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A method for the assessment of operational severity for a high pressure turbine blade of an aero-engine

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Abstract: This paper provides a tool for the estimation of the operational severity of a high pressure turbine blade of an aero engine. A multidisciplinary approach using aircraft/engine performance models which provide inputs to a thermo-mechanical fatigue damage model is presented. In the analysis, account is taken of blade size, blade metal temperature distribution, relevant heat transfer coefficients and mechanical and thermal stresses. The leading edge of the blade is selected as the critical part in the estimation of damage severity for different design and operational parameters. The study also suggests a method for production of operational severity data for the prediction of maintenance intervals.

Keywords: thermo-mechanical fatigue; turbine blades; oxidation; creep

Nomenclature

FEA Finite Element Analysis
HPT High Pressure Turbine
OAT Outside Air Temperature
OEM Original Equipment Manufacturer
MRO Maintenance, Repair Organisation
NGV Nozzle Guide Vane
PCN Relative Rotational Speed (ie relative to 100% rotational speed)
RPM Revolutions per Minute
TBC Thermal Barrier Coating
TET Turbine Entry Temperature
TMF Thermo-Mechanical Fatigue
TOW Take-off Weight

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1 Introduction

The life of the high pressure turbine blades of aero gas turbine engines is significantly affected by thermo-mechanical fatigue (TMF) due mainly to the effect of thermal transients. In addition, the difference in the coefficients of thermal expansion of the blade metal and thermal barrier coating further exacerbates the problem. The requirement for performance and the operating conditions in terms of aerodynamic and structural characteristics determine the design parameters of the blades. Blade life, failure mode and failure location are fundamentally influenced by the changes in the stress/strain regime in the blade which, in turn, is dictated by the blade geometry [1]. There is therefore a need to consider the effect of engine operating conditions on the parameters which affect the life of the turbine blades. An understanding of the interaction of various failure mechanisms and their effect on the life of the blades enables the determination of cost effective maintenance decisions for aircraft operators.

In practice, the lives of the high pressure turbine components have a major influence on maintenance intervals. The intervals are, to some extent, dependent on operating profiles (eg long/short haul and take-off conditions/requirements). Rigorous inspection regimes dictated by the requirements of the principles of 'on-condition' maintenance are used to determine when maintenance action is required. Thus airlines have historically resorted to using empirical data and the operational severity data provided by OEMs to forecast maintenance costing.

The objective of this paper is to present a physics based approach to the operational severity assessment of the hot gas path components of aero gas turbine engines. The approach is straightforward and generic. Engine performance data is used to estimate the basic geometric specifications of the turbine blade which are then fed into a heat transfer model. The heat transfer coefficients and blade temperature profile from the heat transfer model provide the boundary conditions for a thermal finite element analysis (FEA) on a critical section of the blade (in this case, the leading edge). A transient coupled thermal and mechanical FEA produces the principal stresses and strains generated over a reference flight profile. The Simulia ABAQUS finite element solver is used for both the thermal and mechanical modelling. The Neu-Sehitoglu TMF model, which captures the damage accumulation due to creep, low cycle fatigue and oxidation, is used for the assessment of blade life. The model also accounts adequately for the phasing of temperature and mechanical strain. The analysis of operational, design and technological parameters that significantly affect the life of aero engine hot gas path components leads to the estimation of operational severity (the ratio of total damage due to reference flight profile to the damage due to other flight profiles) with and without take-off de-rate. The method is intended for use during the preliminary gas turbine high pressure turbine design stages to enable a first stage assessment of TMF life.

2 Thermo-mechanical fatigue

Components which are subjected to thermal transients and mechanical strain cycles are likely to incur damage due to TMF as a result of interactions between creep, fatigue and oxidation [2]. TMF cycles are classified as either 'in phase' (IP) or 'out of phase' (OP). In IP cyclic loading, the maximum and minimum strains coincide respectively with the maximum and minimum temperatures. Conversely, for OP cycles, the maximum and minimum strains coincide respectively with the minimum and maximum temperatures. Zhuang *et al.* [3] have produced a critical review of models that have been developed to estimate TMF life.

