

Assessment of Thermo-Mechanical Fatigue Performance of an Exhaust Manifold through Simulation

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Abstract

Exhaust manifold of an IC engine typically experiences cyclic thermal and mechanical loading and are prone to TMF failure. Thermo-mechanical fatigue resistance needs to be ensured for exhaust manifold to meet the requirement of durability in order to meet the demanding needs of recent trends in IC engine design. Considering reduced product development cycle time, more accurate design procedure for exhaust manifold through simulation route is preferred. The present work is an attempt in this direction, where methodology to carry out TMF analysis of exhaust manifold through simulation is formulated and successfully implemented. The complete simulation process involved four important stages, namely simplified 1-D simulation of engine, thermal analysis of exhaust manifold, and structural analysis of exhaust manifold and TMF life evaluation of exhaust manifold. The developed methodology has been successfully implemented considering a typical exhaust manifold. Thermal inputs obtained through simplified engine simulation using 1-D gas dynamics and engine simulation software required for thermal analysis of exhaust manifold are found to be satisfactory and has eliminated the need for complex 3-D CFD simulations. TMF life valuated at critical locations indicate that except one location all other locations have life exceeding the LCF limit.

Keywords: Damage Model, Exhaust Manifold, Fatigue Crack, Life Estimation, Thermo-Mechanical Fatigue, FEA

1. Introduction

In automobiles, engine components and subsystems are designed to operate in high temperature environments with high temperature gradients. During repeated engine start-up and shut-down operations, these components are subjected to cyclic strains which are generated both thermally and mechanically. These thermal strains which can be either expansive or contractive are totally or partly constrained and hence thermal stresses are induced. These thermal stresses are superimposed with stresses, which arise from pressures, mechanical loads and constraints during the working cycle of the engine^{1,2}. The synergistic damage caused due to cyclic thermal and mechanical loading is termed as Thermo-Mechanical Fatigue (TMF). During repeated working cycles of the engine, TMF cycles cause micro structural

material damage to the components, and ultimately lead to fatigue crack initiation. Thus, TMF damage occurs in the material under the action of these cyclic temperatures and strains, leading to initiation of crack and subsequent crack growth in the material of the component leading to failure.

Exhaust manifold is one such component which experiences cyclic thermal and mechanical loading and prone to TMF failure. Exhaust manifold is the hottest part of the entire exhaust system, bolted on one side to the engine head and typically connected to a catalytic converter on the other side. TMF resistance needs to be ensured for exhaust manifold to meet the requirement of durability of exhaust system. The recent trend in Integrated Circuit (IC) engine design is to upgrade the performance and in mean time downsize the engine to the possible extent in order to meet fuel economic

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regulations. This trend has led to increased operating temperatures and loads coupled with reduced weight. To meet these requirements detailed and more accurate design procedure through simulation route is preferred³. The present work is an attempt in this direction, where TMF performance of exhaust manifold has been evaluated through simulation route.

The complete simulation process involves four important stages, namely simulation of engine, thermal analysis of exhaust manifold, and structural analysis of exhaust manifold and TMF life evaluation of exhaust manifold. Simulation of engine has been carried out by developing 1-D model of multi cylinder engine including the exhaust manifold. FE model of exhaust manifold has been developed and employed to perform thermal analysis^{4,5}. Following this stage structural analysis has been performed on FE structural model of exhaust manifold to identify critical locations prone to TMF⁶. TMF life of exhaust manifold at these locations has been evaluated through strain-life approach employing damage model based on Manson-Coffin-Basquin equations⁷.

The complete methodology formulated and followed to carry out TMF evaluation of exhaust manifold is summarized in the block diagram shown in Figure 1.

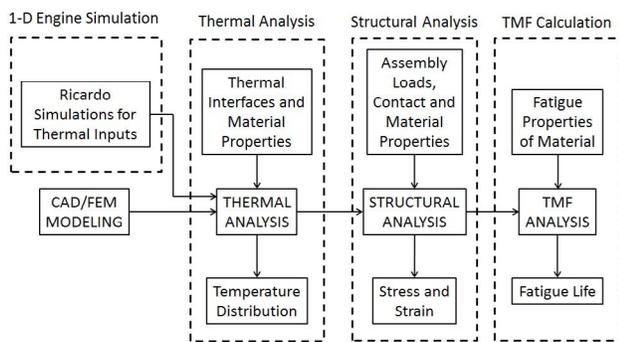


Figure 1. Methodology formulated to carry out TMF analysis of exhaust manifold.

