Design and Stress Analysis of Turbine Blade of Turbocharger

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Abstract - The objective of this paper is to **to analyze the stress on the turbine blade of turbocharger which is used in automotive diesel engine (118 kW). The turbocharger is failure due to high rotational speed, temperature and pressure. The volume flow rate of this turbine is 0.1m^3/s and the speed is 9500 rpm. The calculation of turbine design consists of pressure, number of blades, blade width, input and output turbine blade angles, mass flow rate, tangential force and radial force on turbine blade. The result comes out turbine inlet and outlet blade angles are 86 degree and 25 degree, the tangential force on turbine is 31N, radial force on turbine is 15N and number of blades is 13 blades. The ANSYS 17.0 software is used for modeling and analysis of the turbine blade of turbocharger. The stress on turbine blade is calculated by theoretically and numerically. The suitable material is Structural Steel. The minimum von-Mises stress and effective strain are found in blade numbers 13.**

Indexed Terms – Turbine, Turbine Blade, Turbocharger, Stress analysis, Rotational Speed

I. INTRODUCTION

A turbocharger is an air pump designed to operate on the normally waste energy in engine exhaust gas. Turbocharger is a class of turbo machinery that increases the power of internal combustion engines. This is accomplished by increasing the pressure of intake air, allowing more fuel to be combusted. A turbocharger uses waste energy from the exhaust system to compress air entering the cylinder, thus increasing engine power. Turbocharging system is turbine drives the compressor which is driven by the exhaust gas (residual gas) from the cylinder. These gases drive the turbine wheel and shaft which is coupled to a compressor wheel which when rotating provides high volume of air to the engine combustion chamber [7].

The main components of turbocharger are a compressor, a turbine and centre housing. Compressor is spun by the rotation force created by exhaust gas flowing through the turbine. Clean air from the air cleaner is drawn into the compressor housing and wheel where it is compressed and delivered through a pipe to the engine air intake manifold. Centre housing is comprised of "journal" or "ball bearings" depending upon the application, as well as oil lubrication and drains. The turbine is a section of turbocharger where the exhaust gases of the engine are forced through to cause the turbine wheel to spin. The turbine converts some of the energy contained in the hot engine exhaust gas into mechanical work the pressure and temperature of the exhaust gas decreases. Exhaust gas from the engine enters the turbine and expends, performing work on the turbine shown in Figure. 1. [5]

K. Kumar, S. L. Ajit Prasad and Shivarudraiah studied the strength evaluation in turbo machinery blade disk assembly at constant speed. In this work, 3D finite element analysis of low pressure turbine blade disk assembly is carried out at constant speed loading condition. The main aim is to optimize the geometry of the bladed disk root of the Peterson's stress concentration factor charts. Special investigations were performed based on Neuber formulae. This can be reduced the local peak stresses at the blade and disk root fillet using linear analysis. And the equivalent non-linear stress values are identified by the strain energy distribution. In this paper, the turbine wheel model is generated and analysed the von-Mises stress, equivalent elastic strain and deformation with same rotational speed, tangential and radial forces. Although, the three different materials are used for the best suitable material for turbine wheel for turbocharger [3].

Figure 1 . Turbocharger for Automobile

II. METHODOLOGY

In this research, the design parameter is collected from automotive diesel engine Pajero (4M40), measuring the turbine inlet and outlet temperature by using Infrared thermometer BM 380. And then, calculated the compressor inlet and outlet stagnation pressure, compressor inlet and outlet static pressure, turbine inlet and outlet static pressure, turbine inlet and outlet static temperature, compressor work done , turbine work done, turbine inlet and outlet blade angles, number of blades, blade width, mass flow rate of turbine, turbine tangential force, turbine radial force.

