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Thermo-Structural Analysis of High-Pressure Turbine Blade

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Abstract:
Turbine blade tip clearance plays major role in smooth running of axial turbines. The turbine blade clearance contributes 20-40% of total loss in gas turbine. In Rolls Royce MT2 Turbine with 2% tip to span clearance ratio, tip clearance accounts for 40% of total losses. Turbine blade clearance is necessary as the turbine blade operates at very high temperature up to 1700 ºC and very high centrifugal load. Small turbine tip clearance may forbid expansion of turbine blade which will result in turbine tip rubbing with the casing.

High pressure turbine blade experiences high thermal and centrifugal stress. The objective of this paper is to study the individual and combined effect of these stress. The material used for analysis is cast based nickel alloy IN-738. The melting range of this alloy is 1230-1315 ºC with thermal expansion coefficient of 15.39E-6 per ºC. The turbine blade geometry with height 120 mm is used for analysis. The Mathematical modelling of above geometry shows that the centrifugal force with rotation velocity 100 rad/s produces 0.00252424 mm elongation and combined thermal-centrifugal loading produces 1.46520576 mm elongation.

The results form ANSYS is used for verification and the elongation due to centrifugal stress is 0.0014885 mm and combined stress produces elongation of 1.2608 mm. The total elongation from analytical method and ANSYS are similar. It shows that the effect due to centrifugal force on turbine blade is less compared to thermal effect. For operating condition of 816 ºC temperature and 100 rad/s rotational velocity, the overall stress contributes around 1.22 % elongation of turbine blade span.

Keywords: Clearance, Energy Loss, Elongation, Centrifugal Stress, Thermal Stress

1 Introduction

All new Turbofan Engines uses axial turbines to extract power from thermal fluid. This power is used to drive fan blade which ultimately generate significant Thrust. Extraction of the power from thermal fluid depends mainly on the turbine blade geometry, thermal head and rotational speed [1]. Steam turbines also use axial turbines to generate shaft power, which ultimately drives generators to generate electricity. The temperature distribution on steam turbine is not as high as in Gas Turbines but because of the huge size of these turbine blade, even supersaturated steam turbine temperature results in significant elongation. About 90% of the world's power is generated using Turbo-machines [2].

Axial Turbine blades encounters significant loss in total efficiencies because of tip clearance, frictional loss, viscous effects, vibrations etc. Among these, tip-clearance contributes to 20-40% of the total losses in Gas Turbine [3]. Hence, reduction of tip clearance is of paramount importance. The design for tip clearance includes the study of thermal and thermo-centrifugal strains/ elongation at certain operational speed of the turbine blade. This paper includes the study of influence-of-thermal distribution along the span-wise direction of High-Pressure Turbine blade on turbine-rotor-blade elongation.

1.1 Tip Clearance

High pressure turbine blades are loaded with very high thermal and centrifugal stresses. Because of these stresses elongation of the turbine blades is as high as 1.5 % of their span wise dimension [4]. In order to avoid turbine tip rubbing/interference with the casing, turbine blade clearance is used. The values of the turbine blade tip clearance are as high as 2.1% of the span wise dimension. The tip clearance gap in gas turbine such as Rolls Royce MT2 (with 2% clearance to span ratio (g/h)) is 0.44mm with hub to tip ratio 0.83, which accounts for losses up to 40% of the total efficiency whereas with 0.82% g/h the loss is 32% [5]

1.2 Temperature Distribution profile

Elongation of the turbine blades depends on various factors such as turbine rotational velocity, average turbine inlet temperature, temperature distribution profile along span wise direction, blade geometry and thermo-elastic properties of turbine blade material. Many of these variables are determined from aerodynamic design and state of art in material science and technology. This paper studies the effect of span wise temperature distribution profile in turbine blade elongation. Four cases of thermal distribution are studied in this paper. Figure 1, shows the different profiles of thermal distribution along the high-pressure turbine blades in a typical turbine blade without cooling vanes.

