International Journal of
Scientific Engineering and Technology Research

ISSN 2319-8885
Vol.03,Issue.20
September-2014,
Pages:4173-4180

www.semargroup.org,
www.ijsetr.com

Finite Element Analysis of a Gas Turbine Rotor Blade

HAYDER SALIM LAFTA[1], DR.A.V.S.S.K.S.GUPTA[2]

[1]PG Scholar, Dept of Mechanical Engineering, JNTUH College of Engineering, Hyderabad, India,
& Republic of Iraq council of Ministries Shia Endowment Head office, E-mail: hhhbbb_1970@yahoo.com.
[2]Prof, Dept of Mechanical Engineering, JNTUH College of Engineering, Hyderabad, India, E-mail: avs_gupta@jntuh.ac.in.

Abstract: Turbine is a device designed to convert the heat energy of fuel into useful work. In the present work the first stage rotor blade gas turbine has been analyzed for structural, thermal using ANSYS software14.5, which is a powerful Finite Element analyses In the process to get mechanical and the thermal stresses, the temperature distribution in the rotor blade has been evaluated using this software. The temperature has a significant effect on the overall stress on the rotor blades; it has been felt that a detail study can be carried out on the temperature effects to have a clear understanding of the combined mechanical and thermal stresses for three materials. The mechanical and radial elongations resulting from the tangential, axial and centrifugal forces. The gas forces namely tangential, axial were determined by constructing velocity triangles at inlet and exist of rotor blades. The rotor blade was then analyzed using ANSYS 14.5 for the temperature distribution. The convective heat transfer coefficients on the blade surface exposed to the gas have to feed to the software. The convective heat transfer coefficients were calculated using the heat transfer empirical relations taken from the heat transfer design data book. The radial elongations in the blade were also evaluated. The material of the blade was specified for three materials as titanium alloy, zirconium alloy and super alloy. This material and structural and thermal properties at gas room and room temperatures were taken from the design data books that were available in the library of BHEL(R & D), Hyderabad. The turbine blade along with the groove is considered for the static, thermal, modal analysis. The blade is modeled with the 3D-Solid Brick element. The geometric model of the blade profile is generated with splines and extruded to get a solid model. The thermal boundary conditions such as convection and operating temperatures on the rotor blade are applied on theoretical modeling. Analytical approach is used to estimate the tangential, radial and centrifugal forces. The purpose of this thesis is to study the effect of structure thermal analysis on gas turbine blades, where it was observed that less thermal and mechanical stress.

Keywords: Engineering Applications of the (FEM), Computer Aided Engineering (CAE), ANSYS.

I. INTRODUCTION

The finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems. Although originally developed to study stresses in complex airframe structures, it has since been extended and applied to the broad field of continuum mechanics. that occurs in the titanium alloy and minimum thermal gradient less displacement occur in zirconium alloy and showing that less strain happens in the super alloy By comparing the other two materials the stress capability for Titanium alloy gives better results.

A. Finite Element Method

The finite element method is a numerical method that can be used for the accurate solution of complex engineering problem. It is considered to be one of the best methods for solving a wide variety of practical problems efficiently. It is method (FEM) has now become a very important tool of engineering analysis. Its versatility is reflected in its popularity among engineers and designers belonging to nearly all the engineering disciplines. Whether a civil engineer designing bridges, dams or a mechanical engineers designing auto engines, rolling mills, machine tools or an aerospace engineer interested in the analysis of dynamics of an aero plane or temperature rise in the heat shield of a space shuttle or a metallurgist concerned about the influence of a rolling operation on the microstructure of a rolled product or an electrical engineer interested in analysis of the electromagnetic field in electrical machinery-all find the finite element method handy and useful. It is not that these problems remained unproved before the finite element method came into vogue; rather this method has become popular due to its relative simplicity of approach and accuracy of results. Traditional methods of engineering analysis, while attempting to solve an engineering problem mathematically, always try for simplified formulation in order to overcome the various complexities involved in exact mathematical formulation.

In the modern technological environment the conventional methodology of design cannot compete with the modern trends of Computer Aided Engineering (CAE) techniques. The constant search for new innovative design in the engineering field is a common trend. To build highly optimized product, which is the basic requirement for survival in the global market today? All round efforts were put forward in this direction. Software professional and technologists have developed various design packages. Because of its diversity and flexibility as an analysis tool, it is receiving much attention in engineering schools and in industry.

B. Engineering Applications of the (FEM)

Although the method has been extensively used in the field of structural mechanics, it has been successfully applied to solve several other types of engineering problem, such as heat conduction, fluid dynamics, seepage flow, and electric and magnetic fields. These applications prompted mathematicians to use this technique for the solution of complicated boundary value and other problems. In fact, it has been established that the method can be used for the numerical solution of ordinary and partial differential equations the general applicability of the finite element method can be observing

Civil Engineering Structural: Static analysis of tresses, frames, folded plates, shell roofs; shear walls, bridges, and prestressed concrete structure.

