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Compressor Clearance Control Concepts using Time constant Reduction Approach

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ABSTRACT

The compressor clearance is critical to axial flow compressor of modern commercial, civil aero-engines in terms of performance during engine transient. This research document the development of concepts and their evaluation for the reduction and control of compressor clearance in HP compressors through the reduction in the compressor disc heat expansion time constant. A good compressor clearance will enhance the thermodynamic efficiency of aircraft engine and other gas turbine engines leading to good engine operability and a reduction in fuel consumption. The project involves modelling of potential solutions with 2D multiple cavity rig model using a finite element analysis program known as sc03, in order to investigate the physical principles and show proof of concepts for controlling tip clearance in HP compressors of gas turbine engines during engine transient. The analysis of the time constant (τ) for compressor clearance of RB211-524 rotor and casing models shows that decreasing the time constant of the rotor and increasing the time constant of the casing reduces the clearances in the compressor. This will give a better tip clearance in the engine during transient operations.

KEYWORDS: *Time constant, Clearance, Control, High Pressure, Compressor, Aero-engines*

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I. INTRODUCTION

Tip clearance control is the process of controlling the gap between the rotating blade tip and the casing of an axial compressor during transient. The research is under the New Aero Core Concepts (NEWAC) programme. It was an EU Framework Six programme which covers many areas related to the development of future engine architecture as shown in Figure 1.1. Our research was led by Rolls Royce PLC. The benefits include the **c**ontrol of surge occurrence and reduction in specific fuel consumption. The project involves modelling of potential solutions with 2D multiple cavity rig model and the use of experimental facilities such as the rotating compressor cavity rig, in order to investigate the physical principles and show proof of concepts.

In this study, the rotating cavities with radial inflow and axial throughflow which are directly relevant to this paper are not discussed in detail due to the propriety nature of the work. However, the main features of these flows are discussed and the complexity of the rotationally-induced buoyancy-driven flows are highlighted in the work by Dorfman (1963), Chew (1982), Pincombe (1983), Long (1984), Farthing and Owen (1988), Firouzian (1986) Owen and Rogers (1989), Tucker (1993), Owen and Rogers (1995), Alexiou (2000), Atkins (2013), Childs *et al.* (2006), Tucker (1993) in details, with the various rotating flow configurations. The reader is referred the work of the mentioned authors. It is important to mention that identifying the flow structure and heat transfer inside a rotating cavity is important for designers since temperature gradients generate additional thermal stress and influence the linear expansion of the disc. This effect is noticed during engine transient of (acceleration, deceleration and cruise). During start and take-off condition the discs are colder than the incoming air, which is defined as an inverse temperature situation or heating flow. A normal temperature situation or cooling flow occurs during the cruise and approach when the hot discs are cooled by air (Günther – *W* et al.).