The cooled turbine blades, used in almost all modern aero gas turbine engines, are subjected to combined mechanical loadings (centrifugal and bending forces) and thermal loads that vary significantly across the blade. These loads change rapidly throughout the engine operating cycle. In the cruise condition, where most engines can be expected to spend most of their operating life, the temperatures and mechanical loading conditions are, more or less, constant. Hence the primary damage mechanisms at this flight condition are likely to be time dependent and therefore the life consumption is significantly influenced by steady state creep and oxidation. However, at the high power settings that occur at take-off and landing (reverse thrust), the transient thermal and mechanical load changes lead to fatigue damage. Moreover, the high transient thermal loads experienced within turbine blades at engine start up and shut down due to changes in temperature across the blade material are a significant contributor to TMF damage.

The Neu Sehitoglu model developed for high temperature fatigue and TMF [4–7] was selected for the TMF life assessment. This study emulates the model that was applied to a MAR-M247 nickel based superalloy in [7]. The model accounts for the damage accumulation due to fatigue, oxidation and creep. Damage per cycle from fatigue (D^{fat}), oxidation (D^{ox}) and creep (D^{creep}) are summed to obtain a total damage per cycle (D^{tot}) Thus:

$$D^{tot} = D^{fat} + D^{ox} + D^{creep}. \quad (1)$$

Equation (1) can be rewritten in terms of life (N_f), where damage is expressed as the reciprocal of life:

$$\frac{1}{N_f} = \frac{1}{N_f^{fat}} + \frac{1}{N_f^{ox}} + \frac{1}{N_f^{creep}}. \quad (2)$$

The Neu and Sehitoglu model was originally tested for steels, the nickel based super alloy MAR-M247 and aluminium alloys and the results were satisfactory. The draw back with this model is the large number of material constants that have to be determined experimentally. Nevertheless, unlike the other models that are based on isothermal tests, the Neu and Sehitoglu model is based on TMF tests and captures the relevant damage mechanisms. It is therefore considered a suitable choice for life prediction in this work.

3 TMF life/severity assessment model

The methodology used for the blade life/severity assessment (shown in Figure 1) comprises modules for aircraft and engine performance, blade sizing, stress, thermal and TMF. Due to the lack of availability of data on advanced aero engine materials, the blade material selected for the study was Mar–M247. The temperature dependent material properties for this material were obtained from open sources[1].

The components of the model are as follows:

– **Aircraft/Engine Performance Simulation**: A mature high bypass ratio, two spool turbofan engine for a short/medium haul aircraft was selected to demonstrate the methodology used in this study. The performance simulation [8] was completed using software which has been developed at Cranfield University. The

1 Nickel Development Institute. High temperature High Strength Nickel based Alloys No 393. 1995.

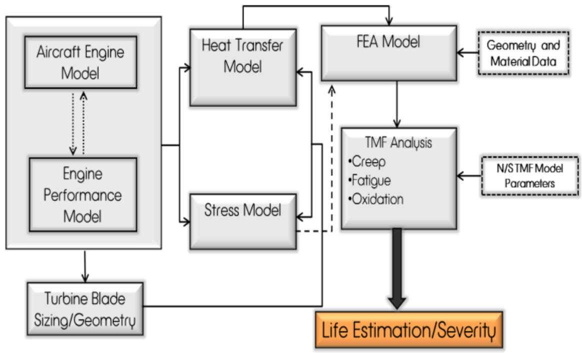

Figure 1: Lifing assessment model.

software has the capability to produce steady state results for engine performance calculations at both design point and off design conditions.

The engine flight performance for given flight conditions and mission profile was then simulated using aircraft performance software also developed at Cranfield University [9]. The software calculates the aerodynamic characteristics of the aircraft and combines these with the engine data to determine the overall aircraft performance at various segments of the flight profile. The calculated duration of each flight segment, along with the associated engine operational conditions (component rotational speed, turbine entry temperature (TET) and cooling flow temperature), are used as inputs to the FEA model and lifing calculations. The flight profile segments modelled are taxi-out, take-off, climb, cruise, descent, approach, landing, reverse thrust, and taxi-in. The flight profile for a medium range (4 hour) flight is shown in Figures 2 and 3.

– **Turbine sizing**: The single stage high pressure turbine blade was sized using the constant nozzle method [10]. The process consisted of initial performance simulation, inlet/outlet annulus geometry sizing, stage efficiency prediction, rotor inlet velocity calculation, constant (NGV) blade design and preliminary rotor blade design at the root, mean and tip locations. The performance simulation and preliminary turbine sizing was based on engine performance data obtained from open sources[2,3].