2. Engine Modeling and Simulation to Predict Thermal Characteristics

In order to carry out thermal analysis of exhaust manifold, parameters such as exhaust gas temperature, exhaust manifold inner wall temperature, convective heat transfer coefficient etc., are required. Generally transient three-dimensional Computational Fluid Dynamics

(CFD) simulations are carried out to predict thermal characteristics of IC engines. Though these methods are accurate, they are complex and time consuming. Hence in the present research work, a relatively simple and quick method has been established using Ricardo WAVE software which is an International Organization for Standardization (ISO) approved 1-D gas dynamics and engine simulation software package to model and simulate the engine⁸.

The developed model of the engine is shown in Figure 2. The modeled engine consists of intake manifold, fuel injector, cylinder and exhaust manifold developed using standard elements. “SIWiebel” combustion model and “Woschni1” heat transfer model are selected in the present simulation. Time based transient analysis was performed for duration of 360 s to predict thermal characteristics. Mean exhaust gas temperature and convective heat transfer coefficient at 11 specified locations of the exhaust manifold are obtained from Ricardo WAVE simulation to capture complete profile of exhaust gas temperature and convective heat transfer coefficient of the exhaust manifold. Results such as exhaust gas temperature, exhaust manifold inner wall temperature, convective heat transfer coefficient etc., are collected through sensors incorporated in the model using live plots from the simulations along with text output.

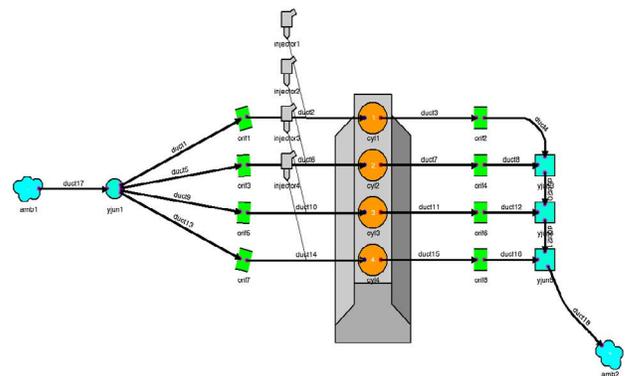


Figure 2. 1-D model of the selected engine with exhaust manifold developed for thermal analysis.

3. FE Modeling and Thermal Analysis of Exhaust Manifold

The exhaust manifold designed for the selected engine is of short equal length runner type made up of SiMo Cast Iron. It has inner diameter of 30 mm at the entry of runner and 45 mm at the exit side and weighs 1.6 kg. CAD model

of the exhaust manifold developed using CATIA is shown in Figure 3.

For the analysis of the exhaust manifold two models are developed, one is the simplified model with only manifold and the second is complete assembled model. The simplified model was used to develop understanding on loading conditions and to monitor the analysis before going into complex analysis of assembled model. The developed CAD model is imported into ANSYS workbench and discretized using 51899 tetra elements of 4 mm size to build FE model for thermal analysis (Figure 4).

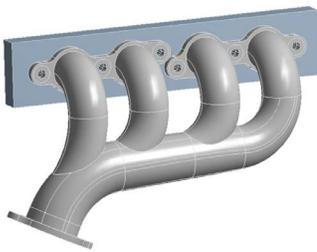


Figure 3. CAD model of exhaust manifold.

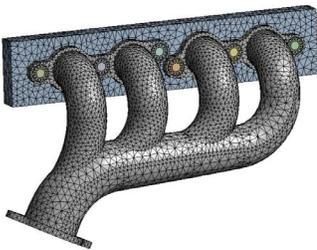


Figure 4. FE model of exhaust manifold.

The complete assembled model consisted of exhaust manifold made of Simon cast iron, engine head made of aluminum alloy and bolts made of steel. The temperature dependent material properties are taken into

consideration for the exhaust manifold material (Simon cast iron). Thermal analysis of exhaust manifold is a transient thermal analysis done by applying time variant exhaust gas heat transfer coefficient and temperature on the inner surface of the manifold. The loads are applied for duration of 360 s with a time step of 10 s which are obtained by engine simulations. Engine head temperature is assumed to vary linearly from room temperature to a maximum temp of 450 K and then it remains constant for remaining analysis time. A convective heat transfer due flow of air is considered on the outer surfaces of the exhaust manifold representing the air flow around the manifold while the vehicle is moving.

