29th Congress of the International Council of the Aeronautical Sciences
St. Petersburg, Russia; September 7-12, 2014

HIGH TEMPERATURES TURBINE BLADES DAMAGE PREDICTION TAKING INTO ACCOUNT LOADING HISTORY DURING A FLIGHT CYCLE

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Keywords: *turbine blade, cycle loading, creep, damage*

Annotation

This paper provides the analysis results using classical and new calculating methods of creep damage and cycle durability of turbine blades and the development of these methods to account for non-stationary processes in conditions of multi-regime operation. A simplified load cycle is used to reduce creep analysis solution time. Study results demonstrate that consideration of the loading history is necessary in order to correctly predict creep damage as well as creep deformation.

Introduction

The turbine blades operate for extensive periods of time under heavy loads in conditions of non-uniform heating and cyclic loading. Properties of materials which are used in turbine blades manufacturing processes are changing over time at high temperatures.

Depending on the component, alloy composition and service condition, the damage may be due to creep, low cycle fatigue (LCF) or creep-fatigue interactions, which are some of the key damaging factors. As internal damage builds up, the resistance of components to deformation under static (creep) or cyclic (LCF) loading is reduced.

Linear damage summation has been used in this study. Damage is assumed to be zero when the material is new and is equal to one at local stress rupture failure.

In its simplest form, creep is the progressive accumulation of plastic strain, in a component under stress at elevated temperatures over a period of time. Creep failure occurs when the accumulated creep-strain results in a deformation of a component that exceeds the design limit. Creep rupture, used sometimes interchangeably with the term stress rupture, is an extension of the creep process to the limiting condition where the stressed component breaks. The interaction of creep with cyclic stressing and the fatigue process is of great importance in aircraft gas turbine technology.

The classical analysis approach is to calculate creep damage and safety factor in each stationary regime separately as follows:

$$K_m = \sigma_{rup}/\sigma_{eqv},\ \Pi = 1/K_m$$

where: σ_{eqv} - equivalent over the duration of regime stress [1], σ_{rup} for - the creep strength of the blade alloy at specific temperatures and duration of the regime. Afterwards, calculated damages are summarized:

$$1/K_m^{eq.} = \sqrt[m_l]{\sum_i^n \left[1/K_m^{(i)} \right]^{m_i}}, \qquad \Pi_m^{eq.} = 1/K_m^{eq.}$$

where $K_m^{i.}$ – local safety factor at i regime, m_i – creep rupture exponent at the i-regime, m_l – creep rupture exponent at the most dangerous regime (one with minimal value of safety factor) $\Pi_m^{eq.}$ - total damage.

The described in this paper methods do not take into account damage accumulation during transient regimes.

The key trend in the development of computational methods of turbine blades damage is to consider the damaging processes on steady and unsteady regimes of mission flight cycles, as well as to determine residual life.

It is essential to use three-dimensional geometric models and the physically nonlinear properties of the material (including creep) for the reliable prediction of creep deformation and stress rupture in turbine components.

Based on the SSS kinetic calculations of turbine blades in the condition of changing speed and temperature classic damage calculation approach was tested. Several alternative (direct) approaches of damage determining in cyclic operation, taking into account the loading history were aslo considered.

Methods

Full 3D finite element analyses of HPT turbine cooling blade (fig. 1) were performed during this study. The blade was modelled for analysis using quadratic hexahedral and tetrahedral 18-x series elements.

Appropriate linear and nonlinear (plastic) properties were used in the analysis. Plasticity was modelled using multi-linear isotropic hardening. A non-linear geometry option (NLGEOM) was turned on during analysis.

Considered blade was made from a single crystal alloy. Material properties were evaluated using test data in the <001> direction. Because the direction of centrifugal load in the airfoil coincides with the primary crystal axis, it was assumed that the <001> data were adequate for this analysis.