– **Blade geometry**: A simplified geometry for the turbine blade was assumed to reduce the computational time and complexity in the FEA thermal model. The geometry of the turbine blade was idealised into 2 parts: a semi cylinder (D shape) representing the leading edge and a triangular flat plate representing the trailing edge. The analogies for the heat transfer in flow over a cylinder and a flat plate [11–13] could therefore be used. The effects of thermal barrier coatings (TBC) and convective cooling were also incorporated in the thermal model. Figure 4 shows the outline geometry for the FEA analysis.

– **Stress model**: Only the centrifugal stress distribution from the root to the tip on the blade was considered. Primarily, this provided initial stress estimates and acted as a verification for the FEA structural analysis. The shaft rotational speed was obtained from the engine simulation software. The axial gas velocity along the span of the blade was assumed constant. The blade was divided into several constant area cross-sections, and the centrifugal stress was calculated at each section.

– **Heat transfer model**: An analytical model was developed from previous work [14] on industrial gas turbines for the heat transfer analysis. The model uses a radial distribution of gas temperature to estimate the temperature variation at each blade section. The approach examines the heat transfer to the leading edge (hot side) and a cooling hole (cold side). The cooled blade is treated as a heat exchanger with the presence of a TBC and is subjected to a mainstream hot gas flow from the combustor. A detailed description of the model can be found in [14]. The heat transfer analysis yields heat transfer coefficients and temperature distributions along the span of the blade for: film cooling, TBC, blade metal (hot and cold sides) and coolant flow as shown in Figure 5.

– **FEA thermal analysis model**: A transient thermal analysis using DC3D8 elements with an average mesh size of 5 mm was used. The element is a linear hexahedral (8 node) heat transfer brick which provided verifiable results and was relatively economical on computer time. Temperature dependent material properties were specified for thermal conductivity, density, specific heat and thermal expansion. Thermal boundary conditions (BC) were applied by specifying blade metal temperatures on the hot side and surface film temperature (cooling air) and heat transfer coefficients on the cold side. These BCs were obtained from the analytical heat transfer model previously described. The blade metal temperature profiles were in-

2 CFM International. CFM International. website. [Online] 2012.[Cited:December 22, 2012.] http://www.cfmaeroengines.com/engines/cfm56-7b#technology, accessed June 2014.

3 IHS Janes. Aero- Engines. 2010. 28.

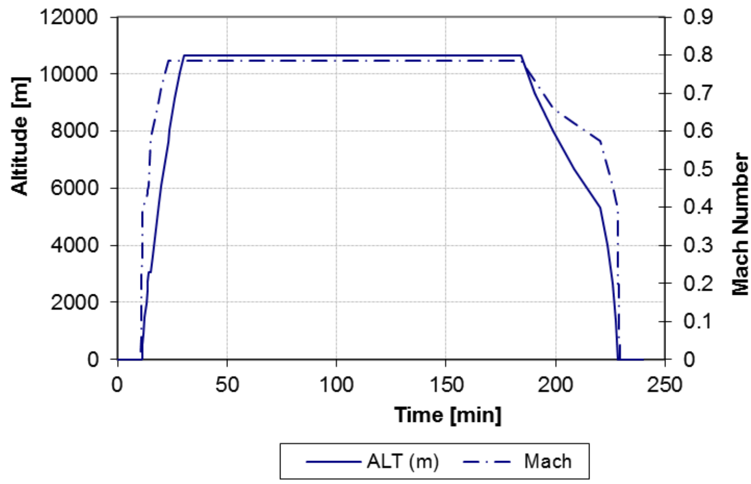

Figure 2: Mach no and altitude variation.

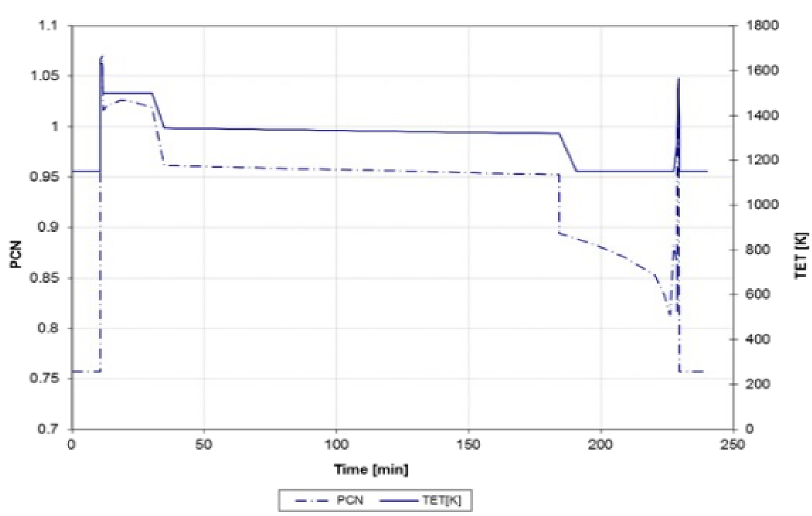

Figure 3: HPT blade RPM and TET variation.

