“Design and Analysis of Diesel Engine Exhaust Manifolds for
Genset Engine”

Mr. Eshwar S. Korade, Prof. B. N. Randhavan
Department of Mechanical Engineering, Sahyadri Valley College of Engineering, Savitribai Phule Pune University.
1eshwar.korade@gmail.com
2bhagwatr4488@gmail.com

Abstract

Exhaust manifold is an important component in an exhaust system of engine. It connects to each exhaust port on the engine's cylinder head, and it funnels the hot exhaust down into one simple exhaust pipe. With the help of the exhaust manifold gaskets, it also prevents the toxic exhaust fumes from sneaking into the vehicle and harming the occupants. This paper is related to design and finite element analysis of exhaust manifold of 4 cylinder diesel engine. Engine capacity is 5678 cc. The finite element analysis in ANSYS software by using materials based on their composition viz. FG220MoCr and SG500/7. In FEA we find out the thermal as well as static structural properties material. Finally the results are validated through experimentation on tensile strength, Izod-Charpy impact testing, and Metallurgical Microscope.

Keywords— Exhaust Manifold, Finite Element Analysis, Modal Analysis.

I. INTRODUCTION

In Exhaust plays a crucial role in the performance of any internal combustion engine. The exhaust system begins with manifolds on the engine and ends with the tail pipe. Basically, it includes an exhaust manifold, heat riser, exhaust pipe, catalytic converter, muffler, resonator (optional), and tail pipe. Following is a closer look at each component.

The exhaust manifold collects the burned gases as they are expelled from the engine cylinders and directs them to the exhaust pipe. The manifold is designed to give minimum back pressure and turbulence. Exhaust system should be designed keeping in mind the allowable back pressure will be half of the maximum permissible. Restriction of backpressure is generally due to pipe size, silencer, and system configuration. Catalyst products utilize dry, water cooled and air shielded water cooled (ASWC) manifold designs, based on application and design requirements. Dry manifolds are the preferred manifold design. They are cost effective and by providing the maximum possible exhaust energy to the turbocharger, they offer the highest overall efficiency. Dry manifolds, however, also radiate the most heat and reach the highest surface temperatures.

In this paper we create a three dimensional model of Exhaust manifold in CATIA V5R modeling software. Static structural analysis done in ANSYS 14.5 (FEA) software by using two different materials based on their composition. Exhaust manifolds are manufactured using cast iron. So the exhaust manifold material FG220MoCr is replaced by material such as SG500/7.

II. LITERATURE REVIEW

The fuel manifold is an import accessory through which the fuel enters in combustor, after measuring in fuel control system. The component test results of fuel manifolds show that, when the starting fuel supply is given and the primary fuel manifold relative unfold pressure is at constant, the adjustment of the secondary fuel manifold turn-on pressure has effects on fuel flow through the secondary fuel manifold and the time of fuel into the combustion chamber. The verification test of the secondary fuel manifold unfold pressure influence on engine starting performance has been conducted, showing that the unfold pressure variation of the secondary fuel manifold has great influence on the engine start performance. The test research results have important guidance and reference meaning for confirming the secondary fuel manifold unfolds pressure. [1]
The computational challenges encountered in turbocharger turbine and exhaust manifold flow analysis. The core computational method is the Space-Time Variational Multiscale (ST-VMS) method, and the other key methods are the ST ISO geometric Analysis (ST-IGA), ST Slip Interface (ST-SI) method, ST/NURBS Mesh Update Method (STNMUM), and a general-purpose NURBS mesh generation method for complex geometries. The ST framework, in a general context, provides higher-order accuracy. The VMS feature of the ST-VMS addresses the computational challenges associated with the multiscale nature of the unsteady flow in the manifold and turbine, and the moving-mesh feature of the ST framework enables high-resolution computation near the rotor surface. The ST-SI enables moving mesh computation of the spinning rotor. The mesh covering the rotor spins with it, and the SI between the spinning mesh and the rest of the mesh accurately connects the two sides of the solution. The ST-IGA enables more accurate representation of the turbine and manifold geometries and increased accuracy in the flow solution. The STNMUM enables exact representation of the mesh rotation. The general-purpose NURBS mesh generation method makes it easier to deal with the complex geometries we have here. An SI also provides mesh generation flexibility in a general context by accurately connecting the two sides of the solution computed over no matching meshes. That is enabling us to use no matching NURBS meshes here. Stabilization parameters and element length definitions play a significant role in the ST-VMS and ST-SI. For the ST-VMS, we use the stabilization parameters introduced recently, and for the ST-SI, the element length definition we are introducing here. The model we actually compute with includes the exhaust gas purifier, which makes the turbine outflow conditions more realistic. We compute the flow for a full intake/exhaust cycle, which is much longer than the turbine rotation cycle because of high rotation speeds, and the long duration required is an additional computational challenge. The computation demonstrates that the methods we use here are very effective in this class of challenging flow analyses. [2]