Aircraft structure: Static analysis of air craft wings, fuselages, fins, rockets, spacecraft, and missile structure.

Heat conduction: Steady –state temperature distribution in solids and fluids.

Geomechanics: Analysis of excavation, retaining wall, underground openings, rock joints, and soil –structure interaction problem: stress analysis in soils, dams, layered piles, and machine foundations.

Hydraulic and water resources engineering: Analysis of potential flows, free surface flows, boundary layer flows, viscous flows, transonic; analysis of hydraulic structures and dams.

Nuclear engineering: Analysis OF nuclear pressure vessels and containment structure; steady –state temperature distribution in reactor components.

Biomedical engineering: Stress analysis of eyeballs, bones, and teeth; load –bearing capacity or implant and prosthetic systems; mechanics of heart values.

Mechanical design: Stress concentration problems; stress analysis of pressure vessels, pistons, composite materials, linkages, and gears.

Electrical machines and electromagnetic: Steady – state analysis of synchronous and induction machines, eddy current, and core losses in electric machine, magneto statics.

II. CONSTRUCTIONAL FEATURES OF GAS TURBINE ROTOR BLADE

The purpose of turbine technology are to extract the maximum quantity of energy from the working fluid to convert it into useful work with maximum efficiency by means of a plant having maximum reliability, minimum cost, minimum supervision and minimum starting time. The gas turbine obtains its power by utilizing the energy of burnt gases and the air which is at high temperature and pressure by expanding through the several ring of fixed and moving blades. To get a high pressure of order 4 to 10 bar of working fluid, which is essential for expansion a compressor, is required. The quantity of ten working fluid and speed required are more so generally a centrifugal or axial compressor is required. The turbine drives the compressor so it is coupled to the turbine shaft. If after compression the working fluid were to be expanded in a turbine, then assuming that there were no losses in either component, the power developed by the turbine can be increased by increasing the volume of working fluid at constant pressure or alternatively increasing the pressure at constant volume. Either of these may be done by adding heat so that the temperature of the working fluid is increased after compression. To get a higher temperature of the working fluid a combustion chamber is required where combustion of air and fuel takes place giving temperature rise to the working fluid. Gas turbines have been constructed to work on the following: Oil, natural gas, coal gas, producer gas, blast furnace and pulverized coal.

A. Construction of Gas Turbine Rotor Blade and Its Components

The gas turbine engine was first developed some forty years ago and by the early 1950s it was a commonplace power unit for both military and civil aircraft as shown in Fig.1. However, in more recent years the gas turbine has become the prime power unit in many diverse applications including military and commercial land transport and marine propulsion systems. It is in the latter role where the greatest number of corrosion problems occurs, these being particularly severe within the turbine section of engines used in ships, hovercraft and helicopters. A simple gas turbine is comprised of three main sections: a compressor, a combustor and a turbine. The gas turbine operates on the principle of the Brayton cycle where compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is expanded through a turbine to perform work.

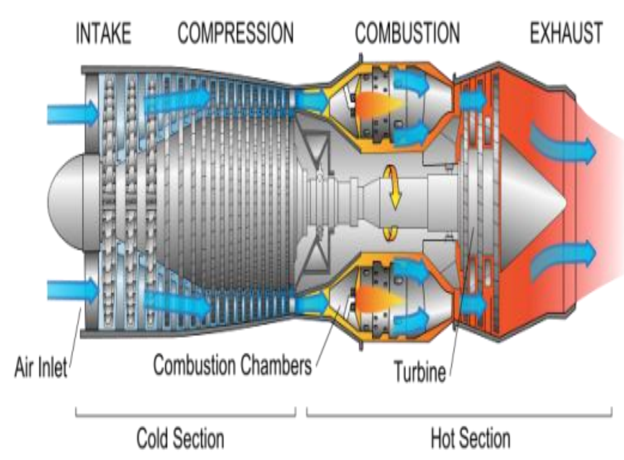

Fig.1. Gas Turbine Engine.

A compressor is a mechanical device that increases the pressure of a gas by reducing its volume. Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. As gases are compressible, the compressor also reduces the volume of a gas. Liquids are relatively incompressible; while some can be compressed, the main action of a pump is to pressurize and transport liquids. A combustion chamber is the part of an engine in which fuel is burned. A turbine is a rotary engine that extracts energy from a fluid flow and converts it into useful work. Energy is added to the gas stream in the combustor, where fuel is mixed with air and ignited. In the high pressure environment of the combustor, combustion of the fuel increases the temperature. The products of the combustion are forced into the turbine section. The simplest turbines have one moving part, a rotor assembly, which is a shaft or drum with blades attached. Moving fluid acts on the blades, or the blades react to the flow, so that they move and impart rotational energy to the rotor.

