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Modelling of Thermo-mechanical Fatigue in an Aeroderivative Gas Turbine Blade made of Inconel 738LC

A.M. Orah, A. Nasir, A.B. Hassan, I. Bori

Department of Mechanical Engineering, Federal University of Technology, Minna, Niger State, Nigeria.
Tel: +234(0) 802 819 8356. ***Emails:*** orahmohammed@yahoo.com (OMA), a.nasir@futminna.edu.ng (AN),
abhassan@futminna.edu.ng (ABH), Ige.bori@futminna.edu.ng. *(IB)*

Abstract

The hot gas section of the gas turbine engine, especially the blades, are usually subjected to high thermal and mechanical loading, as a result suffer thermo-mechanical fatigue. The design process usually involves appropriate selection of the turbine blade materials, it is therefore necessary to carry out thermo-mechanical fatigue studies on gas turbine blades to predict blade life. This study models the thermo-mechanical fatigue on gas turbine blade made of nickel based super alloy IN738LC. Simulink was used to develop thermal models to compute the heat transfer coefficient on the cold and hot sides of the blade, and a stress model to compute the centrifugal tensile stress. The heat transfer coefficients, Reynold's number, and Stanton number at different velocities on the hot and cold section of the blade was obtained. The relationships between the Heat transfer coefficient and the Reynold's number with the change in velocities at the hot and cold sections of the blade was also established. The stress model computed the centrifugal tensile stress acting on the blade at 31.41GPa.The heat transfer and stress models are therefore necessary for TMF calculations to predict the creep life of the blade to prevent engine failure.

Keywords: blade, thermo-mechanical fatigue, model, thermal, stress.

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1. INTRODUCTION

The hot gas section of the gas turbine engine, especially the blades, are usually subjected to high thermal and mechanical loading, as a result suffer thermo-mechanical fatigue. The design process usually involves appropriate selection of the turbine blade materials, it is therefore necessary to carry out thermo-mechanical fatigue studies on gas turbine blades to predict blade life. This study models the thermo-mechanical fatigue on gas turbine blade made of nickel based super alloy, Inconel 738 Low Carbon (IN738LC). Simulink was used to develop thermal models to compute the heat transfer coefficient on the cold and hot sides of the blade, and a stress model to compute the centrifugal tensile stress. A finite element analysis to examine the thermal and stress loading on the turbine blade was also done. Thermomechanical fatigue (TMF) is caused by combined thermal and mechanical loading with both the temperatures and stresses varying with time. These types of loadings are most frequently found in start-up and shut-down cycles of high temperature components and equipment [1]. Thermo-mechanical fatigue (TMF) refers to a form of non-isothermal fatigue in which a material is simultaneously subjected to varied temperatures and independently controlled loading. Because the mechanical properties of a material are temperature dependant, the variation in temperature associated with TMF, certainly leads to different damage mechanisms taking place [2]. During TMF loading, the fatigue, oxidation, and creep damages can be induced; and the relative contributions of these damages will vary with the different materials and loading conditions [3]. The heat transfer coefficient for the hot and cold sections of the blade was successfully modelled. The heat transfer coefficients, Reynold's number, and Stanton number at different velocities on the hot and cold section of the blade was obtained. The relationship between the Heat transfer coefficient and the Reynold's number with the change in velocities at the hot and cold sections of the blade was also established. The stress model computed the centrifugal tensile stress acting on the blade at 31.41GPa.The heat transfer and stress models are therefore necessary for TMF calculations to predict the creep life of the blade to prevent engine failure.

2. Methods

The blade material considered in this study was Inconel 738LC, a nickel-based superalloy predominantly used in gas turbine engines. The composition of Inconel 738LC is shown in Table 1 [4].

The Eqs. (1) to (3) [5] were used to model the heat transfer on the cold side of the blade using Matlab Simulink.

