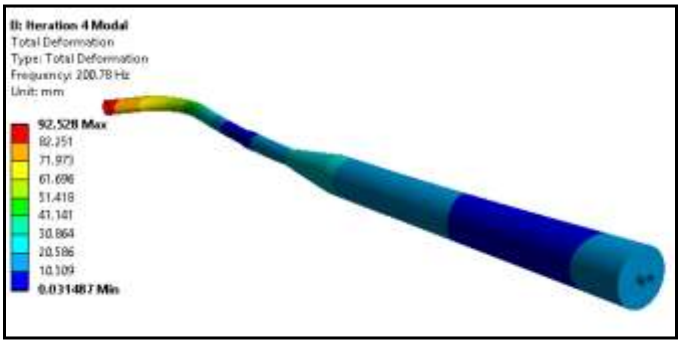

Fig-25: First frequency mode shape plot iteration 4 @ 200.78 Hz

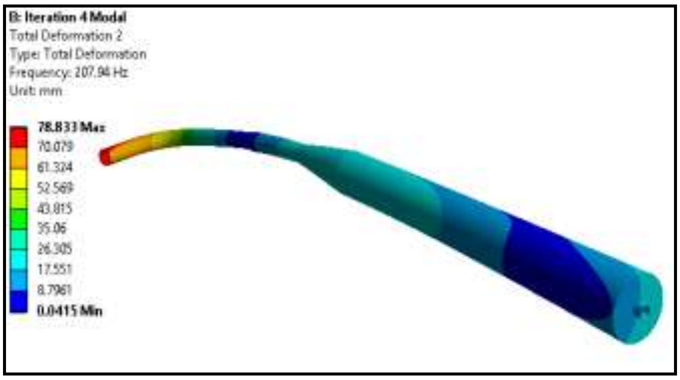

Fig-26: Second frequency mode shape plot Iteration 4 @ 207.94 Hz

Second frequency plot for the iteration 4 models is shown above with frequency of 207.94 Hz. Similarly all six frequencies of the iteration 4 model are checked and are found not deviated from the baseline model frequencies and mode shapes are also similar.

Table 1: Frequencies of the modal analysis

Mode No.	Iteration 4	Baseline	Change	% Change
1	200.78	200.73	0.05	0.02%
2	207.94	207.89	0.05	0.02%
3	548.95	548.02	0.93	0.17%
4	554.18	552.98	1.2	0.22%
5	772.55	769.98	2.57	0.33%
6	845.26	842.29	2.97	0.35%

IV. RESULTS AND DISCUSSION

Table-2: Result summary table CFD

Design	Pressure Drop (Kpa)	Pressure Drop Reduced
Baseline	17.3	
Iteration 1	18.1	-0.8
Iteration 2	17.8	-0.5
Iteration 3	17.5	-0.2
Iteration 4	5	12.3

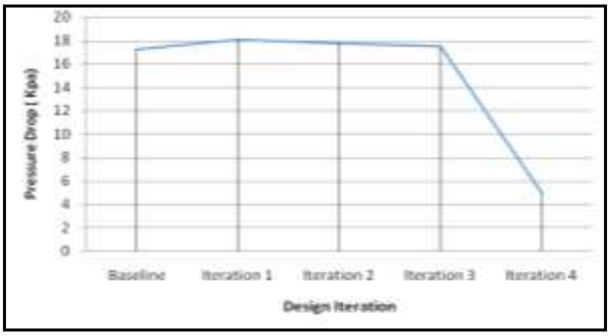

Chart-1: Chart of Pressure drop across the silencer vs Design iteration

Table 2 and graph plotted above in fig 29 shows that results for iterations which says baseline design has pressure drop across the system 17.3 Kpa . Iteration 1st- Length of chamber C increased by 10 mm gives pressure drop of 18.1 KPa .

Iteration 2nd- Length of chamber C reduced by 15 mm gives pressure drop of 17.8 KPa . Iteration 3rd- Length of chamber C reduced by 40 mm pressure drop to shift to 17.5 KPa. Iteration 4th length of exhaust pipe at starting reduced by 50 mm and removing the obstruction to flow in chamber D pressure drop is changed to 5 KPa across the system.

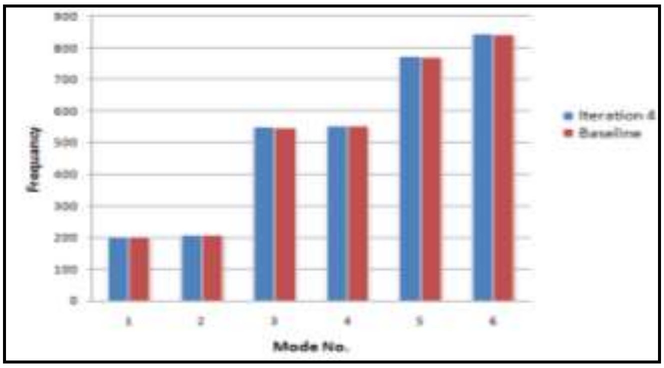

Chart-2: Graph of frequency

First natural frequency of the exhaust system is 200.78 Hz in baseline model and which is not changed at all in iteration4 models which are observed as 200.73 Hz in FEA modal analysis

V. CONCLUSION

In this present work flow analysis on the two wheeler exhaust system is performed. It is found out that approximately 70 % pressure drop can be reduced if length of exhaust pipe at starting reduced by 50 mm and restriction to the flow in D chamber is removed. It can be seen that first 3 iterations show slight increase in the pressure drop across the exhaust system which will result in to increased work for the two wheeler engine to overcome the resistance by exhaust system. In iteration 4 design pressure drop across the exhaust system drop down by 12.3 KPa and it is observed to be 5 KPa which reduces the required work by the engine to force exhaust gases out of the system drastically. This will result in increased engine efficiency and low fuel consumption for similar work production by engine. First natural frequency of the exhaust system is 200.78 Hz in baseline model and which is not changed at all in iteration4 models which are observed as 200.73 Hz in FEA modal analysis. No need to run pressure pulsation transient analysis as frequencies are not changed by much and pressure s in the system are reduced.

VI. FUTURE SCOPE

The scope of study can be expanded by also considering effect on Noise, Vibration and Harshness by the changes. Pulsating pressures on the walls of the exhaust system due to flow and perform static structural analysis to find out structural fatigue caused by the flow in the joints of exhaust system. Also analyze the vibrations by provision of vibration absorber or vibration isolator. Effect of different welding processes on the silencer can be examined.

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