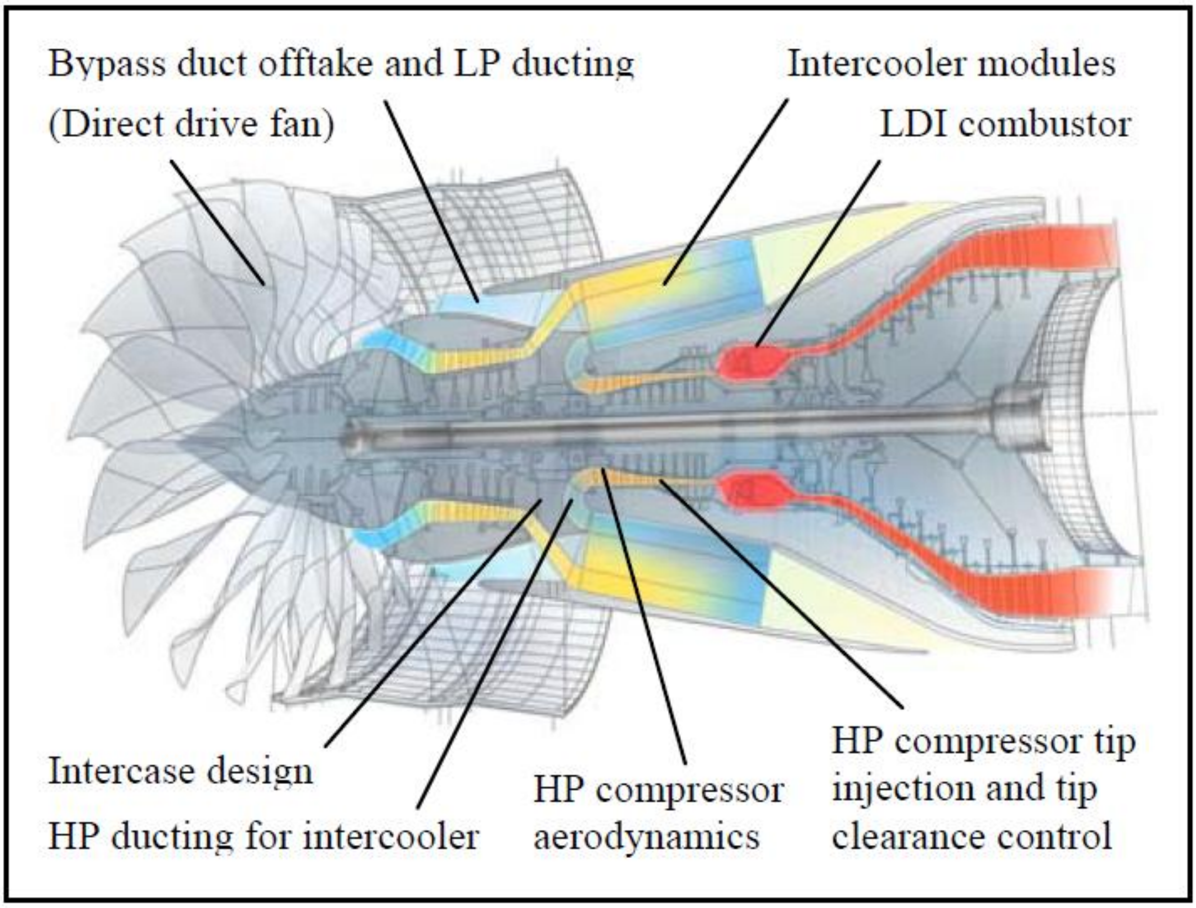

Figure 1.1: Intercooled core concept from Rolt and Kyprianidis (2010)

II. METHODOLOGY

A sensitivity analysis was carried out to determine the quantitative effect of time constants on tip clearance control. The study uses a simplified lumped parameter spreadsheet model in conjunction with a full axisymetric thermo-mechanical SC03 HPC drum and casing model, where a mesh is generated before other analysis are performed. Figure 2.1 shows the geometry of the multiple cavity rig model meshed with six-node triangular elements in 2D. The cycle use is known as the Square cycle shown as Figure 2.2. This cycle includes start, idle, acceleration to maximum take-off (MTO), stabilisation at MTO, deceleration to idle and stabilisation at idle. For a given cycle, clearance depends on casing displacement and rotor displacement. The displacement of casing relative to rotor displacement is called Closure.