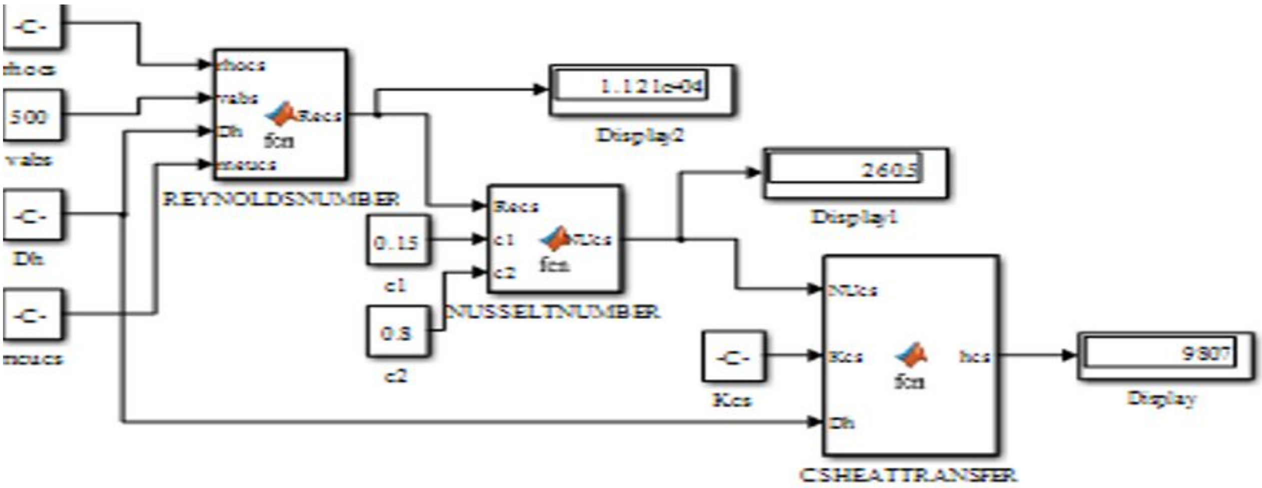
$$\mathrm{Re}_{cs} = \frac{\rho\mathrm{cs} \times \mathrm{V}_{\mathrm{abscs}} \times \mathrm{D}_h}{\mu\mathrm{cs}} \tag{1}$$

$$\mathrm{NU}_{cs} = 0.15 \times (\mathrm{Re}_{cs})^{0.8} \tag{2}$$

Table 1: Chemical composition of nickel base superalloy.

C	Cr	Co	Mo	T_a	T_i	Al	W	Si	Mn	Nb	Fe	Ni
0.105	16.00	8.60	1.75	1.80	3.40	3.40	2.70	0.09	0.03	0.82	0.30	Bal.

Source: [4]



(a) Simulink Model For the Cold Side Heat Transfer

Figure 1: (a) Simulink Model For the Cold Side Heat Transfer.

$$\mathrm{h}_{cs} = \mathrm{NU}_{cs}\left(\frac{\mathrm{K}_{cs}}{\mathrm{D}_h}\right) \tag{3}$$

Where ρ_{CS} is the density of air on the cold side of the blade, $\mathrm{V}_{\mathrm{abscs}}$ is the absolute velocity of the cold air, D_{h} is the hole diameter, μ_{CS} is the kinematic viscosity of the cold air, $\mathrm{NU}_{\mathrm{CS}}$ is the Nusselt number, $\mathrm{Re}_{\mathrm{CS}}$ is the Reynold's number of the cold air, k_{CS} is the thermal conductivity of the cold air and h_{CS} is the heat transfer coefficient at the cold side of the blade.