1. Working Cycle:

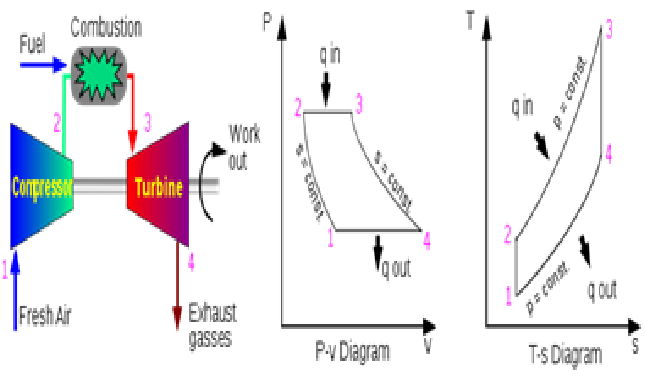

Fig.2. Working Cycle.

The Brayton cycle is a thermodynamic cycle that describes the workings of the gas turbine engine, basis of the air breathing jet engine and others. It is named after George Brayton(1830–1892), the American engineer who developed it, although it was originally proposed and patented by Englishman John Barber in 1791.[1] It is also sometimes known as the Joule cycle. The Ericsson cycle is similar but uses external heat and incorporates the use of a regenerator. The working cycle of the gas turbine engine is similar to that of the four-stroke piston engine as shown in Fig.2. However, in the gas turbine engine, combustion occurs at a constant pressure, whereas in the piston engine it occurs at a constant volume. Both engine cycles show that in each instance there is induction, compression, combustion and exhaust. These processes are intermittent in the case of the piston engine whilst they occur continuously in the gas turbine. In the piston engine only one stroke is utilized in the production of power, the others being involved in the charging, compressing and exhausting of the working fluid. In contrast, the turbine engine eliminates the three 'idle' strokes, thus enabling more fuel to be burnt in a shorter time; hence it produces a greater power output for a given size of engine.

Due to the continuous action of the turbine engine and the fact that the combustion chamber is not an enclosed space, the pressure of the air does not rise, like that of the piston engine, during combustion but its volume does increase. This process is known as heating at constant pressure. Under these conditions there is no peak or fluctuating pressures to be withstood, as is the case with the piston engine with its peak pressures in excess of 1,000 lb. per sq. in. It is these peak pressures which make it necessary for the piston engine to employ cylinders of heavy construction and to use high octane fuels, in contrast to the low octane fuels and the light fabricated combustion chambers used on the turbine engine. The working cycle upon which the gas turbine engine functions is, in its simplest form, represented by the cycle shown on the pressure volume. Point 1 represents air at atmospheric pressure that is compressed along the line 1-2. From 2 to 3 heats is added to the air by introducing and burning fuel at constant pressure, thereby considerably increasing the volume of air. Pressure losses in the combustion chambers (Part 4) are indicated by the drop between 2 and 3. From 3 to 4 the gases resulting from combustion expand through the turbine and jet pipe back to atmosphere. During this part of the cycle, some of the energy in the expanding gases is turned into mechanical power by the turbine; the remainder, on its discharge to atmosphere, provides a propulsive jet. Because the turbo-jet engine is a heat engine, the higher the temperature of combustion the greater is the expansion of the gases. The combustion temperature, however, must not exceed a value that gives a turbine gas entry temperature suitable for the design and materials of the turbine assembly.

B. Turbine Blade Cooling

Unlike steam turbine blading, gas turbine blading need cooling as shown in Fig.3. The objective of the blade cooling is to keep the metal temperature at a safe level to ensure a

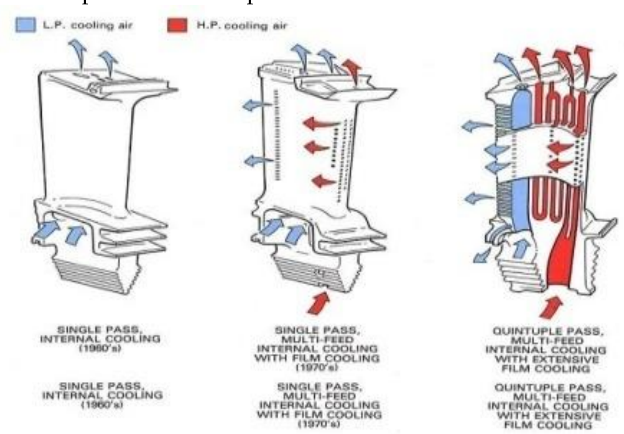

Fig.3. Turbine Blade cooling.

long creep life and low oxidation rates. Although it is possible to cool the blades by liquid using thermo siphon and heat pipe principal, but the universal method of blade cooling is by cool air or working fluid flowing through internal passage in the blades. The mean rotor blade temperature is about 350^0 c below the prevailing gas temperature after efficient blade cooling. Due to corrosion and corrosion deposits turbine blades fail. To protect it from corrosion, the uses of pack-aluminized coatings are used. The main elements used are aluminum, nickel, and chromium.

