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Design and Thermal Analysis of Radial Turbo Charger Using Finite Element Method

Paulson Ouseph A¹, T Mahender², Subramanyam Pavuluri³

PG Student, Department of Mechanical Engineering, MLR Institute of Technology, Hyderabad, Telangana, India¹

Assistant Professor, Department of Mechanical Engineering, MLR Institute of Technology, Hyderabad, Telangana,

India^{2&3},

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 iste 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. The project mainly deals with 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.

KEYWORDS: Thermo-Mechanical Fatigue, Duty Cycle, In-Phase Loading, Out-Phase Loading.

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. However, a turbocharger differs in that the compressor is powered by a turbine driven by the engine's own exhaust gases. A turbocharger is a turbine driven supercharger. The turbine is driven by iste exhaust gas. Its benefit lies with the compressor increasing the pressure of air entering the engine (forced induction) thus resulting in greater performance (for either, or both, power & efficiency). Popularly used with internal combustion engines (e.g. four-stroke engines like Otto cycles and Diesel cycles). Turbochargers have also been found useful compounding external combustion engines.

II. LITERATURE SURVEY

A basic literature survey is done to understand the process of Thermo-Mechanical Fatigue estimating metal temperature evaluating stresses and TMF life predicting tools. During repeated start-ups and shut-downs engine hot section components experience cyclic strains, which are induced both thermally by rapid exhaust gas temperature changes and mechanically by centrifugal force and pressure difference. However predicting the stress and strain response of components and hence their lives under this TMF loading is a great challenge. Some of the references which give basic idea regarding TMF analysis are illustrated.

Cristiana Delpretea [5] he is analysed 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 are correlated to the experimental measurements for model verification. Analytical transient FEA analysis is utilized to understand the effect of thermal loading on the turbine housing. The model is 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.



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Farid Ahdad et.al.[6] establishes guidelines for the FEM of turbine housing. Finite Element Objectives. It provides guidelines for the determination of the thermo-mechanical behaviour of the Turbine housing using Finite Element Analysis. This includes the steps of acceptability criterion of stress analysis results for turbine housing is based on the monotonic stress-strain behaviour of the material. The maximum Von-Mises stress should less than the yield strength at the corresponding local metal temperature. This criterion is applicable only to the external regions of the housing are can reduce the stress by adding some material and modifying the local design.

Farid Ahdad et.al.[7] is discusses fatigue model based on a cumulative damage approach 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 are 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

Farid Ahdad et.al.[9] discusses 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 is 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 are 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 is 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 kilometres.

III. EXPERIMENTAL SETUP

The turbine housing is shown in blue, the centre housing in violet and the compressor housing in red. It shows the flow of the exhaust gas pass through turbine housing where pressure energy is converted to kinetic energy, which is used to drive the turbine wheel. In centre housing there is lubricant oil around the shaft to reduce the friction between the meeting parts of the shaft and housing (bearings) and it is also used to reduce the heat due to high speed of the shaft rotating. In compressor housing the fresh air enters and its compressed to high pressure air which enters the engine.



Fig.1 Components of Turbocharger.



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Thermodynamic Cycle of Turbocharger:



Fig.2 Thermodynamic cycle of turbocharger.

Fig.2 shows the thermodynamic cycle of the turbocharger operation processes consists of compressing the intake air to an internal combustion engine utilizing the energy in the exhaust gas stream to run a turbine that is directly connected to the compressor feeding air into the engine. The station 1 is the ambient condition. Station 2 is the compressed air is injected into the engine. Station 3 is the exhaust from the engine. Station 4 exits the turbine back to atmosphere.

a)Thermo-Mechanical Fatigue:

The high temperature components of most industrial systems such as turbine components are exposed to large thermal fluctuations during operation for example start up and shut down and running in different conditions like highway city and normal etc. Associated thermal strains plus any additional mechanical cyclic strain result in complex thermomechanical fatigue (TMF) cycles. Creep and low cycle fatigue properties of materials obtained from isothermal tests are widely used for assessing design lifetime of high temperature components. However, 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. For example, high temperature exposure may allow the relaxation of stresses imposed at lower temperatures extending life or alternatively cause oxidation exacerbating low temperature damage.

In TMF (Thermo-Mechanical fatigue) analysis, the component may be loaded in two types of loading conditions those are In-Phase loading and Out-Phase loading. In in-phase loading (IP), the maximum strain occurs at the maximum temperature and in out-of-phase loading (OP) the maximum strain occurs at the minimum temperature. The variation of thermal, mechanical and total strain components with time in OP and IP cases are illustrated. These two types of phasing reproduce many of the mechanisms that develop under TMF. The mechanical strain (ϵ mech) is the sum of the elastic and inelastic strain components, while the total strain (ϵ tot or ϵ t) is the sum of thermal and mechanical strain components.