HPT blades are characterized by a complex stress state, but most of the characteristics are experimentally obtained by uniaxial tension. To compile these data on complex stress state von Mises equivalent stress is used, which is defined as follows:

$$\sigma = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where, σ_1, σ_2, σ_3 – principal stresses; μ - Poisson ratio.

ANSYS provides 13 creep equations for use with implicit creep. These range from the simple Norton law to the hyperbolic sine form. In this study, creep equation # 1 (according to the ANSYS library) [3] is used:

$$\upsilon_{cr} = C_1 \cdot \sigma^{C_2} \cdot \varepsilon_{cr}^{C3} \cdot e^{\frac{-C_4}{T}}$$

where: ε_{cr}–creep strain, υ_{cr} – creep rate, σ – stress (MPa), T – temperature (K), τ - time (hr), C_1 - C_4 –material dependent coefficients.

Creep damage is defined as follows:

$$\Pi = \int_0^{\tau} d\tau / \tau_r = \sum_{i=1}^{n} \frac{\Delta t_i}{\tau_{ri}},$$

where i –regime, τ_{ri} –rupture time under average stress σ_i and temperature $T_{i,}$. n – number of time steps (Δt_i) time of regime is divided into.

Several approaches of damage determination in cyclic operation were considered.

Approach I – «traditional», based on the linear damage rule. Damage is calculated on each of the k-cycle stationary regimes: $\Pi = \sum_{j=1}^{k} \Delta\Pi_j$ [1].

Approach II – «direct», based on mission-by-mission creep analysis. Damage calculation is performing in consecutive order for every j-th regime of the mission for the entire period of work: $\Pi = \sum_{j=1}^{2000} \Delta\Pi_j$. I.e loading history is taken into account.

Approach III - «simplified» proposed in [3]. Creep analysis was performed on the blade using load cycles with an increasing sequence of temperatures and speeds (cruise- maximum) III*b* and a decreasing sequence of temperatures and speeds (maximum - cruise) III*a*.

Example of HPT blade creep damage calculation using different approaches

The blade was assumed to operate under two conditions within a model mission, maximum and cruise. Table 1 shows the parameters of considered regimes. Figure 1 shows temperature distribution over the blade at two regimes.

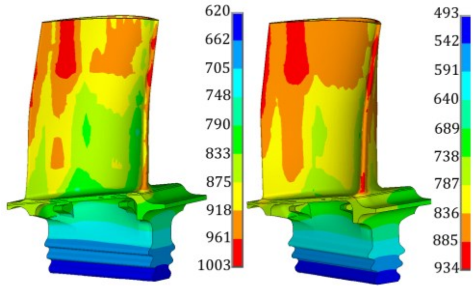

Fig. 1 - The temperature field distribution over the blade at Maximum (left) and cruise regimes (°C)

The hold times within a mission for these conditions were multiplied by the number of missions (1000) to determine cumulative hold times at the conditions (790 hr overall).

Table 1 – Parameters of regimes

Regime	RPM	τ_i, s	τ_{Σ}, *hr*
Max	15995	432	120
Cruise	14064	2416	670

Transient regimes are not considered in this study. Loads are assumed to change instantly. Fig. 2 shows the distribution of creep damage over the considered blade (zones with darker color have more creep damage) and the "dangerous" zones location.

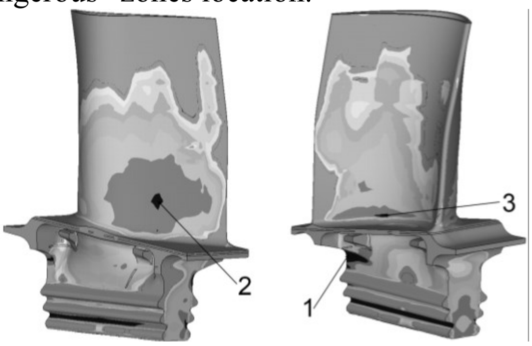

Fig. 2 - The distribution of creep damage over considered blade at Maximum regime

Figure 3 shows stress relaxation and damage accumulation curves for the "dangerous" zones of blade for the condition of maximum regime of total duration 120 hr.