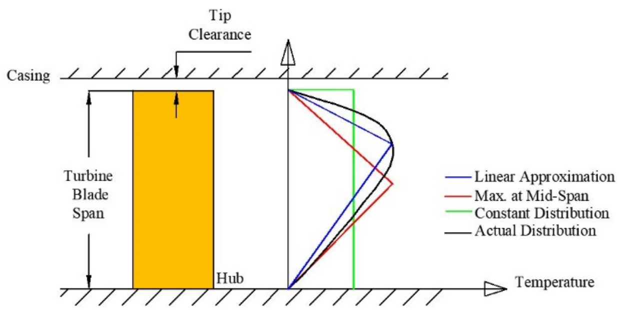

Figure 1: Span-wise temperature distribution

2 Geometry and Material Property

Table 1: Chemical Composition of IN 738 alloy

Element	Composition, weight percentage	
	High Carbon IN-738C	Low Carbon IN-738LC
Carbon	0.15-0.20	0.09-0.13
Cobalt	8-9	3-9
Chromium	15.70-16.30	15.7-16.3
Molybdenum	1.50-2	1.5-2
Tungsten	2.4-2.8	2.4-2.8
Tantalum	1.5-2.0	1.5-2
Aluminum	3.2-3.7	3.2-3.7
Titanium	3.2-3.7	3.2-3.7
Aluminum+Titanium	6.5-7.2	6.5-7.2
Boron	0.005-0.015	0.007-0.012
Nickel	Balance	Balance

Turbine blades are subjected to significant rotational and thermo mechanical stress. Few of the difficulties associated with turbine inlet is very high temperature (1400-1500 ºC), high pressure, high rotational speed, turbine vibrations and so on. Titanium based alloy are used in compressor for their light weight property [6]. The maximum temperature limit for this alloy is about 315-degree C. The temperature limitation for titanium alloys prevents its use in hottest part of engine. Also, the aluminum and titanium based wrought alloys have forgeability and hot working problems [7]. Despite having more weight than titanium alloys, Cast Nickel based alloys overcome all the above-mentioned problems and can be used in turbine blades. Also, the intrinsically cast components are stronger than forgings at high temperatures due to coarse grain size of casting [8]. The IN738 super alloy is one of the best nickel-based super alloys that has been used in modern turbine blades [9]. The chemical composition of IN 738 alloy [10] is shown in Table 1. For the mathematical calculation and computer simulation IN 738 alloy has been used in this paper.

Similarly, the blade profile used for simulation is adopted from NASA Energy Efficient Engine. The turbines using above blade material has turbine efficiency of 92.4% at Mach 0.8, and 35,000 ft. altitude [11]. The geometrical parameters used for calculations and analysis are shown in Table 3.

Table 2: Mechanical and Thermal property of IN 738

Density	8.11 g/cu cm °F
Melting Range	1230-1315 C
Specific Heat	0.17 Btu/lb/F (at 1800 °F)
Thermal Conductivity	176 Btu/ft^2/in/hr/°F (at 1800 °F)
Coefficient of Thermal Expansion	8.85E-6 °F for 70-188 °F
Modulus of Elasticity	20.3 psi at 1800 °F
Poisson's Ratio	0.3
Tensile Strength	159,000 psi (for IN-738C)
0.2% Yield Strength	138,000 psi (for IN-738C)

Table 3: Parameters of blade profile

	Value	Unit
Blade height (h)	120	mm
Chord length (c)	177	Mm
Blade inlet angle	22.37	Deg
Blade outlet angle	54.67	Deg

Assumptions made during the calculations:

a) Four different location of the maximum temperature has been chosen for the analysis of turbine blade elongation.

Limitations of the research

a) The deformation of blade wasn't verified through experiments.
b) The blade analysis for other materials was not carried out.
c) Turbine blade cooling was not considered.