At estimating the low-cycle and high-cycle fatigue life of a turbocharged Diesel engine exhaust manifold. First, a decoupled thermo-structural Finite Element analysis has been performed to investigate low-cycle fatigue phenomena due to the thermal loadings applied to the exhaust manifold. High/low temperature cycles causes stress-strain hysteresis loops in the manifold material whose related dissipated energy can be directly correlated to low-cycle thermal fatigue. Afterwards, a dynamic harmonic analysis has been performed aiming at investigating the existence of high-cycle fatigue phenomena due to vibration loading applied to the exhaust manifold during the duty cycle. Three direction acceleration experimental loadings have been applied to the model. An ad-hoc methodology has been developed to superimpose thermo-structural results to dynamic harmonic analysis results.

In particular, quasi-static thermo-structural results have been employed to identify the mean stress values of vibration fatigue cycles, while alternate stress values have been derived from harmonic analysis. Different combinations of frequencies and phases of the acceleration input signals have been considered to create different high-cycle fatigue loadings. Each cyclic load case has been processed employing the multiaxial Dang Van fatigue criterion. [3]

Some mechanical components are subjected to thermo-mechanical fatigue, which occurs when both thermal and mechanical loads vary with time. Due to the complexity of the components geometry, stresses and strains field becomes multiaxial, worsening the fatigue resistance. In this paper several damage models are applied and compared on a case study, an automotive exhaust manifold simulacrum replying the material and the geometrical features of the commercial component. A complete thermo-structural FE analysis has been run and results have been post-processed by means of a numerical code implementing several multiaxial damage models available in literature and based both on a critical plane approach (Kandil-Brown-Miller, Fatemi-Socie) and strain-based models (Von Mises, ASME Code and Sansino-Grubisic). The model calibration has been carried out by means of literature experimental data referred to commercial exhaust manifolds of similar geometry and material. [4]

Out-of-phase thermo mechanical fatigue (OP-TMF) tests between 600qC and 950qC have been conducted for three cast austenitic alloys with different metal-carbide (MC) morphologies: dense skeleton, sparse skeleton and blocky carbides. The alloy with dense skeleton-like MC exhibited longer TMF life than the other two, even though their chemical composition and casting process were similar. Fractographic analysis indicated that the fatigue cracks initiated from the specimen surface for all the alloys in this study. The morphology of Nb (C, N) has an obvious effect on inelastic deformation. Alloys with skeleton-like Nb(C, N) precipitates have better ductility as compared to alloys with isolated blocky precipitates. Dense skeleton-like Nb(C, N) is found to delay OP-TMF crack initiation and propagation, resulting in longer TMF lives. [5]

Due to the more stringent and upcoming laws in terms of environment protection field, the required temperatures in combustion chamber need to be higher in order to reduce particles emissions. This target is reached by engine downsizing (see FIAT and Ford) together with the application of turbochargers, but the new altered conditions lead to a design of exhaust gas manifold that has to take into account an improvement in terms of temperature up to 1050°C. Above all, materials characterization has to be carried out in order to represent, as close as possible, real operative conditions. Usually, materials for exhaust gas manifold are characterized from HCF, LCF and TMF point of view by testing on cylindrical specimens, but this way it’s not possible to detect the effect given by rolling process.
In these last years CRF has designed and developed a particular kind of anti-buckling in order to allow LCF and TMF characterization on flat specimen at high temperatures with fully reversed strain cycle. This paper will show the results of LCF characterization carried out on flat specimen (th=1.5 [mm]) in strain ratio condition Rz=−1 at temperatures of 600[°C] and 800[°C]. Furthermore, results of several TMF tests will be showed. [6]

