Quest Journals
Journal of Research in Mechanical Engineering
Volume 7 ~ Issue 8 (2021) pp: 01-06
ISSN(Online) : 2321-8185
www.questjournals.org

Research Paper

The Influence of Rotor BladeMaterial Propertyon Gas Turbine Engine performance

Ekong, Godwin I.
Department of Mechanical Engineering Akwa Ibom State University (AKSU) and A Former Researcher, Rolls-Royce supported University Research Centre for Aero-Thermal Systems and Thermo-Fluid Mechanics Research Centre, University of Sussex, Brighton, BN1 9QT, UK.

Abstract
Rotor blade is the rotating component inside the compressor or turbine of a gas turbine engine or of the jet engine. The choice of component materials for the rotor blade with appropriate thermal expansion coefficients (α) is very essential for the control blade tip clearance. This Paper presents the Influence of rotor blade material property on gas turbine engine performanceand hence the overall impact on compressor clearance. The gas turbine engine employed in this analysis is known as RB211-524 G/H-T and a finite element software known as the SCO3 with inbuilt heat transfer coefficient correlations was used to modelled the analysis. The analyses were performed with two materials known as QMP Titanium alloy and TBB Titanium alloy; designated as TBB with α =9.347E-06 and QMP with α =1.48E-05 respectively with different thermal expansion coefficients. The choice of the two materials was based on their regular used by the industrial partner in their engines such as the Rolls Royce Plc. The results of analyses show that a material known as QMP, with a higher thermal expansion coefficient gives a good reduced tip clearance compared to the material known as TBB.
Keyword: *Clearance control, Gas turbine, High Pressure compressor, Heat transfer, Thermal expansion, Materials,Titanium alloy.*

Received 14 August, 2021; Revised: 26 August, 2021; Accepted 28 August, 2021 © The author(s) 2021. Published with open access at www.questjournals.org

I. INTRODUCTION

In an aircraft engine, different materials are used for different components depending on their strength, fatigue life and temperature limits, among others. The choice of component materials with appropriate thermal expansion coefficients (α) is very essential forthe of control blade tip clearance. This analysis will examine the effect changing the material has on the temperature and movement of the rotor blade relative to the casing in an RB211-524 G/H-T HP compressor engine model; and hence the overall impact on compressor clearance.An example of material used in a component of a gas turbine engine in aero engine is Titanium. It isa chemical element with the symbolTi, atomic number 22, low density, and high strength. Titanium alloys are used in aircraft components such as rotor blades due their excellent strength-to-weight ratio, high corrosion resistance, high crack resistance, fatigue resistance and capability to endure high temperatures. Titanium alloy is used for this study.

II. REVIEW OF LITERATURE

The work presented is relevant to the material used to enhance the clearance control in High Pressure (H.P) compressors, hence giving an inside to fluid flow and heat transfer mechanism in the disc and rotor blades of the H.P. compressor. The discs inside the rotating cavities behave as a free disc as such the free disc analysis is used as a starting point in this review. A schematic diagram of the flow structure due to a free disc is shown in Figure 2.1 according to (Schlichtling, 1979). This is plane disc, which has an outer radius b, and rotates with angular velocity Ω around the z-axis, in an initially stationary fluid of density ρ , kinematic viscosity ν , thermal conductivity k and specific heat Cp.