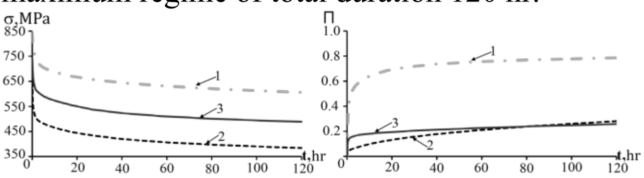

Fig. 3 - Stress relaxation (left) and damage accumulation (right) curves

Creep strains, damage and blade elongation obtained using approach I are shown at table 2

Table 2 – Approach I calculation results

regime	# zone	1	2	3
Max	*T*,°C	744	863	807
	ε_{cr}, %	0.50	0.66	0.66
	Δ, *mm*	1.40		
	Π	0.75	0.26	0.24
Cruise	*T*,°C	662	808	756
	ε_{cr}, %	0.16	0.35	0.34
	Δ, *mm*	1.22		
	Π	0.14	0.09	0.06
	$\sum\varepsilon_{cr}$, %	0.66	1.01	1.00
	Π_{Σ}	0.89	0.36	0.30

Stresses in "dangerous" zones obtained during mission-by-mission analysis are shown at Figure 4. Table 3 shows creep damage as well as total accumulated strain and maximum elongation.

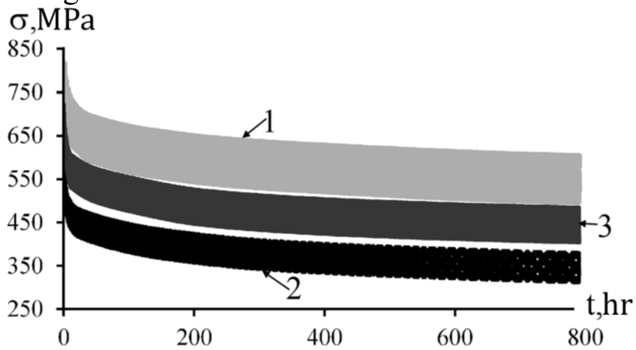

Fig. 4 - Stress changes in "dangerous" zones obtained using approach II

Table 3. Approach II calculation results

№	Π_{Σ}	$\varepsilon_{cr\Sigma}$, %	*Δ*, mm
1	0.66	0.54	1.41
2	0.25	0.70	
3	0.19	0.70	

Total stress curve (figure 4) was divided into 2 parts (referred to high and low regime) in order to show the effect of cyclic loading on the stress relaxation (solid lines at figure 5). Dotted lines at figure 5 (indicated as "const") correspond to the stress relaxation curve which were obtained without consideration of loading history (approach I). All calculation results presented in Figure 4 correspond to zone 1, but in other zones, results are similar.

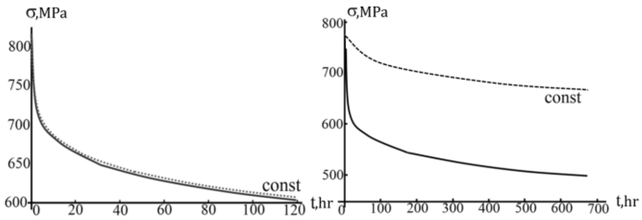

Fig. 5 - Comparison of stress relaxation in the "dangerous" zone # 1 obtained using approaches I, II at maximum (left) and cruise regime

One can see that there is a significant difference between results corresponding to the cruise regime.

Figure 5 shows equivalent stress in dangerous zones obtained using approaches IIIa and IIIb.

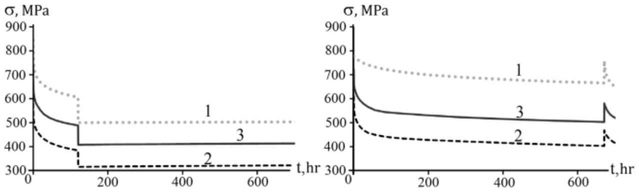

Fig. 6 - Stress changing curves

Creep strains and creep damage from these three analyses are compared in table 4.