A naturally aspirated, direct injection diesel engine investigating of combustion and emission characteristics of CH4-CO2 and CH4-CO2-H2 mixtures has studied. These aspirated gas mixtures were pilot-ignited by diesel fuel, while the engine load was varied between 0 and 7 bar IMEP by only adjusting the flow rate of the aspirated mixtures. The in-cylinder gas composition was also investigated when combusting CH4-CO2 and CH4-CO2-H2 mixtures at different engine loads, with in cylinder samples collected using two different sampling arrangements. The results showed a longer ignition delay period and lower peak heat release rates when the proportion of CO2 was increased in the aspirated mixture. Exhaust CO2 emissions were observed to be higher for 60CH4:40CO2 mixture, but lower for the 80CH4:20CO2 mixture as compared to diesel fuel only combustion at all engine loads. Both exhaust and in-cylinder NOx levels were observed to decrease when the proportion of CO2 was increased; NOx levels increased when the proportion of H2 was increased in the aspirated mixture. In-cylinder NOx levels were observed to be higher in the region between the sprays as compared to within the spray core, attributable to higher gas temperatures reached, post ignition, in that region. [7]

The current scenario of high growth rate of automobile usage, the automobile industry is forced to adopt the government emission norms to keep the environment green. Latest technologies have been developed in the automotive exhaust system to acknowledge the emission norms. Diesel oxidation catalyst and Muffler both are playing major roles in reducing emission and noise level as well. Diesel oxidation catalyst reduces CO and unburned HC emissions. Muffler reduces noise level of exhaust gases. Nowadays automobile industry is using CFD software extensively to analyze the flow properties inside the diesel oxidation catalyst and Muffler. Flow analysis helps to optimize the geometric design of Diesel oxidation catalyst to oxidize the CO and unburned HC of exhaust gases.

In this present work we studied pressure drop and uniformity index of an existing exhaust system which consists of close couple catalytic converator, under body catalytic converator and muffler. Exhaust system has been modeled by using CATIA V5 which is advanced CAD software. The substrate has been modeled as porous medium for analysis purpose. These models have been imported in CFD tool for analysis. After importing the CAD data inside the CFD software, with proper boundary conditions, the CFD analysis has been carried out. Based on the study, individual system contributions to the total pressure drop and flow uniformity have been analyzed and improvement areas of the existing system for better flow uniformity have been suggested. [8]

Intake manifold water injection (IMWI) is an effective way to control combustion temperature and NOx emission for diesel engines. The various effects of IMWI on diesel combustion and emissions reflect on the dilution effect, thermal effect and chemical effect. However, researchers have paid little attention to investigate the three effects. In this study, the dilution, thermal and chemical effects of IMWI on the combustion and emissions characteristics of a four-stroke, direct injection as well as turbocharged diesel engine are investigated by CFD simulation. The results indicate that IMWI reduces the in-cylinder mean pressure and temperature, and the ignition delay becomes longer. IMWI leads to a remarkable decrease of NOx and Soot emissions. Comparing to the thermal effect and chemical effect, the dilution effect of IMWI on engine combustion and emissions plays a dominant role. [9]

The automotive exhaust system with respect to its in-service conditions and selection of suitable materials for exhaust manifold, downpipe silencer/ muffler box and tail pipe which comprises the exhaust system. The functions of each component were discussed, highlighting how they function as part of the exhaust and Cambridge Engineering Software (CES) software was employed in the material selection process. Mass, cost, high temperature (>800°C for exhaust manifold and >400°C for downpipe silencer/ muffler box and tail pipe) and high corrosion resistance were used as basic criteria for the material selection. Variety of materials including Nickel-based super alloys, stainless steel, Nickel chromium alloys were obtained in the material selection route for exhaust manifold. Similarly, Low alloy steels, stainless steel, grey cast iron, Nickel-based super alloys, Nickel-chromium alloys were obtained in the material selection for downpipe silencer/ muffler box and tail pipe. Nickel-based super alloys and Nickel-chromium alloys possess suitable properties for this application, but were not considered due to their high densities and high cost. Low allow steels were not selected because they tends to exhibits poor corrosion resistance when exposed to salt on the road surface and condensate from the exhaust system. Grey cast iron has low tensile strength and elongation and therefore not exhibit enough toughness required to withstand the severe working conditions. However, stainless steel (Ferrite stainless steel and Austenitic stainless steel) was considered as a better choice of material for automotive exhaust systems due to its considerable price and density, acceptable strength at elevated temperatures and excellent corrosion resistant it possesses as a result of the protective film of chromium oxide which forms on the surface of the metal. [10]