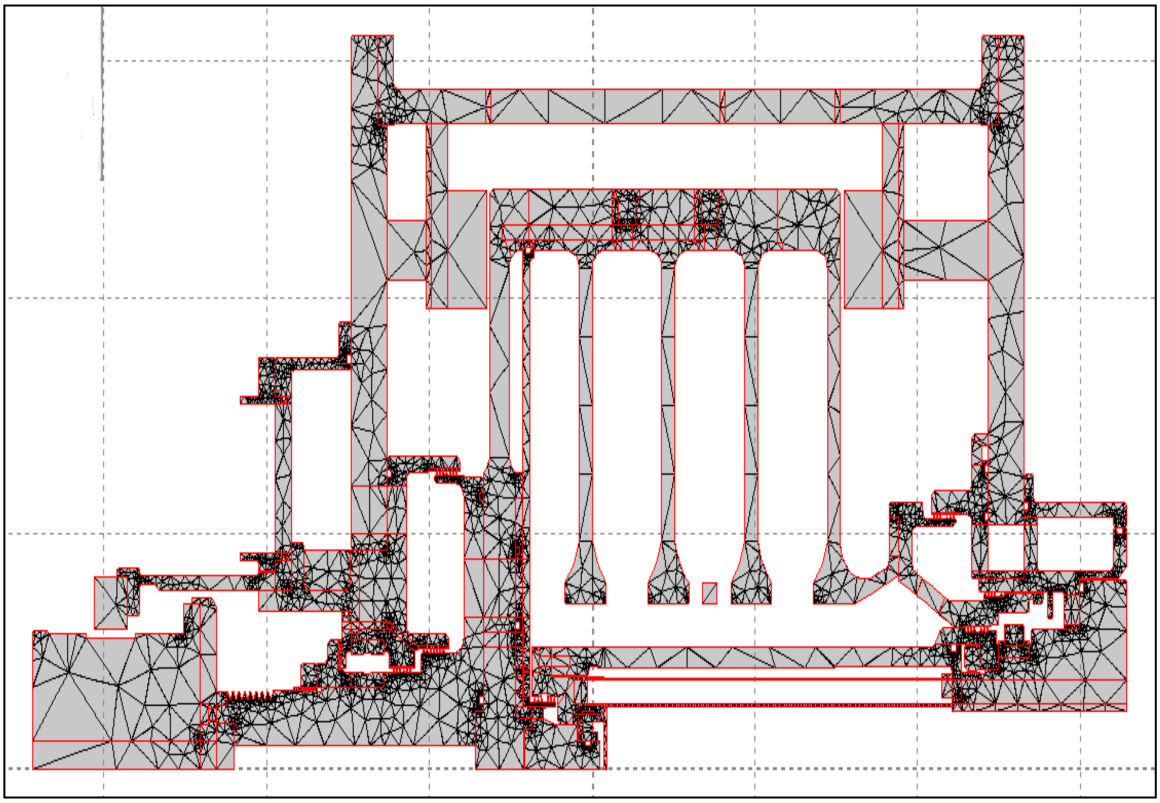

Figure 2.1: The geometry of the multiple cavity rig model meshed with six-node triangular elements in 2D.

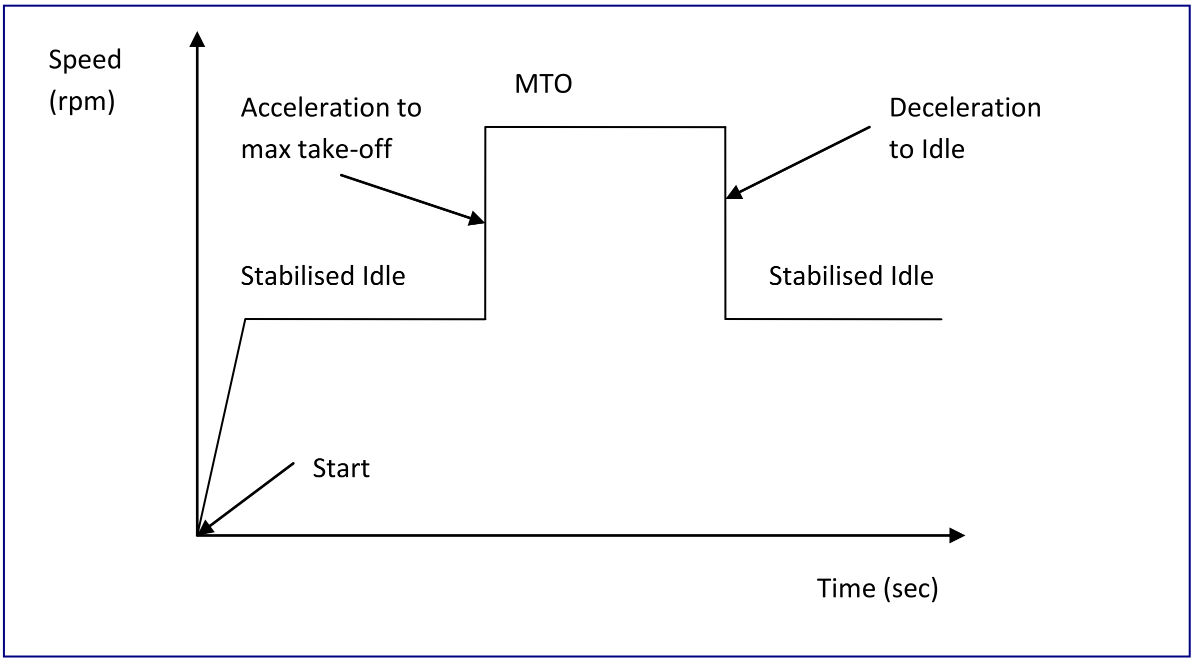

Figure 2.2: A typical engine square cycle with speed in revolutions per minute against time in seconds.