4. FE Modeling and Structural Analysis of Exhaust Manifold

During the operation of exhaust manifold, the flowing hot gases heat the manifold and try to expand it which is constrained by the bolts holding the manifold onto the engine head. The bolt forces applied during the assemblage of the manifold with the engine head also produce stresses. These loads are considered while performing structural analysis of the manifold.

Under the action of combined thermal and mechanical loading, the material of the exhaust manifold experiences high thermal and mechanical strains. To incorporate this effect during structural analysis temperature sensitive Elasto-Visco-Plastic model⁹ of the material is employed as shown in the Figure 5. The bolt forces required to be applied to hold the assembly of exhaust manifold and cylinder head is calculated considering pressure of exhaust gas and the number of bolts employed. The calculated bolt force is applied as bolt pre-tension in the FE model appropriately.

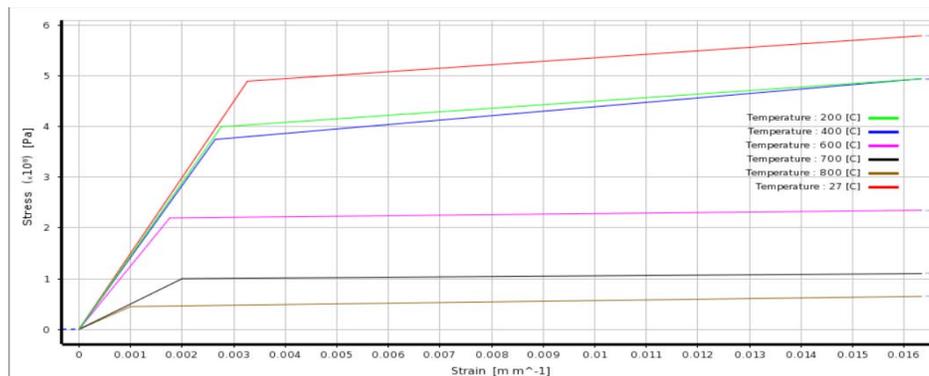


Figure 5. Elasto-visco-plastic bi-linear stress strain curve of SiMo cast iron.

5. Evaluation of TMF Performance of Exhaust Manifold

During engine operation cycle, the exhaust manifold is subjected to high temperatures and plastic deformations and hence elasto-visco-plastic material models are used to quantify deformation. Due to the existence of these plastic deformations during loading cycle exhaust manifold loading falls in Low Cycle Fatigue regime which is strain based. To quantify LCF life of exhaust manifold, one of the commonly used fatigue damage model based on Basquin-Manson-Coffin equation is used. This model represents strain-life approach, where the estimation of fatigue life is based on the total strain amplitude as represented by equation 1:

$$\frac{\Delta \varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad (1)$$

Where $\Delta \varepsilon$ is the strain amplitude, σ'_f is fatigue strength coefficient, ε'_f fatigue ductility coefficient, b is fatigue strength exponent, c is fatigue ductility exponent, E is Young's modulus and N_f is number of cycles to fail.

The equation 1 is incorporated in a excel program developed, providing necessary LCF material properties is used to evaluate TMF life. The strain data corresponding to critical locations obtained from structural analysis is given as input to the excel program to evaluate TMF life.

6. Results and Discussion

6.1 Thermal Characteristics of Flow in Exhaust Manifold

Transient thermal characteristics of the exhaust manifold are obtained using 1-D simulations in terms of exhaust gas temperature and convective heat transfer coefficient. The exhaust gas temperature is found to reach maximum value of 1100 K after 120 s when the engine is running at constant speed at 5000 rpm. Mean exhaust gas temperature and convective heat transfer coefficient at 11 specified locations of the exhaust manifold are obtained from Ricardo Wave simulation (Figure 6 and Figure 7). From the engine simulation results it is observed that the exhaust gas temperature and convective heat transfer coefficient values reach maximum after the engine running at constant speed for at least 120 s. The exhaust gas temperature is found to be higher at the outlet where

all the four cylinder gases meet compared to the gas temperature at the inlet of manifold. It is also observed that there is a raise in convective heat transfer coefficient values at/near junctions where one stream of gas meet the other due to the effect of turbulence occurring at the junction.

