

Thermo-structural analysis of HP stage gas turbine blades having helicoidal cooling ducts

Chandrakant R Kini, Dr. Satish Shenoy B, and Dr. N. Yagnesh Sharma

Abstract— In most of the practical gas turbines, the turbine blades of HP stage are usually too small to employ the turbine blade cooling techniques effectively. The growing need for effective blade cooling techniques is a direct consequence of the continuous quest for greater fuel economy. It is very well known that the thermal efficiency and power output of gas turbines increase with increasing turbine entry temperature (TET). The current TET level in advanced gas turbines is far above the melting point of the blade material. An attempt has been made in this paper to computationally analyze the thermo-structural analysis of HP stage turbine blade for effective cooling using innovative cooling passages within the blade. A helicoidal shaped duct has been analyzed corresponding to different cross section, diameters and pitch length. It is found from the analysis that helicoidal cooling duct of circular cross section of pitch length 6 mm radius 2 mm having turbulators ($e/D = 0.08$ and 0.75 mm rib thickness) and helicoidal cooling duct of elliptical cross section of pitch length 6 mm, major axis 2 mm and minor axis 2.5 mm result in better cooling effects and in turn reduces structural distortion.

Keywords— thermo-structural analysis, helicoidal cooling ducts, structural deformation

I. Introduction

Gas turbines have become one of the most important prime movers especially in aircraft propulsion, land-based power generation, and industrial applications. The gas turbine is a power plant, which produces comparatively greater energy per unit size and weight. Its compactness, low weight and multiple fuel application make it a natural power plant for many applications. It is clear from Brayton cycle that the increase in pressure ratio increases the gas turbine thermal efficiency accompanied with increase in Turbine Entry Temperature (TET). The increase in pressure ratio increases the overall efficiency at a given temperature. However, increasing the pressure ratio beyond a certain value at any given TET can actually result in lowering the overall cycle efficiency [4]. As the TET increases, the heat transferred to the blades in the turbine also increases. The level and variation in the temperature within the blade material which causes thermal stresses must be limited to achieve reasonable durability goals. Also the TET is far above the permissible metal temperature,

there is a greater need to cool the blades to operate without failure. Therefore, along with high temperature material development, a sophisticated cooling scheme must be developed for HP stage turbine blade for continuous safe operation with high performance. Several research works are being carried out to address the above problems [1-4]. Kini et al. in earlier research work [5, 6 and 7] found from CFD analysis that helicoidal cooling duct of circular and elliptical cross sections provides a significant improvement in turbine blade cooling. This work has been taken up with a view to assess the structural stability of the blade provided with an innovative helicoidal cooling duct subjected to thermal and pressure loading on the blades.

II. Computational domain for the analysis

While the configuration of the internal cooling ducts in real gas turbine airfoil can be highly complicated, in the present analysis, a simplified geometric model with different ducts of varying geometry is being studied for the effective cooling consideration. In general, the coolant air enters the cooling ducts from the blade root, flows through entire length of ducts and finally leaves from blade tip as shown in Figure 1. The cooling process is entirely by internal convective cooling only.

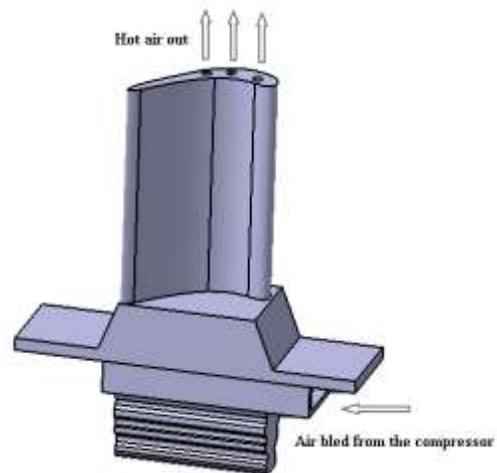


Figure 1: Schematic of turbine blade with cooling ducts

The helicoidal ducts of pitch length of 4 mm and 6 mm with circular cross section with hole radius of 1.5 mm and 2 mm, helicoidal ducts of pitch length of 6 mm with hole radius 2 mm having turbulator ($e/D = 0.08$ and 0.75 mm rib thickness), helicoidal ducts of pitch length of 6 mm with elliptical cross section having a) major axis 1.5 mm and minor axis 2.5 mm b) major axis 2 mm and minor axis 2.5 mm are considered.