III. PROBLEM STATEMENT

As power and torque increases the temperature of exhaust gases increases, this high temp fails the exhaust manifold with current material FG220MoCr. Hence we are selecting a new material without compromising functionality of Exhaust Manifold. Also thermal stresses should be kept as minimum.
IV. OBJECTIVES
- To select a new material for Exhaust manifold.
- To create three-dimension models of diesel engine exhaust manifold using CATIA V5R modeling software.
- To perform FEA analysis using ANSYS Software.
- To study Thermo Mechanical Strength analysis.
- To analyze the result of software and experimental tests.

V. METHODOLOGY
- Theoretical calculation of four cylinder diesel engine exhaust manifold.
- Solid model of four cylinder exhaust manifolds.
- Meshing of 3-D entity of exhaust manifold.
- Finite element analysis in ANSYS14.5.
- Computational results.
- Experimentation on material.
- Compare theoretical, FEA and experimental result.

VI. ENGINE SPECIFICATIONS

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Type</th>
<th>4 Cylinder Diesel Engine (Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Capacity of engine</td>
<td>5678 cc</td>
</tr>
<tr>
<td>2</td>
<td>Number of cylinder</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Bore × Stroke</td>
<td>97mm × 128 mm</td>
</tr>
<tr>
<td>4</td>
<td>Type of Injection</td>
<td>DI</td>
</tr>
<tr>
<td>5</td>
<td>Prime power</td>
<td>115 kw @ 1500 rpm.</td>
</tr>
<tr>
<td>6</td>
<td>Maximum Torque</td>
<td>732 Nm @ 1500 rpm.</td>
</tr>
<tr>
<td>7</td>
<td>Compression Ratio</td>
<td>17.5:1</td>
</tr>
</tbody>
</table>

VII. ANALYSIS BY ANSYS SOFTWARE

Engine Exhaust Back Pressure: exhaust gas pressure that is produced by the engine to overcome the hydraulic resistance of the exhaust system in order to discharge the gases into the atmosphere. For this discussion, the exhaust back pressure is the gage pressure in the exhaust system at the outlet of the exhaust turbine in turbocharged engines or the pressure at the outlet of the exhaust manifold in naturally aspirated engines. The term back pressure can be also spelled as one word (backpressure) or using a hyphen (back-pressure).

Back Pressure Limits: All engines have a maximum allowable engine back pressure specified by the engine manufacturer. Operating the engine at excessive back pressure might invalidate the engine warranty.

Table 4.2 VERT maximum recommended exhaust back pressure

<table>
<thead>
<tr>
<th>Engine Size</th>
<th>Back Pressure Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 50 kW</td>
<td>40 kPa</td>
</tr>
<tr>
<td>50-500 kW</td>
<td>20 kPa</td>
</tr>
<tr>
<td>500 kW and above</td>
<td>10 kPa</td>
</tr>
</tbody>
</table>

The designed 3D models of exhaust manifolds in catia software as shown in below figure:

Figure No. 7.1 3d Model of Exhaust manifold in Catia Software
a) Apply Load and boundary condition

Applying Load and Boundary Conditions

Material properties play an important role in the result of the FE analysis. The material properties are one of the major inputs to perform the FEA and optimization. Applying the boundary conditions and exact loading of the exhaust manifold is very essential to obtain accurate results for the analysis. Here (Thermal) static structural analysis is done on the exhaust manifold.

Loads and boundaries
Number of FORCE sets: 1
Number of SPC sets: 1

![Figure No.: 7.2 Manifold – Boundary conditions for Modal Analysis](image)

b) Temperature Assumptions

Temperature is an independent property for modulus of elasticity & thermal expansion coefficients are taken for the analysis as temperature dependent.

For Exhaust Manifold ~750°C
Exhaust Manifold Clamps~650°C
Turbocharger, EGR flange & surrounding region~650°C
Head region surrounding manifold face~200°C
Bolt thread region in side head~200°C
Bolt region at manifold contact~650°C

![Figure No.: 7.3 Displacements – Thermal Analysis of Exhaust Manifolds](image)

Subcase 1 - Thermal
Maximum displacement is 0.971E+05 at grid 1431.

c) Analysis of Exhaust Manifolds-
Analysis of Exhaust Manifolds-
Material: FG220MoCr

Ultimate Compressive Strength = 220 MPa - 550 MPa
Poisson ratio: 0.3
Density: - 7500 kg/m3
Young’s Modules: 200 GPa.