The square cycle is used to study the effect of potential clearance in displacement analysis and it also provides data for the scaling calculation that is employed to investigate clearances at other engine conditions. A propriety finite Element program known as SC03 is use for an automatic analysis system to process the results from a cycle run. The results are usually processed and presented in four different ways, such as contour plots, 'get values', time plots, and user-defined graphs. This is after a thorough model check of fluid type for boundary conditions other than air only, mass flows, fluid temperatures, fluid pressures, heat transfer coefficients, and material type.

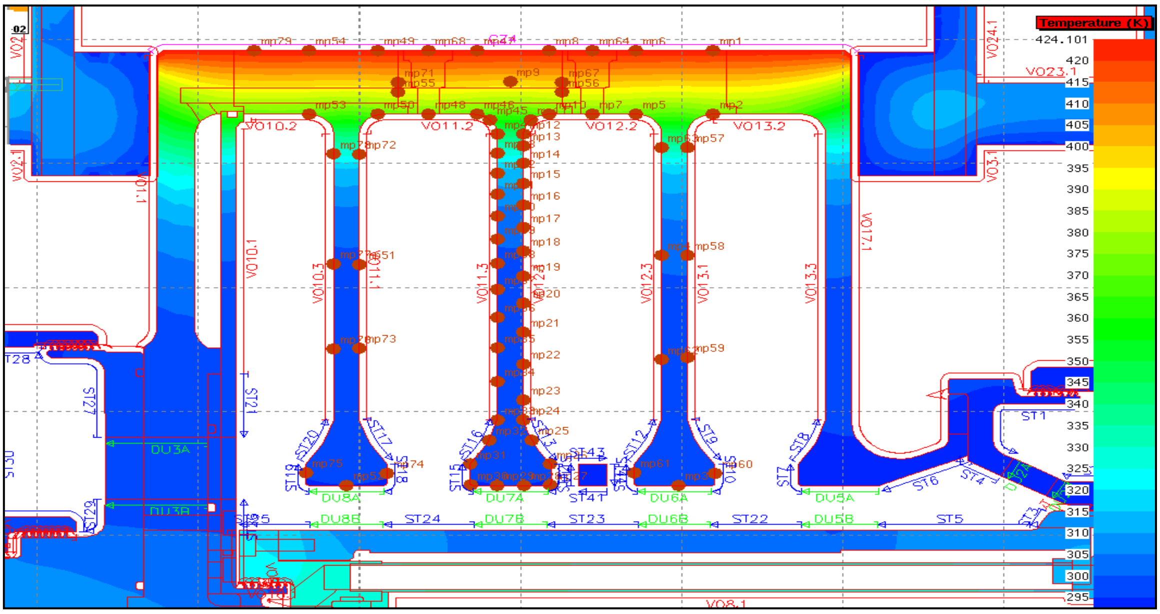

Figure 2.3: Temperature contour plots

The contour plots provide a qualitative understanding of the predicted temperature, stress, and distribution in and around a component. Figure 2.3 shows the temperature contour plots, of the multiple cavity rig model. For the determination of the absolute value at a point on the model, the 'get values' result type is used, which has the capability to determine the value at a specific point on the model at specific times during the analysis cycle and whose values are at the nearest mesh node as shown in Figure 2.4. The reader is referred to detail modelling of the multi cavity rig model by Ekong (2014), Ekong *et al.* (2013) and Ekong *et al.* (2012).