C. Applications of Gas Turbine

The following are the applications of gas turbine

Land applications:

i. Locomotive propulsion

ii. Central power stations

- Standby plants for hydro installations
- Fully automatic booster stations at end of transmission lines
- Standby and peak load plants for small system
- Bomb proof power plants
- At location where water is not available

iii. Industrial Pumping stations

Space applications:

i. Turbo jet

ii. Turbo propulsion

Marine applications:

i. Gas turbine propulsion

III. CALCULATIONS

A. Evaluation of Gas Forces on the Rotor Blades

At T he inlet of the first stage rotor blades,

Absolute flow angle $\alpha_2 = 23.85^0$

Absolute velocity $V_2 = 462.21$ m/s

Diameter of blade mid-span $D_m = 1.3035$ m

Design speed of turbine N = 3426 RPM

Number of blade passages in first stage rotor n = 120

Blade angle at inlet, $\theta_2 = 135.017\ ^0$

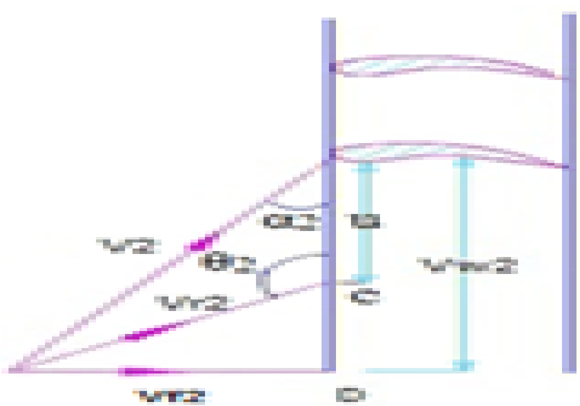

Fig.4. Inlet velocity triangles of I-stage rotor blades.

The velocity triangles at inlet of first stage rotor blades were constructed as shown in Figs.4, 5 and 6.

Peripheral speed of rotor blade at its mid span

$$U = \pi DN/60 \quad (1)$$

Whirl velocity, $V_{w2} = V_2 \cos \alpha_2$

Flow Velocity, $V_{f2} = V_2 \sin \alpha_2$

Relative velocity, $V_{r2} = \sqrt{[(Vw2 - U)^2 + Vf2^2}$

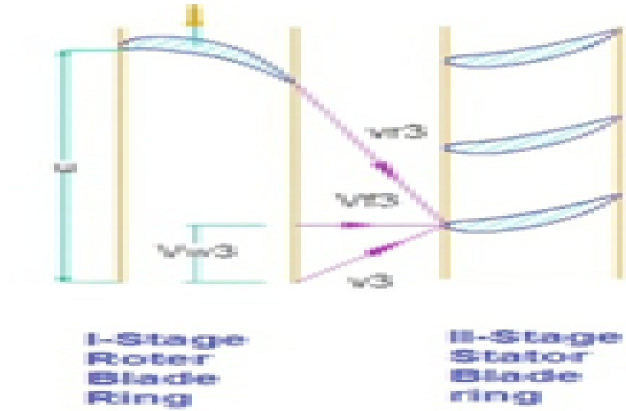

Fig.5. Exit velocity triangles of I-stage rotor blades.

At the exit of first stage rotor blades,

Flow velocity, $V_{f3} = 180.42$ m/s

Relative flow angle, $\phi_3 = 37.88\ ^0$

Relative velocity, $Vr3 = V_{f3} / \sin \Phi_3$

Whirl velocity, $V_{w3} = U - (V_{f3} \cos \phi_3)$

$$F_T = M\,(V_{w2} - (+V_{w3})] \quad (2)$$

$$F_A = M\,(V_{f2} - (+V_{f3})] \quad (3)$$

$$M = \rho_2 * \pi * (D_0^2 - D_i^2)/4 * V_{f2} \quad (4)$$

$$Ft = \frac{FT}{NO.OF\ BLADE} \quad (5)$$

Number of blade passages in first stage rotor n = 120

$$Fa = \frac{FA}{NO.OF\ BLADE} \quad (6)$$

B. Centrifugal Forces Experienced By the Rotor Blades

The distance

$$x = \frac{m_1x_1 + m_2x_2 + m_3x_3}{m_1 + m_2 + m_3} \quad (7)$$

Where m_1, m_2, m_3 are masses of volumes 1,2 and 3 and x_1, x_2 and x_3 are distances of the Centroid of volumes 1,2 and 3 from axis of revolution.