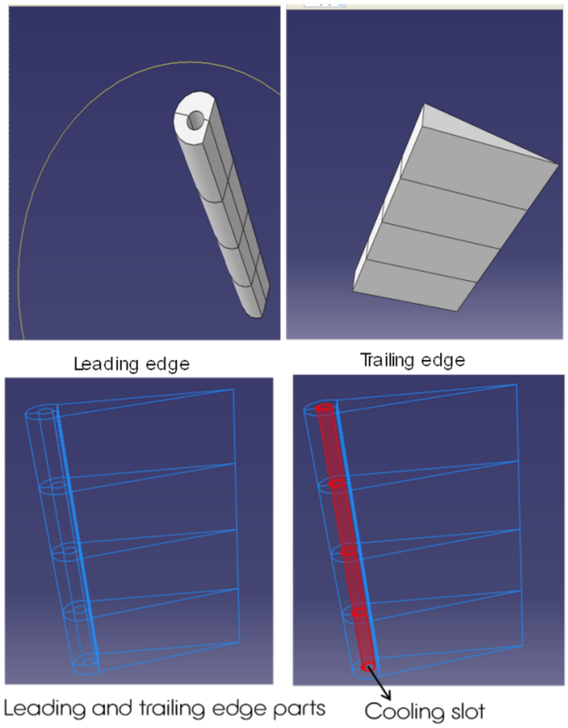

Figure 4: Outline blade geometry for FEA analysis.

tegrated into the FEA software using analytical fields and varying amplitude factors for both the cooling air temperature and heat transfer coefficients to account for the variations in time specified by the given flight profile. The flight profile was divided into four steps: Ground idle and taxi, take off/climb, cruise and descent/landing.

– **FEA stress analysis model**: A static stress analysis was performed using an elastic/plastic material behaviour. C3D8R elements (linear 8 node bricks with reduced integration and 'hour glass' control) with the same mesh size as used in the thermal analysis were employed. Although turbine blade materials are usually anisotropic, a simplified isotropic case was assumed. The defined temperature dependent material properties were Young's modulus, Poisson's ratio and yield strength. Thermal loads were applied via a predefined temperature field calculated previously from the thermal analysis. Mechanical loads (centrifugal) were applied as uniformly rotational body forces. Time variations were included by means of amplitude factors in the same way as in the thermal analysis. The blade root was restrained by applying the mechanical boundary condition "Encastre". Thus the nodes at the blade root had zero translation and rotation.

4 Results and discussion

4.1 FEA implementation

The outputs from the heat transfer model are used as thermal BCs for the FEA. The thermal BCs are the time dependent span wise metal temperature distribution for the blade hot side, the cooling air temperature and heat transfer coefficients for the cold side. These are applied as 3rd order polynomial correlations in the thermal FEA model as shown in Figure 6.

The outputs from the thermal FEA model are the spatial time dependent blade metal temperature and heat flux distribution at the leading edge. On the hot side, the temperature distribution should be close to that of the applied boundary condition. On the cold side, the temperature distribution is computed by the FEA software from the heat transfer coefficients and the cooling temperature specified, based on the heat transferred to the coolant. Hence, the temperature distribution is dependent on the heat conduction from the hot side, leading to a thermal gradient between the hot and cold sides. The results of the FEA are verified by comparison with the temperature profiles from the analytical heat transfer model. From these temperature distributions the variation of thermal gradients along the blade span and throughout the given flight are determined. The approach adequately captures the transient thermal gradients which are fundamental to the TMF assessment (since the transient changes produce associated thermal stresses). The blade temperature distribution calculated from the FEA thermal model is then used as an input to the thermo-mechanical stress analysis. In addition, a rotational body force associated with the HPT shaft speed is applied to generate the centrifugal mechanical stresses. The stress distributions along the span of the blade for a single flight condition are shown in Figure 7.