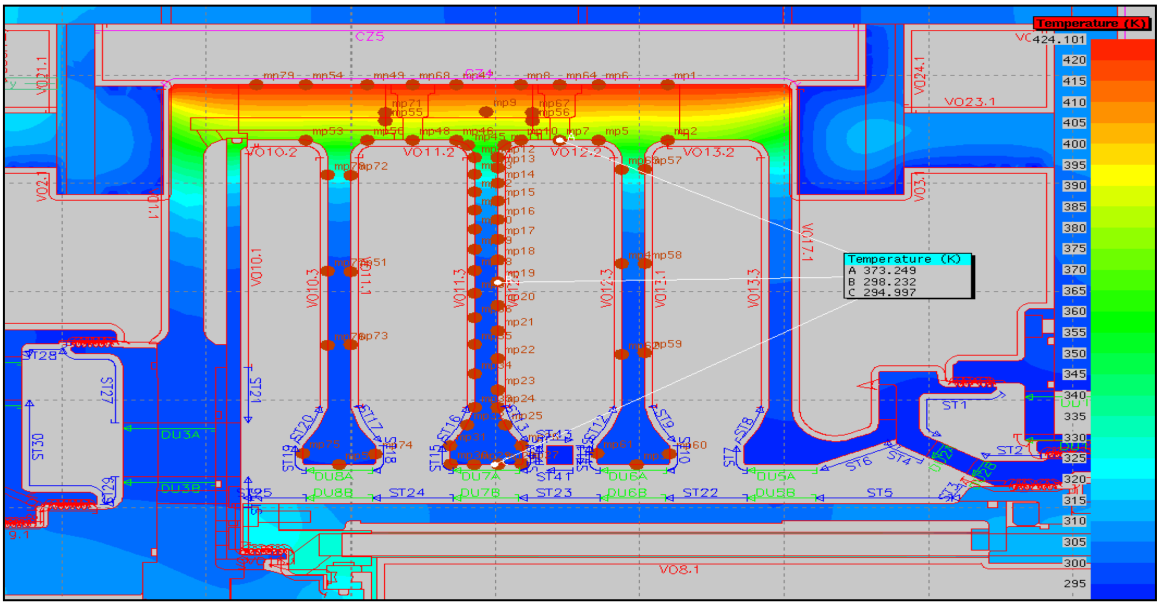

Figure 2.4: Get values result plot

Other ways of presenting the analysis results, are through time plots, which are capable of generating a graph of the result at a specific point on the model for the complete analysis cycle, as shown in Figure 2.5. User-defined graphs, enable results values to be combined with each other or with external data such as engine measurements by defining the points at which results are to be graphed using 'reference points' and using the graph layout panel to manipulate the plot variables depending on the desired result. Another way of presenting results is the user-defined result technique; this is in the form of metal temperature or displacement difference between two points in the model.

