THREE DIMENSIONAL STRESS-STRAINS ANALYSIS OF A TYPICAL GAS TURBINE BLADE USING FINITE ELEMENT METHOD

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ABSTRACT

Energy is extracted in gas turbine systems by expanding hot gases through several passages between fixed stator and moving rotary blades. These blades must have maximum reliability, durability, yield strength and minimum material cost. In this study, High Speed Steel alloys (HSS) and Titanium alloys (Ti-6Al-2Sn.) have been used in the 3D axial turbine blade. The turbine blade has been modelled using Solid works software using finite element analysis to calculate stress, strain, deflection and many other parameters based on a numerical computational method using ANSYS software. An attempt has been made to compute the equivalent of stress, strain and displacement of a typical rotary blade of the gas turbine system and to compare the results obtained with the available data. Attention has been focused on the stress-strain field analysis on the upper and lower surfaces of the blade, and on the turbine blade chord line. The results show the complication of the stress-strain field over turbine blade. From computational results, the use of High-Speed Steel alloys (HSS) in these applications under such cases and assumptions is more preferable to increase the reliability, durability and availability of turbine blades.

KEYWORDS: Turbine Blade, Stress, Strain, Finite Element Method, Three Dimensional Analysis

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INTRODUCTION

Gas turbine systems are mechanical elements that extract thermal energy from high temperature and high pressure gases and convert it into rotary motion through a system of stator-rotor blades. Rotor and stator blades are subjected to different types of loading such as gas forces, inertia loads and centrifugal forces [1, 2, 3]. Due to these combinations of forces, different types of stresses are induced in rotor blade. So stresses and strains on rotor blade provide vital information concerning turbo machine design and lead to design of critical blade section to give maximum strength and blade efficiency [2-4]. The present paper deals with stress-strain analysis of a typical rotor blade made of high speed alloy, which is subjected to known velocity gradient that creates sever-stress-strain components on rotor blade to dynamic fluid forces. Due to the complexity of the geometry, a three dimensional solid modeling of the blade was first created, and a finite element package is used for analysis. Stress and strain analysis was done taking into consideration the material behavior of the turbine blade.

A finite element method [FEM] geometrical modeling and mesh generation of the blade were made using a finite element package [ANSYN]. Generally, gas turbine rotor blades have complex three dimensional geometrical structures and behavior, and therefore, numerical simulation methods, can only be used to study stress-strain analysis over these blades. This study provides a simplified approach for the three dimensional rotor blade using a customized 3D FEM.

An introduction to the basic theory of a simplified gas turbine blade design is presented in [4 and 5]. The

papers[6 and 7] studied design and modeling of three dimensional rotor gas turbine blade using MATLAB to solve stress-strain distribution over a turbine blade.

Gas Turbine Blade Materials

The material used in gas turbine blades should have high temperature performance, high tensile and yield strength as a major requirements. Stress concentration and stress rapture life and creep properties, also of great importance. A wide range of high performance materials such as iron base, steel alloy, and titanium base and super alloys are used for construction of turbines blade. In this paper (HSS) base metal alloy is used and tested, here is the main properties of Ti alloy and HSS blade material. Table 1 and 2 Show such properties.

Table 1: Ti Alloy Properties

Model Reference	Properties
Name: Ti-6Al-2Sn-2Zr-2Mo-2Cr-0.25Si (SS)
	Model type: Linear Elastic Isotropic
	Default failure criterion: Max von Mises Stress
	Yield strength: $1.07 \times 10^9 \text{ N/m}^2$
	Tensile strength: $1.16 \times 10^9 \text{ N/m}^2$
	Mass density: 4650 kg/m^3
	Elastic modulus: $1.23 \times 10^{11} \text{ N/m}^2$
	Poisson's ratio: 0.33
	Thermal expansion coefficient: $9 \times 10^{-6} / \text{Kelvin}$

Table 2: HSS Properties

Model Reference	Properties
Name: M4 Hss (1)
	Model type: Linear Elastic Isotropic
	Default failure criterion: Max von Mises Stress
	Yield strength: $2.07 \times 10^6 \text{ N/m}^2$
	Tensile strength: $2.29 \times 10^6 \text{ N/m}^2$
	Compressive strength: $2.07 \times 10^6 \text{ N/m}^2$
	Elastic modulus: $2.27 \times 10^{11} \text{ N/m}^2$
	Poisson's ratio: 0.285
	Mass density: 7920 kg/m^3
	Shear modulus: $8.8 \times 10^{10} \text{ N/m}^2$
	Thermal expansion coefficient: $11.3 / \text{Kelvin}$

Assumptions

Due to complexity of 3D stress-strain field, and due to strong relationship between mechanical and physical properties and temperature variation, and also due to the need of simplified 3D FEM model, the material is assumed to be linear elastic material, which means that the material may be deformed and will return to its original configuration when load released, also the material is symmetric with respect to every plane and every axis, then the elastic properties are identical in all directions, and also the material is homogeneous, and obeys Hooke's law.