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III. Boundary Conditions

The required boundary conditions implemented in the study of blade profile are presented here. The boundary conditions are derived from the practical gas turbine operating conditions, corresponding to HP stage blade that are generally exposed to high temperature and velocity. The through flow of hot gases over the turbine blade has a free stream temperature of hot gas at 1561 K and convective heat transfer coefficient of hot gas is taken as 2028 W/m²K [9, 10]. The physical properties for the blade material are given in table below [12].

Table 1: Physical properties of blade material

Specific Heat, J/kg°C	419
Thermal Conductivity, W/m°C	10.89
Coefficient of Thermal Expansion 10⁻⁶/°C	12
Youngs Modulus, GPa	188

IV. Numerical solution procedure

The Finite element analysis of the gas turbine blade was carried out after steady state thermal analysis was performed. This was achieved by first taking into account the results of fluid flow analysis obtained from ANSYS FLUENT. Then the static structural analysis was carried out using the results of thermal analysis as well as the results of fluid flow analysis obtained from ANSYS FLUENT. The solid domain was built using the ANSYS Workbench as the preprocessor.

The steady state thermal analysis was carried out by importing the 3D gas turbine blade geometry into ANSYS Workbench 14. The blade is re-meshed with an unstructured mesh containing 3D tetrahedral elements. Thermal loads of ambient convective boundary condition corresponding to hot gas surrounding the blade [8] and the interface temperature at the cooling ducts were imported from fluid flow analysis computed from ANSYS FLUENT.

The static structural analysis was carried out by re-meshing the blade with an unstructured mesh containing 3D tetrahedral elements. The pressure load was applied on the blade surface [8] and pressure load at the interface of the cooling duct were imported from fluid flow analysis ANSYS FLUENT run. The body temperatures determined by thermal analysis were also imported in order to carry out static structural analysis

V. Results and Discussion

The results of the thermo-structure multiphysics analysis in each case discussed below corresponding to parametric considerations of the geometry of the cooling duct are detailed below. The results analyses follow the structural capabilities of helicoidal duct of various pitch lengths and cooling duct diameter. Six different models consisting of solid blade with helicoidal cooling duct of varying pitch length and cooling duct diameter are analyzed to find out optimum pitch length and cooling duct diameter.

Thermo-structural analysis of the blade having helicoidal duct of pitch length of 4 mm and 6 mm with circular cross section with hole radius of 1.5 mm and 2 mm, helicoidal

ducts of pitch length of 6 mm with hole radius 2 mm having turbulator (e/D = 0.08 and 0.75 mm rib thickness).

