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Aero-engine turbine blade life assessment using the Neu/Sehitoglu damage model

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ABSTRACT

Suitable models and software were integrated to provide a life assessment tool for aero jet engine blades. The approach combines aircraft and engine performance, turbine blade sizing, heat transfer, finite element analysis (FEA), and thermo-mechanical fatigue life assessment (TMF) using the Neu/Sehitoglu (N/S) TMF model. For a typical medium range flight mission, we find that the environmental (oxidation) effect drives the TMF blade life and the blade coolant side is identified as the critical location. Furthermore, a parametric and sensitivity study of the N/S model parameters suggests that in addition to four previously reported parameters, the sensitivity of the phasing to oxidation damage (ξ^{ev}) could be critical to overall TMF life.

1. Introduction

The rotor blades of gas turbines are subjected to severe thermal and mechanical loads during operation. At these severe conditions, the blades are prone to failure. Generally, failure due to the contribution of both thermal and mechanical loading is termed Thermo-mechanical fatigue (TMF) [1]. TMF has become more critical to the life of gas turbine blades; due to the use of improved blade cooling technologies that enable higher gas temperatures, thereby improving gas turbine efficiencies. TMF conditions produce significant damage contributions from creep, low cycle fatigue and oxidation mechanism. This is mainly due to the effect of thermal stresses from thermal gradients and transients in the blade, as well as from the different coefficient of expansion between the blade material and coatings (for coated blades).

Historically, lifing methods derived from isothermal fatigue (IF) tests at the maximum operating temperature have been used for TMF life assessment. These results are not primarily suited to study: the phase relationships between temperature and mechanical loadings; thermal transients that occur in the operation of gas turbines, particularly, the cooled aero gas turbine blades; and the interaction of fatigue, creep and oxidation damage mechanisms [2]. The methods based on TMF tests better describe the damage process under varying thermal and mechanical loading and provide reliable results for life assessment of gas turbine blades.

Currently, many TMF experiments have been conducted on specimens wherein temperature gradients were limited to a range of maximum and minimum temperatures, and stress loads. Their application to typical aero-engine operating flight conditions characterized by variable temperature and stress loadings for a given duration should give a more apt assessment of the effect of TMF on aero engine blade life. Therefore, based on a review of suitable TMF models conducted [3], the Neu/Sehitoglu model [4] was chosen in this work to examine aero-engine blade life for a typical flight mission.

The N/S model employs constitutive equations describing creep, fatigue and oxidation behavior and their interactions under thermo mechanical fatigue loading. The model also accounts for the phasing of temperature and mechanical strain, which dictate the damage, induced in a turbine blade. However, the material parameters needed for the N/S TMF model are many (about 20 parameters), and require costly and long TMF testing time. To experimentally determine the N/S TMF parameters for each turbine blade material is therefore a tedious process. Hence, sensitivity studies of the model parameters have been examined to determine the critical ones, in order to obtain optimal N/S model parameters for a given nickel material [5]. Using the operating conditions for a reference flight mission, similar sensitivity analysis carried out in this work reveals an additional parameter to the four critical parameters determined by Amaro and co-workers [5].

2. Thermo-mechanical fatigue – overview

2.1. TMF life approaches and models

Different approaches have been used to account for TMF and the complex interaction of the damage mechanisms. The following

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four approaches are identified by Christ et al. [6]: (i) empirical, (ii) damage mechanics, (iii) fracture mechanics and (iv) physical. The importance of the physical approach is in providing the physical background for empirical and damage mechanics models. However, the complex physical concepts of modeling the interaction of damage mechanisms limit the significance of these models for TMF life prediction. The damage mechanics concept is rarely applied to complex loading [7], while fracture mechanics is used, preferably, if a material contains a flaw from the start or if cracks are initiated quickly at the start of cyclic life. Nevertheless, the empirical approach is a widely used concept for TMF life prediction. Although there has been reasonable agreement between experimentally observed TMF life and the results from empirical means, the lack of a physical basis limits its use to specific conditions [6]. Koberl et al. [8] also suggests that such lifetime calculation models are only applicable within a limited range defined by temperature, strain constraining, and their combination.

Out of the numerous crack initiation models that have been used for TMF, the following are considered the most popular: Damage Summation (DS), Frequency Separation (FS), Ductility Exhaustion (DE), Strain-range partitioning, Total-Strain Version of SRP (TS-SRP), and strain energy partitioning (SEP). A critical review of these models is contained in Zhuang and Swansson [9]. Recently, the works of Minichmayr and co-workers [10], as well as Riedler et al. [22,23] have shown the energy based criteria to be very practical for TMF lifetime estimation.

