DESIGN AND ANALYSIS OF THERMO MECHANCIAL LOADING FOR A TURBINE HOUSING USING FEA

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***Abstract*:** Turbochargers are the fastest and easiest way for an engine to increase its power. It increases engine's power up to 40% without any increase in the physical size of the engine and much extra weight. Turbochargers are also efficient in design because it utilizes the waste exhaust of the engine to power itself. A Turbocharger is a device that uses the energy of exhaust gases coming out from an engine to compress the air going into the engine. It must have at least four openings one for the engine exhaust gas to enter, second for the exhaust gas to exit, third is opening for intake air to enter the turbocharger, and fourth for the intake air to exit the turbocharger on its way to the engine intake. A turbocharger will also have one additional opening to vent excess air pressure. In this work an attempt is made to study the two important objectives firstly design of turbocharger in CATIA and finding out the critical thermal stresses in turbine housing of a turbocharger under thermo-mechanical loading using ANSYS. Secondly, to find out the Thermo-Mechanical fatigue life at different places of a turbocharger and finally computing the results.

***Index Terms*:** Turbocharger, thermal stresses and thermo-mechanical fatigue life

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I. INTRODUCTION

A Turbocharger is an air compressor used for forced-induction of an internal combustion engine. Like a supercharger, the purpose of a turbocharger is to increase the mass of air entering the engine to create more power. A turbocharger is a turbine driven supercharger. The turbine is driven by waste exhaust gas. Its benefit lies with the compressor increasing the pressure of air entering the engine thus resulting in greater performance. Popularly used with internalcombustionengines. Turbochargers have also been found useful compounding externalcombustionengines

Turbocharger system are measured by the amount of pressure the compressor can output above ambient. This pressure is commonly called Boost pressure or Boost. Compressing the air increases its temperature, which lowers the density of the charge air and creates a less efficient cycle and loss of power. The temperatures can also have detrimental effects on the materials and structure of the engine. Increases the power of the engine because of the increased density of the air. Increased air density means more oxygen molecules, which means the engine can respond by increasing the amount of fuel it mixes with that oxygen. When the fuel and oxygen are burned, the result is a more powerful explosion with each piston stroke and thus more power coming out of the engine. This issues that the compressed air needs to be cooled in order to achieve maximum power and maintain the structural integrity of the pistons. A heat exchanger or intercooler is installed between the compressor and engine inlet to cool the charger air. Increasing the intake air pressure going into an engine can increase the engine's power, but too much air pressure can damage the engine increasing the pressure. The high temperature components of most industrial systems such as turbine components are exposed to large thermal fluctuations during operation.The combined effect of thermal and mechanical cyclic loading can produce very different results to the addition of the damage from the isothermal components of that exposure.

The purpose of this paper is to find out the critical thermal stresses in turbine housing under thermo-mechanical loading. And to find out the Thermo-Mechanical fatigue life of different duty cycles like lab test duty cycle and field data duty cycles and comparing the results.

Cristiana Delpretea [1] states that outlines of multi axial fatigue life calculation and qualification procedure of turbine housing subjected to various duty cycles in the field. Both analytical and experimental techniques are adopted in this work. Results of the analytical model were correlated to the experimental measurements for model verification. Analytical transient FEA analysis was utilized to understand the effect of thermal loading on the turbine housing. The model was calibrated against engine measurement during engine cyclic testing. After calibration the model is used to optimize the housing design. They compared different fatigue life models to calculate fatigue life and also the material properties.

Investigation of FaridAhdad, Carol Cai [2] **s**tates that theguidelines for determination of the thermo-mechanical behavior of the Turbine housing using Finite Element Analysis. This includes the steps of:1) Geometry simplification 2) Meshing process 3) Transient thermal analysis 4) Static thermal stress analysis 5) Vibration analysis 6) Post processing Result.

FaridAhdadet.al[3] have developed the fatigue model based on a cumulative damage approach (Chaboche model [1]) that is used to predict crack initiation. To determine the transient stress and temperature distributions due to the high rates of convection from the gas, and the complexity of the design, conjugate heat transfer CFD simulation is performed. The tongue of the turbine housing is a critical region in which cracks initiate within a short time. Heat transfer coefficients (HTC) and bulk temperature predictions from CFD, in general, can be validated by thermal measurement. But because of the geometry and the location of the tongue, it is impossible to measure the metal temperature. For this work 2 methods were presented: HTC calibrated by thermal measurement and HTC from CFD heat transfer Conjugate method, steady state analysis. The design of turbine housing is optimized based on this TMF methodology and shows very good results in testing

The experimental investigation of FaridAhdadet.al [5] have developed an approach to perform quick TMF predictions for a complex duty cycle. To assess TMF failure, it is very critical to accurately estimate metal temperature of these components subjected to complex duty cycle where exhaust gas temperature vary significantly with time. The method was applied to evaluate the fatigue damage of turbine housing under actual condition. The transfer function for metal temperature and elastic stress are mainly function of material and heat transfer co-efficient.