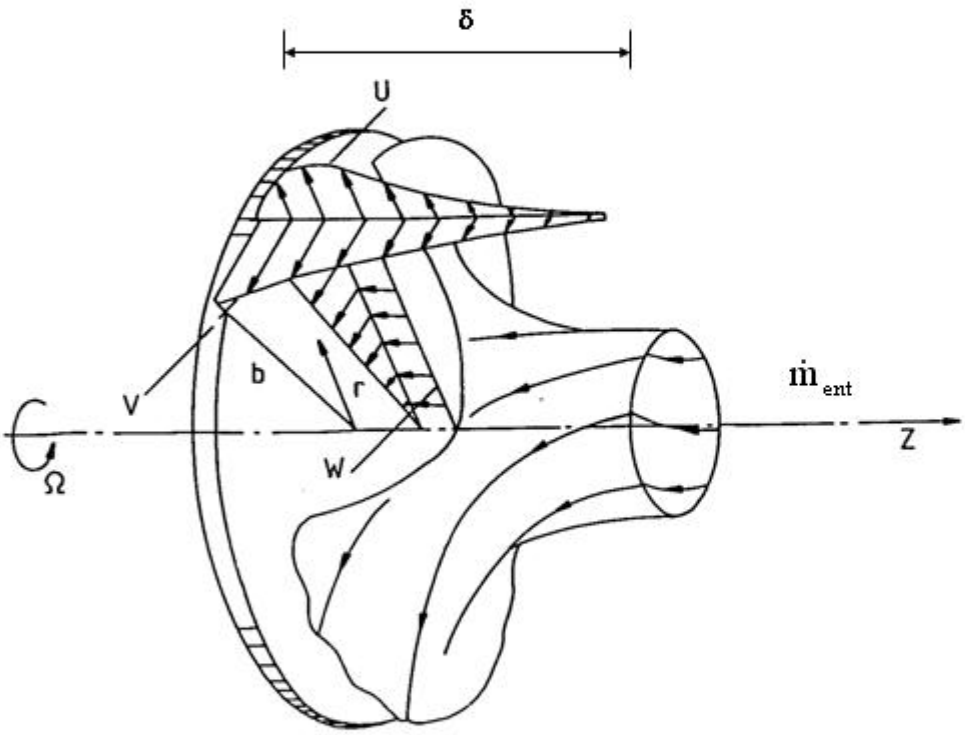

Figure 2. 1: A Schematic Diagram of the Flow due to a Free Disc (Schlichtling, 1979)

In the area near the disc, the fluid has axial, radial and tangential velocity components W, U and V respectively relative to the stationary axis. As it rotates, the flow pattern is affected by a combination of two main effect, namely the viscous friction at the disc surface and the centrifugal effect, hence the need to study the material properties of the disc and the rotor blade.These effect causes the flow to push radially outwards from the boundary layer that was formed on the disc. As the flow is pumped out radially outwards it is replaced by an axial entrainment flow into the boundary layer thereby maintaining mass continuity. It will be recall that the Rotating flows are frequently described by two main non-dimensional parameters namely the rotational Reynolds number ReØ, and the throughflow Reynolds number Cw.For a more detailed discussion on the Fluid Dynamics, Heat Transfer of Rotating Flows and Free disc the reader is referred to Dorfman (1963), Chew, J. W. (1982), Owen and Rogers (1989), Owen and Rogers (1995) and Childs (2011). And with reference to the rotor tip effect, the reader is also referred to Kusterer et al. 2007,Deng et al. (2005,Inoue et al. (2004).

III. METHODOLOGY

A sensitivity analysis was performed with RB211-524 HP Rolls-Royce compressor engine models, MATLAB programme and a one-dimensional spreadsheet were used to study the effect of heat transfer and time constant on the rotor and casing closure characteristics to quantify the effect of material selection of the rotor blade on compressor clearance during transient operation, taking into consideration, the effect of disc heat transfer coefficient increased (or decrease) on disc time constant at the tip of the rotor, hence the overall impact on compressor clearance. In view of the choice of the two Titanium alloy materials based on their regular used by the industrial partner in their engines, there was the need for certification to ascertain the best in term of tip gap control during engine transient. In this study, the relevant heat transfer coefficient correlations were used such as the natural convection from upper surfaces of hot horizontal plates, lower surfaces of cool horizontal plates, natural convection from a vertical plate or cylinder and forced convection from a free disc with laminar or turbulent flow.The effect of variation in the time constant of the rotor blade was observed in the closure and clearance characteristics of two schemes namely (+/-30% τ). The time constant study was performed with the assumption that the disc or casing section behaves as a lumped mass. In this regards, a lumped mass approximation of the time constant (τ) is represented by Equation 3.1.