Overall, TMF has usually been treated isothermally, using an equivalent maximum cycle temperature and applied mechanical loading. This allows useful simplifications, but limits the application to actual TMF conditions. TMF conditions that are not captured by high temperature isothermal fatigue (IF) include: changes in the material properties of the component with temperature; complex geometry constraints (that induce thermal gradients as the structure expands when heated); and during start-up and shutdown, thermal transients that appear which contribute to oxidation [11]. Hence, the loads applied under TMF conditions can be more damaging when compared to isothermal fatigue (LCF) at the maximum operating temperature. This difference can be more than an order of magnitude. Thus, the estimation of life under TMF conditions is usually lower than that predicted under isothermal LCF experiments at the maximum temperature of operation [8,9]. IF methods for aero-engines would therefore not adequately capture the operating conditions of the turbine blade.

2.2. TMF in aero engines

In aero engines, TMF damage may accumulate over a range of temperatures and strains under both steady-state and/or transient flight conditions [12]. As flight operating conditions change during a mission, strong thermal gradients are developed. These coupled with the mechanical loads induce TMF damage in the aero engine; particularly, in the turbine blade that bears severe temperatures and high centrifugal stresses.

During straight and level flight, aero-engines are basically at constant temperatures and mechanical loading. At this condition, steady-state creep and the influence of oxidation are the primary damage mechanisms. However, at take-off and landing, the transient demand for more power causes load and temperature changes that lead to fatigue damage. Usually, each flight would be considered as one fatigue cycle with an imposed hold time, wherein creep and fatigue would be acting independently; as well as creep–fatigue interactions influenced significantly by oxidation [12]. Engine start up and shut down also present strong thermal and applied mechanical loads transients, which are fundamental to TMF damage. Some of the severest damage will usually occur during the transient operations in aero engines. The interested reader is referred to [1] and [12] for detailed description of the TMF process in gas turbine engines

2.3. Neu/Sehitoglu TMF damage model

The N/S TMF model considers fatigue, oxidation and creep damage to predict the life [4,15,16,24,25]. The damage induced in the material is dictated by the mechanical strain range, strain rate, temperature and the phasing between the temperature and mechanical strain, and incorporated in the model. The total damage per cycle, D_{tot}, is calculated from the sum of fatigue, oxidation and creep mechanisms. Assuming linear damage, and damage equal to 1 at failure; D_{tot} can be expressed in terms of life, N_f, taking the damage as the inverse of N_f .

$$\frac{1}{N_f} = \frac{1}{N_f^{fat}} + \frac{1}{N_f^{ev}} + \frac{1}{N_f^{creep}} \tag{1}$$

where N_f^{fat}, N_f^{ev} and N_f^{creep} represent the number of cycles to failure from fatigue damage, environmental damage (oxidation) and creep damage, respectively.

2.3.1. Fatigue damage terms

The fatigue life term N_{fat} is represented by the strain-life relation, which is the most common description of the process. For the fatigue calculation, the equation used in [13] involves two terms since it proposes the use of stress as a life parameter.

$$\frac{\Delta\varepsilon_{mech}}{2} = \frac{\sigma'_f}{E}\left(2N_f^{fat}\right)^b + \varepsilon\prime_f\left(2N_f^{fat}\right)^c \tag{2}$$

where $\Delta\varepsilon_{mech}$ is the mechanical strain, σ'_f is the fatigue strength coefficient, b is the fatigue strength exponent and ε'_f is the fatigue ductility coefficient. c is the fatigue ductility exponent and E is the elastic modulus. In [4] the corresponding pure fatigue life was correlated by Eq. (3), implying a power law strain-life relationship.

$$\frac{\Delta\varepsilon_{mech}}{2} = C\left(2N_f^{fat}\right)^d \tag{3}$$

where C and d are material constants.

In [14], the fatigue damage module includes an orientation dependent term $f_{in}(w)$. This term accounts for directionally solidified or single crystal material orientation with respect to the loading. The pre-factor and exponential terms are both fit to lower-temperature low cycle fatigue data to minimize environmental and creep effects

$$N_f^{fat} = C_{in} f_{in}(w)(\Delta\varepsilon_{mech})^{d_{in}} \tag{4}$$

2.3.2. Environmental damage terms

The environmental damage term $\frac{1}{N_f^{ev}}$ is based on measurements of surface and crack tip oxidation and γ' depletion kinetics. This damage reflects environmentally induced crack nucleation and growth. Oxide damage will occur when the strain range exceeds a threshold for oxide cracking.

$$\frac{1}{N_f^{ev}} = \left[\frac{h_{cr}\delta_0}{B\Phi^{ev}\left(K_{peff}^{ev} + K_{peff}^{\gamma'}\right)}\right]^{-1/\beta} \frac{2(\Delta\varepsilon_m)^{\frac{2}{\beta}+1}}{\dot{\varepsilon}^{1-\frac{b}{\beta}}} \tag{5}$$

$$K_{peff} = \frac{1}{t_c}\int_0^{t_c} D_0 e^{\frac{-Q}{RT(t)}} dt \tag{6}$$

where h_{cr} is a critical crack length where environmental (oxidation) attack trails behind crack growth and δ_0 is a measurement of oxide plus γ' depleted zone ductility. B is a material coefficient, Φ^{ev} is the phasing factor for oxidation damage and β is the time related mechanical strain range exponent. $\dot{\varepsilon}$ is the mechanical strain rate,