As expected, centrifugal stresses are highest at the blade root and reduce towards the tip. The thermal stresses have a significant effect on the overall thermo-mechanical stress distribution. In addition, the thermal stresses generated are predominantly tensile on the cold side and compressive on the hot side. These counteracting thermal stresses and the TMF component damage mechanisms influence the blade TMF life. The results of the stress/strain analysis are implemented in the Neu Sehitoglu damage model and the results which apply to a short haul (1.4 hour reference flight length) are shown in Figure 8. In tabular form, the minimum lives for each damage mechanism are shown in Table 1:

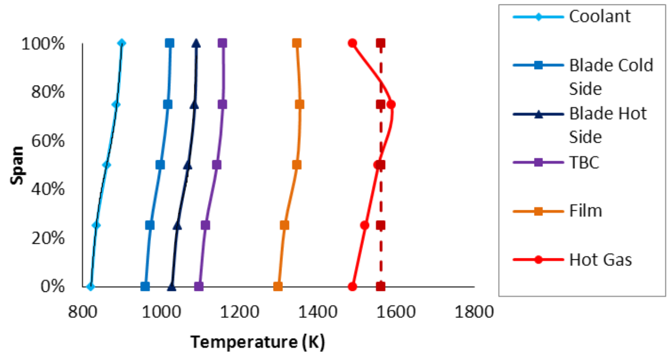

Figure 5: Span wise temperature profiles at take-off conditions.

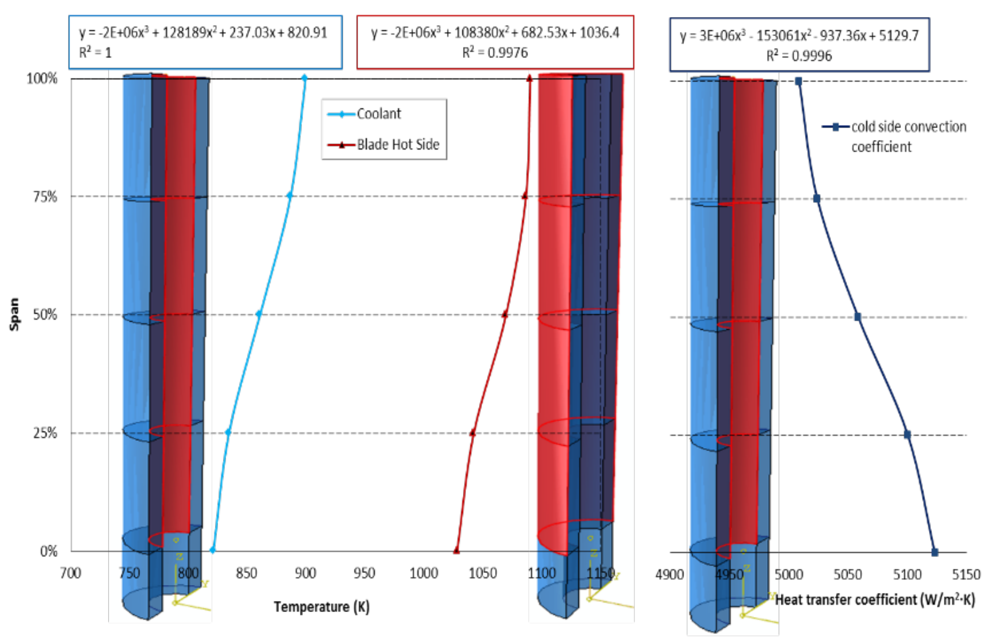

Figure 6: FEA hot and cold sides with thermal boundary conditions.