Thermal and elastic stress analytical methods were component with FE approach for complex geometry and duty cycle. From the comparison study result from analytical method are matching quite with FE results. The Elastic-plastic stress was determined by Glinka method which is based on strain energy density. Turbine Housing of turbocharger has been considered which a quite expensive component operating at a very high temperature. The life prediction show that the tongue region will start to fail only after 87000 kilometers.

II. FINITE ELEMENT MODEL GENERATION

The Finite element method is the dominant discretization technique in structural mechanics. The basic concept in the physical interpretation of the FEM is the subdivision of the mathematical modal into non-overlapping components of simple geometry called finite elements or elements for short. The response of each element is expressed in terms of a finite number of degrees of freedom characterized as the value of an unknown function at a set of nodal point.

The response of the mathematical model is then considered to be approximated by that of the discrete model obtained by connecting or assembling the collection of all elements. The disconnection-assembly concept occurs naturally when examining many artificial and natural systems

i)Element Type

Finite element method generationwill generate a finite element mesh of node and geometric element type. These geometric element types are relative to the ANSYS element name via an element variant number. The element variant mapping for ANSYS may be displayed by using the FEMGEN.

a)Element used for Thermal Analysis

SOLID 87 (3-D 10-Node Tetrahedral Thermal Solid)

Figure 1shows the element typeSOLID 87 is well suited to irregular meshes the element has element has one degree of freedom, temperature, at each node. The element is applicable to 3-D, Steady-State or transient thermal analysis.

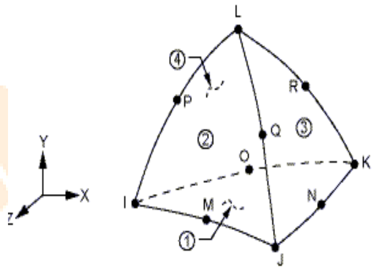


Figure1: SOLID 87 Element Type

b)Element used for Structural Analysis

SOLID 92 (3-D 10-Node Tetrahedral Structural Solid)

Figure 2 show the element type SOLID 92 have a quadratic displacement behavior and are well suited to model irregular meshes. The element is defined by ten nodes having three degrees of freedom at each node: translations in the x, y, and z directions. Temperature and fluencies may be input as element body loads at the nodes. The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities.

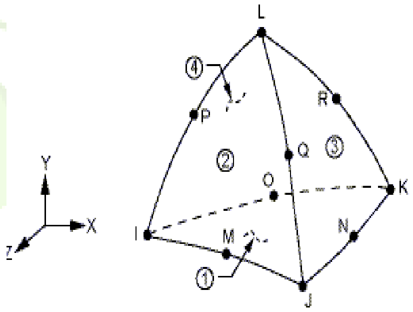


Figure 2: 3D 10-node Tetrahedral Solid Element Type

III. EXPERIMENTAL APPROACH

a)METHODOLOGY

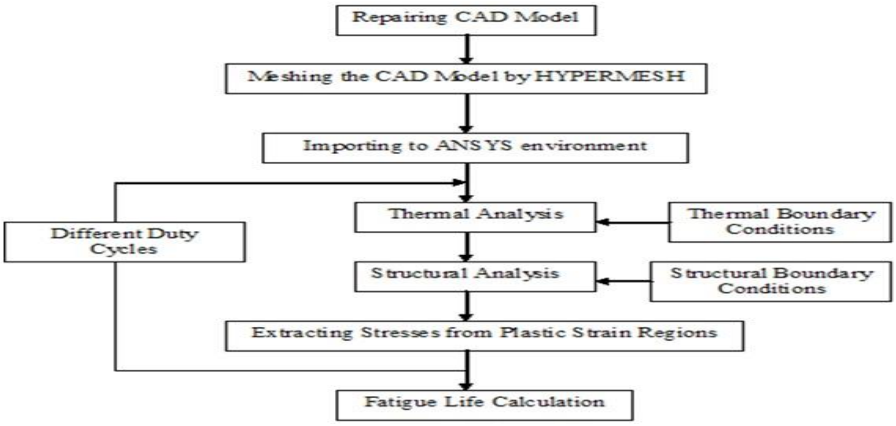


Figure 3: Methodology for thermo mechanical fatigue life

Figure 3shows the methodology followed to find out the Thermo-Mechanical Fatigue life. This fatigue life is nothing but the number of cycles required to initiate the crack in the component.