Air was considered as the gas on the cold and hot sides of the blade at temperatures of 623K and 1100k, since the properties are readily available. While Eqs. (4), (5), (6) and (7) [5] were used to model the heat transfer on the hot side of the blade.

$$\mathrm{Re}_g = \frac{\rho_g \times \mathrm{V}_{\mathrm{absg}} \times \mathrm{C}_b}{\mu_g} \tag{4}$$

$$St_g = 0.258 \times (\mathrm{Re}_{cs})^{-0.37} \times Pr_g^{-0.667} \tag{5}$$

$$A_g = \pi D_m H \cos\alpha_2 \tag{6}$$

$$h_g = St_g \times C_{pg} \times \left(\frac{m_g}{A_g}\right) \tag{7}$$

Where ρ_g is the density of hot gas, V_{abscg} is the absolute velocity of the hot gas, C_b is the chord of the blade, μ_g is the kinematic viscosity of the hot gas, St_g is the Stanton number, Re_g is the Reynold's number of the hot gas, Pr_g is the Prandtl number, A_g is the hot gas cross sectional area, D_m is the mean blade row diameter, H is the blade height, α_2 is the flow outlet angle, c_{pg} is the specific heat at constant pressure, m_g is the gas mass flow and h_g is the heat transfer coefficient at the hot side of the blade.

The high rotational speed of the rotor blades give rise to stresses at the root. The most predominant stress in the blade is the centrifugal tensile stress. The Eq. (8) was used to model the centrifugal stress on the blade.

$$(\alpha_{ct})\,\mathrm{max} = \frac{4}{3} \times \pi N^2 \rho_b A \tag{8}$$

Where $\sigma_{ct}\,\mathrm{max}$ is the maximum centrifugal tensile stress acting on the blade, N is the rotational speed of the blade, A is the annulus area and ρ_b is the density of the blade material.

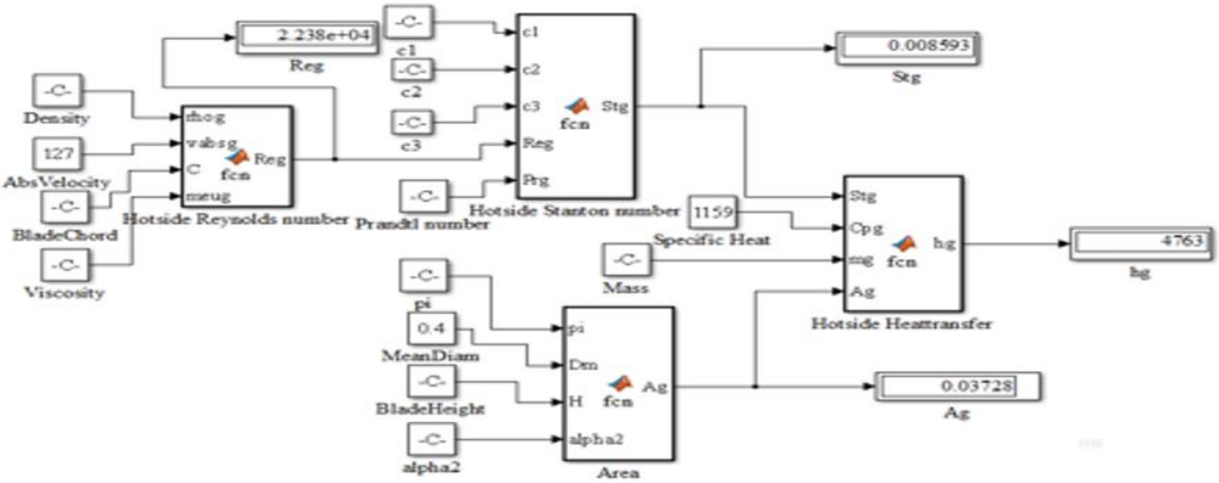
Results showed that the centrifugal stress is concentrated at the roots of the blade and is less at the blade tip.

3. FINDINGS AND DISCUSSIONS

The heat transfer models of the cold and hot sides were developed using simulink as shown in Fig. 1(a) and (b), and the graphs showing the relationship between the heat transfer coefficient (HTC), the Reynold's number (Re) and the absolute velocities, obtained for the hot and cold sections of the blade.

The results for the cold section indicated that there was steady increase in both the Reynold's number and heat transfer coefficient of the blade as shown in Fig. 2.

Fig. 3 illustrates the graph of the HTC, Re and absolute velocity for the hot section. It showed that an increase in velocity results to a consequent increase in



(b) Simulink Model for the Hot side Heat Transfer

Figure 1: (b) Simulink Model for the Hot side Heat Transfer.