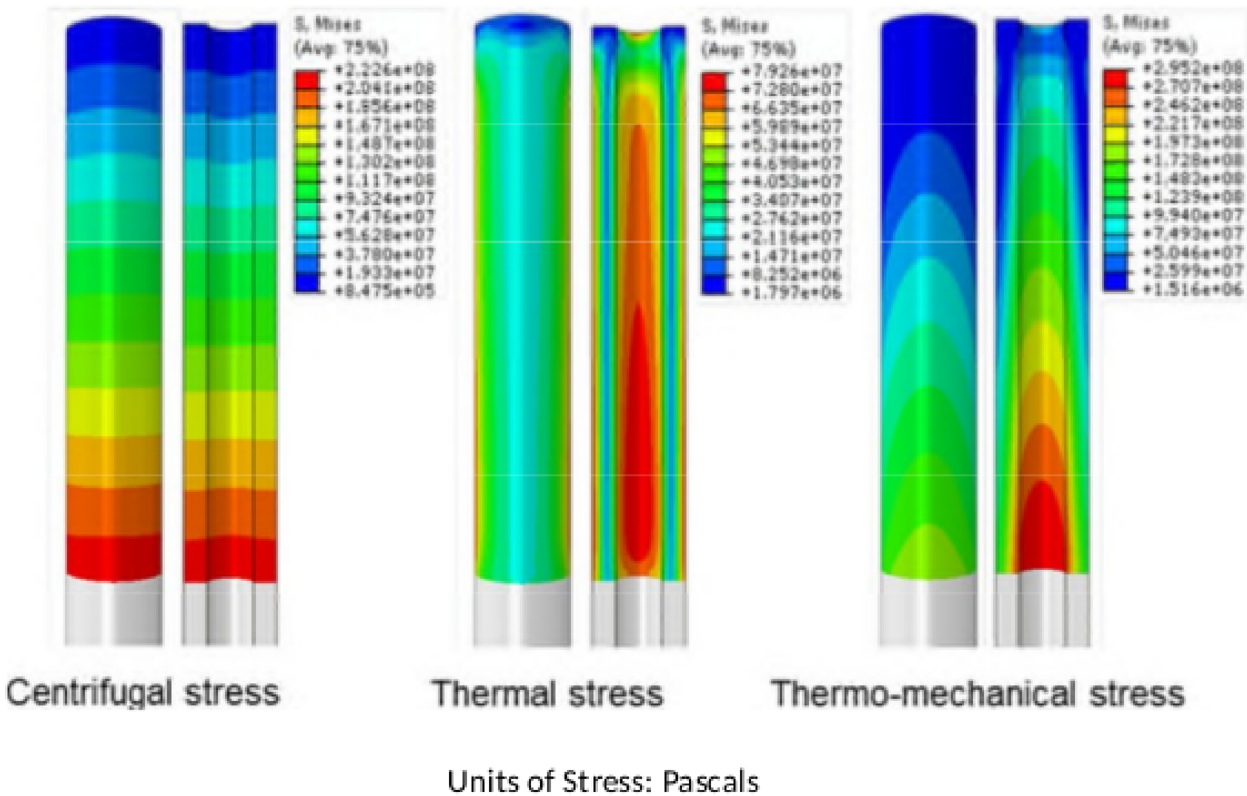

Figure 7: Stress distributions for hot and cold sides.

Table 1: Minimum cyclic lives for individual damage mechanisms.

	Hot Side	Cold side
Fatigue	1.74E+007	1.15E+006
Oxidation	2.14E+005	1.66E+004
Creep	4.24E+009	1.34E+008
TMF	2.13E+005	1.63E+004

The minimum life associated with the oxidation damage mechanism on the cold side of the blade is taken as the blade life. The blade TMF life of about 16,400 cycles (23000 hours) calculated using Neu Sehitoglu is conservative compared to isothermal fatigue methods. The oxidation damage is the main mechanism driving the blade TMF life, while the blade cold side was identified as the critical damage region.

4.2 Operational severity study

The blade TMF life values can be converted to relative factors and compared in terms of severity. Severity is defined as the ratio of total damage due to a given flight profile to the total damage of a reference profile [15]. The cyclic life is the inverse of the total damage as shown in Equation (3).

$$\begin{aligned} Severity &= \frac{New\ mission\ damage}{Reference\ mission\ damage} \\ &= \frac{\frac{1}{New\ mission\ life}}{\frac{1}{Reference\ mission\ life}} \\ &= \frac{Reference\ mission\ life}{New\ mission\ life}. \end{aligned} \quad (3)$$

Hence, a TMF severity of less than one indicates an increase in blade life, while a severity greater than one shows a reduction in the life. The turbine blade damage severity depends on various operational parameters including take-off de-rate, flight length and outside air temperature (OAT). The evaluation of the effect of these operational parameters on severity and maintenance interval (Time on Wing or TOW) can be used to predict the engine direct operating costs. Invariably, the thermal and mechanical loads imposed by the operational conditions of the aircraft and engine are the main cause of damage to the HPT blade. In this study, the reference mission is taken from the maintenance and repair organisation (MRO) baseline for operational severity calculations