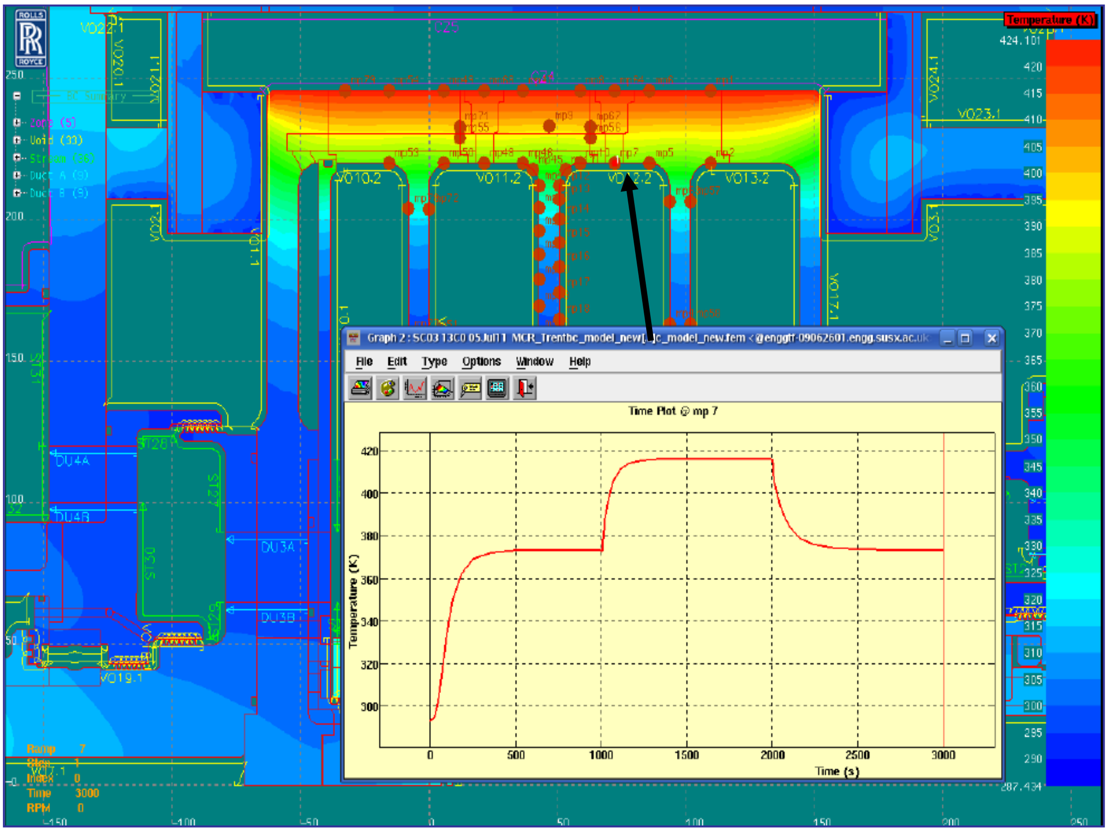

Figure 2.5: Time plot at a specific model point

III. RESULTS AND DISCUSSION

Based on the choice of a passive clearance control scheme involving the control of the disc and casing thermal response using TRIZ process, a sensitivity analysis was carried out. This was to determine the quantitative effect of various parameters on the closure behaviour of the various high-pressure compressor stages, hence the overall effect on clearance. The parameter consider in this report is the time constants. The effects of this parameter are analysed using the drum and casing models of the RB211-524 model high pressure compressor (HPC).

The concept postulates that if the mass, volume and the area of the solid are constant, that increasing or decreasing the heat transfer coefficient of the body will result in the reduction or increase of the time constant. The intent of this study was to decrease the time constant of the drum by increasing the relevant heat transfer coefficients. This will cause the compressor drum to heat up faster, hence narrowing down the large gap that existed at the beginning of engine transient operation between the casing and the blade. This would effect a reduction in the cruise clearance and a reduction in clearance at first acceleration (max take off) and hence reductions in the overall specific fuel consumption giving rise to higher engine efficiency.

The RB211-524 G/H-T HPC engine model and spreadsheet were used to study the effect of the time constant on the rotor and casing closure characteristics, and the results are presented graphically in Figures 3.1 through to Figure 3.3. The time constant study was undertaken assuming the disc or casing section behaves as a lumped mass. Assuming a lumped mass approximation, the time constant (τ) is represented by Equation 1.

Time constant, $\tau = \dfrac{mC}{hA}$ **(**1)

Some concept to note, while analysing the clearance control in high pressure compressor includes casing displacement, rotor displacement, closure analysis and clearance analysis.

- **Closure:** Compressor closure is the displacement of the casing relative to rotor displacement in a compressor.

$$\delta_{close} = \delta_c \_ \delta_r \quad (2)$$

- **Clearance:** This is the addition of the cold build clearance (CBC) to closure in a square cycle.

$$\delta = \delta_{CBC} + \delta_{close} \quad (3)$$

Where δ = displacement,

c = casing,
r = rotor,
CBC = Cold build clearance and
close = closure.
The method for controlling tip clearance indicates that for a given square cycle, tip clearance depends on:

- Casing displacement
- Rotor displacement

Two essential analyses are performed to determine the compressor clearance during transients over a square cycle, namely:

- The closure analysis
- The clearance analysis

In the clearance control analysis, a positive y-axis on the graph represents clearance plots while a negative y-axis represents closure plots. In the clearance graph, the point zero on the graph represents the touching of blade and casing while a negative number indicates the rubbing between the blade and the casing.

Figure 3.1 shows 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. This value was suggested by the industrial partner. It is noted that the SCO3 model uses inbuilt heat transfer coefficient correlations natural convection from the upper surfaces of hot horizontal plates and 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 reducing the drum time constant on the closure characteristic is presented. This example shows +/-30% reduction in time constant for stage 1 of a RB211-524 HPC. Figure 3.1 shows the variation of rotor tip thermal growth with time over a square cycle of stage 1 HP compressor for a RB211-524 engine with (+/-30%) time constant (τ) during transient operation while Figure 3.2 shows the effect (+/-30%) time constant (τ) on closure characteristics.

Figure 3.1 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%. However, 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.