TABLE I: Damnation Of Rotor Blade

L	t mm	h mm	w mm	k mm	m mm	Z mm	S mm	Acs mm^2
117	5	27	27	49	9.4	12	3.8	384

Where V_1, V2 and V_3 are volumes of portions1, 2 and 3 of rotor blades

Volume of portion (1) $V_1 = Ac * L$

$$x_1 = \frac{D}{2}$$

$$x_2 = \frac{D1}{2} - \frac{t}{2}$$

$$x_3 = \frac{D1}{2} - [t + \frac{h}{2}]$$

Centrifugal force (Fc) for the material super alloy:

$$F_c = M * (2\,\pi\, N/60)^2 * (x) \quad (8)$$

N = Rotor speed, RPM

Volume of portion (1) $V_1 = Ac * L$

C. Convective Heat Transfer Coefficients Over The Blade Surfaces

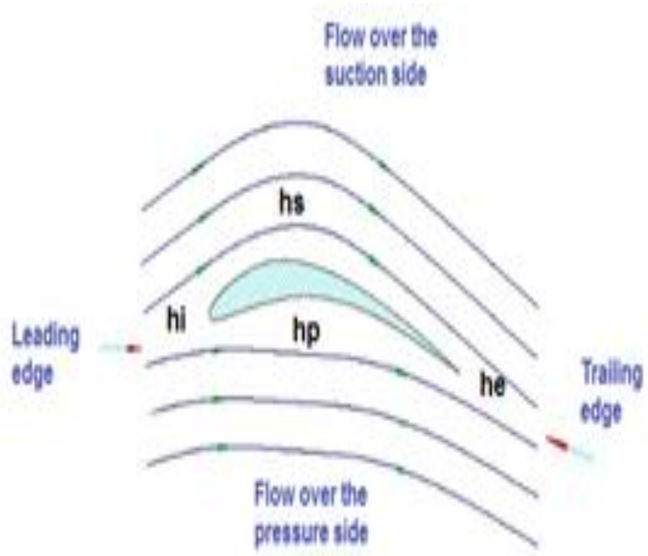

Fig.6. Gas Flow over suction and pressure side of rotor blade.

$$T_{mf} = \frac{T_i + T_i}{2} \quad (9)$$

Average relative velocity,

$$V_{r=} = \frac{V_{r2} + V_{r3}}{2} \quad (10)$$

Reynolds number

$$Re = \frac{V_{r2} * D_{ch}}{v} \quad (11)$$

$$NuD = C\, ReD^m Pr^{0.333} \quad (12)$$

$$hs = \frac{N_u D * K}{Dch}$$

$$Nu = 0.664\, Pr^{1/3} \quad Re^{1/2} \quad (13)$$

$$U = \pi\, DN/60$$

Reynolds number,

$$Re = \frac{U * w}{v} \quad (14)$$

$$Nu = 0.664\, Pr^{1/3} \quad Re^{1/2}$$

For flat plate,

$$N_U D = \frac{hi * w}{k} \quad (15)$$

$$hi = \frac{N_u D * K}{w}$$

$$U = \pi\, DN/60$$

Reynolds number,

$$Re = \frac{U * w}{v} \quad (16)$$

$$Nu = 0.664\, Pr^{1/3} \quad Re^{1/2}$$

For flat plate,

$$N_U D = \frac{he * w}{k} \quad (17)$$

$$h_e = \frac{N_u D * K}{w}$$

TABLE II: Theoretical Results from Calculation

Materials	He (w/m2.k)	Hi (w/m2.k)	Hp (w/m2.k)	hs (w/m2.k)	Fc (N)	Ft (N)	Fa (N)
Titanium			20833.				
Super Alloy	458.8	3.8	40018.	228.	231.	284.2	360
zirconium			31606.				

IV. ANALYSIS USING ANSYS

Resulting of an analysis is as shown in Figs.7 to 14.