Time constant, $\tau = \frac{mC}{hA}$ **(3.1)**

In this analysis, a computation of stage 1 rotor blade thermal growth and tip clearance was performed with TBB, and a second analysis was carried out by replacing the TBB with QMP to compare the effect, each material has on tip clearance during transient operations over an engine operating cycle known as the Square cycle, which is presented as Figure 3.1. This is a simple design point engine cycle in aero-engine consisting of a start, stabilisation at idle, acceleration to maximum, stabilisation at maximum take-off (MTO), deceleration to idle, and stabilisation at idle. It provides a basic understanding of temperature, displacement, and clearance response in the cycle. This is the first cycle that is run in the SCO3Finite Element Analysis (FEA)program to verify model behaviour in gas turbine aero-engine, hence ascertaining the strength and functionality of the component, based on material properties of the components for a more detailed discussion on themodelling of compressor clearance with SCO3, the reader is referred to Ekong et al. (2011) and Ekong et al. (2013). This a typical engine square cycle shows the speed in revolution per minute (rpm) against time in seconds, with an indication of the start point, acceleration to maximum take-off (MTO), maximum take-off (MTO), Deceleration to Idle and stabilisation at idle (stab. Idle) in the cycle.The square cycle helped in the study of various effects on the potential performance of the engine with respect to the material used in the various components. The heat transfer coefficient which is the proportionality coefficient between the heat flux and the temperature difference is employed in calculating the heat transfer by convection or phase transition between a fluid and a solid. The heat transfer coefficient has SI units in watts per square meter Kelvin as presented in Equation 3.2.

$$h = \frac{Q}{A \Delta T} \quad \text{W/ (m}^2\text{K)} \qquad \textbf{(3.2)}$$

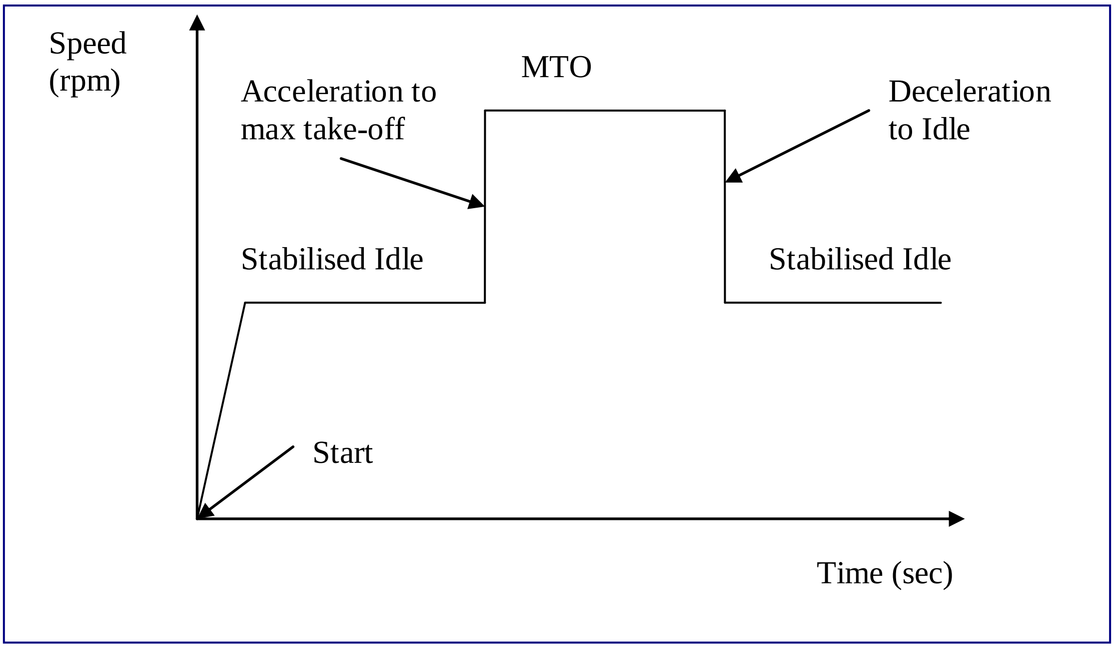

Figure 3.1: A typical engine square cycle with speed in revolutions per minute against time inseconds

The engine data, environmental parameters and the values of the relevant heat transfer coefficient correlations used in the modelling of flow in RB211-524 G/H-T HPC engine model are restricted due to the proprietary issue. The rotor thermal growth characteristics for stage 1 of the RB211-524 aero engine model; with the effect of a change in a 30 percent reduction and 30 percent increase in the rotor time constant during engine transient operation are presented in Section 4.