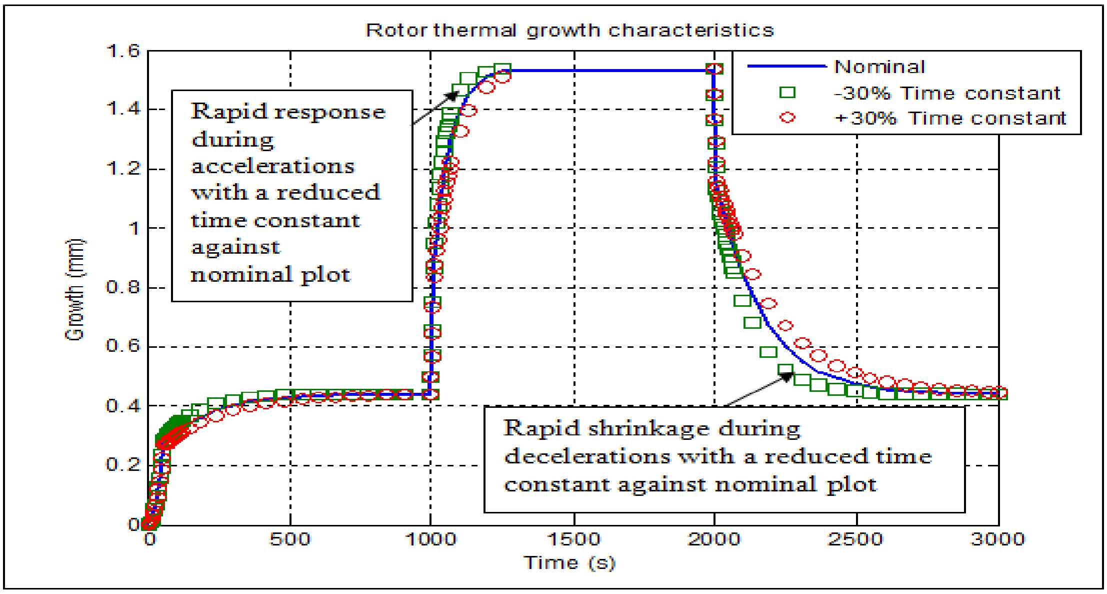

Figure 3.1: The variation of rotor tip thermal growth with time over a square cycle of stage 1 HP compressor for RB211-524 engine with (+/-30%) time constant (τ) during transient operation.

The effect of this different time constant of the rotor is observed in the closure characteristics of the two schemes (+/-30% τ) as shown in Figure 3.2. The analysis shows that with a 30% reduction in time constant, there is a reduction in closure characteristics during acceleration and with an increase in closure during deceleration in comparison to the nominal case. But with a 30% increase in time constant, an increase in closure characteristics can be observed during acceleration and decrease in closure during deceleration.

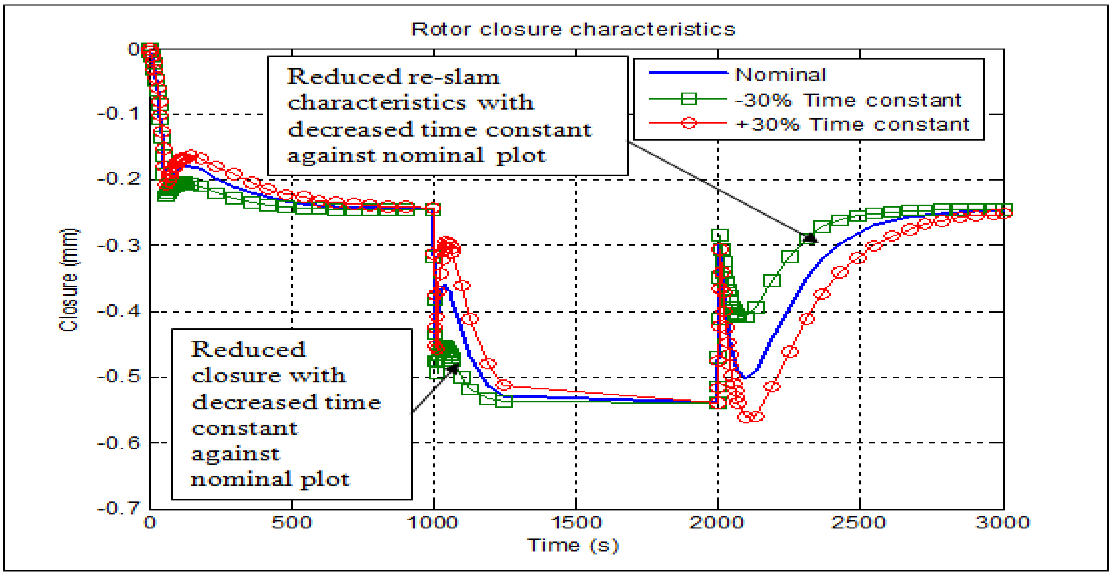

Figure 3.2: The variation of rotor closure characteristics with time over a square cycle for stage 1 of the RB211-524 aero engine model with the effect of (+/- 30%) time constant (τ) during transient operation.

