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Finite Element Structural Integrity Analysis of First Stage Gas Turbine Rotor Blade Assembly Under Thermo- Mechanical Loads

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ABSTRACT: Turbines are used in the power plant due to high speed capacity. In the power plants, high speed is required to obtain higher rate of change of flux linkages by which more power can be produced. Since turbines rotate at higher speeds, inertia is very important parameter in increasing the stresses so, the material safety is very important under thermo-mechanical loads.

In the present work, from standard formulas and using given input data the Forces, Temperature generation, and convective Heat transfer co-efficient are calculated for I stage rotor system. The model is designed with CATIA and ANSYS MIXED APPROACH SOFTWARE. The material used is NiCrome alloy. In first case only rotational load is applied and later along with the gas force, results are obtained for displacements and vonmises stresses. Coupled field analysis is carried out to find the structural safety. Finally Modal analysis has been performed to find resonance frequency in the assembly. The results shows developed stresses and deflections are within the allowable limit and also the complete safety of the problem.

KEYWORDS: Turbine blades, Finite element analysis, structural analysis, coupled-field analysis, modal analysis, meshing.

I. INTRODUCTION

The gas turbine is a power plant, which produces a great amount of energy for its size and weight. A gas turbine is an engine where fuel is continuously burnt with compressed air to produce a steam of hot, fast moving gas. This gas stream is used to power the compressor that supplies the air to the engine as well as providing excess energy that may be used to do other work. Turbine Blades are most important component and the major cause of break down in turbo machine is the failure of rotor blade this failure of the rotor blade may lead to catastrophic consequences both physically and economically.

ElizavetaGordeliy et.al [1] carried out the transient thermal analysis of infinite medium with a circular nano-scale cavity. A two-dimensional, transient, uncoupled thermo elastic problem of an infinite medium with a circular nano-scale cavity is considered. Mehdi Tofighi Naeem et.al [2], studied on failure analysis of gas turbine blades. the investigation was carried out by mechanical and metallurgical analysis. It is found that the blade failure was not directly related to centrifugal and gas loading .G. Sánchez Sarmiento et.al [3], reviewed several finite element models for the determination of mechanical and thermal stresses in the SHS (Secondary Heat Sink) System. The models were developed by ABAQUS/CAE, solving with ABAQUS/Standard the problems of temperature distribution. M.

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MuraliKrishna et.al [4], presented a three-dimensional finite element analysis (FEA) of bolted flange joints carried out by taking experimentally obtained loading and unloading characteristics of the gaskets. I. J. Kumar et.al [5], presented Steady state thermal analysis and deformations in a hollow circular cylinder being head at the internal surface by a source which is sinusoidal along the length of the cylinder. Muhammad Abid [6], carried out analysis to investigate joint strength and sealing capability under combined internal pressure and different steady-state thermal loading, a 3D nonlinear finite element analysis (FEA) of a gasketed flange joint is carried out and its behavior is discussed.

STEVEN E.BENZLEY et.al [7] describes paper on comparison of all hexagonal and all tetrahedral finite element meshes for elastic and elastoplastic analysis. This paper compares the accuracy of elastic and elastoplastic solid continuum finite element analyses modeled with all hexahedral or all tetrahedral meshes. S.Gowreesh et.al [8],studied the first stage rotor blade of a two stage gas turbine has been analyzed for structural, thermal, modal analysis using ANSYS11.0. The temperature distribution in the rotor blade has been evaluated using this software. A. Kandil et.al [9] presented a complete analysis of thermal stresses within a thick-walled cylinder under dynamic internal temperature gradient. A complete evaluation of temperature and stress distributions, in a non-steady state, is obtained using a numerical model. SANFORD FLEETER et.al [10] describes fatigue life prediction of turbo machine blading.HCF of turbo machinery blading is a significant design problem because fatigue failures can result from resonant vibratory stresses sustained over a relatively short time. ANGELO ARNALDI et.al [11] describes paper on repair and coating technologies for new gas turbine blades. In this paper, blade operating and service conditions are taken into consideration. The factors are inspection results, coating stripping, and cracks due to thermo mechanical stresses. Mr.P.N.TENGII et.al [12] describes advantages in manufacturing of turbine blade for aircraft engine. In this paper, geometry, data collection, reverse engineering, solid modeling, CNC machining, electrochemical machining, inspection by coordinate measuring machine is explained. M. Pradeep [13] describes the influence of taper, twist, thickness in rotor blade using Finite element analysis. Turbo machine rotor blades are subjected to different types of loading such as fluid or gas forces, inertia loads and centrifugal forces. Due to these forces various stresses are induced in rotor blades.