b) THERMAL FATIGUE LIFE PREDICATION FOR TURBINE HOUSING

One of the root causes of the engine performance loss is failure of the turbine housing, which is mainly due to the transient thermal loading from the inlet exhaust gas. The cyclic stress generated under cyclic loading varies with temperature. In general, the traditional way to optimize the design of the turbine housing is based on FE Method

This involves: 3D FE Mesh generation of Turbine housing,

- Thermal Analysis with boundary conditions such as heat transfer coefficient and bulk temperature to predict metal temperatures under transient condition
- Transient Metal temperature is used as an input for elastic plastic analysis.

The turbine housing of turbocharger is mounted on Diesel Engine and is made up of Ductile Iron material. FE analysis carried out assuming under free conditions with no effect of the external load [6].

Material Properties

Changes in temperature can significantly vary the material properties. Therefore, both the high and low temperature extremes associated with the application should be considered. For applications subjected to large temperature variation, you'll need to take into account the dimensional change when assembled/bound with other materials of different coefficient of thermal expansion. Following factors that need to be considered when the operating temperatures are above normal room temperature. Part dimensions increase proportional to length, temperature increase, and coefficient of thermal expansion and contraction. Strength and modulus will be lower than at room temperature shows that strength decreases with increasing temperature. Material may exhibit a rubber-like behavior with low modulus and high degree of drawing. The material properties are changes with the temperature such as yield stress, young’s modules and poison ratio.

Thermal Analysis:

Finite element Model is imported to ANSYS to change element type from SOLID 92 to SOLID 87 for TETRA element with Thermal boundary conditions. The thermal boundary conditions applied at the different parts of the housing is tabulated in table 1. These data can be obtained from determined utilizing information regarding the flow velocities inside the volu11te as determined by computational fluid dynamics analysis or turbine gas temperatures measurements calibrated from tests.. The material properties utilized in this analysis were input as a function of temperature as shown in table

Table1: Thermal Boundary Conditions

Sl.No	Component	Convection Coefficient(W/m2° C)
1	Inlet Volute	900
2	Wheel Contour	500
3	Outlet Section	500
4	A-Surface	150
5	External	50

The thermal simulation solutions enable to model thermal response including all the modes of heat transfer which could be affecting the response simultaneously. The object of the thermal study is often to understand thermal response of the structure. Meshing quality and density will have an influence on the final stress value and deformation. A refined mesh grid should be created in order to obtain an accurate result, especially in the following region:

- Regions of large stress gradient, such as the area around the tongue
- Stress concentration regions, such as at a locating pin hole
- Regions which cracked or failed during the testing or application process
- Other regions, such as on a contact surface.

If there is an external pressure load applied, it is better to use a mapped mesh. Once the loads are applied on the nodes, this will help to eliminate the extra moment caused by the force loads. Another important issue is to select the thermal component when doing the mesh. The ANSYS default requires that the maximum strain increment occurring within one load step not exceed 15%. Thus, during a large temperature or stress gradient time period, more load steps are recommended in order to aid the convergence. Time point density should be more concentrated during time periods when plasticity is likely to occur.

IV. RESULTS

4. 1 Thermal Plots

Thermal results are presented with the following guidelines:

1. Temperature distribution at different time point and different angle of view, particularly to show the Maximum Temperature of the component.
2. Figure 4.1 shows temperature for lab test duty cycle.
3. Figure 4.2 shows temperature for City road duty cycle.
4. Figure 4.3 shows temperature for Motorway road duty cycle.
5. Figure 4.4 shows temperature for Country road duty cycle.
6. All the values have been scaled to 0-100.