In this paper, it includes of three main parts, which are;
A: Design Consideration of Turbocharger
B: Theoretical Analysis of Turbocharger
C: Numerical Analysis of Turbocharger

A. Design Consideration of Turbocharger
Ambient pressure and ambient temperature are 1.013 bar and 25˚ C.

Firstly calculate the brake mean effective pressure,

$$Bp = P_b LAN \frac{cycle}{sec} \quad (1)$$

Secondly pressure ratio of turbine is required, to calculate the turbine inlet and outlet pressure.

$$P_{01} = P_1 \left[\frac{T_{01}}{T_1}\right]^{\frac{k}{k-1}} \quad (2)$$

$$\frac{P_{04}}{P_{03}} = \left[\frac{T_{04}}{T_{03}}\right]^{\frac{k}{k-1}} \quad (3)$$

$$P_3 = \frac{P_{03}}{\left[1 + \frac{(k-1)M^2}{2}\right]^{\frac{k}{k-1}}} \quad (4)$$

$$P_4 = \frac{P_{04}}{\left[1 + \frac{(k-1)M^2}{2}\right]^{\frac{k}{k-1}}} \quad (5)$$

$$T_4 = \frac{T_{04}}{\left[\frac{P_{04}}{P_4}\right]^{\frac{k-1}{k}}} \quad (6)$$

For calculation of work done of compressor and turbine, the temperature of compressor and turbine are required.

$$W_c = Cp_a (T_{02} - T_{01}) \quad (7)$$

$$W_t = Cp_g (T_{03} - T_{04}) \quad (8)$$

After turbine blade angle is calculated by using the following equations

$$C_3 = \sqrt{2CpT_3 \left[1 - \left(\frac{P_4}{P_3}\right)^{\frac{k-1}{k}}\right]} \quad (9)$$

And also the absolute velocity is calculated

$$U_3 = \frac{\pi D_3 N}{60} \quad (10)$$

And then calculate turbine inlet blade angle

$$\cos\beta_3 = \frac{U_3}{C_3} \quad (11)$$

By using the NASA design rule for calculating the rotor outlet hub and tip diameter of turbine.

$$D_{4t} = 0.7D_3 \quad (12)$$

$$D_{4h} = 0.4D_{4t} \quad (13)$$

$$D_{4m} = \frac{\sqrt{D_{4t}^2 + D_{4h}^2}}{2} \quad (14)$$

Radial outlet velocity and absolute outlet velocity are required to calculate the turbine outlet blade angle. In the calculation of radial outlet velocity, slip factor is concerned. So, slip factor is calculated.

$$\sigma_f = 1 - \frac{\sqrt{\sin\beta_3}}{z^{0.7}} \quad (15)$$

Absolute velocity is calculated by using combining energy and momentum equation.

$$h_4 + \frac{1}{2}W_4^2 - \frac{1}{2}U_4^2 = h_3 + \frac{1}{2}W_3^2 - \frac{1}{2}U_3^2 \quad (16)$$

Also calculate turbine outlet blade angle

$$\sin(\beta_4) = \frac{V_{r4}}{V_4} \quad (17)$$

In the design of turbine blade of turbocharger, number of blade is important. So number of blade is calculated by this equation.

$$z = 6.5 \frac{D_3 + D_{4m}}{D_3 - D_{4m}} \sin\left(\frac{\beta_3 + \beta_4}{2}\right) \quad (18)$$

In the blade design, outlet blade width and mass flow rate of turbine are calculated by the following equation.

$$b_4 = \frac{Q_4}{(\pi D_4 - zt_4 \operatorname{cosec}\beta_4) W_4} \quad (19)$$

$$m_t = Q\rho = Q \frac{P_4}{RT_4} \quad (20)$$

Tangential force and radial force are affected on the turbine blade due to mass flow rate and rotational speed. Therefore, tangential force and radial force are calculated by the following equation.

$$F_{t1} = \left(C_3 \sin\alpha_3 + C_4 \sin\alpha_4\right)\frac{m_t}{z} \quad (21)$$

$$F_{r1} = \left(C_4 \sin\alpha_4 - C_3 \sin\alpha_3\right)\frac{m_t}{z} \quad (22)$$

Table 1: Result Data of Turbocharger

Parameters	**Symbol**	**Value**	**Unit**
Work done of compressor	W_c	162.81	kW
Work done of turbine	W_t	197.599	kW
Number of blade	n	11	blades
Turbine outlet blade width	b	7.28	mm
Mass flow rate of turbine	m_t	0.45	Kg/s
Outlet diameter of turbine blade	D	16	mm
Tangential force on turbine	F	31	N

Table 1 shows the calculated work done of compressor and turbine, number of blades, blade width, outlet diameter and tangential force.