IV. RESULTS & DISCUSSION

This analysis examines the effect of component material properties on the temperature and movement of the rotor blade relative to the casing of a gas turbine engine. The results of the thermal response of the rotor blade, the clearance and the corresponding variation in terms of clearance due to differences in material components during engine transient are presented in Figure 4.1, Figure 4.2 and Figure 4.3 respectively.

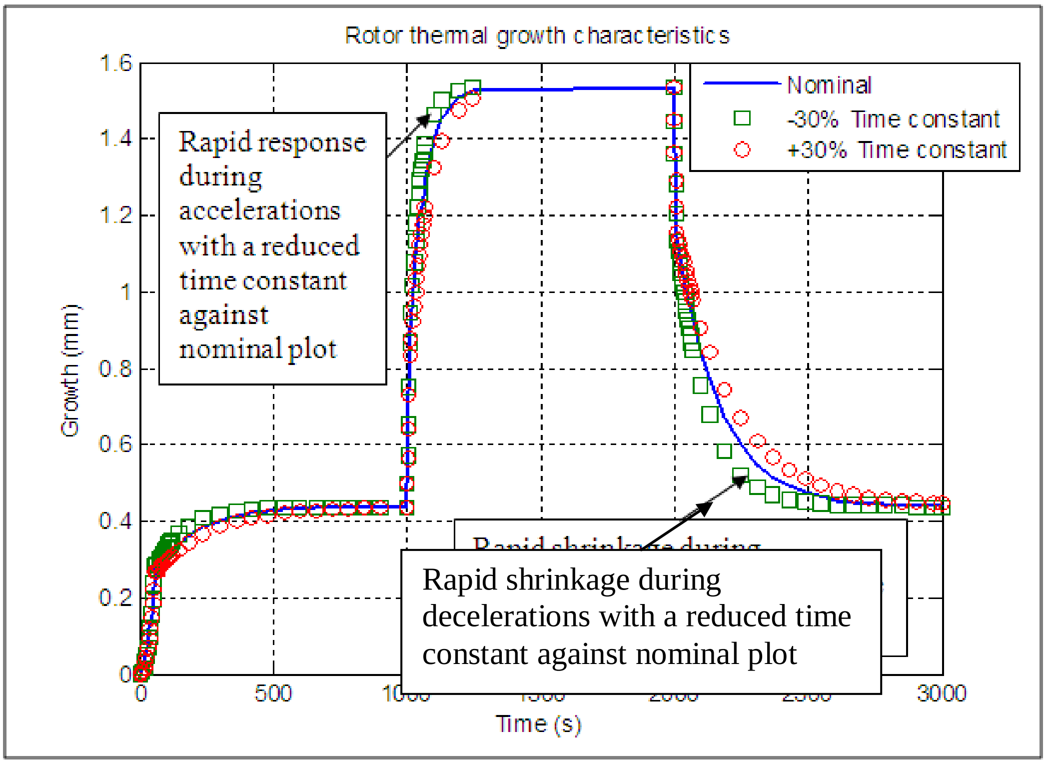

Figure 4.1: The variation of rotor tip thermal growth with time over a square cycle of stage 1 HP compressor for RB211-524 engine with (+/-30%) time constant (τ) during transient operation

Figure 4.1 shows a more rapid response from the rotor during engine accelerations and a more rapid shrinkage during engine decelerations when the time constant is reduced by 30% against a nominal plot. A slower response from the rotor during engine accelerations and decelerations respectively is observed when the time constant is increased by 30% when compared to the baseline analysis.This thermal growth effect affects the clearance characteristics as shown in Figure 4.2. This indicates a reduced clearance throughout the cycle with decreased time constant against the nominal plot.