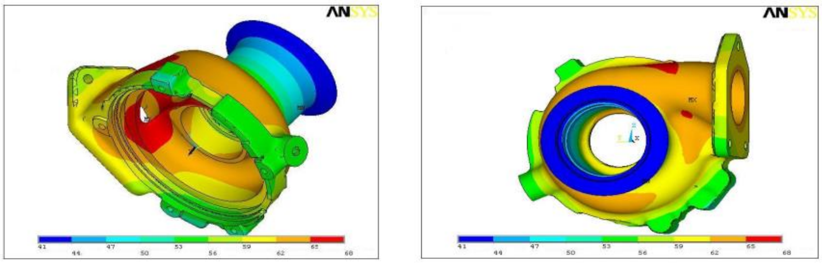


Figure 4.1: - Thermal Plot for Lab Test Duty Cycle

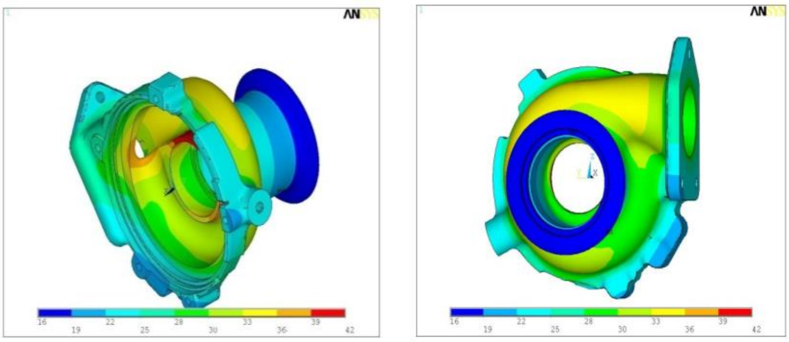


Figure 4.2: - Thermal Plot for City Road Duty Cycle

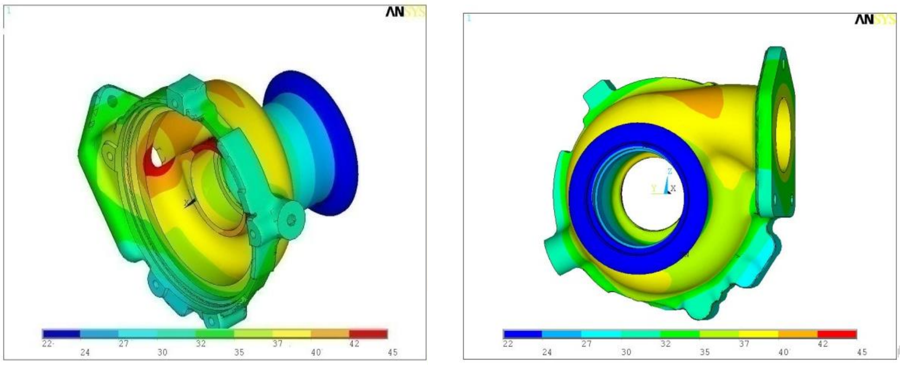


Figure 4.3: - Thermal Plot for Motorway Road duty Cycle

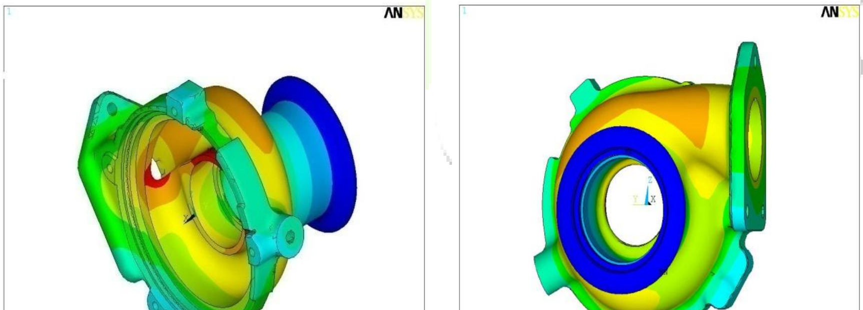


Figure 4.4: - Thermal Plot for Country Road duty Cycle

4. 2 Structural Analysis Plots:

Elasto-Plastic structural analysis results are presented with stress distribution plots for Von-Mises Stress and Plastic Strain. The views are taken with special care to clearly show critical regions that exceed material strength which are likely to fail due to TMF. For non-linear analysis, plastic strain intensity plots are generated.

4. 3 Von-Mises Stress plots

Figure 4.5 shows the Von-Mises stress plots represents the beginning of yielding for material due to higher tensile stress the region represents in red color distribution is having higher values and blue color shows the lower yielding stress value. The maximum Von Mises generated in the Turbine housing at tongue region because the thickness of the housing is less at that section, and also as the temperature distribution was more. We can observe the temperature distribution in the Figure4.1 to Figure 4.4

