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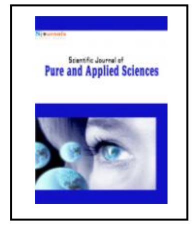

Original article

Numerical simulation and prototype testing of gas turbine with hot spinning process

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ABSTRACT

The gas turbine is normally operating in high temperature environment and its blades / rotor are constantly contacting gas with extremely high temperature. To prolong the life cycle and improve the function of these critical turbine components, the cooling methods should be applied to reduce the temperature in turbine disc area. But the potential problem is that the cooling methodology reducing the central rotor temperature can enlarge the temperature gradients leading excessive thermal stresses in gas turbine components including turbine wheel. One computational simulation model is introduced in this paper to describe the mechanism of mechanical and thermal stresses produced in gas turbine to illustrate the influence of some important parameters on this gas turbine function and help to optimize the turbine wheel design. Since there are few related numerical analytic simulations that have been done in this research field, this paper intends to provide the numerical simulation methodology to investigate and understand the stress mechanism in gas turbine operation. The turbine model has also been prototyped and tested to compare the numerical simulation results. All these studies can help to optimize future gas turbine design and improve the performance.

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1. Introduction

The mechanical and thermal stresses produced in high speed gas turbine system are being studied to determine the parametric effects in different turbine speed and component expansions at various temperatures (Singh et al., 2011). There are few researches have been conducted in numerical analysis to optimize the turbine disc profile design and improve turbine systematic performance. The cooling conditions should be assumed to the turbine wheel when analyze the parametric effects and determine the superposed mechanical and thermal stresses (Ogbonnaya et al., 2010). The feasibility of these analytic methods should be validated by combining the generated mechanical and thermal stress components to compare the material tensile yield strength at given temperature conditions (Christodoulou et al., 2011). If the system is not properly designed, the turbine components including wheel disc will deform beyond the material yield strength due to high speed and temperature conditions (Silva et al., 2011). The produced stresses in turbine wheels during operation are centrifugal stresses due to high speed rotation and it also brings the residual stresses (Vallee et al., 2009). The high speed rotation of turbine wheel must be maintained at a temperature a little higher than surrounding atmospheric temperature to keep turbine wheel from material brittle fracture. This is the technique of hot spinning used to analyze the gas turbine wheel rotating in high temperatures (Carey, 2010). The quality of a turbine wheel can be justified by method of low cycle fatigue life to evaluate the turbine disc in various areas that the material might be failed, such as opening slots of cooling air entrance in turbine wheel (Beebe, 2009). The low cycle fatigue life of turbine wheel can be increased by adding mass to the turbine wheel area so that the tangential stress can be reduced in wheel. Since it also adds weight to the disc rim, this process is not a good way to lower the combined stresses in turbine wheel (Ogbonnaya, 2011). In order to reduce the static / tangential stresses and enlarge the low cycle fatigue life of turbine components, a better way is to bring the extra compressive residual stress to the turbine wheel rim when it is being made by manufacturing with hot spinning (Kim et al., 2011). The hot spinning process can uniformly heat the turbine disk to a predefined high temperature to provide proper thermal gradient between turbine disk and rim through decreasing the rim temperature by cooling method (MacLeod et al., 2010). As the turbine wheel rim is cooled to a specific temperature, a thermal gradient is generated between the wheel disc and rim causing the compressive residual stress produced in turbine wheel rim. The hot spinning methodology can cost-effectively increase the low cyclic fatigue life, well implement the processing equipment, easily add predefined residual stress to the turbine wheel, and add no additional material weight in the process (Komandur et al., 2008). This paper introduces the analytic model of numerical analysis / computational simulation on this gas turbine design with hot spinning components. The experiment on prototyped design is also performed to verify the results from computational modeling and numerical simulation.