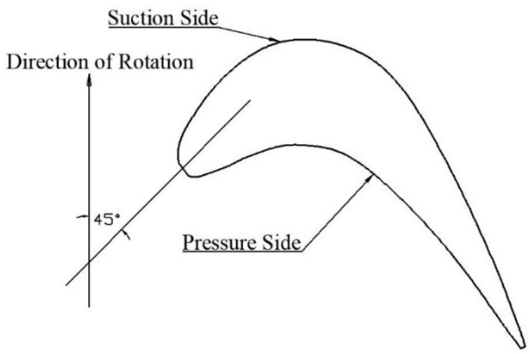

Figure 2: Profile of gas turbine blade used for analysis

3 Mathematical Modelling

During the operation of gas turbine, the stresses produced on the turbine blade are thermal and centrifugal due to high temperature and rotation respectively.

The effect of thermal and centrifugal stress on total deformation, is studied into two parts:

1. Elongation due to thermal effect when the blade is static ($Dl_{thermal\text{-}static}$)
2. Elongation due to centrifugal force and thermal induced elasticity ($Dl_{thermal\text{-}centrifugal}$)

3.1 *Thermal Deformation*

Consider a turbine blade having hub radius ‘a’ and blade span ‘b’. The blade profile is considered to have a uniform cross section area ‘A’. The blade has material properties such as density ‘ρ’ and Young’s modulus of elasticity ‘E’ which rotates at angular speed of ‘ω’ rad/s.

The energy of combustion ‘J’ is distributed throughout the span of blade based on different temperature profile. For simplicity, we consider density of material ‘ρ’, specific heat ‘C’ and linear expansivity ‘α’ to be constant while elasticity is assumed to be varying with change in temperature.

The energy ‘J’ with constant temperature profile throughout the blade span is given by equation 1

$$J = M * C * DT \tag{1}$$

For varying temperature profile, the energy J is given by equation 2, where m is mass of an elemental section

$$J = \int (\mathrm{m} * \mathrm{C} * \Delta\mathrm{T}) = \int (\rho * \mathrm{A} * \mathrm{dy} * \mathrm{C} * \Delta\mathrm{T}) \tag{2}$$

$$\mathrm{J} = \rho * \mathrm{A} * \mathrm{C} * \int (\Delta\mathrm{T} * \mathrm{dy}) \tag{3}$$

Equation 3 shows that the energy distribution depends on variation of the temperature throughout the blade span.

Further, with varying temperature distribution the static thermal expansion is given by equation 4.

$$\mathrm{Dl}_{\mathrm{thermal-static}} = \int (\mathrm{dy} * \alpha * \Delta\mathrm{T}) = \alpha * \int (\Delta\mathrm{T} * \mathrm{dy}) \tag{4}$$

Comparing equation (3) and (4), it can be seen that for combustion energy J, the change in temperature profile has no effects on the static thermal expansion of blade.

3.2 *Thermal Centrifugal Deformation*

Considering the coupled thermal- centrifugal expansion of the blade, the elasticity of material decreases with increase in temperature, so the temperature distribution plays important role.

Consider an elemental section ‘dy’ at a distance of ‘y’ from the rotational axis. The mass in the direction of tip tries to elongate the section as a result of centrifugal force.

The elementary elongation in this section is

$$d\left(Dl_{centrifugal}\right) = dy * strain = dy * \frac{\sigma}{E} = dy * \frac{F}{A * E}$$

$$= dy * \frac{\mathrm{m} * \bar{y} * \omega^2}{A * E} \tag{5}$$

$$Mass = \left(\rho * A * (a + b - y)\right)$$

Location of centroid = $\frac{a+b+y}{2}$

Substituting the expression for mass and location of centroid in equation (5) and integrating throughout the blade span,

$$\mathrm{Dl}_{\mathrm{centrifugal}} = \int \frac{(\rho * \omega^2 * ((a+b)^2 - y^2)}{2E} \mathrm{dy}$$

$$= \rho * \frac{\omega^2}{2} \int \frac{(a+b)^2 - y^2)}{E} \mathrm{dy} \tag{6}$$

For Nickel Alloy IN-738, the elasticity at different temperature [10] is curve fitted which gives an approximated linear trend line as shown by equation 7.