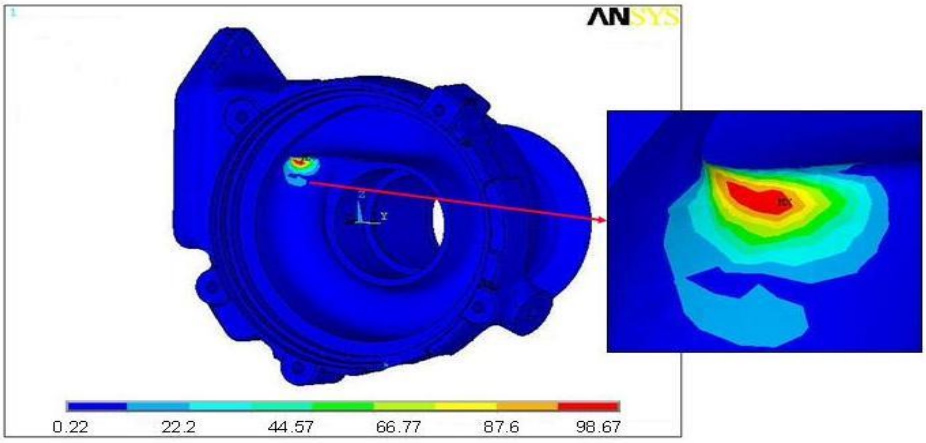


Figure 4.5: Von-Mises stress Plot

4.4 Plastic Strain Intensity Plot:

The figure 4.6 shows the plastic strain in the turbine housing due to thermo-mechanical fatigue. From the figure we can find the strain is max is at the tongue region, which is named as Location: 1. and also other regions where plastic strain may occur are also considered. Those locations are named as Location: 2 and Location: 3, which are considered at neck regions. As there is an abrupt change in geometry stresses may occur at these locations also.

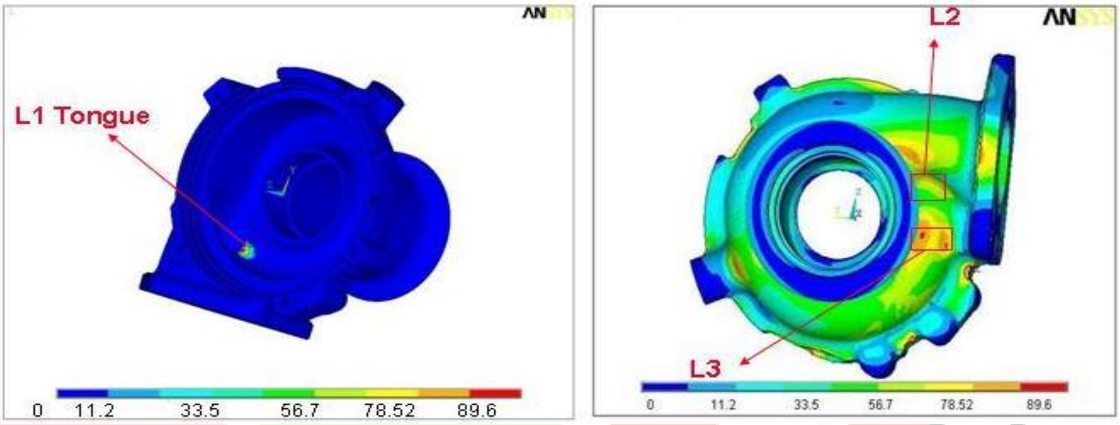


Figure 4.6: - Plastic Strain Plot

V. CONCLUSIONS

The fowling studies were performed on the turbine housingwith the objective to find the Thermo-Mechanical Fatigue life of different duty cycles and to find out the most severe duty cycle. In this study we mostly concentrated mostly on TMF life calculation not on optimization as it requires Computational Fluid Dynamic analysis over the flow of exhaust gas.

1. 3D Thermal, Elastic and Plastic FEA Analysis of the housing with different duty cycles.
2. Stress distribution over the component with comparison of temperature.
3. Thermo-Mechanical Fatigue life calculation by using Chaboche Model for all duty cycles.

5.1 Lab test duty cycle

The figure 4 has shown the comparision of stress distribution, temperature and time. It was obsorbed from the figure that the out-Phase type loading where, as the temperature increases the 3rd principal stress dominates compared to 1st principal stress. Signed Von-Mises stress was used to predict the life as there is a change in shift in between 1st principal stress and 3rd principal stress.