Stuart Moffat [14] describes paper on blade forced response prediction for industrial gas turbines. In this paper forced response prediction is given. The mode shapes and natural frequencies are determined by finite element analysis.Dr. K. Ramachandra, [15] describes need for analysis of stress concentration factor in inclined cutouts of gas turbine blades. In this paper, aero engine gas turbine blades are aerofoil in cross -section and are twisted mounted on annular plate, which in turn is fixed to rotating disc.

II. METHODS AND METHODOLOGY

➢ Finite Element Method

The FEM was first developed in 1956. It is originated as a method of stress analysis. It consists of three modules; a pre-processor, a solver, and a post processor. In this method of analysis, a complex region defining a continuum is discretized into simple geometric shapes called finite elements.

➢ ANSYS Analysis

A typical ANSYS analysis has three distinct steps:

- Build the model.
- Apply loads and obtain the solution.
- Review the results.

○ Loading

The word Loads in ANSYS terminology includes boundary conditions and externally or internally applied forcing functions. Loads are divided into six categories:

DOF constraints, Coupled-field loads, Inertia loads, Body loads, Surface loads, and Forces (concentrated loads)

➢ Solution

In the solution phase of the analysis, the computer takes over and solves the simultaneous set of equations that the finite element method generates.

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- **Post Processing**
  - How high are the stresses in this region?
  - How does the temperature of this part vary with time?
  - What is the heat loss across this face of my model?

The postprocessors in the ANSYS program can help the user answer these questions and others. Post processing means reviewing the results of an analysis

- **PROBLEM DEFINITION**

Initially Static analysis has carried to find deformation and vonmises stresses, coupled field analysis under thermo-mechanical loads is carried out to find the structural safety, Contact pairs using Targe170 and Contac174 elements are defined between the interface of disc and the blade finally modal analysis is carried out to find structural safety is the main definition of the problem. The objectives include

- Modelling of the Turbine blade with rotor
- Meshing and analysis
- Checking for the dynamic stability
- Checking for the structural safety

- **METHODOLOGY**
  - Literature on Turbine & Turbine blades
  - Three dimensional modelling
  - Meshing
  - Analysis for static loads
  - Contact pressure plot
  - Modal analysis
  - Coupled-field analysis under Thermo-Mechanical loads

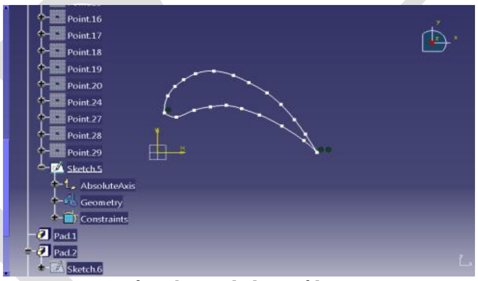

Fig.1: Key points of Turbine Blade Profile using CATIA software

The turbine blade is modeled in CATIA software using key points as shown in Fig.1.

MATERIALS;

In the present work the material used is **Ni Crome alloy**

Material properties of NiCrome alloy (80%Ni, 20%Cr)

Density 8314 Kg/m3

Modulus of elasticity 220Gpa

Poisson's ration 0.33

Thermal expansion coefficient 1.340e-5K

Thermal conductivity 12.6 W/m-K

Melting point temperature 1400 degree Celsius

Max.Operating Temperature 1200 degree Celsius

Constraint Equations or Boundary Conditions: Two structural boundary conditions namely displacement and force were applied on the rotor blade model. Due to cyclic symmetry nature, cyclic symmetry boundary conditions are

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applied on the model. Since the gas forces were assumed to be distributed evenly, the tangential and axial forces acts throughout the centroid of the blade. The centrifugal force also acts through the centroid of the blade and in radial direction.