$$E\ (at\ T\ K) = (219.33 - 0.0529 * T) * 109 \tag{7}$$

So, equation (7) converts to

$$\mathrm{Dl}_{\mathrm{thermal-centrifugal}} = \frac{\rho * \omega^2}{2E(0K)} \int \frac{(a+b)^2 - y^2}{\left(1 - 0.38 * \frac{T}{T_{mp}}\right)} \mathrm{dy} \tag{8}$$

Neglecting the thermal effect equation (6) converts to

$$\mathrm{Dl}_{\mathrm{centrifugal}} = \frac{\rho * \omega^2}{2 * E(298K)} \int \left((a+b)^2 - y^2\right) \mathrm{dy} \tag{9}$$

For mathematical calculations material properties;

ρ = 8110 kg/m^3, E (298K) = 2.0356*10^{11}

T_{mp}= 1300 ^{0}C, α= 15.39e-6/^{0}C

Blade Dimensions: a = 360 mm, b = 120 mm

4 Results and Discussion

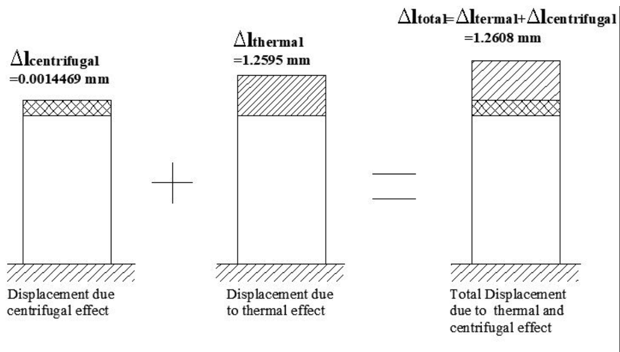

Figure 3: Results of elongation from computer simulation

From analytical calculations, maximum elongation due to only centrifugal force is found to be 0.00252424 mm.

For constant temperature distribution profile with T = 816.67^{0}C, the thermal deformation is found to be 1.46205616 mm and thermal-induced centrifugal deformation is 0.00314960 mm resulting in total deformation of 1.46520576 mm.

The energy required for achieving constant temperature of T = 816.67^{0}C is J= M*C_p* (816.67-T_{amb}). This energy results in constant thermal-static deformation of 1.4620561 mm. The differences only lie in the thermal-centrifugal deformation.

For the piecewise linear temperature profiles, the blade root temperature and the maximum temperature are set to 600 ^{0}C and 1000 ^{0}C respectively. The position of the maximum temperature is varied as shown in Table 4. To keep the combustion energy constant, the variation of blade tip temperature also takes place.

The thermal-centrifugal deformation from analytical calculation with varying location of maximum temperature is shown in Table 4. The total deformation from analytical calculation and from ANSYS with varying location of maximum temperature is shown in Table 5.

The total deformation is plotted against the location of maximum temperature as shown in Figure 4. It can be seen that the deformation decreases as the maximum temperature is located towards the blade tip. This result also matches with result from ANSYS with reasonable error of 13.9 % for total deformation. The thermo-structural analysis was performed using ANSYS 15.0. It is found that the thermal analysis performed shows the maximum deformation of 1.2595 mm at the tip section of turbine blade. The results can be seen in Figure 6.

Table 4: Thermal-centrifugal deformations with varying locations of maximum temperature

S. No.	Location of T_{max} (in % from blade root)	$Dl_{thermal-centrifugal}$(mm) Analytical Results
1.	33	0.003197
2.	50	0.0031737
3.	67	0.0031496
4.	83	0.0031249

Table 5: Total deformations with varying locations of maximum temperature

S. No.	Location of T_{max} (in % span from blade root)	Dl_{total} (mm) Analytical Results	Dl_{total} (mm) ANSYS Results
1.	33	1.465253	1.260892
2.	50	1.465230	1.260865
3.	67	1.465206	1.260832
4.	83	1.465199	1.260803