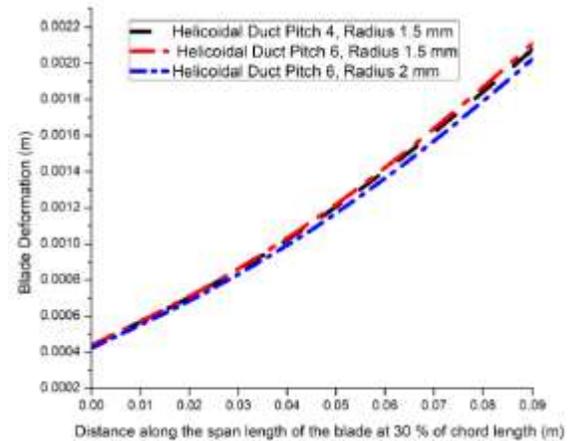


Figure 2: Deformation along the span length of the blade

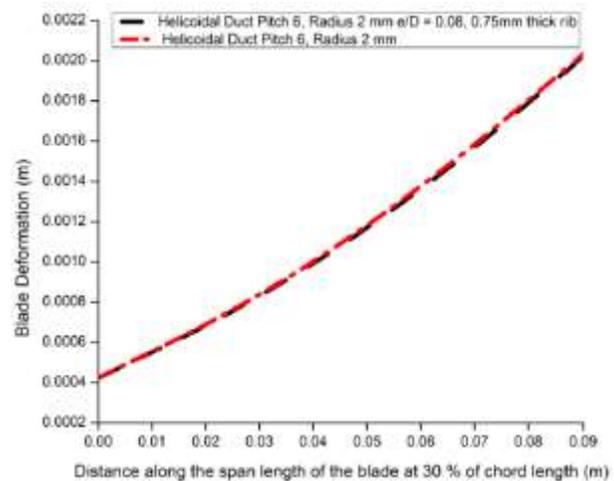


Figure 3: Deformation along the span length of the blade

Figure 2 shows deformation of the exposed blade surface along the span at 30 % of the chord length. This deformation is taken at this position for all the different cases for purpose of comparison. It is seen from the figure that maximum deformation for helicoidal cooling duct of pitch length 4 mm and radius of 1.5 mm is 0.0020792 m and for pitch length 6 mm and radius of 1.5 mm it is 0.0021112 m followed by for pitch length 6 mm radius 2 mm it is 0.0020346 m. From this it is obvious that for helicoidal cooling duct of pitch length 6 mm and radius of 2 mm deformation is relatively lower due to increased convective area for heat transfer and turbulence that is brought about due to path of the cooling duct.

Figure 3 shows the deformation plot for helicoidal cooling duct of pitch length 6 mm and radius of 2 mm with and without turbulators. It can be seen that placement of turbulators in the cooling duct has decreased the blade deformation (0.0020255 m) due to increased convective heat transfer coefficient. In general it can be seen that helicoidal cooling duct with turbulators plays a vital role in turbine blade cooling process resulting in lower deformation.

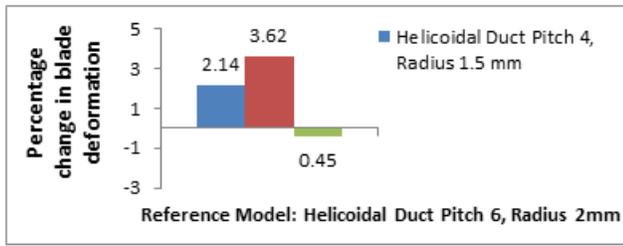


Figure 4: Change in deformation with respect to span length of the blade

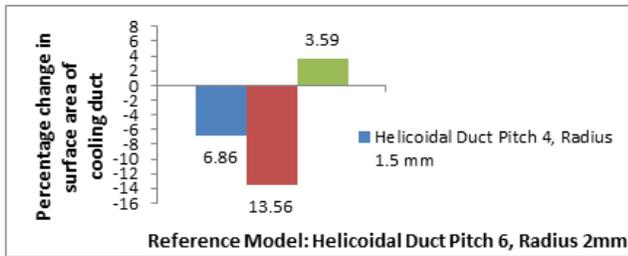


Figure 5: Change in Surface area with respect to cooling duct

Figure 4 shows change in deformation with respect to span length of the blade and Figure 5 shows change in surface area with respect to cooling duct. Considering helicoidal cooling duct of pitch length 6 mm and radius of 2 mm as reference model it can be seen that for helicoidal cooling duct of pitch length 4 mm and radius of 1.5 mm due to 6.86 % reduction in surface area of cooling duct the deformation has increased by 2.14 %, for pitch length 6 mm and radius of 1.5 mm due to 13.56 % reduction in surface area of cooling duct the deformation has increased by 3.62 % and for pitch length 6 mm radius 2 mm having turbulators ($e/D = 0.08$ and turbulator thickness 0.75 mm rib thickness) due to 3.6 % increase in surface area of cooling duct the deformation has reduced by 0.44 % . Therefore it is possible to conclude that for pitch length 6 mm radius 2 mm having turbulators ($e/D = 0.08$ and 0.75 mm rib thickness) has resulted in lower deformation due to increased surface area, turbulence and Nusselt number (19.26 %).