 $\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{mech} = \alpha(T-T0) + \varepsilon_{mech}$





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During rapid heating, thin sections heat up quickly, and try to expand against thicker sections which are still relatively cool early in the transient. During rapid cooling, the thin sections cool down quickly, trying to shrink away from thicker sections which remain relatively hot. Due to this transient temperature difference, there is a compressive stress during the heating phase and a tensile stress during the cooling phase, which results in thermal cracking due to Thermo-Mechanical Fatigue. In the present work, we considered turbine housing which comes under low-cycle fatigue and calculating the Thermal stresses at different duty cycles, this variation in duty cycle can give us basic idea of how material is behaving. So that there will be a chance to modify the material properties. Here we considered the critical regions where plastic strain is occurring and extracted all the stresses from those nodal locations. The extracted stresses are used to calculate crack initiation life at those specific regions.

b)Thermo-Mechanical Fatigue Life Calculation:

Turbine housings must be designed to operate under severe thermal and pressure loads from the exhaust gas, external loads and vibration from the adjacent components and should be able to contain turbine wheel in case of burst. Some of the important Turbine housing failure are:

- Thermo-mechanical fatigue
- Turbine housing Containment
- Creep failure

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 [12].

c)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 behaviour with low modulus and high degree of drawing. The material properties are changes with the temperature such yield stress and tangent stress and table I shows the variation of material properties which changes with temperature, which for the structural and thermal analysis for the turbine housing [5]. Bi-Linear Kinematic model is used for non-linear material properties. Fig.5 show the bilinear material properties stress vs. strain.

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Properties	Units	Material Properties							
Temperature	°C	25	100	300	400	500	700	800	900
Expansion coefficient	1x10-6/C	12.0	12.0	12.0	12.35	12.83	13.71	13.9	14.1
Thermal conductivity	W/mC	48.5	48.5	48.5	48.2	47.85	47.70	47.70	46.50
Young's modulus	GPa	160	156	146	143	138	98	70	43
Poisson ratio		0.3	0.3	0.3	0.3	0.3	0.306	0.314	0.324
Density	Kg/m ³	7100							
Yield Stress	MPa	469	453	409	379	313	138	95	53

Table I Material Properties



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d)Duty cycles:

Lab Test Duty Cycle: Fig.6 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 800 oC and the minimum temperature at cooling phase is 200oC.In order to get exact regions where plastic strain is occurring we considered this much phase differ. Field Data Duty Cycle: The following Fig. 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 800oC. Exhaust Gas Temperature over a period of time can be observe in the following Charts for various road conditions.





Fig. 9 Exhaust gas temperature at country road.

e)Thermal Analysis

Finite element Model is imported to ANSYS to change element type from SOLID 92 to SOLID 87 for TETRA element apply Thermal boundary conditions. Thermal Analysis is performed for duty cycles as shown in Fig.6, Fig.7, Fig.8 and Fig.9. The thermal boundary conditions applied at the different parts of the housing is tabulated in table II The thermal BCs should take into account factors such as flow velocities, gas temperature and geometric parameters. These data can be obtained from determined utilizing information regarding the flow velocities inside the volute as determined by computational fluid dynamics analysis or turbine gas temperatures measurements calibrated from tests. Different boundary conditions are applied for the heating phase. Heat transfer coefficient for the cooling cycle is less compared to that of the heating phase due to lower mass flow rates. The material properties utilized in this analysis are input as a function of temperature as shown in table II.



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Table. II Thermal Boundary Conditions

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

Fig.10 shows the mesh for the Turbine housing in Ansys. This has 4300 nodes and 5674 elements and is generated in hyper mesh FE Mesh Generation software. For thermal stress analysis of a THSG, usually TETRA solid meshing (10 node TETRA element) is used. Based on the computer resources the total number of nodes should not exceed 380,000. The fig.11 shows the thermal boundary condition applying at the different part of the turbine housing and with a different temperature boundary condition and different thermal expansion. Brief explain about the thermal boundary condition applied.



Fig.10 FE model of turbine housing



Fig.11 Thermal boundary conditions of turbine housing



conditions.

IV. EXPERIMENTAL RESULTS OF POST PROCESSING

1) Thermal plots

Thermal results are presented with the following guidelines:

- Temperature distribution at different time point and different angle of view, particularly to show the Maximum Temperature of the component.
- All the values have been scaled to 0-100.