2. Materials and methods

2.1. Methods of 3D modeling and computational simulation

The produced stress in turbine components including wheel and rotor can be analyzed by defining boundary conditions (BC) with radial stress in wheel rim equaling the stress externally exerted on centrifugal blade. The BC can be considered that the radial stress is set to zero at inner radius of disc central hole and radial stress of disc is equal to the tangential stress acted at disc center. Because of the symmetrical geometry, a quarter portion of turbine wheel has been analyzed in computational modeling and numerical simulation. Figs. 1 and 2 display the quarter portion of turbine wheel and rotor.

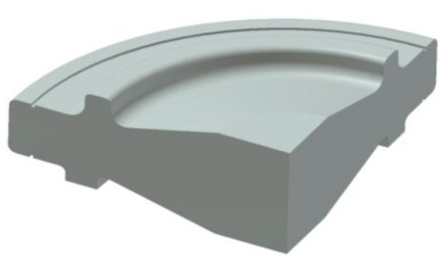

Fig. 1. Quarter portion of turbine wheel.

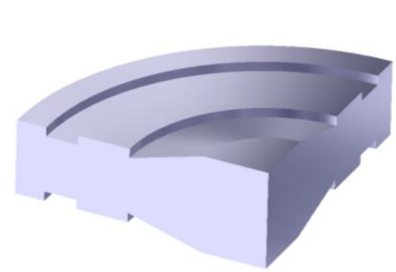

Fig. 2. Quarter portion of turbine rotor.

The mathematical modeling and differential equations of disc and rotor elements with different thickness in numerical simulation and computational analysis are shown as follows (Saravanamuttoo et al., 2009).

$$R*T*\frac{d\delta_R}{dR}+R*\delta_R*\frac{dT}{dR}+T*\delta_R-T*\delta_T=-\gamma*\alpha^2*R^2*T \tag{1}$$

or

$$\frac{d}{dR}(R*T*\delta_R)-T*\delta_T=-\gamma*\alpha^2*R^2*T \tag{2}$$

Here, γ – wheel and rotor material density (Kg/m3); T - disc thickness at radius r (m); δR – radial stress (N/m2); δT – hoop stress (N/m2); R – disc radius at any point (m);

The above differential equation can be modeled and calculated through numerical and computational simulation. The radial temperature gradient produced in turbine wheel disc due to heat conduction from turbine bucket to wheel disc causes thermal tensile and compressive stresses in the disc radial and tangential directions respectively. The thermal stresses due to temperature gradient reach the maximum near rim area but it can be moved away from rim area if temperature profile can be properly adjusted. This paper analyzes the turbine disc at the 2nd stage of a 65 MW prototyped gas turbine. The maximum stress generated during turbine operation can be calculated and analyzed through computer-aided modeling and numerical simulation. Fig. 3 shows the meshing with triangular / quadrilateral elements on quarter portion of turbine wheel disc.

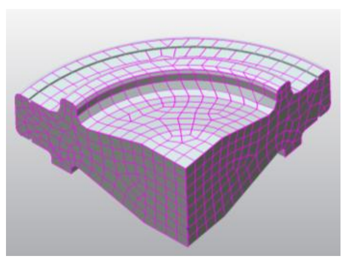

Fig. 3. Mesh setup for quarter portion of turbine wheel disc.

The load and boundary conditions can be defined as: the centrifugal forces are exerted due to disc angular velocity (turbine blade is mounted at the wheel circumference in x-direction) and turbine wheel is constrained in bolt location at the y-direction. Fig. 4 displays the thermal boundary conditions for thermal analysis.