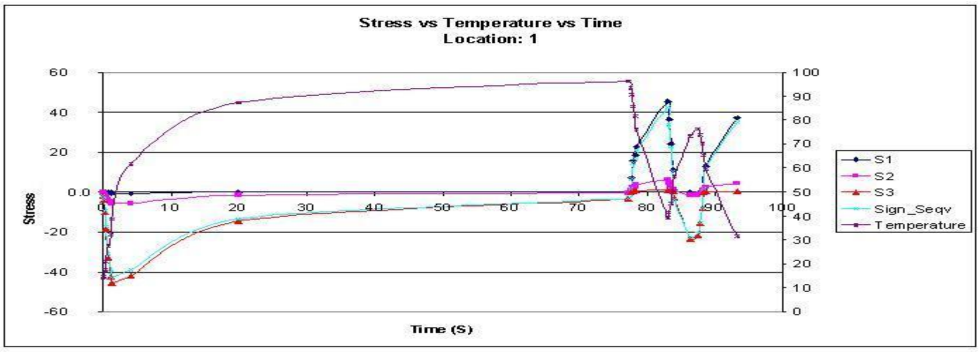


Figure 5.1: 1-Stress Distribution lab test duty cycle

City road duty cycle

The figure 5 has shown the comparision of stress distribution, temperature and time. It was obsorbed from the figure that the out-Phase where, as the temperature increases the 3rd principal stress dominates compared to 1st principal stress. Here all the values are scaled between 0-100 and the maximum temperature was 500^{0}C.

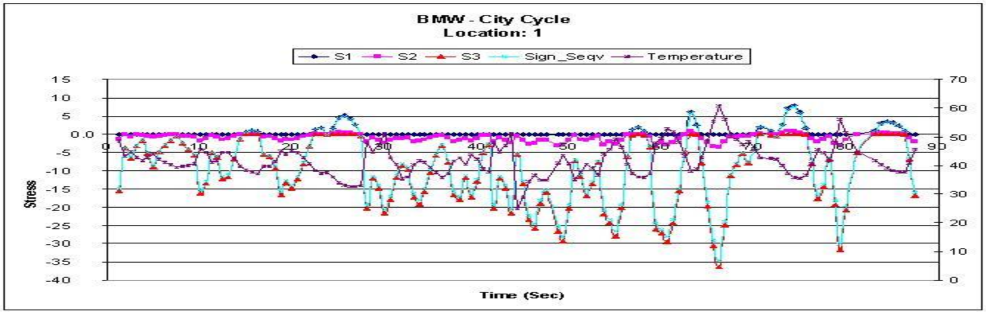


Figure 5.2: 2 Stress Distribution a City road cycle

Motorway road duty cycle

The figure 6 has shown the comparision of stress distribution, temperature and time. It was obsorbed from the figure that the observe Out-Phase where, as the temperature increases the 3rd principal stress dominates compared to 1st principal stress. Here all the values are Scaled between 0-100 and the maximum temperature was 500^0 C.

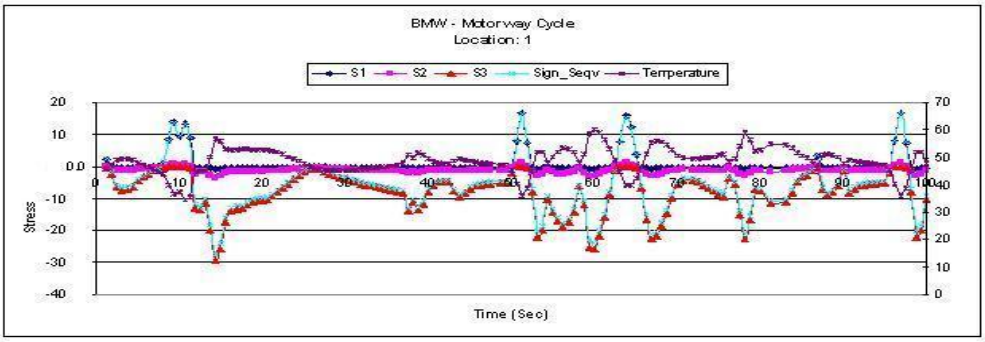
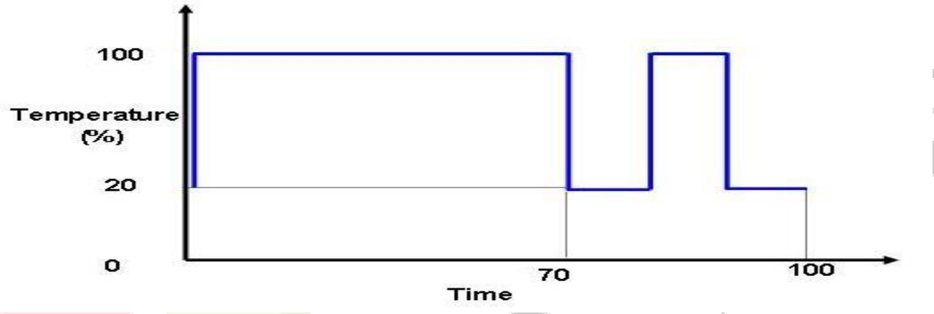