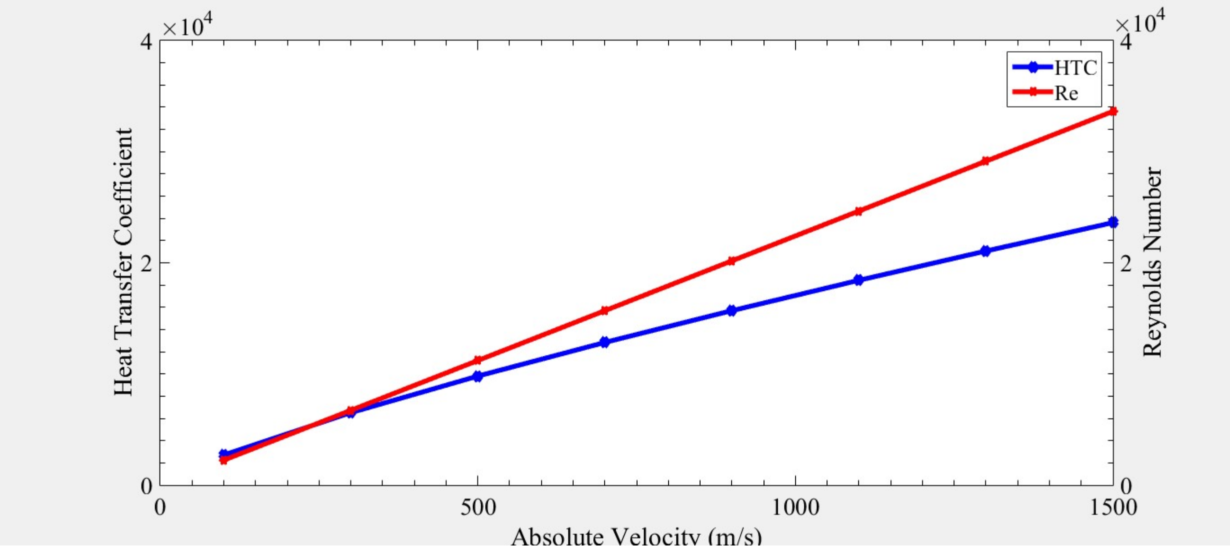


Figure 2: The effect of absolute velocity on Heat Transfer Coefficient and Reynolds Number (Cold Side).