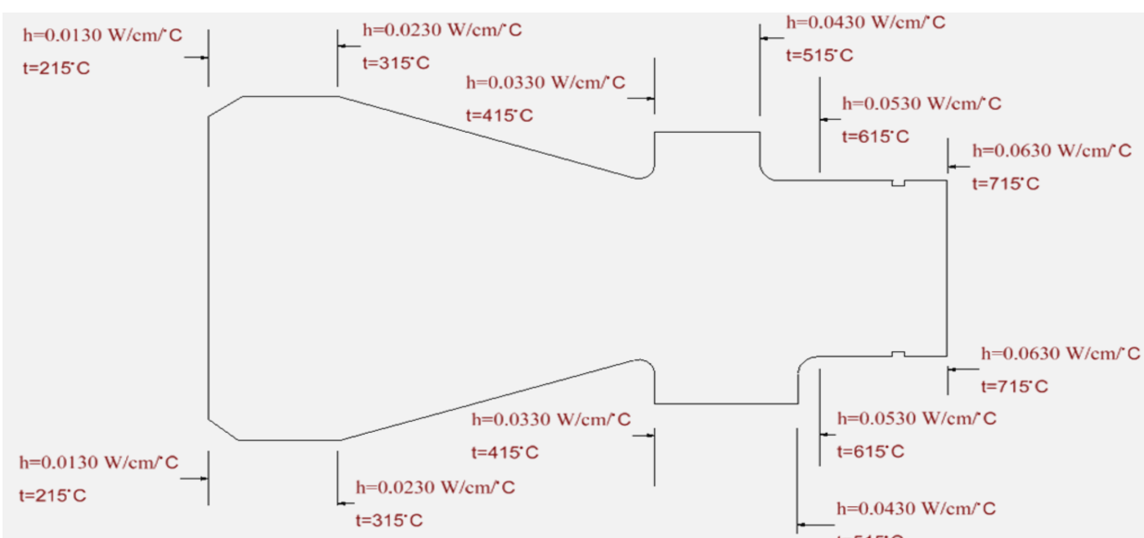

Fig. 4. Boundary conditions for thermal analysis.

3. Results and discussion

Considering the cooling air temperatures varying from 2150C to 7150C with h changing from 0.0130 to 0.0630 (w/cm/°C). Heat flow can be assumed zero at the disc inner radius. The centrifugal force caused by angular speed of 530 rad/s is specified at disc outer ring and disc inner ring is set with all degrees of freedom. Cooled air flow causes heat flowing from disc outer ring to the remaining disc surface. Heat exchange takes place from hot gases at disc outer ring via heat conduction and thermal flux releases to cooling air via heat convection. Figs. 5 and 6 show the boundary conditions in computational modeling and numerical simulation for structural and thermal analysis respectively.

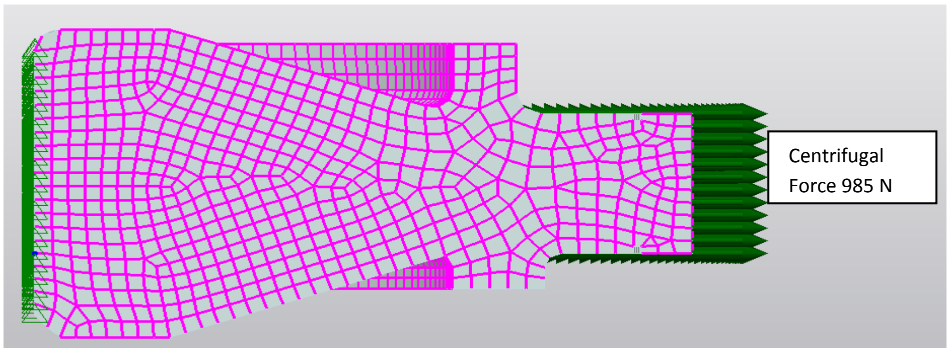

Fig. 5. Boundary conditions in structural/stress analysis.

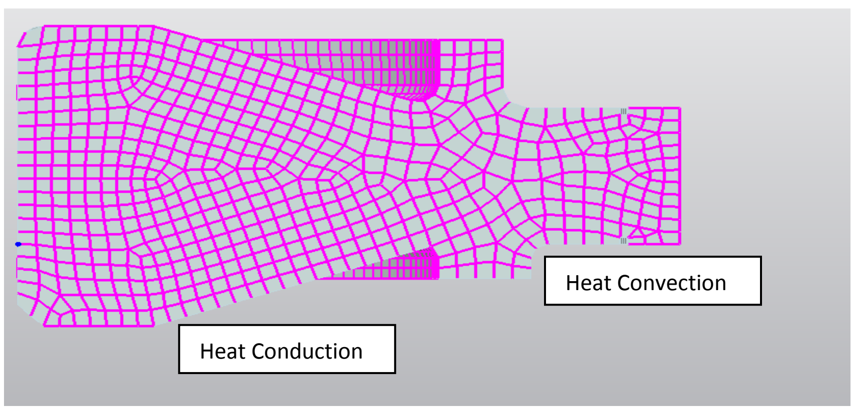

Fig. 6. Boundary conditions in thermal/heat transfer analysis.