A new file was opened in ANSYS and the thermal module of ANSYS was activated. The rotor blade model was copied into this file from which the previous structural analysis files ‘X’. The structural boundary conditions which were applied previously on the rotor blade model were deleted. The element type was stitched from structural to its equivalent thermal element type. The material properties were same as those in the previous file of structural analysis two boundary conditions namely Heat flux and Convection were applied on the rotor blade model. The solution part of ANSYS was opened and Heat flux = 0 was applied on the areas shaded and numbered in fig.

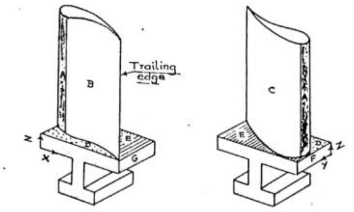

Fig.2. Thermal Boundary conditions
(Applied on the areas shown in fig)

FORCE AND TEMPERATURE CALCULATIONS

At the inlet of the first stage rotor blades,
Absolute flow angle α2 = 23.850
Absolute velocity V2 = 462.21 m/s
Diameter of blade midspan D = 1.3085 m
Design speed of turbine N = 3426 rpm

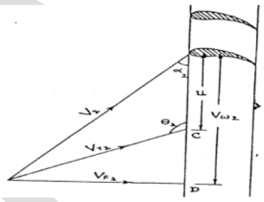

Fig.3. Inlet velocity triangles

From the inlet velocity triangles in fig we get,
Whirl velocity Vw2 = 422.74 m/s
Flow Velocity Vf2 = 186.89 m/s
Relative velocity Vr2 = 265.09 m/s

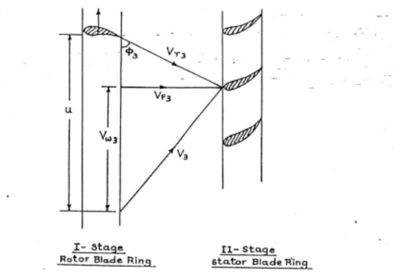

Fig.4. Exit velocity triangles

Using Fig.3 & Fig.4, shows Inlet and Exit velocity triangles of first stage gas turbine rotor blades using these triangles Whirl velocity, Flow Velocity and Relative velocity are calculated.

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At the exit of first stage rotor blades,
Flow velocity Vf3 = 180.42 m/s
Relative flow angle θ2 = 37.88 0

From the exit velocity triangles we get,
Whirl velocity Vw3 = 2.805 m/s
Relative velocity Vr3 = 293.83 m/s
Mass flow rate of gases through the turbine
M = 65.08 kgs/sec

Total Tangential force: Ft = M (Vw2 – (+Vw3)] in Newtons
Total Axial Force: FA = M (Vf2 – (+Vf3)] in Newtons
Power developed (P): P = m {Vw2 U – (+Vw3 U)} (From Euler's energy equation)
Ft = 27329.35 Newtons
Fa = 421.06 Newtons.
P = 6.40 Mega Watts

EVALUATION OF CONVECTIVE HEAT TRANSFER COEFFICIENTS OF FIRST STAGE ROTOR BLADES

Temperature of gases at inlet Ti = 839.22^0 c
Temperature of gases at exist Te = 732.88^0 c
Mean fluid temperature, $Tmf = \frac{Ti - Te}{2}$
The flowing properties of air at Tmf were noted.
Reynolds number
$Re = \ldots\ldots\ldots \frac{Vr * D}{V}$
$NuD = C\ ReD.^m Pr^{0.333}$
NuD = 247.329
$NuD = \ldots\ldots \frac{Hs * D}{K}$
Hs = 379.92 w/m^2 k
Hp = 284.95 w/m^2 K
Convective heat transfer coefficients at inlet
hfi = 231.195 w/m^2 K
Convective heat transfer coefficients at exist
hfe = 224.73 w/m^2 K