Finite Element Formulation

Finite element analysis is a computer based numerical method used to calculate stress, strain, temperature, deflection and many other parameters based on a solution of discretized set of an algebraic equation for a basic form of PDE. In finite element calculations the specified structure is broken down into large number of elements. Each individual element can be described by a simple set of equations, joined together to build the whole structure through a certain shape function, and the generated stiffness matrix here in is a simplified (FEA) model for stress- strain equations of a turbine blade. Internal forces in a gas turbine blade are called stresses. In a finite element a symmetric stress strain tensor components are written as:

$$\sigma^T = (\sigma_x \quad \sigma_y \quad \sigma_z \quad \tau_{xy} \quad \tau_{yz} \quad \tau_{zx}) \quad (1)$$

Also strain can be written as:

$$\epsilon^T = (\epsilon_x \quad \epsilon_y \quad \epsilon_z \quad \gamma_{xy} \quad \gamma_{yz} \quad \gamma_{zx}) \quad (2)$$

The magnitude of the unit surface q_x , q_y and q_z are related to stresses as:

$$[q]^T = [\hat{\sigma}][n]^T \quad (3)$$

Where

$$[q]^T = [q_x \quad q_y \quad q_z], \text{ and } [n]^T = [n_x \quad n_y \quad n_z]$$

The effective Von-Mises stress is used to calculate the values of local stress components. Now finite element approximation is used for the displacement equations for u , v and w as follows:

$$u = u(x, y, z) = N_i u_i \quad (4)$$

$$v = v(x, y, z) = N_i v_i \quad (5)$$

$$w = w(x, y, z) = N_i w_i \quad (6)$$

Where: u_i , v_i , w_i are nodal degrees of freedom, $N_i = N_i(x, y, z)$ are suitable interpolation shape function. The final solution can be written as:

$$u(x, y, z) = \begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} N_1 & 0 & 0 & N_2 & 0 & \dots \\ 0 & N_1 & 0 & 0 & N_2 & \dots \\ 0 & 0 & N_1 & 0 & 0 & \dots \end{bmatrix} \begin{bmatrix} u_1 \\ v_1 \\ w_1 \\ \dots \end{bmatrix} = N^T d \quad (7)$$

The elements of strain vector can be computed as:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{bmatrix} = \mathbf{B}^T \mathbf{d} \quad (8)$$

Where $\mathbf{B}$ is the gradient matrix given as:

$$\mathbf{B}^T = \begin{bmatrix} \frac{\partial N1}{\partial x} & 0 & 0 & \frac{\partial N2}{\partial x} & \dots \\ 0 & \frac{\partial N1}{\partial y} & 0 & 0 & \dots \\ 0 & 0 & \frac{\partial N1}{\partial z} & 0 & \dots \end{bmatrix} \quad (9)$$

Where $\mathbf{d}$ vector can be written as:

$$\mathbf{d} = \begin{bmatrix} u_1 \\ v_1 \\ w_1 \\ u_2 \\ v_2 \\ w_2 \\ \dots \end{bmatrix} \quad (10)$$

And the elements of the stiffness matrix $\mathbf{K}$ are evaluated as:

$$\mathbf{K} = \iiint_V [\mathbf{B}]^T [\mathbf{D}] [\mathbf{B}] dV \quad (11)$$

RESULTS AND DISCUSSIONS

The turbine blade is represented as shown below in fig.1 below. It is fixed from one end as shown and the flow is over the free surfaces of the blade.

Figure 1: Turbine Blade Model.

Fig.2 shows the meshing of the studied blade.

Figure 2: Mesh of the Turbine Blade.

Fig. 3 and 4 shows the Von-Mises stresses distribution in both Titanium alloys and HSS blades

Figure 3: Von-Mises Stresses on the Ti Alloy Blade.

Figure 4: Von-Mises Stresses on HSS Blade.

It can be noticed that the stresses distribution on the blade is the same but with different values of the maximum and minimum values of stress as shown in Fig.3 and 4. The maximum value of stress in the case of Ti alloy is more than HSS blade. Fig. 5 and 6 show the displacement in x-direction of the blade for both Ti alloy blade and HSS blade respectively.

Figure 5: Displacement of Both Blades in x-Direction for Ti Alloy.

Figure 6: Displacement of Both Blades in x-Direction for HSS Blades.

Fig.7 and 8 show the resultant displacement for both types of blades respectively.

Figure 7: Resultant Displacement of Ti Blades.

Figure 8: Resultant Displacement of HSS Blades.

Fig. 9 and 10 show the strain in both types of blade.

Figure 9: Strain of Ti Alloy Blade.

Figure 10: Strain of HSS Blade.

Fig.11 and 12 show the stress distribution on the blades surface of the two blades' types.

Figure 11: Stress Distribution on the Surface of Ti-Alloy Blade.

Figure 12: Stress Distribution on the Surface of the HSS Blade.

Figure 13 and 14 show the stress values for both types of blades along the blade points along the blade span.

Figure 13: Stress Values of the HSS Blade.

Figure 14: Stress Values of the Ti Alloy Blade.

It can be noticed from last two figures that HSS blades stress values are higher than that of Ti blades as the blade span from fixed end increases. This is related to material properties of the blade. So with the same conditions of work for the two blades HSS can possess more stress and then it is preferable than Ti alloy blades.

CONCLUSIONS

In this study, structural analysis of a finite element of 3D axial turbine with two different types of turbine blades made of two different material compositions i.e. High-Speed Steel alloys (HSS) and titanium alloys (Ti-6Al-2Sn.) in the high stress zone was done.

Three parameters which are stress, displacement and strain were calculated based on a numerical computational method using ANSYS software. The computational results were fully analyzed. From the analysis it was observed that:

Three parameters were calculated: stress, displacement and strain based on the method of numerical calculation using ANSYS software. The computational results were fully analyzed. From the analysis it was observed that:

- It was found that the equivalent stress, displacement and strain in High-Speed Steel alloys (HSS) are higher than that of Titanium alloys (Ti-6Al-2Sn).
- From computational results, the use of High-Speed Steel alloys (HSS) in these applications under such cases and assumptions is more preferable to increase the reliability, durability and availability of turbine blades

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