B. Theoretical Analysis of Turbocharger:
Structural behaviour (von-Mises stress, effective strain) of turbocharger are calculated by theoretical approach.

The most important components of static stresses are centrifugal stress and gas bending stress. The centrifugal stress equation is

$$\sigma_c = \frac{\rho\omega^2}{2}\left(r_t^2 - r_r^2\right) \quad (23)$$

The gas bending stress is determined by the following equation.

$$\sigma_{gb} = \frac{m^\circ\left(V_{w\text{-}in} + V_{w\text{-}out}\right)\times h_R}{2\times n_R \times z \times c_R^3} \quad (24)$$

For calculation of principal stresses,

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \frac{1}{2}\sqrt{\left(\sigma_x - \sigma_y\right)^2 + 4\tau_{xy}^2} \quad (25)$$

The von-Mises stress equation is

$$\sigma_V = \frac{1}{2}\sqrt{\left(\sigma_1 - \sigma_2\right)^2 + \left(\sigma_2 - \sigma_3\right)^2 + \left(\sigma_3 - \sigma_1\right)^2} \quad (26)$$

For calculation of effective strain,

$$\varepsilon_1 = \frac{1}{E}\left[\sigma_1 - \upsilon\left(\sigma_2 + \sigma_3\right)\right] \quad (27)$$

$$\varepsilon_2 = \frac{1}{E}\left[\sigma_2 - \upsilon\left(\sigma_1 + \sigma_3\right)\right] \quad (28)$$

$$\varepsilon_3 = \frac{1}{E}\left[\sigma_3 - \upsilon\left(\sigma_1 + \sigma_2\right)\right] \quad (29)$$

Effective strain, $\bar{\varepsilon}$

$$\bar{\varepsilon} = \left[\frac{2}{3}\left(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2\right)\right]^{\frac{1}{2}} \quad (30)$$

Table 2 Theoretical Result of Turbocharger

Von-Mises Stress, (MPa)	Effective Strain, $\bar{\varepsilon}$ ($\times 10^{-5}$)
2.7405	1.686

Table 2 shows the theoretical results of the von-Mises stress and effective strain for turbine wheel.

C. Numerical Analysis of Turbocharger;
To estimate the following stresses and strains distribution of turbocharger, ANSYS software has been used.

(1). Model of Turbine Wheel for Turbocharger:

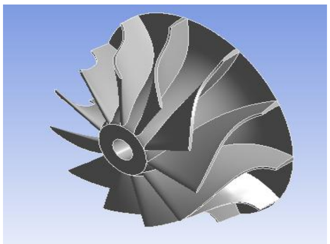
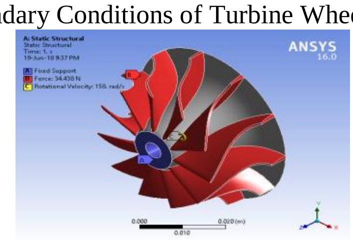


Figure 2. 3D Model of Turbocharger

Figure 2 shows the model of turbine wheel for turbocharger which is drawn by ANSYS and SolidWorks Software 2016.

(2) Boundary Conditions of Turbine Wheel



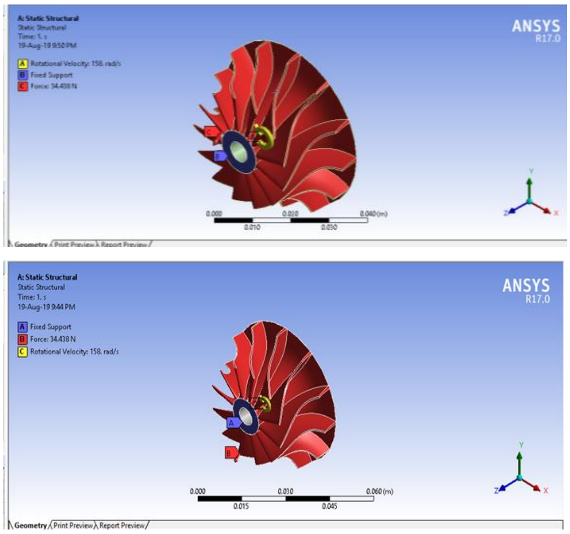


Figure 3. Boundary Conditions of Turbine Wheels with Three Different Turbine Blades

Figure 3 shows the boundary conditions of turbine wheel with three number of turbine blades. Fixed supports are provided at top of the cone surface. The tangential and radial forces are applied at the surface of turbine blades. The rotational velocity is supplied the surface of shaft.