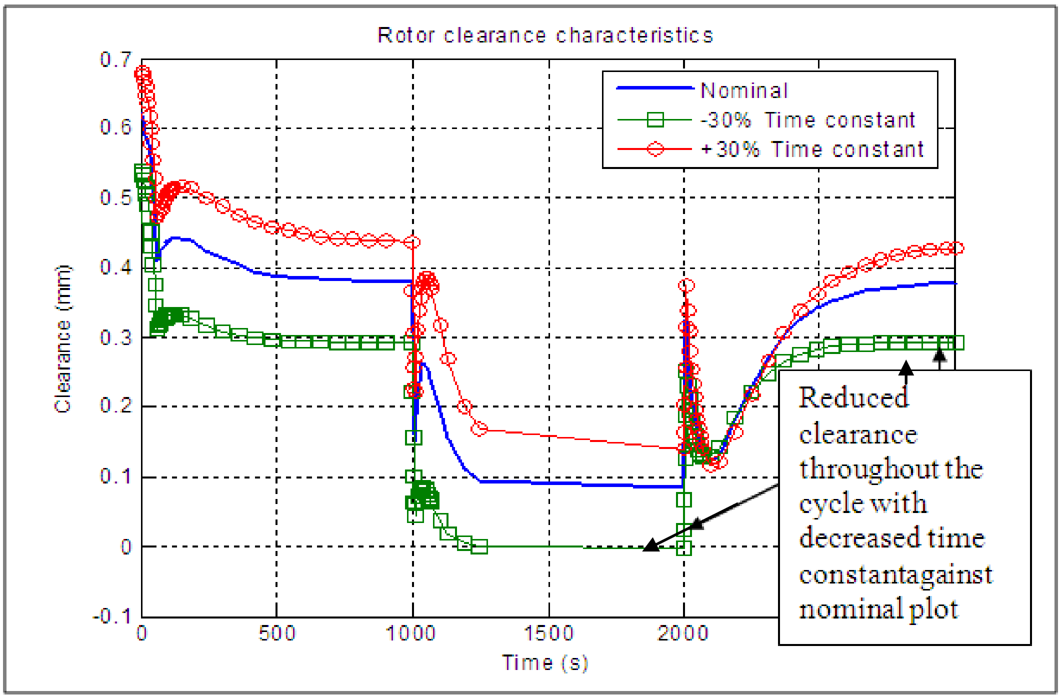

Figure 4.2: The variation of rotor clearance characteristics with time over a square cycle for stage 1 of the RB211-524 aero engine model with the effect of (+/- 30%) time constant (τ) during transient operation

*Corresponding Author: Ekong, Godwin I.

Finally, the disc time constants are found to depend on the heat transfer coefficient of the disc. An increase in the heat transfer coefficient reduces the disc time constant. Hence, increasing the thermal response of the high pressure compressor (HPC) drum will reduce the reslam characteristic at t = 2100 s of the drum, therefore reducing the cold build clearance (CBC) and hence the reduction in clearance.

The coefficient of thermal expansion of material which isa measure of a material in response to a change in temperature is very essential for the control of clearance. It is important to note that materials expand as temperature increase and contract as temperatures decrease. The change in length of the material is therefore proportional to changes in temperature and is denoted with a symbol α.

In this analysis, a computation of stage 1 rotor blade thermal growth and tip clearance was performed with TBB Titanium alloy and a second analysis was carried out by replacing the TBB Titanium alloy with QMP Titanium alloy to compare the effect each material has on tip clearance during transient operations over an engine square cycle.