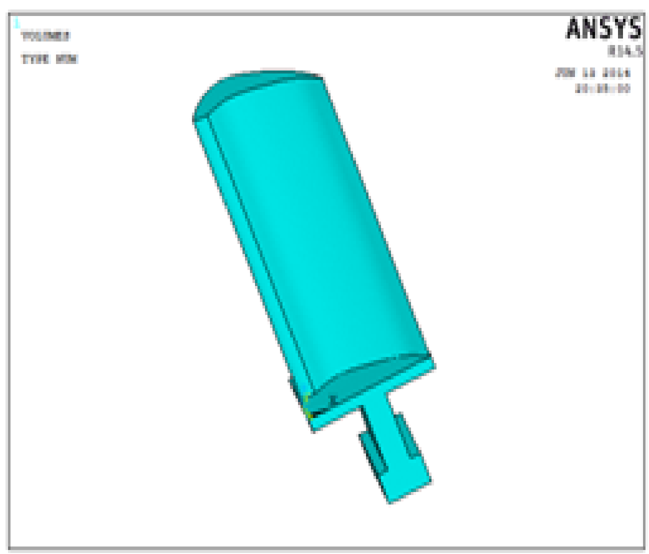

Fig.7. titanium model rotor blades.

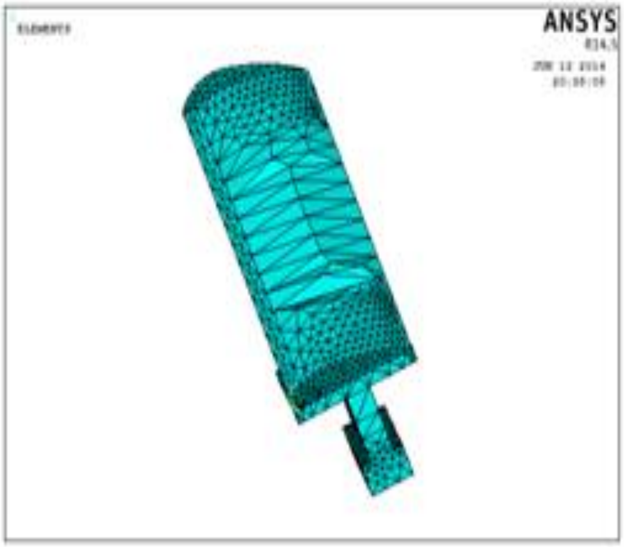

Fig.8. titanium Finite Element model.

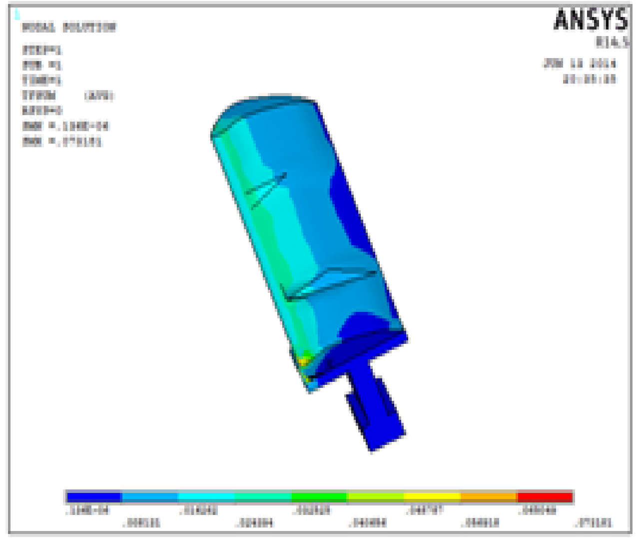

Fig.11. titanium Thermal fluxes Vector sum (w/mm^2).

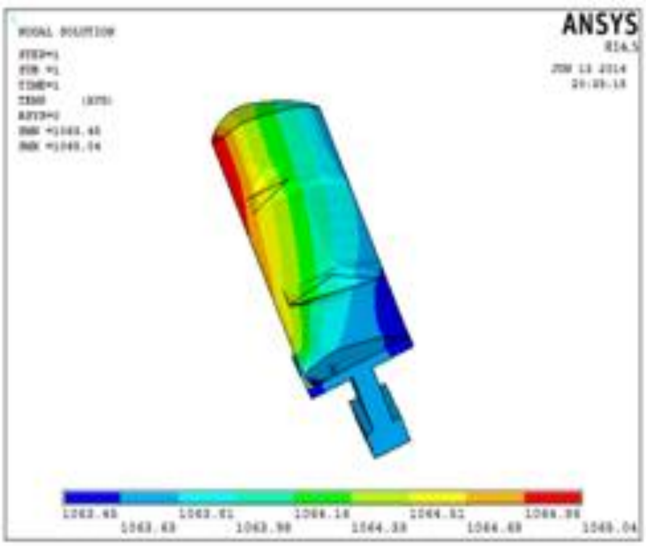

Fig.9. titanium temperature vector(K).