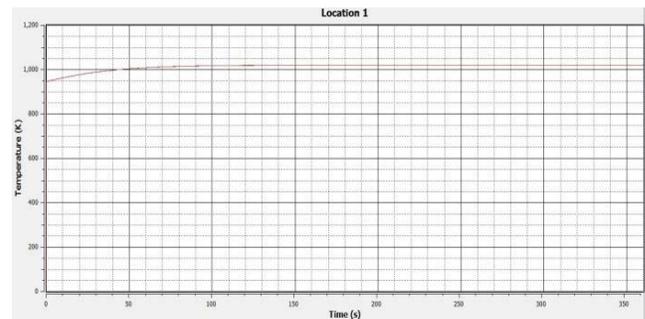


Figure 6. Time dependent mean exhaust gas temperatures output from Ricardo WAVE engine simulation.

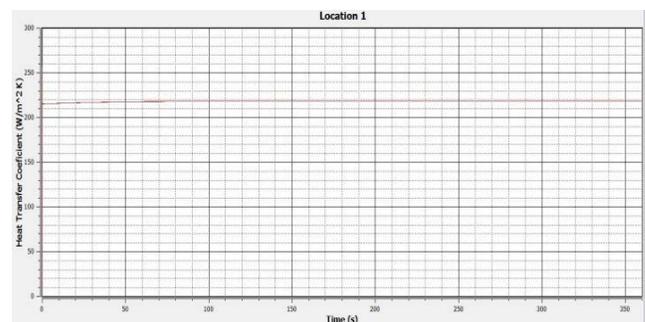


Figure 7. Time dependent mean convective heat transfer coefficient output from Ricardo WAVE engine simulation.

6.2 Temperature Distribution from Thermal Analysis

Thermal analysis was conducted to obtain the temperature distribution in the entire manifold after the time laps of 360 s, using the input exhaust gas temperature, exhaust manifold inner wall temperature, convective heat transfer coefficient obtained from engine simulation. The temperature distribution plot obtained from thermal analysis is shown in Figure 8. As seen from the temperature distribution, temperature gradually increases as moved away from engine head towards manifold exit reaching a maximum value of 935.4 K at the exit. The temperature distribution profile obtained matches qualitatively very well with generally observed trend¹⁰, validating the accuracy of the analysis. This predicted temperature distribution is utilized for structural analysis.

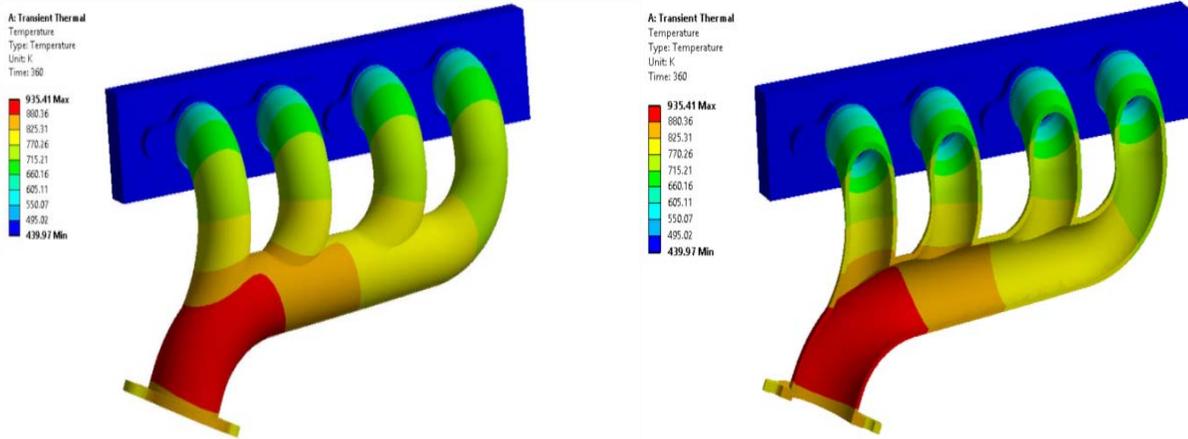


Figure 8. Temperature distribution in exhaust manifold.