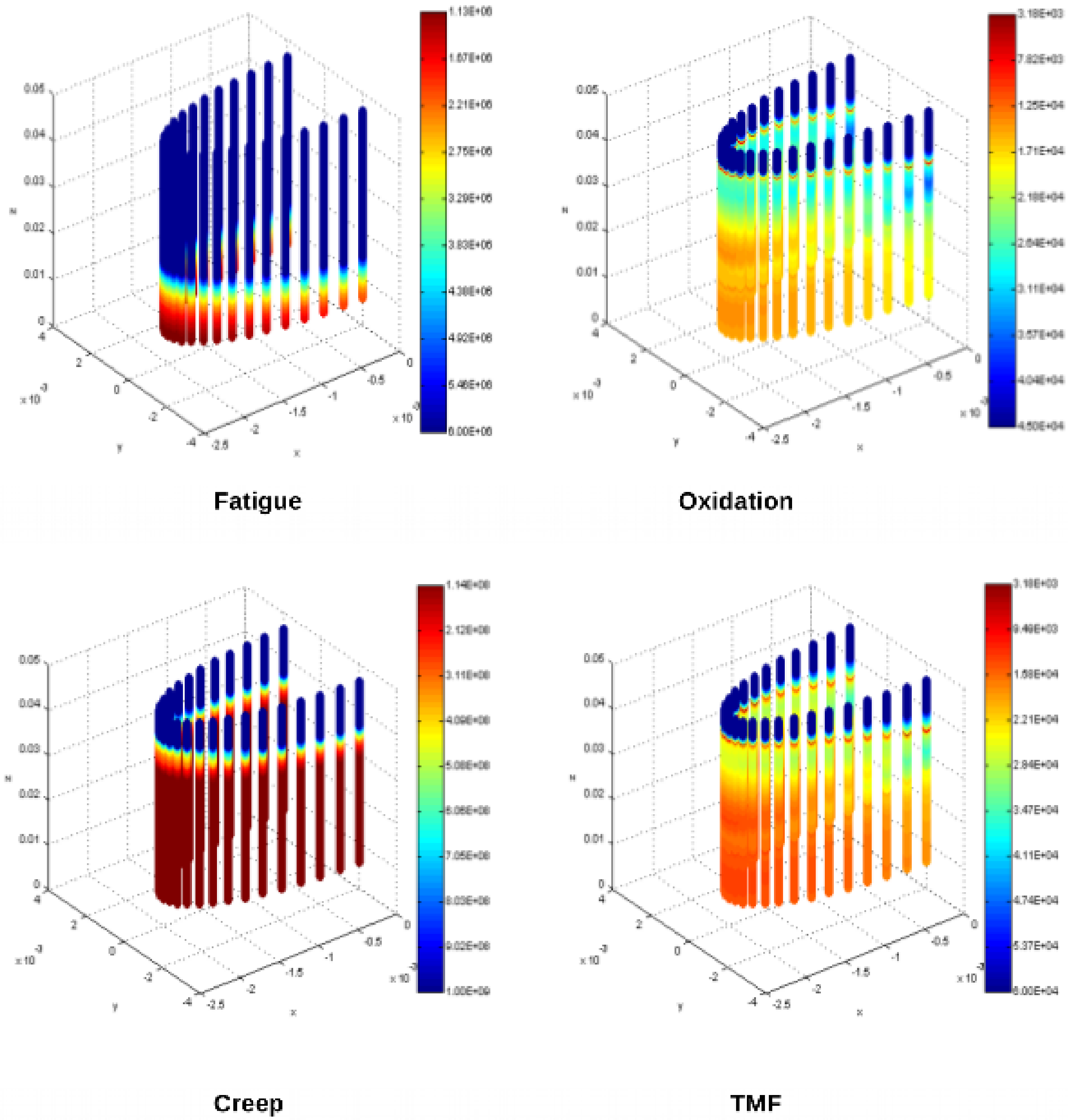

Figure 8: Life distribution for damage mechanisms.

for short haul aircraft which is a 1.4 hr flight, at ISA+3 and 10% de-rated take-off thrust.