The temperature profile in Fig. 7 shows the maximum temperature of 814 °C at disc bore area and minimum temperature of 373.4 °C at outer ring of turbine wheel.

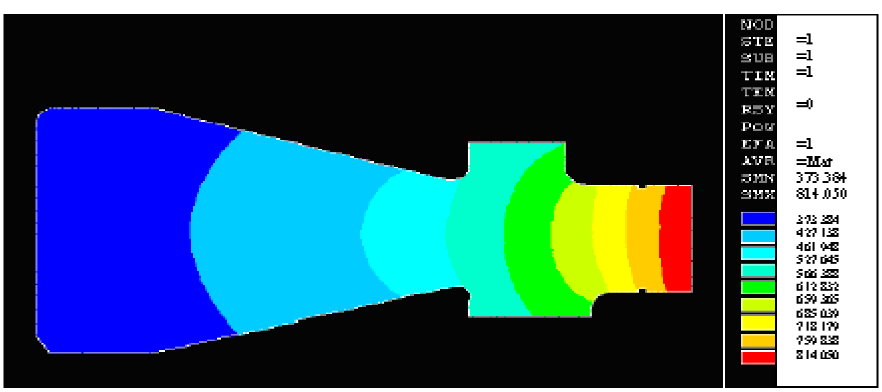

Fig. 7. Temperature profile/gradient in disc radial direction.

The radial temperature gradient is formed due to heat conducted from turbine buckets to the disc. The outer portions of wheel are under high temperature and free to expand. Since the inner portions of wheel are constrained, the tensile thermal stresses in radial direction and compressive thermal stresses in tangential direction are produced. Fig. 8 displays the thermal stress profile in wheel radial direction with a maximum value of 259999 KPa.

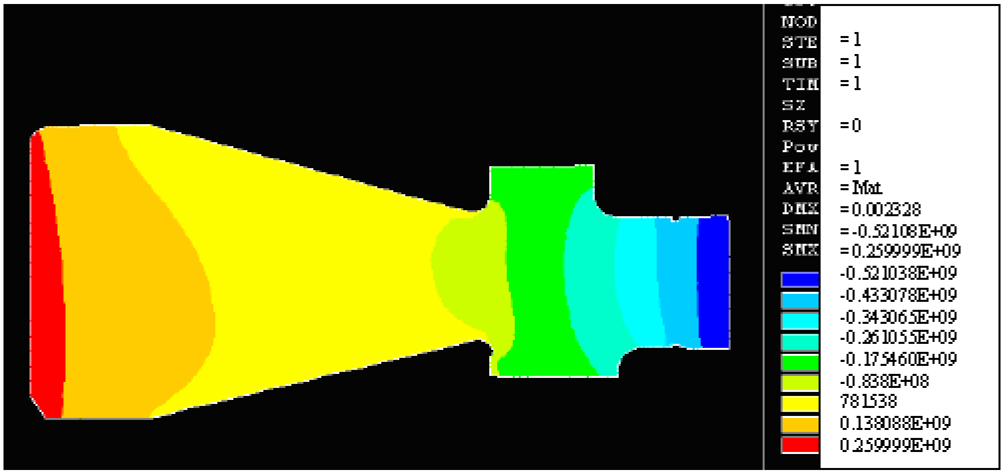

Fig. 8. Thermal stress profile along radial direction of turbine wheel.

The turbine blades mounted to wheel rim have added local stresses when an angular velocity of 530 rad/s is applied at the disc rim. Fig. 9 shows the stress profile in radial direction with maximum centrifugal tensile stress of 267001 KPa.