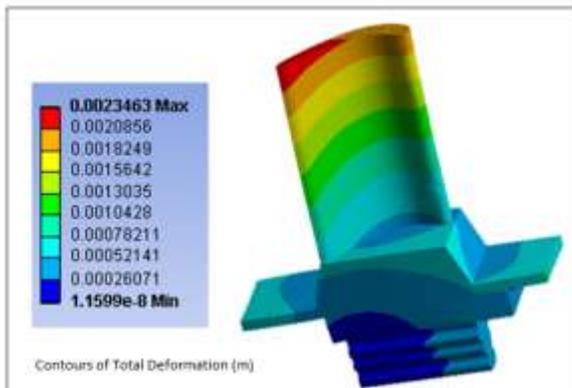


Figure 6: Contours of Blade Deformation for Helicoidal cooling duct of Pitch 4 mm and radius of 1.5 mm

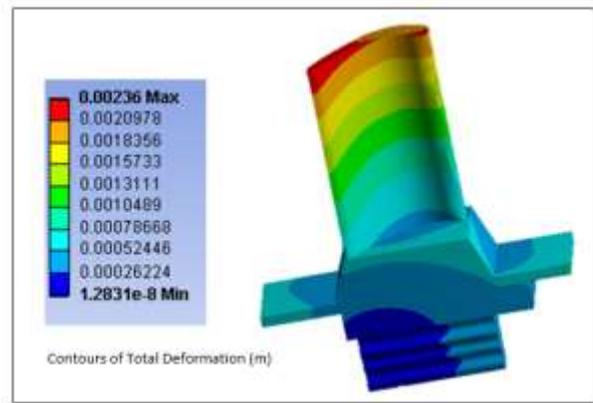


Figure 7: Contours of Blade Deformation for Helicoidal cooling duct of Pitch 6 mm and radius of 1.5 mm

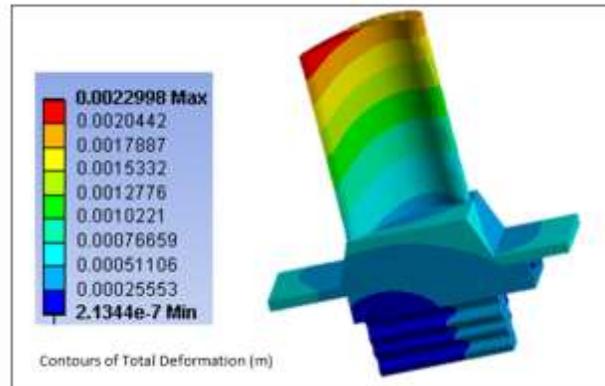


Figure 8: Contours of Blade Deformation for Helicoidal cooling duct of Pitch 6 mm and radius of 2 mm

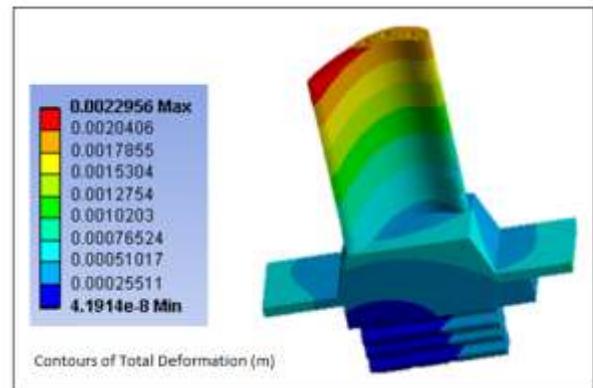


Figure 9: Contours of Blade Deformation for Helicoidal cooling duct of Pitch 6 mm and radius of 2 mm having turbulators of $e/D = 0.08$ and 0.75 mm rib thickness

VI. Conclusions

- i) It is seen that an innovative helicoidal cooling passage, provides an augmented convective area for better heat dissipation resulting in lower structural deformation.
- ii) The diameter and pitch length of the helicoidal duct of plays relatively a major role in cooling of the gas turbine blade.



iii) Helicoidal cooling duct of circular cross section of pitch length 6 mm radius 2 mm having turbulators ($e/D = 0.08$ and 0.75 mm rib thickness) and helicoidal cooling duct of elliptical cross section of pitch length 6 mm, major axis 2 mm and minor axis 2.5 mm result in better cooling effects and in turn reduces structural distortion.

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Nomenclatures

e: Radial thickness of turbulator rib (mm)
 D: Outer diameter of helicoidal duct (mm)
 MjA: Major axis
 MiA: Minor axis

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