(3). Meshing of Turbine Wheel

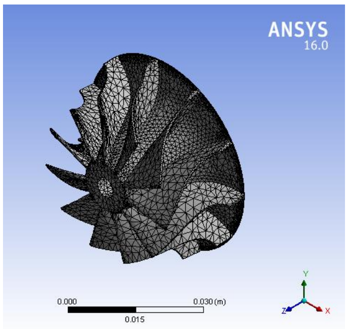


Figure 4. Meshing of Turbine Wheel

Figure 4 shows the meshing of turbine wheel. The boundary condition are applied on the turbine wheel after finishing the mesh of the disc which fixed at the tip of the turbine wheel and surface of shaft, the tangential and radial forces are applied to the surface of blades and rotational speed are applied on the surface of shaft. The boundary condition of the turbine wheel is as shown in Figure 3.

(4). Stresses and Strains Analysis of Turbine Wheel

(1) Stresses and Strains Analysis of Turbine Wheel with 11 Number of Turbine Blades

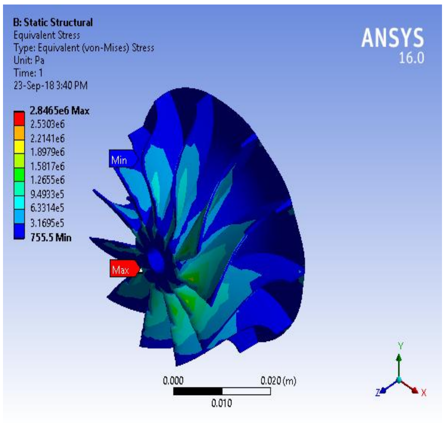


Figure 5 Von- Mises Stress of Turbine wheel

Figure 5 shows the maximum equivalent (von-Mises) stress on the turbine wheel for the structural steel is 2.8465 MPa. The maximum von-Mises stress occurred at the engage between the surface of cone and blade edges.

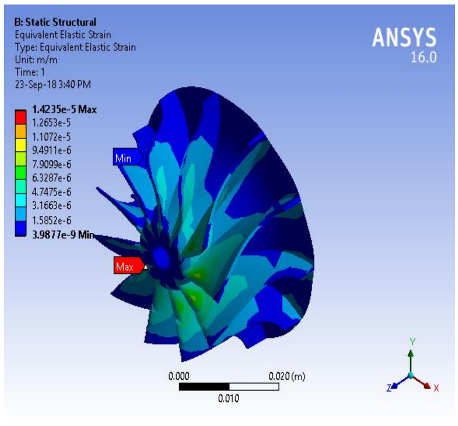


Figure 6: Effective Strain Distribution of Turbine wheel

Figure 6 shows the simulation results of equivalent elastic strain using structural steel. The maximum equivalent elastic strain on the turbine wheel is 1.4235×10^{-5}.

(2) Stresses and Strains Analysis of Turbine Wheel with 12 Number of Turbine Blades

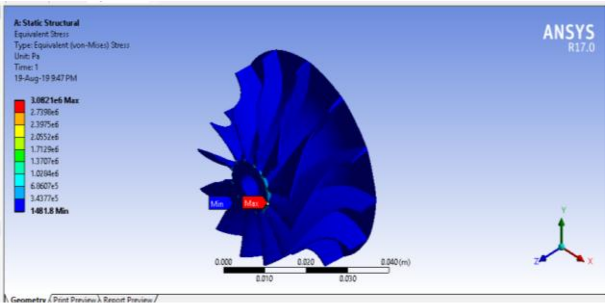


Figure 7 Von-Mises Stress of Turbine Wheel

Figure 7 shows the maximum equivalent (von-Mises) stress on the turbine wheel for the structural steel is 3.0821 MPa. The maximum von-Mises stress occurred at the engage between the surface of cone and blade edges