Table 4 - Calculation results using different approaches

#	approach	I	II	IIIa	IIIb
1	Π_Σ	0.89	0.66	0.75	0.50
	$\varepsilon_{cr\Sigma}$, %	0.66	0.54	0.50	0.55
2	Π_Σ	0.36	0.25	0.27	0.27
	$\varepsilon_{cr\Sigma}$, %	1.01	0.70	0.67	0.69
3	Π_Σ	0.30	0.19	0.25	0.14
	$\varepsilon_{cr\Sigma}$, %	1.00	0.70	0.67	0.69
	Δ, mm	1.40	1.41	1.40	1.41

Values of blade elongation determined using different approaches are pretty close. Accumulated damages and strains determined using different approaches differ significantly.

Figures 6 - 8 shows results from these three analyses, where damage obtained using approach 1 is shown as a dot. It can be seen that this estimation approach does not take into account the acceleration of stress relaxation in cruise regime, which leads to an underestimation of design life.

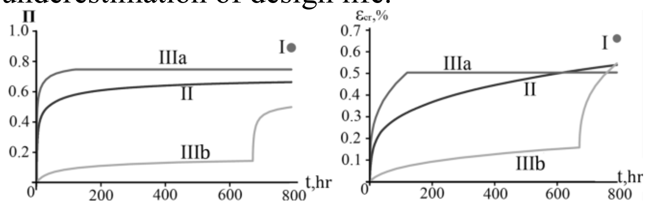

Fig. 7 - Accumulation of damage (left) and creep strain in first zone of interest obtained using different approaches

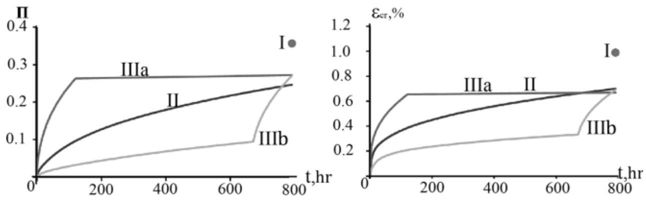

Fig. 8 - Accumulation of damage (left) and creep strain in second zone of interest obtained using different approaches

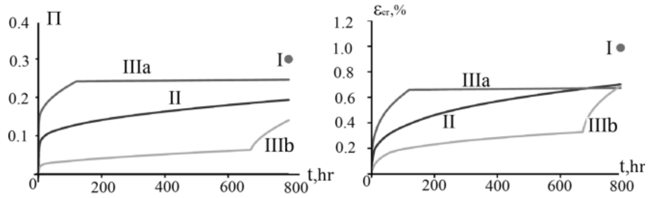

Fig. 9 - Accumulation of damage (left) and creep strain in third zone of interest obtained using different approaches

Solid curve II shows the results of mission-by-mission analysis. The top and bottom curves in Figures 6-8 correspond to the results obtained by approaches of IIIa and IIIb respectively. The results indicate that using approach III results in predictions that match the mission- by-mission analysis more closely compared to the classical approach. There is an influence of sequence of operating conditions (high-low or low-high) on analysis results. Approach II results lay between results obtained using IIIb and IIIa. Using approach IIIa is more safe.

The solution time for mission-by-mission analysis is more than 20 times more compared to approach III solution time. It is seen clearly that using approach III is far more efficient than mission-by-mission analysis.

Total damage calculation

The expected life is calculated, based on stress and temperature history in critical areas that are identified from the design mission.

Miner's rule simply sums the fractional life consumed by each type of damaging cycle identified, e.g. stop-max, idle-max. The number of cycles to crack initiation for each major and minor damaging cycle is determined by referring to the appropriate strain conditions on the minimum design ε-N curves. This rule, sometimes known as Miner's rule is widely accepted and used in the industry for LCF summation.