Fig.13Thermal plot for lab test duty cycle





Fig.14 Thermal plot for city road duty cycle



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Fig.15 Thermal plot for motorway road duty cycle



Fig.16 Thermal plot for motorway road duty cycle

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.

3) Von-Mises stress plots and Plastic strain intensity plot

Fig.17 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 is more. We can observe the temperature distribution in the Fig.13 to Fig15.



The fig.18 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.

As the intensity of the lab test cycle is more we can easily find the critical regions where plastic strain is occurring. So we used those critical regions for finding TMF in field data duty cycles like City road, Motorway road and Country road duty cycles.

V. RESULTS & DISCUSSIONS

The following studies are performed on the turbine housing with 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 concentratedon TMF life calculation not on optimization as it requires Computational Fluid Dynamic analysis over the flow of exhaust gas.

- 3D Thermal, Elastic and Plastic FEA Analysis of the housing with different duty cycles.
- Stress distribution over the component with comparison of temperature.



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• Thermo-Mechanical Fatigue life calculation by using Chaboche Model for all duty cycles.

The results obtained from these studies are summarized below.

1) FEA results

a)Lab test duty cycle and City road duty cycle

Fig.19 to 21 shows the stress distribution at location: 1, Location: 2 and Location: 3 respectively throughout the lab test duty cycle as time as X-axis. It represents all the stresses like principal stresses, Von-Mises stress, Signed Von-Mises stress and temperature. Here temperature is used as secondary Y-axis to show how stress distribution varies with it. It represents both In-Phase type loading and Out-Phase. Here, we can observe Out-Phase type loading at Location: 1 where, as the temperature increases the 3rd principal stress dominates compared to 1st principal stress. Signed Von-Mises stress is used to predict the life as there is a change in shift in between 1st principal stress and 3rd principal stress.





Fig.19 Lab test duty cycle: Stress distribution at location 1



Fig.21 Lab test duty cycle: Stress distribution at location 3

Fig.20 Lab test duty cycle: Stress distribution at location 2



Fig.22 City road duty cycle: Stress distribution at location 1

Fig.22 to 24 shows the stress distribution at location: 1, Location: 2 and Location: 3 respectively throughout the City road duty cycle. Here, we can observe Out-Phase type loading at Location: 1 where, as the temperature increases the 3rd principal stress dominates compared to 1st principal stress. Here the maximum temperature is 500°C.



Fig.23 City road duty cycle: Stress distribution at location 2

Fig.24 City road duty cycle: Stress distribution at location 3

c)Motorway road duty cycle and Country road duty cycle

Fig.25 to 27 shows the stress distribution at location: 1, Location: 2 and Location: 3 respectively throughout the Motorway road duty cycle. Here, we can observe Out-Phase type loading at Location: 1 where, as the temperature increases the 3rd principal stress dominates compared to 1st principal stress. Here the maximum temperature is 500°C.



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Fig.25 Motorway road duty cycle: Stress distribution at location 1



Fig.26 Motorway road duty cycle: Stress distribution at location 2



Fig.28 Country road duty cycle: Stress distribution at location

Fig.28 to 30 shows the stress distribution at location: 1, Location: 2 and Location: 3 respectively throughout the Country road duty cycle. The maximum temperature is 600°C.



Fig.29 Country road duty cycle: Stress distribution at location 2



Fig.30 Country road duty cycle: Stress distribution at location 3

2) 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 (cyclic stress in the elasto-plastic region). The fatigue life is highly dependent on the plastic strain amplitude. 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. As the stress is varying with temperature we can't directly use the stress values for calculating the fatigue cycles. 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, we may think as the low cycle fatigue plays mostly on strain. The reason in considering this model is because of Bi-linear kinematic hardening of the material. 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.



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Table III represents fatigue life at all the three locations of all duty cycles. Such as Lab Test duty cycle, City road duty cycle, Motorway road duty cycle and Country road duty cycle. Out of all field data duty cycles Country road duty cycle is more severe. From these results we can say that the damage due to lab test duty cycle is the percentage distribution is 40% of Country road 30% of City road and 30% of Motorway road duty cycles.

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
4.	Country road	4.45E03	1.50E07	1.76E05

Table. III THERMAL BOUNDARY CONDITIONS

VI. CONCLUSIONS

- Thermo-mechanical analysis on turbine housing of turbocharger suggested high thermal stresses occurring at tongue region of volute.
- Thermo-mechanical fatigue life is 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 is predicted in such a way that the sum of damage percentage of each field data duty cycle match to it

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