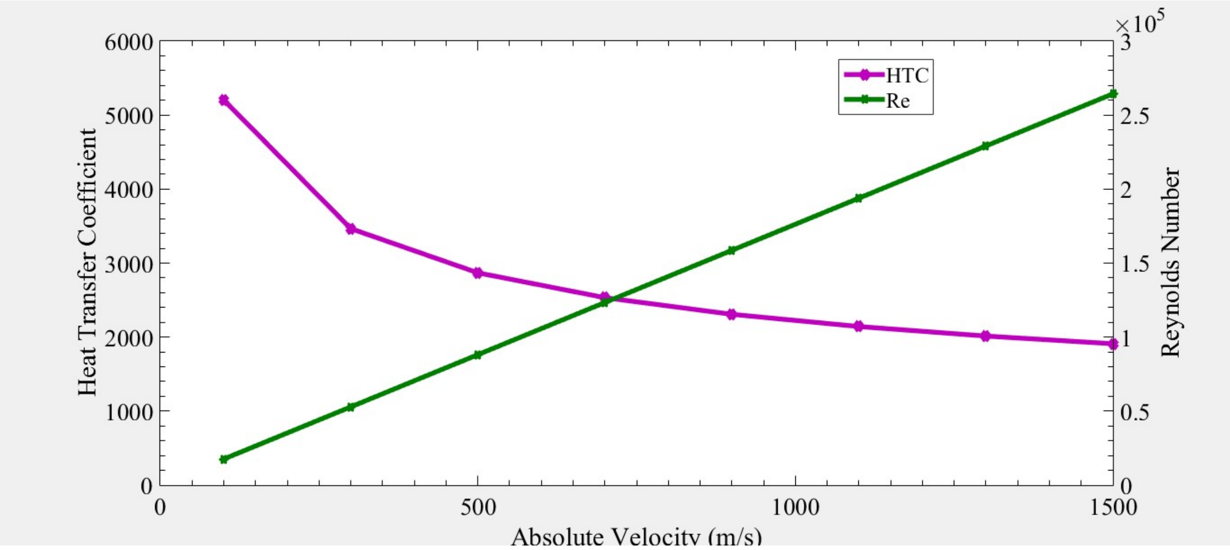


Figure 3: The effect of absolute velocity on Heat Transfer Coefficient and Reynolds Number (Hot Side).

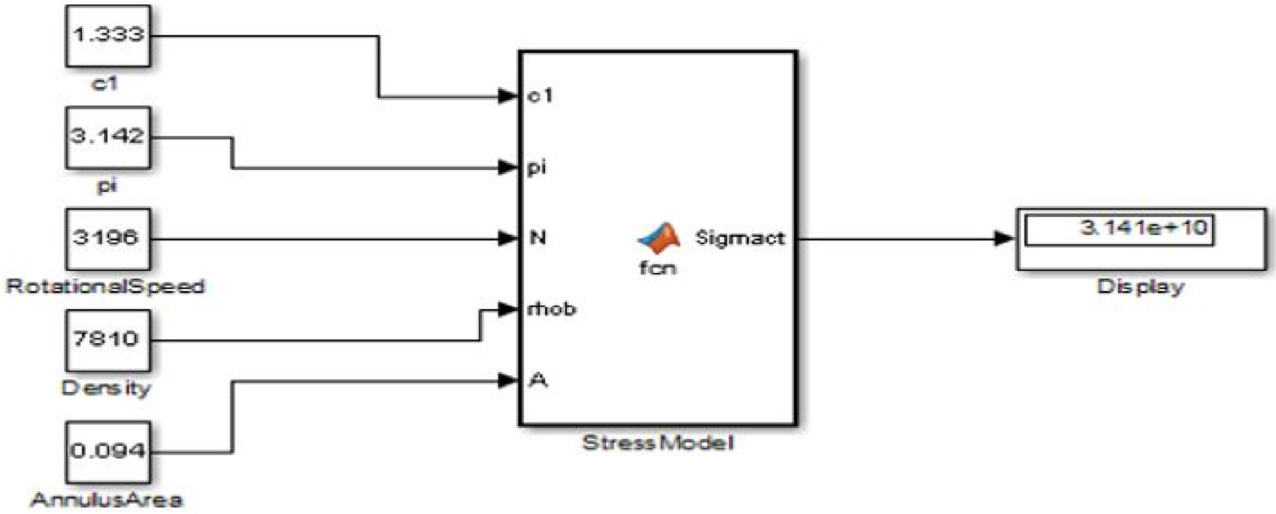


Figure 4: Simulink model for Stress computations on a gas turbine blade.

the Reynold's number; however, there is a steady decrease in the heat transfer coefficient, which could be as a result of the high temperture difference at the hot section of the blade.

The simulink model shown in Fig. 4, computed the centrifugal tensile stress acting on the blade, from the root to the tip as it spins at 3196 rpm. The centrifugal stress was found to be 31.41GPa which is high enough to cause growth, distortion, and surface irregularities in the material which could result in damage and deterioration of the microstructure.

4. CONCLUSION

The heat transfer coefficient for the hot and cold sections of the blade was successfully modelled, and the heat transfer coefficients, Reynold's number, and Stanton number at different velocities on the hot and cold section of the blade obtained. The relationship between the Heat transfer coefficient and the Reynold's number with the change in velocities at the hot and cold sections of the blade was also established. The heat transfer coefficient could be used as a boundary condition in the study of TMF of the blade material, in this study, Inconel 738LC. The stress model computed the centrifugal tensile stress, arising from the high rotational speed, which would be used for TMF calculations for the blade made of Inconel 738LC to predict creep life of the blade.

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