The effects of these two schemes (+/-30% time constant) are converted into clearance characteristics of the rotor in the cycle during transient operation by applying the clearance control Equation 3. When the cold build clearance is added to the closures in the cycle, the results obtained are the overall clearances in the cycle as shown in Figure 3.3.

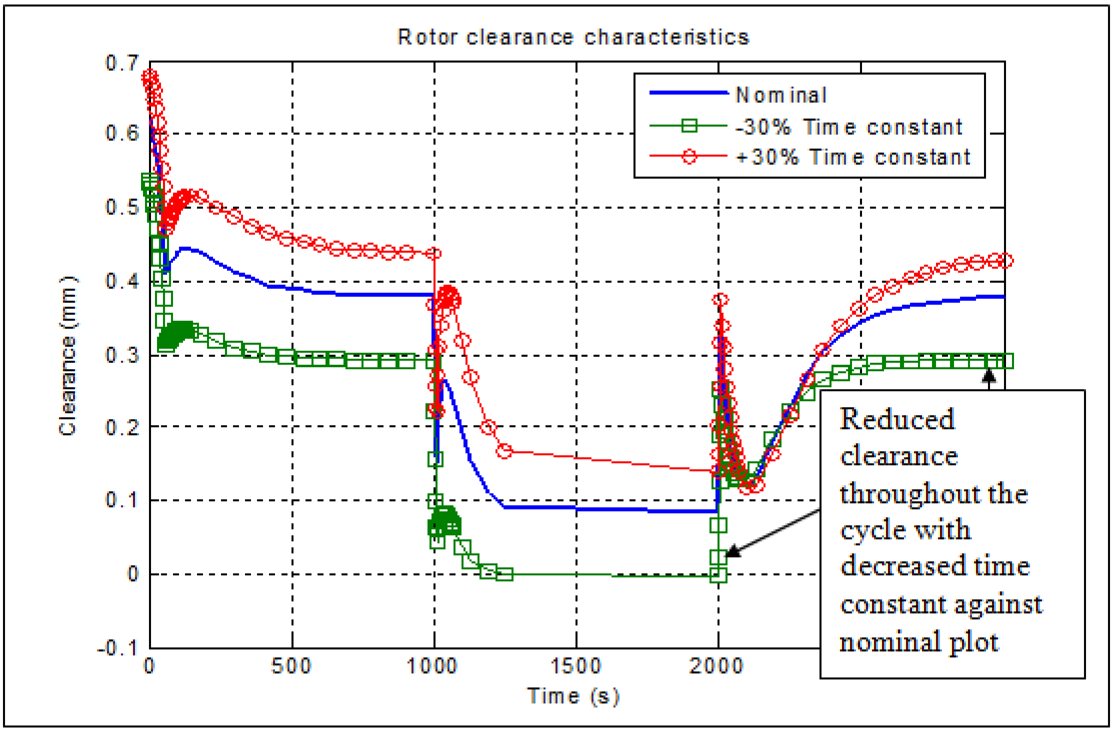

Figure 3.3: The variation of rotor clearance characteristics with time over a square cycle for stage 1 of the RB211-524 aero engine model with the effect of (+/- 30%) time constant (τ) during transient operation.

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 point, at which the clearance is '0', indicates the touching of the casing and the blade during the transient operation.

IV. CONCLUSIONS

This study shows that a decrease in the time constant of the drum will reduce the re-slam characteristics of the drum hence a reduction in closure. This will reduce cruise clearance and will impact positively on the compressor operability hence an improvement on compressor tip clearance throughout the engine operating cycle. The 2D modelling of MCR is used to validate the MCR experimental data.

From the time constant (τ) analysis for compressor clearance of RB211-524 rotor and casing models, it is concluded that decreasing the time constant of the rotor and increasing the time constant of the casing reduces the clearances in the compressor. This will give a better tip clearance in the engine during transient operations.

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