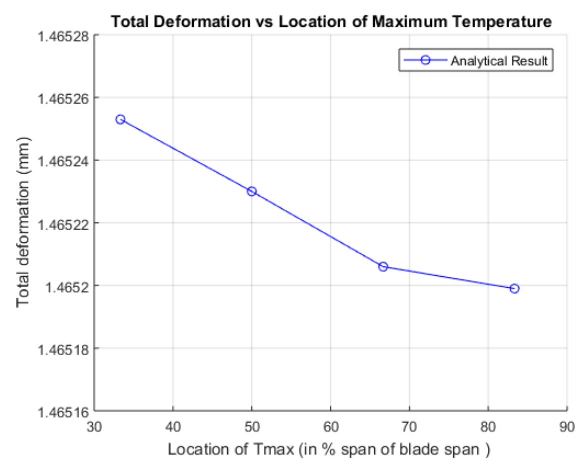

Figure 4: Analytical results of thermal-centrifugal deformation

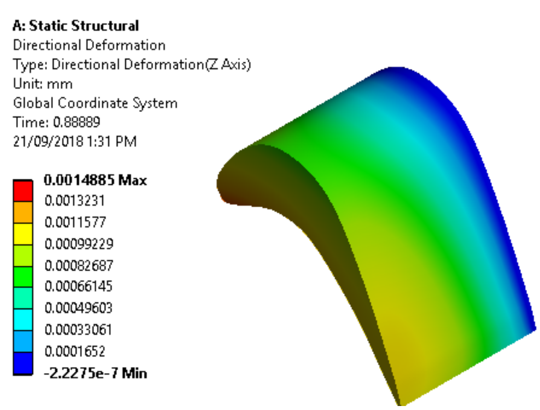

Figure 5: Deformation due to Centrifugal force

Similarly, the centrifugal force produces maximum deformation of 0.0014885 mm at root tip. The combined analysis of thermal and centrifugal stress produces 1.2608mm maximum deformation at tip itself. The above results are the summary of maximum temperature being at 2/3 location of blade span from hub. The results can be seen in Figure 5 and Figure 7.

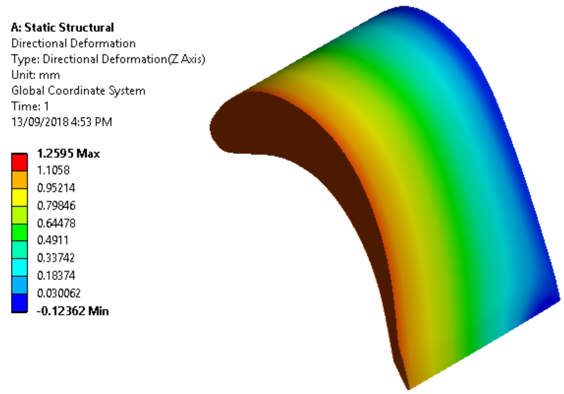

Figure 6: Deformation due to Thermal force

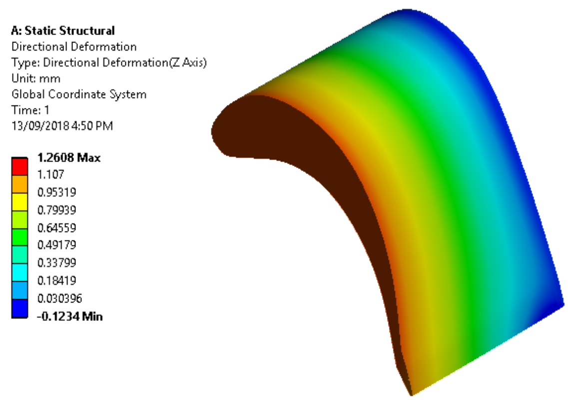

Figure 7: Deformation due to both centrifugal and thermal effect

5 Conclusion

The centrifugal load produces 0.0025 mm expansion which is 0.17% of total elongation. The combined effect of centrifugal and thermal stress produces 1.4652 mm expansion which is 1.22% of 120 mm blade span. This result has been verified from ANSYS with marginal error. From the above results it can be concluded that the centrifugal force contributes only small fraction of expansion compare to thermal effects in a high-pressure turbine blade.

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