![Figure No.: 7.4 2D & 3D Von Mises analysis of Exhaust Manifolds](image)
Maximum 3-D element stress is 0.587E+04 in element 82674
Minimum 3-D element stress is 0.1166E+02 in element 64079.

Figure No.: 7.5 2D & 3D Maximum Principal Stress analysis
of Exhaust Manifolds
Maximum 3-D element stress is 0.1129E+09 in element 2802
Maximum 3-D element stress is 0.6877E+06 in element 7502

Figure No.: 7.6 2D & 3D Minimum Principal Stress analysis
of Exhaust Manifolds
Minimum 3-D element stress is 0.1028E+09 in element 211
Minimum 3-D element stress is 0.2434E+06 in element 7356

Figure No.: 7.7 Exhaust Manifolds Mass Chart Window
(4.677 Kg)

B) Material: SG500/7
Ultimate Compressive Strength = 320 MPa - 416 MPa
Poisson ratio: 0.29
Density: 7100 kg/m3
Young’s Modules: 205 MPa.

Table No. 7.2 Chemical Composition of SG 500/7 Material

<table>
<thead>
<tr>
<th>Sample Identification</th>
<th>Chemical Composition %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C  Si  Mn  S  P  C  N  Ni  Mo  Fe</td>
</tr>
<tr>
<td>SG500/7</td>
<td>3.3 6 0.1 0.1 0.00 5 5 5 5 5</td>
</tr>
</tbody>
</table>

Figure No.: 7.8 Displacements – Thermal Analysis of
Exhaust Manifolds
Subcase 1 - Thermal
Maximum displacement is 0.9784E+05 at grid 1431.

Minimum 3-D element stress is 0.8271E+05 in element 211
Minimum 3-D element stress is 0.1959E+03 in element 7356

Maximum 3-D element stress is 0.9088E+05 in element 2802
Minimum 3-D element stress is 0.05534E+03 in element 7502

VIII. EXPERIMENTAL TEST RESULT
a) Analysis Result:

Result Summary

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Material Identification</th>
<th>Maximum Von Mises (N/mm²)</th>
<th>Displacements (mm)</th>
<th>Maximum Principal Stress (N/mm²)</th>
<th>Minimum Principal Stress (N/mm²)</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FG22 0MoCr</td>
<td>0.587E+04</td>
<td>0.978E+05</td>
<td>0.1129E+09</td>
<td>0.1028E+09</td>
<td>4.667</td>
</tr>
<tr>
<td>2</td>
<td>SG50 0/7</td>
<td>0.5534E+04</td>
<td>0.971E+05</td>
<td>0.9088E+09</td>
<td>0.8271E+05</td>
<td>4.285</td>
</tr>
</tbody>
</table>
b) Metallurgical Test Result:

All the samples of two materials are observed under microscope. These tests are conducted on Microphotograph with maximum magnification of 100x for FG220MoCr and SG 500/7. Results are shown as follows.

Result of FG 220MoCr

Comments: It shows graphite flake in the ferritic matrix with dark band of pearlite of the cell boundaries. Over all dendritic pattern. Flake size is ASTM B TYPE size is about ASTM 3. Large casting defect (shrinkage pore, Figure No: - 7.1) was observed in the final fracture portion of this sample.

Result of SG 500/7

Comments: It was in fact needed to combine the images taken by SEM, the fracture surface is relatively less flat as compared to FG220MoCr consistent with the observed lower fatigue life for this SG500/7 Perlitess structure with grain boundary cementite is observed. It shows graphite flake with interdendric segregation. Flakes are mainly type D (Random Orientation). It some are the type E (Preferred Orientation) possibly due to inadequate inoculation.

IX. Conclusion

Finite Element Analysis
- The maximum displacements appear for new material is less than the original material.
- The stresses induced in new material also less than nearly 5% than original material.
- An experimental stress and FEA results gives close agreement, within 7% difference.

X. Future Work

In this paper we have more scope for to find out the thermal properties of exhaust manifolds with temperature variation because Temperature is independent properties for modulus of elasticity. Experimental tensile, Compressive, BHN, also impact testing will be conduct for different materials with kept function ability of materials

References