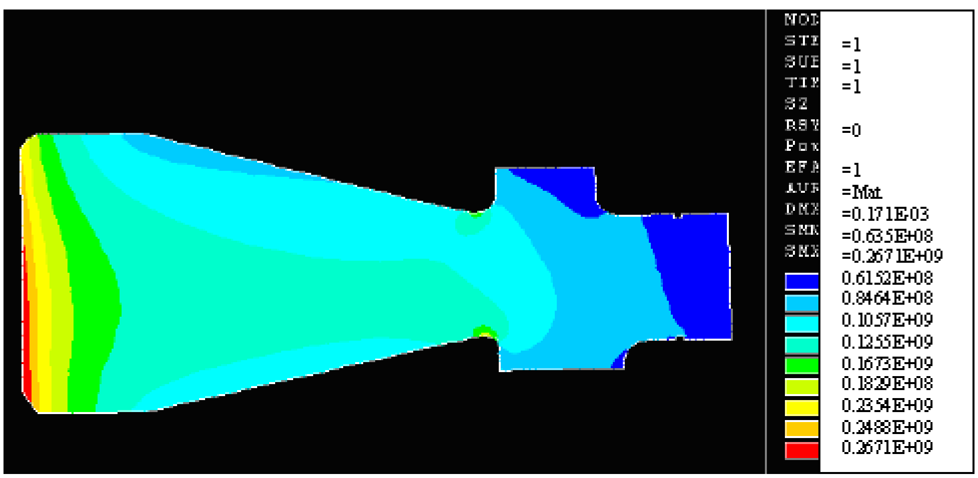

Fig. 9. Centrifugal tensile stress profile along wheel radial direction.

Since both centrifugal and thermal stresses are tensile at the centre, a sudden failure of wheel and rotor materials might occur if these stresses are too high. Fig. 10 displays the combined centrifugal and thermal stresses at turbine bore area in radial direction with combined maximum tensile stress of 526000.4 KPa.

The simulation analysis in Fig. 11 shows that, after hot spinning process, the residual stresses are superimposed to the thermal stresses at an operating speed of 530 rad/s.

Since the residual stresses induced in wheel are in negative values, the resultant stresses are reduced. Comparing simulation results in Figs. 10 and 11, the combined stress reduces from 526000.4 KPa to 195899.8 KPa due to hot spinning process of wheel and rotor components.

3.1. Prototype testing

The prototyped unit has been tested under the same load and boundary conditions as in computational modeling and numerical simulation, such as load directions, boundary constrains, temperature profile, angular speed, and thermal gradient.

Table 1 displays the experimental results of prototype at temperature of 814 °C in turbine disc hole area.