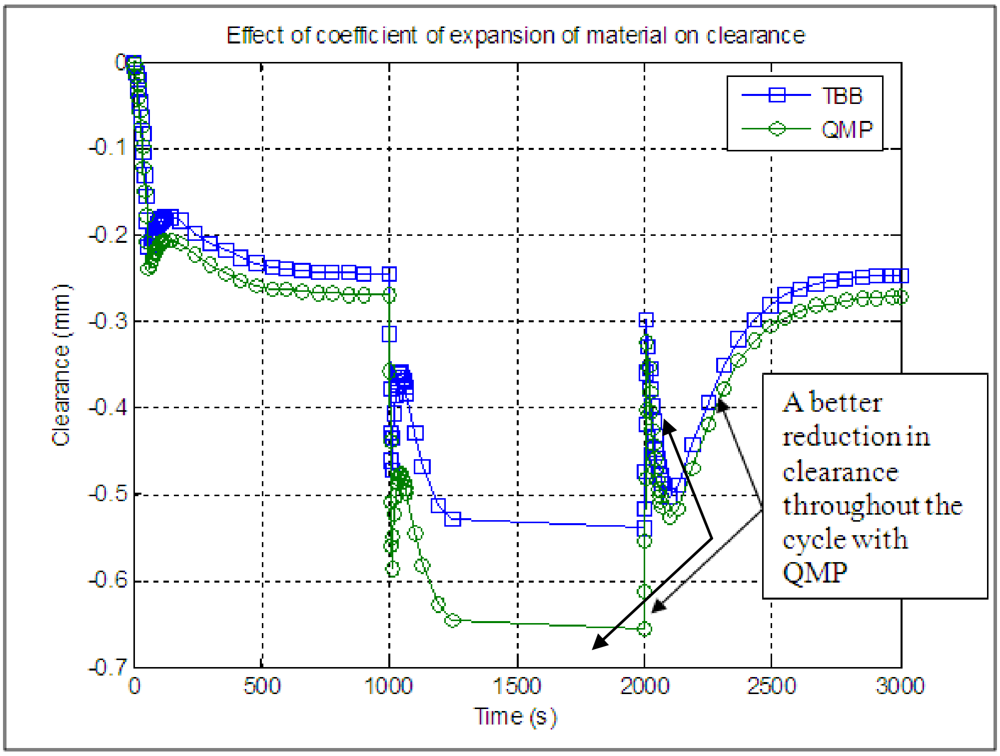

Figure 4.3: The variation oftip clearance with time over a square cycle for the basic model with material TBB and the modified rotor blade design model with material QMP for stage 1 HP compressor of RB211-524 engine

The result of the analysis is presented in Figure 4.3. Figure 4.3 shows tip clearance as a function of time for the basic model TBB and the modified rotor design model QMP. The material selection analysis results show that QMP, with a higher thermal expansion coefficient gives a reduced tip clearance compared to TBB. Hence the reason for using the material with a higher thermal expansion coefficient in the rotor blade of the last stages of the HP compressor so as to withstand the high thermal stress and complex flow behaviours.Hence, the basic rotor blade model of the RB211-524 G/H-T HP compressor engine consists of TBB of stages 1 and 2 of the rotor blade, while QMP was used for stages 3 to 6.

V. CONCLUSION

This study was to determine the quantitative effects of different material employed in the rotor blades of the high-pressure compressor stages, hence, the corresponding impact on compressor clearance and overall performance of the engine. The most promising ideas were analysed using the drum and casing models of the RB211-524 model engine.The intention of this study was to decrease the time constant of the drum by increasing the relevant heat transfer coefficients. This helpsthe compressor drum to heat up faster, hence narrowing the large gap that existed at the beginning of engine transient operation between the casing and the blade. This would result in the reduction of the cruise clearance, a reduction in clearance at first acceleration (max takeoff) and hence, giving rise to a higher engine efficiency. The material selection analysis results show that QMP, with a higher thermal expansion coefficient gives a reduced tip clearance compared to TBB. Hence, the reason for using the material with a higher thermal expansion coefficient in the rotor blade of the last stages of the HP compressor so as to withstand the high thermal stress and complex flow behaviours. Therefore, the basic rotor blade model of the RB211-524 G/H-T HP compressor engine consists of TBB of stages 1 and 2 of the rotor blade, while QMP are employed in stages 3 to 6 for higher engine efficiency.

ACKNOWLEDGMENTS

I acknowledged my supervisors during my research years at Thermo-Fluid Mechanics Research Centre, University of Sussex, Brighton, BN1 9QT, United Kingdom Prof. Peter R. N. Childs, Dr. Christopher A. Long and Dr. Nick. R. Atkins for their training and encouragement throughout my years at University of Sussex. Thanks to Rolls-Royce Plc for giving me the opportunity to do a research with this highly respectable company in the world and to be involved in the New Aero Core Concept (NEWAC), a European Union (EU) Framework 6 programme.

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