- **MESHING**

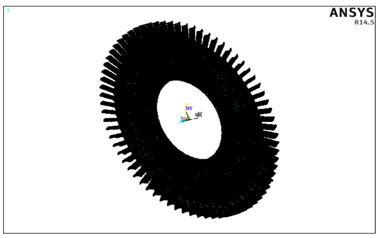

Fig.5. Expanded Mesh View (using cyclic symmetry)

The figure shows meshed geometry. The geometry is meshed with tetrahedral elements to ease contact pair creation and execution. Targe170 and contac174 elements are used for interface Contact preparation.

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III. RESULTS

The turbine disc and blade assembly is analysed for various loading conditions.
First the analysis has been made for normal rotational load condition and later checked for gas load conditions. Then coupled field analysis is carried out for structural safety. Contact pairs using Targe170 and Contac174 elements are defined between the interface of disc and the blade. Finally modal analysis is carried out to find the dynamic stability of the turbine blade disc assembly. The results are presented for all the load cases

➢ Case 1: For Rotational load condition

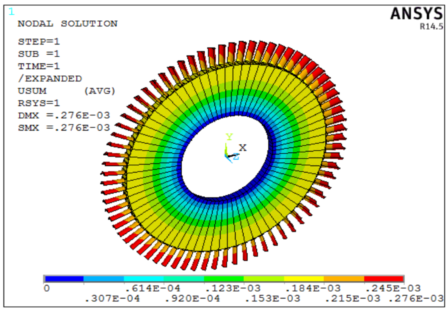

Fig.6. Displacement Plot for Rotational Load

The figure shows displacement plot of the turbine assembly. Maximum displacement is observed on the blade compared to the disc and it is around 0.276mm or 0.000276m.

➢ Case 2: With Gas Loads

The analysis is carried out with the structural loads as calculated in Force and Temperature calculations. The cyclic symmetry option is used to obtain the results

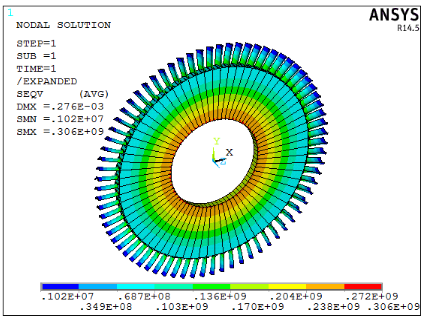

Fig.7. Vonmises Stress plot for the Rotational Load

The figure shows, Maximum stress is 306Mpa and at the inner boundary is observed and is Minimum at the outer boundary.

➢ Coupled Field Analysis Results

In the aero structures, the engine runs by burning of the gases. Temperature effects are very important in the structural stability. The materials are selected in such a ways as to reduce the thermal expansion coefficient of the materials. Also the temperatures reduce the yield strength of the material. So in the present analysis, temperature effects are considered to find the structural stability of the problem. The temperature boundary conditions are applied as discussed in the thermal loads

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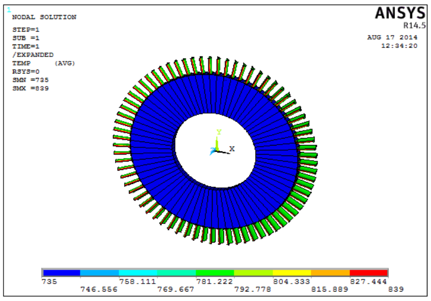

Fig.8. Temperature distribution plot

The figure shows, the temperature variation is between 735 degrees to 839 degrees Maximum temperature is observed at the leading edge blade due to application of the thermal boundary conditions.