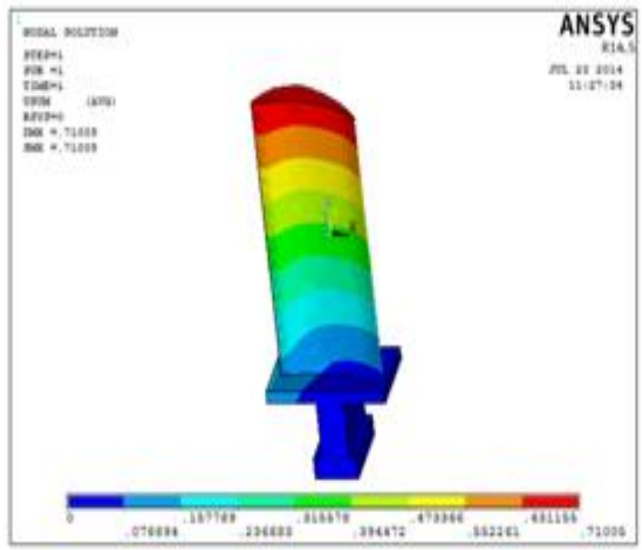

Fig.12. titanium alloy Displacement Vector (mm).

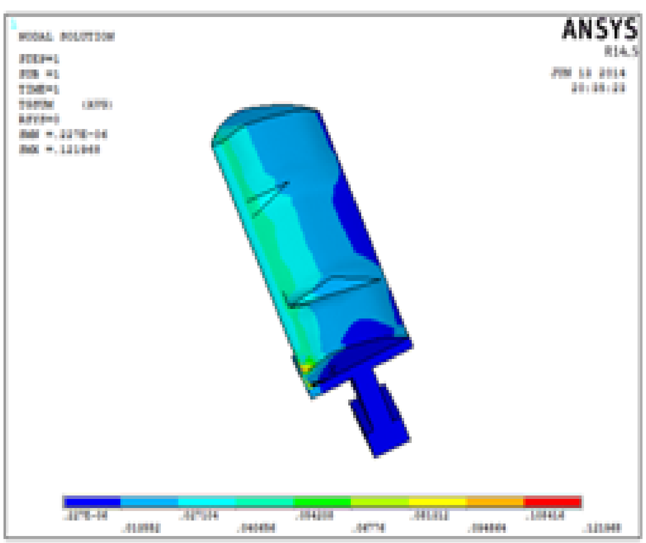

Fig.10. titanium thermal Gradient Vector sum (K/mm).

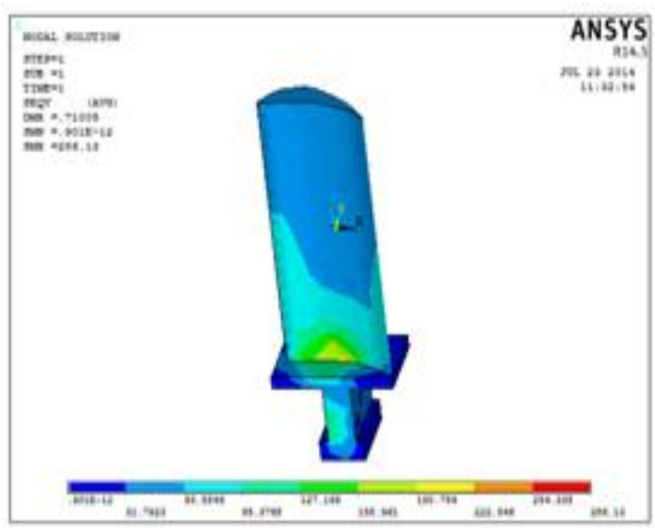

Fig.13. titanium alloy Von Mises.

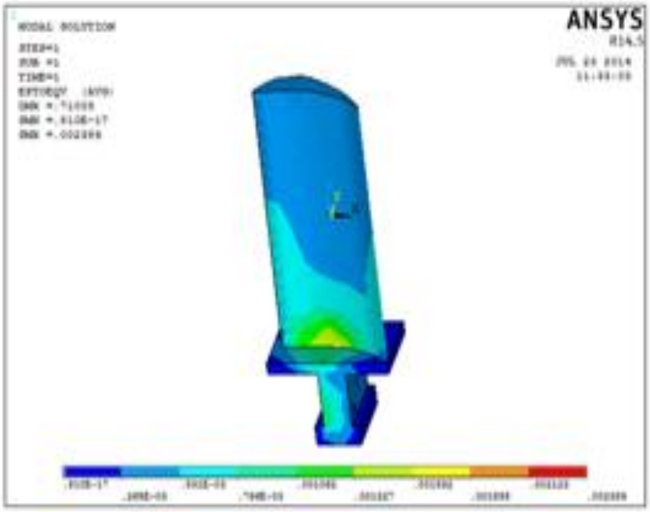

Fig.14. titanium alloy Total mechanical.