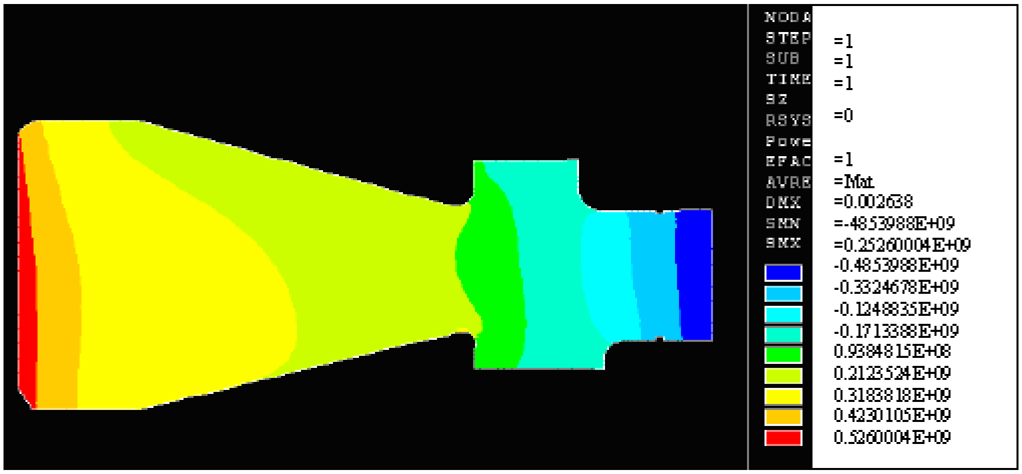

Fig. 10. Combined stress profile along disc radial direction

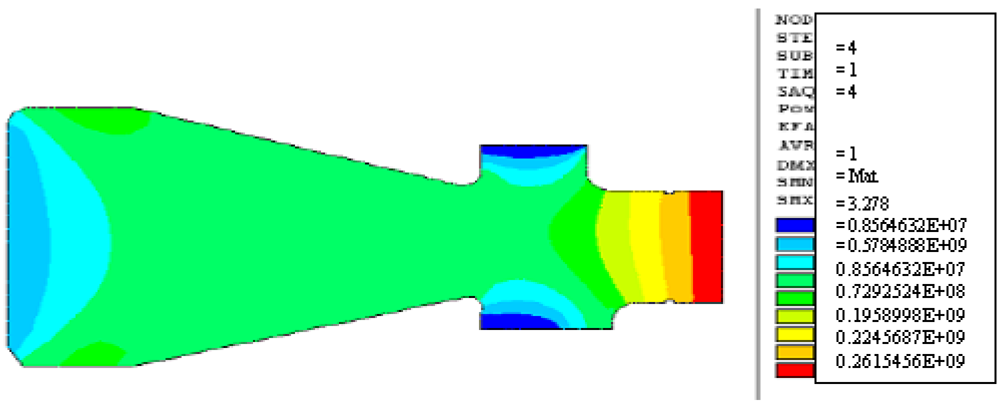

Fig. 11. Combined stress profile with residual stresses induced along disc radial direction (with hot spinning process).

Table 2 shows that the results from computational modeling / numerical simulation are very close to the results from prototype experiment which validates the credibility of analytic methodology applied in this research.

4. Conclusion

This paper studies the gas turbine performance via computational modeling / numerical simulation and prototype experiment. The computer-aided modeling / numerical simulation can properly justify the turbine performance and improve the design without needs of manufacturing real turbine parts. This can save the design cost and speed up the product design / development processes. The simulation results indicate the important features of hot spinning process because the combined stress from thermal and mechanical contributions has been significantly decreased in gas turbine functioning parts. The combined stress of hot spinning components is about 62.5 % lower than the components without hot spinning. A computational modeling methodology is proposed in this paper to help understanding the structure and mechanism of thermal and centrifugal stress, verify the combined stress profiles generated in gas turbine, determine the effect of important turbine parameters, and continuously improve gas turbine design. One prototyped unit has been built and tested to verify the computational modeling and numerical simulation. The computational simulation shows very close results compared to the prototype testing and this validates the analytic methodology applied in this research. The future improvement on this research will be continuously analyzing the gas turbine performance by trying different composite material, modifying turbine design parameters for system optimization, and planning more prototype experiment.

Table 1
Prototype experimental results.

Results / Test #	Thermal stress in radial direction (KPa)	Centrifugal stress in radial direction (KPa)	Combined stress in radial direction (KPa)	Combined stress in radial direction (hot spinning} (KPa)
1	259998	266997	525999	195902
2	259998	266999	526001	195901
3	260003	267003	526002	195898
4	260001	267001	526003	195897
5	259998	267002	525999	195902
6	260001	266998	526003	195897
7	259997	266999	525998	195898
8	260003	267002	526003	195897
9	259999	267003	526002	195902
10	259997	267002	525999	195898
Average	259999.5	267000.6	526000.9	195899.2

Table 2
The comparison of computer-aided analysis and prototype experiment .

Results / Methods	Thermal stress in radial direction (KPa)	Centrifugal stress in radial direction (KPa)	Combined stress in radial direction (KPa)	Combined stress in radial direction (hot spinning} (KPa)
Computer aided simulation	259999	267001	526000.4	195899.8
Prototype testing	259999.5	267000.6	526000.9	195899.2

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