6.3 Thermo-Mechanical Stresses from Structural Analysis

The purpose of structural analysis is to predict stress distribution under the action of combined thermal and structural loading and to locate probable critical locations prone to thermo mechanical fatigue. Distribution of von-Mises stress in the exhaust manifold is shown in the Figure 9. It is clear from the stress distribution plots that the stresses are high at the bolt clamping regions reaching a maximum value of 426.9 MPa, due to the bolt tension applied for manifold assemblage. Apart from that the stresses are also high at the bends and the region where there is sharp geometry change. These locations are the critical locations identified as prone to thermo mechanical fatigue. The identified critical locations are verified with data available in literature and found to be in good agreement¹⁰. The state of stress and state of strain at these locations are extracted for evaluating thermo

mechanical fatigue life.

6.4 Predicted TMF Life

For all the 11 critical locations identified based on the state of stress, strain component data were extracted for one element at that region from the manifold model to determine equivalent effective strain. Strain components were extracted under minimum and maximum temperature loading conditions corresponding to engine operation cycle to determine strain amplitude. TMF life predicted through strain life approach employing a commonly used damage model based on Manson-Coffin-Basquin equation lies in the range of 604 cycles to 1334 cycles, minimum life of 604 cycles being at the region close to the runner. The location corresponding to minimum value of fatigue life is the most critical location with highest probability of crack initiation.

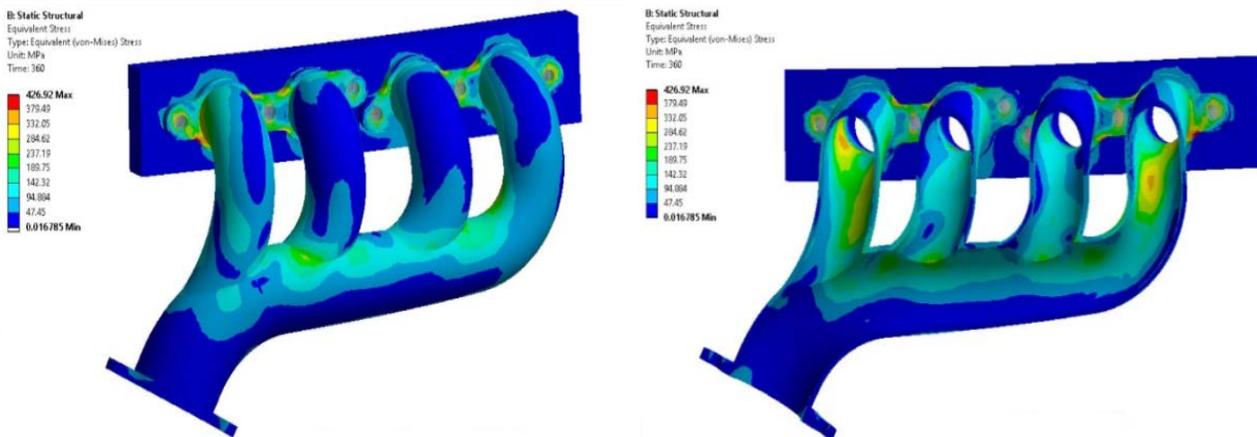


Figure 9. Stress distribution obtained from structural analysis.

7. Conclusions

Methodology to carry out TMF analysis of exhaust manifold through simulation is formulated and successfully implemented on a typical exhaust manifold. The complete simulation involved four stages, namely 1-D simulation of engine, thermal analysis of exhaust manifold, structural analysis of exhaust manifold and finally TMF life evaluation. Thermal inputs required for thermal analysis of exhaust manifold were obtained through simplified engine simulation using 1-D gas dynamics and engine simulation software package which has eliminated the need for complex 3-D CFD simulations. The accuracy of thermal analysis is validated qualitatively by comparing the temperature distribution profile obtained with generally observed trend. The structural analysis helped in identifying all critical locations prone to TMF. TMF life evaluated show that except one location all other locations have life exceeding the LCF limit and the location corresponding to minimum value of fatigue life is the most critical location with highest probability of crack initiation.

8. Acknowledgements

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9. References

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