Figure 5.3: 3-Stress Distribution Motorway road cycle

5.2. Duty Cycles

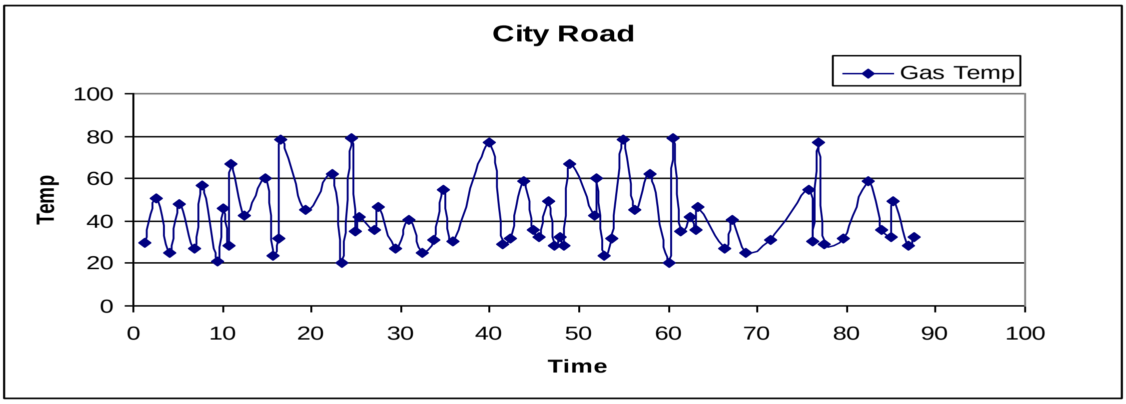
Lab Test Duty Cycle: Graph: 5.1 shows the thermal duty cycle with respective time period. The total cycle time is 800 Sec. Out of that first 70% will be continuous heating then there will be sudden change i.e. cooling phase will happen. The remaining 30% will be alterations of the phases are applied. The maximum temperature of the heating phase is 800c and the minimum temperature at cooling phase is 200c.In order to get exact regions where plastic strain is occurring we considered this much phase differ



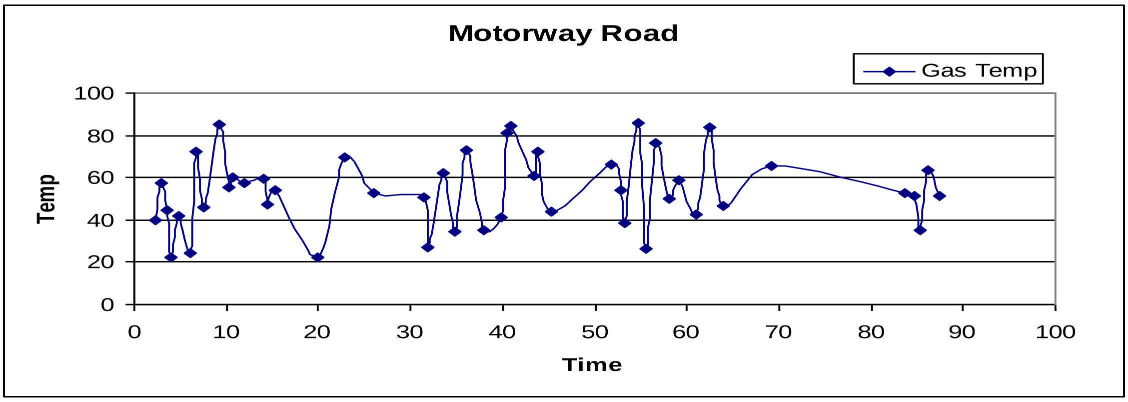
Graph: 5.4-Lab Test Duty Cycle

Field Data Duty Cycles:

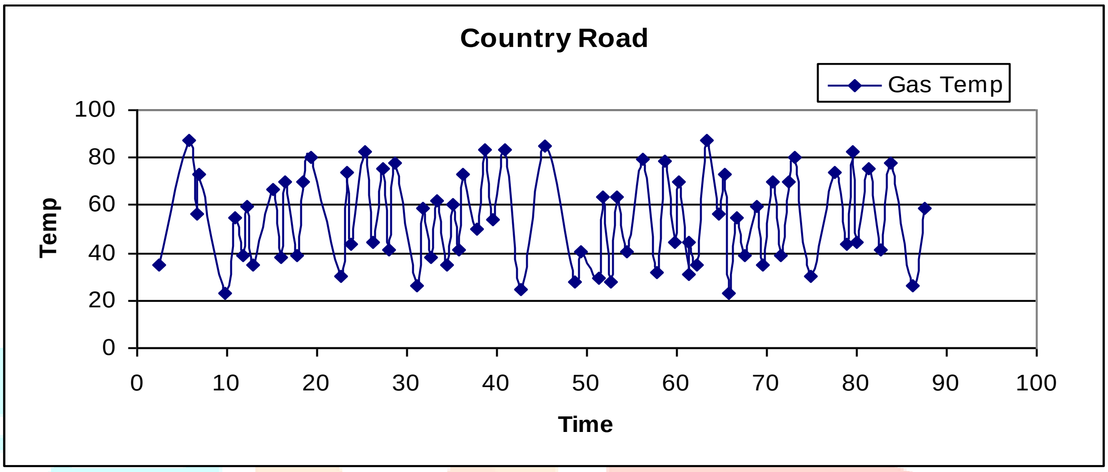
The following graphs shows the different field duty cycles which are obtained from different road conditions, like City road, Motorway road and Country road. The maximum time points in these graphs are 800Sec and the Temperature points also 800Deg C. Exhaust Gas Temperature over a period of time can be observe in the following Charts for various road conditions.



Graph: 5.5-Exhaust Gas temperature at City road



Graph: 5.6-Exhaust Gas temperature at Motorway road



Graph: 5.7-Exhaust Gas temperature at Country road

5.3 .FATIGUE LIFE CALCULATION

The life estimation of the components before crack initiation is calculated by Chaboche's fatigue model. The causes of cracks during thermal shock testing are low cycle fatigue. If the plastic strain is not varying during the cycle, the material behavior is in the high cycle fatigue regime, where as if plastic strain varies through the cycle, the material behavior is in the low cycle fatigue regime. For design optimization the analyst and designer should minimize the plastic strain amplitude and the tensile stress, when it is occurred at high temperature, as much as possible. Hence we need to normalize or the Signed Von-mises the stress with the tensile strength, evaluated at the instantaneous metal temperature, throughout the thermal cycle. The Closer to UTS the elasto -plastic stress is, the shorter the expected life. But the Chaboche's model is a stress based model, this bilinear kinematic property of material shows that, if there is a small change in stress creates large change in strain. That result would not be a realistic one.

Analytical Equation for Fatigue life calculation

Chaboche's fatigue damage model is proposed with normalized stress concept of constant amplitude is given by

$$N_f = \frac{\langle S_u^* - S_{\max} \rangle}{\alpha \langle S_{\max} - S_l \rangle} \left[\frac{S_{\max} - \bar{S}}{C_{nor}} \right]^{-\beta} \quad (1)$$

Where

$$\bar{S} = \frac{\bar{\sigma}}{SU(T)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; (2)$$

$$\ldots\ldots\ldots S_{\max} = \frac{\sigma_{\max}}{SU(T)} \ldots\ldots\ldots\ldots \; (3)$$

$$S_l(\bar{S}) = S_{l0}\left(1 - b_{nor}\,\bar{S}/S_u\right) \ldots \; (4)$$

$$C_{nor}(\bar{S}) = C_{nor0}\left(1 - b'_{nor}(\bar{S})/S_u\right) \; (5)$$

Equation 1 to Equation 5 represents the formulation to calculate fatigue life (N*f)*. In equation.2 SU(T) represents ultimate tensile strength at instantaneous temperature, as the material properties was changing with temperature mean stress was divided by ultimate tensile strength. Such as Lab Test duty cycle, City road duty cycle, Motorway road duty cycle . Out of all field data duty cycles Country road duty cycle was more severe. From these results we can say that the damage due to lab test duty cycle is the percentage distribution was 40% of Country road 30% of City road and 30% of Motorway road duty cycles

Table 2: Fatigue life results

Sl.no	Duty Cycle	Location: 1	Location : 2	Location: 3
1.	Lab Test	2.54E03	1.52E04	2.68E04
2.	City Road	1.04E05	2.86E07	8.49E06
3.	Motorway Road	8.58E05	2.02E09	6.39E06

Thermo-mechanical analysis on turbine housing of turbocharger suggested high thermal stresses occurring at tongue region of volute. Thermo-mechanical fatigue life was calculated and compared at the regions where plastic strain is occurring for different field data duty cycles.

Fatigue life results show Country road duty cycle is more severe than the other field data duty cycles like City road and Motorway road.

A lab test duty cycle was predicted in such a way that the sum of damage percentage of each field data duty cycle match to it1.Study on change in material properties of turbine housing.

Shape optimization of tongue region to reduce stresses, but it is dependent on aerodynamic performance of the turbocharger.

VI. REFERENCES

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