TABLE III: Structural Results

MATERIAL	DISPLACEMENT mm		STRESS Mpa		STRAIN	
	Min.	Max.	Min.	Max.	Min.	Max.
Titanium	0	0.7100	$0.901e^{-12}$	286.13	$0.810\ e^{-17}$	0.002389
Zirconium	0	0.1174	$0.137\ e^{-11}$	400.57	$0.151\ e^{-17}$	0.00410
Super Alloy	0	0.6301	$0.176\ e^{-11}$	490.46	$0.862e^{-17}$	0.002234

TABLE IV: Thermal Results

MATERIAL	NODAL TEMPERATURE k		THERMAL GRADIENT k/mm		THERMAL FLUX W/mm²	
	Min.	Max.	Min.	Max.	Min.	Max.
Titanium	1063.45	1065.04	$0.227\ e^{-06}$	0.121968	$0.136\ e^{-06}$	0.073181
Zirconium	1054.55	1078.96	$0.249\ e^{-05}$	3.34249	$00424\ e^{-07}$	0.056822
Super Alloy	1056.75	1075.88	$0.162\ e^{-05}$	2.4333	$0.404\ e^{-07}$	0.060589

V. RESULT AND DISCUSSION

The finite element analysis for structural and thermal analysis of gas turbine rotor blade is carried out using ANSYS 14.5 the temperature has a significant effect on the overall turbine blades. Maximum elongations and temperature are observed at the tip section and minimum elongation and temperature variation at the root of the blade the structural analysis shows that the variation of stress and strain for different materials along with the deformation for the three materials. The strain graphs are obtained as shown in the Graph (6.3) .it is observed that the maximum strain is 0.00410 for Zirconium alloy, 0.002389 for Titanium alloy and for Super Alloy the strain value is 0.002234. The deformations are obtained as shown in the Graph (6.1), and it is observed that the maximum deformation is 0.71005 mm, 0.630135mm and 0.117457 mm for Titanium alloy, Super Alloy and Zirconium alloy respectively By comparing the above results the minimum stress to Titanium minimum strain to Super Alloy and minimum deformation is for Zirconium alloy .The variation in the temperature is plotted and by analyzing the plots of the three different materials the material Zirconium alloy, shows high withstanding in temperature around 1078.96 k which can withstand without causing any damage to the blade. We observed the temperature variation from the tip at leading edge to trailing edge of blade the temperature is gradually decreasing and also we observed the maximum value temperature at the tip section of the blade is gradually decreasing to the root of the blade. Where always maximum curvature is occurs the temperature variation is less at the root of the blade .the temperature variation along X-direction is varying on front side. Inside and on the backside of the blade. The temperature decreases gradually along Z-direction. There is very small temperature gradient is occurring along Y-direction at the blade leading edge, on the suction side of blade and at the exits side of the blade.

VI. CONCLUSION

The thermal stress analysis together with the mechanical stress analysis will yield more valuable information about the actual magnitudes of the overall stresses encountered in turbine blades. In this research work analyze we will make comparing with many materials.

- The temperature has a significant effect on the overall stresses in the turbine blades.
- Maximum elongations and temperatures are observed at the blade tip section 0.71005 mm, 1078.96 k and minimum elongation at the root and temperature variations at the root and the trailing edge of the blade.
- Temperature distribution is almost uniform at the maximum curvature region along blade profile.
- Maximum stress induced is within safe limit.
- Maximum thermal stresses are set up when the temperature difference is Maximum from outside to inside.
- Maximum stresses and strains are observed at the root of the turbine blade and upper surface along the blade roots.
- Elongations in X-direction are observed only at the blade region in the along the blade length and elongation in Z-direction are gradually varying from different sections along the rotor axis.
- It could be concluded that these contour maps and profiles enables us to ascertain the areas of rotor blades that are vulnerable for failure.
- 11- By comparing the other two materials the stress capability is for Zirconium alloy it is 400.577 Mpa and for Super Alloy it is 490.466 Mpa so the material Titanium alloy gives better results 286.13 Mpa.
- 12-If cost of the materials is not a primary issue we can select the titanium alloy which have lesser stress, lesser value.

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Author's Profile:

Hayder Salim Lafta, awarded his Technical Diploma Degree in Machine and Equipment /Automotive Dept from The Institute of Technology-Kufa / Foundation of Technical Education, Received his Bachelor Degree in Mechanical Engineering & Education from University of Technology -Baghdad, IRAQ. Presently he finished his Master of Technology (Thermal Engineering) in Jawaharlal Nehru Technological University, Hyderabad, INDIA. His research interest.

Dr. A.V. S. S. K. S .Gupta Professor of Examinations Mechanical Engineering Areas of Interest**:** Thermodynamics, Combined Cycles, Clean Coal Technological FEM. Specialized in Thermal Engineering. His Research interests include Thermodynamics, Fluidized Bed Combustion, Combined Cycle, and Heat Transfer.