➢ Overall Displacement Plot

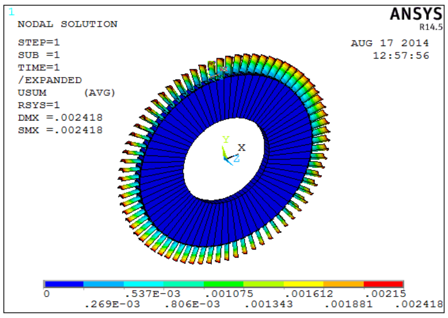

Fig.9. Overall Displacement Plot

The figure shows, Maximum displacement is around 2.418mm or 0.002418m. Maximum displacement is observed at the tip of the blade and is less in the disc region since it is nearer to the constraint region.

➢ Modal analysis

Modal analysis has been performed to find resonance frequency in the assembly due to the rotating members with high speed. Generally for industrial applications, it is very much desirable to have the first natural frequency as high as possible as or at least higher than the maximum applied frequency for the system. Modal analysis is used to determine the natural frequencies and mode shapes of a structure. The procedure for modal analysis consist of four main steps

- ➢ Build the model
- ➢ Apply loads and obtain the solution
- ➢ Expand the modes
- ➢ Review the results

Table.1. Natural Frequencies

SL .No	Frequency(Hz)
1	409.75
2	900.03
3	1741
4	3012.5
5	4016

Table.1 shows different natural frequencies & these are the natural frequencies obtained from modal analysis

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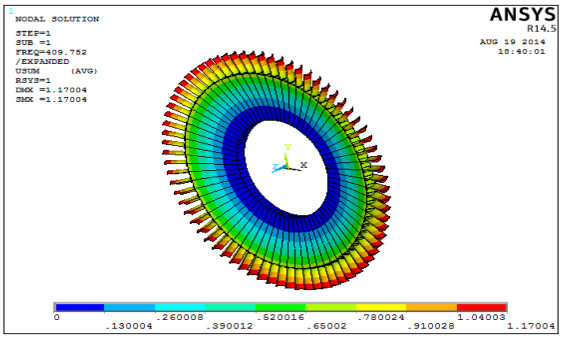

Fig.10. Mode Shape corresponding to the Natural Frequency 409.752Hz

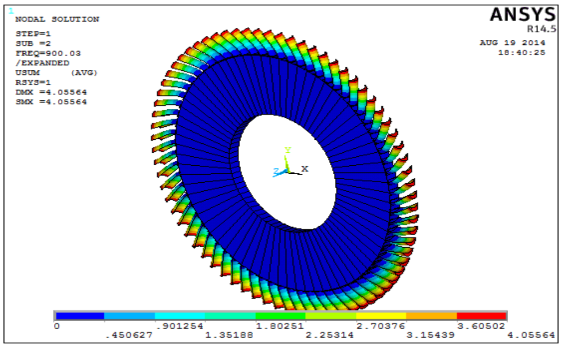

Fig.11. Mode Shape corresponding to the Natural Frequency 900.03Hz

Fig.10 & Fig.11 shows the different mode shapes obtained for the corresponding natural frequencies 409.752Hz and 900.03Hz using modal analysis and these frequencies are greater than operational frequencies, so the system is dynamically stable.

IV. CONCLUSIONS

Gas turbine blade assembly is analysed for various load cases to find the structural stability. The overall summary is as follows.

- Initially the loads and Convection heat transfer coefficients are calculated from the given input data by using velocity triangles and as per the standard thermal formulations.
- The theoretical estimates for centrifugal force, tangential and axial loads are calculated for the given load data
- By specifying heat flux and convection on the faces of the turbine rotor and the disc the analysis the thermal analysis is carried out carried out for rotational load alone. Later the analysis is carried out for rotation along with the gas forces.
- Further modal analysis is carried out to find the dynamic stability of the rotor system. The results shows the natural frequencies obtained are much higher than the operational frequency. So the system is dynamically stable.

➢ **FURTHER SCOPE**

- The analysis can be further analysed for transient boundary conditions
- Can be integrated to all stages of gas turbine
- Spectrum analysis can be carried out
- Composite usage for the problem can be checked.
- Design optimization can be carried out. Also topology can be changed for better results.

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