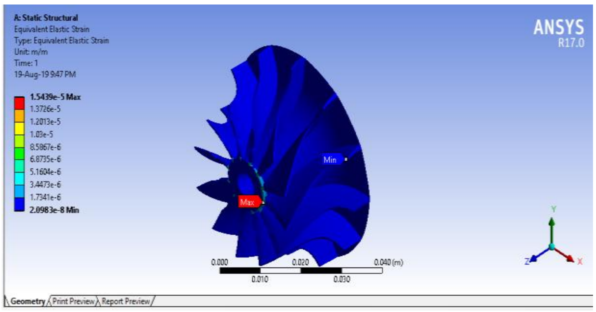


Figure 8 . Effective Strain Distribution of Turbine wheel

Figure 8 shows the simulation results of equivalent elastic strain using structural steel. The maximum equivalent elastic strain on the turbine wheel is 1.5439×10^{-5}.

(3) Stresses and Strains Analysis of Turbine Wheel with 13 Number of Turbine Blades

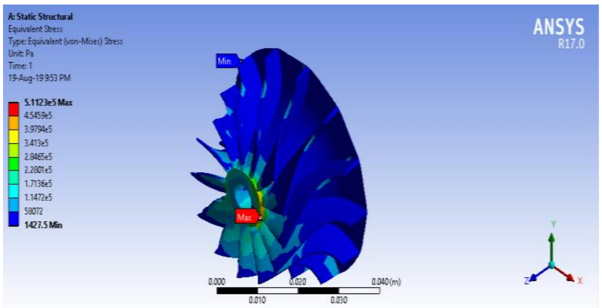


Figure 9 Von-Mises Stress of Turbine Wheel

Figure 9 shows the maximum equivalent (von-Mises) stress on the turbine wheel for the structural steel is 5.1123×10^{5} Pa. The maximum von-Mises stress occurred at the engage between the surface of cone and blade edges.

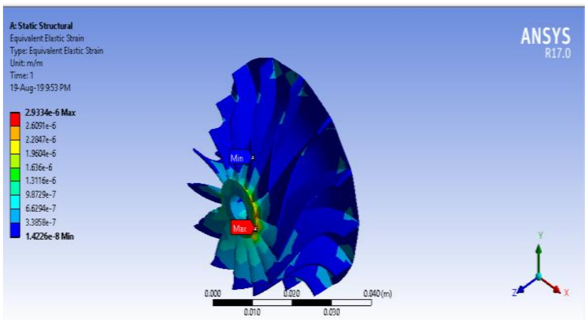


Figure 10: Effective Strain Distribution of Turbine wheel

Figure 10 shows the simulation results of equivalent elastic strain using structural steel. The maximum equivalent elastic strain on the turbine wheel is 9.0178×10^{-8}.

Table 3: Comparison of Von-Mises Stress and Effective Strain with Three Different Number of Turbine Blades (n= 11, 12, 13)

Blade Numbers, n	**Simulation Results of von-Mises Stress, σ(Pa)**	**Simulation Results of Euivalent Elastic Strain, $\bar{\varepsilon}$**	**Simulation Results of Total Deformation**
n=11	2.8465×10^{6}	1.4235×10^{-5}	1.3799×10^{-6}
n=12	3.0821×10^{6}	1.5439×10^{-6}	9.6636×10^{-8}
n=13	5.1123×10^{5}	2.9334×10^{-6}	9.0178×10^{-8}

Table 4 shows the comparison of von-Mises stress and effective strain for three different number of turbine blades.

III. RESULT AND DISCUSSION

In this research paper, the results of three different numbers of turbine blades, the minimum von-Mises stress and effective strain are occurred in number of blades 13 for structural steel. Therefore, suitable number of turbine blades for Structural Steel is 13 turbine blades. Structural Steel is suitable than the other two turbine blades. The blade model is drawn by visual RTD software and SolidWorks software.

IV. COCLUSION

In this paper has been studied the structural analysis of turbine wheel for turbocharged diesel engine. Simulation results the turbine wheel with the different number of blades (11, 12 and 13). The minimum von-Mises stress is 5.1123×10^{5}Pa but it does not exceed the yield strength of structural steel. The minimum equivalent elastic strain and deformation results are 2.9334×10^{-6} and 9.0178×10^{-8} respectively, which is occurred in 13 turbine blades. So, this design is satisfactory.

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