- **Effect of derate**: Derate entails the reduction of the take-off thrust by a certain percentage. Derate at take-off significantly reduces the thermal and mechanical loads that affect the HPT blade damage severity and is extensively used to reduce component damage and engine maintenance cost[4] [15]. Low OATs allow for lower take-off thrust requirement and therefore engine derating. Figure 9 shows the derived severity curves for different derate settings and flight lengths. The gradients of the severity curves reduce significantly at take-off de-rates above 10% specially for the shorter flight lengths. At these derate settings, the thermal gradients are quite small leading to a reduction in the effect of the thermal strains and stresses on the blade. This suggests that below a certain OAT, not much benefit will be derived from further derate at take-off.
- **Flight length**: Severity characteristics for various flight lengths, with respect to take-off derate are commonly used by MROs. As the flight length reduces, large parts of the total flight are spent on take-off and climb power settings[4]. Thus, the engine experiences a greater portion of the flight under the severest thermal and mechanical loading associated with the take-off and climb phases. Accordingly, in calculating the TMF life, the impact of time on the creep and oxidation terms dominate the thermal and mechanical stress parameters. In Figure 9, the shorter flight lengths show more damage severity leading to a higher deterioration rate of the HPT blade and reduced TOW for the engine. The gradients of the curves increase with reducing flight length and the short haul flight (1.4 hours) curve indicates a significant effect on severity of up to about 15% derate. Also, the impact of takeoff derate in reducing severity is greater at the higher thrust settings (higher temperatures and shaft speeds) as reflected by the gradients of the curves within the -10% to 5% take-off derate region.
- **OAT at take-off conditions**: An aircraft engine will inevitably be operated in various environments over its service life. The OAT in a particular environment will therefore influence both the performance of the aero engine and its useful life. As the OAT increases the air density reduces. This leads to a decrease in the total thrust due to the reduction in pressure ratio and mass flow to the engine. Turbofan engines are flat rated to a specific OAT limit to compensate for this effect. To maintain the required thrust, the TET at take-off and climb increases as OAT increases up to the rated limit. The effect of OAT on the TMF severity of the turbine blade was examined by varying the OAT at take-off conditions from ISA -15 to ISA +15 while keeping the take-off thrust constant. Figure 10 confirms that engines operated at higher OATs environment experience more damage and consequently lower TOW. The curves also show that the application of higher take-off de-rates are marginally beneficial at lower OATs.

5 Conclusions

A generic physics based method was used for evaluating the influence of design parameters and operating conditions on the life and operational severity of high pressure turbine blades in aero gas turbine engines. An integrated approach for lifing of gas turbine blades has been demonstrated in conjunction with a simplified geometry at a critical location. The implementation of a TMF model allowed the effects of various damage mechanisms (creep, fatigue and oxidation) to be assessed. Oxidation damage on the coolant side of the blade was found to be the main driving mechanism in life estimation of the blade. In addition, the lifing results obtained from the model were more conservative than those published for isothermal based lifing studies on similar blades. The life model was further exploited to produce operational severity data based on a reference short haul flight profile. The severity data, in general, indicated that TOW was dependent on derate settings, OAT and flight length. However, at low OATs, the benefits derived from high thrust de-rate are marginal. Moreover, ir-

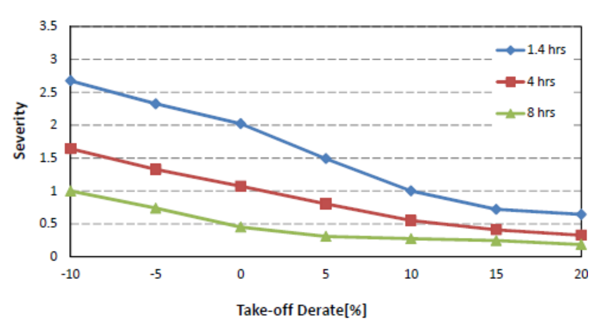

Figure 9: Severity characteristics for variation in take-off derate and flight length.

4 Ackert S., Engine Maintenance Concepts for Financiers: http://www.aircraftmonitor.com accessed June 2014.

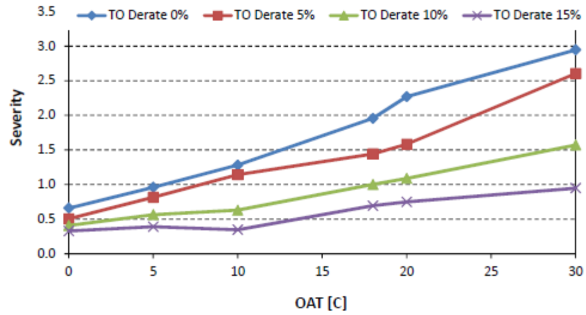

Figure 10: Severity characteristics for the variation in OAT and take-off derate.

respective of flight length, the application of thrust derate is beneficial, in the reduction of turbine blade damage.

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