The number of cycles to crack initiation (N_f) and cyclic damage (Π_N^Σ) can be calculated as it follows:

$$\frac{1}{N_f} = \sum_{i=1} \frac{N_i}{N_{Ri}}, \qquad \Pi_N^\Sigma = 1/N_f,$$

where N_i – number of missions, N_{Ri} - number of cycles to failure at a given strain amplitude. To determine the strain reversals rainflow method can be used [4].

There are two significant shortcomings of these linear theories. The order of application of various stress levels is not taken into account. Damage is assumed to accumulate at a constant rate for a given stress level, regardless of component loading history

Figure 10 shows stress - total accumulated strain (including creep strain) dependence for first "dangerous" blade zone. Analysis of results demonstrate that for a considered blade stress-strain range in "Maximum - Cruise" mission over the life time remains nearly constant.

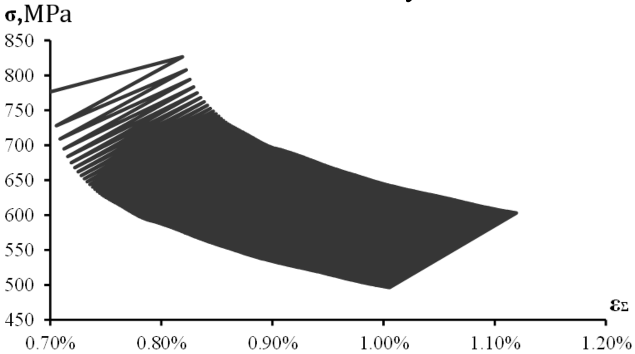

Fig. 10 - Dependence of the "stress - total deformation" zone 1 in the model cycle

It should be noted that for zones with plastic deformation results might be very different.

It is clear that for the considered blade one may determine the cyclic damage using strain amplitude from the results of the first mission (Table 5).

Table 5 - Cycle damage calculation results

Zone #		0-Max-0	Cruise-Max-Cruise	Π_N^{Σ}
1	Π_i	6.15E-05	1.00E-5	1.01E-02
	$N \cdot \Pi_i$	6.15E-05	1.00E-2	
2	Π_i	3.23E-05	1.00E-5	1.00E-02
	$N \cdot \Pi_i$	3.23E-05	1.00E-2	
3	Π_i	2.45E-05	1.00E-5	1.00E-02
	$N \cdot \Pi_i$	2.45E-05	1.00E-2	

In order to calculate total damage it is necessary to consider both static and cyclic loading. Linear damage rule can be used as well. Static damage (Π_τ) can be obtained by approach IIIa. Total damage is calculated as follows:

$$\Pi_\Sigma = \Pi_N + \Pi_\tau \qquad K_\Sigma = 1/\Pi_\Sigma$$

Conclusion

Analysis of the numerical studies results have shown that the loading history influence is significant when calculating the kinetics of SSS, accumulated strain and predicting blades service life. Compared with the traditional method of calculating using linear damage rule accumulated for separate independent regimes considered direct calculation approach gives 30-50% less total value of damage in “dangerous” areas of the blade. Accumulated strain, calculated using the direct way was 20-40% less than that obtained by the traditional method.

The analysis of results showed that using a high-low sequence of operating conditions (as defined by metal temperatures and/or speed) allows for a reasonably accurate estimation of creep deformation and damage compared to a mission-by-mission analysis. The simplified load cycle used in creep analysis of blades reduced analysis times significantly. Compared with the direct method of calculating the differences ranged from 8 to 30% of the total of damage and 1.5-7% of accumulated strain.

Value of blade elongation is almost independent of the method of calculation.

Thus, despite the fact that the numerical analysis is carried out only under the model cycle, it can be concluded that the direct method of calculations (taking into account the history of cyclic loading) will improve the accuracy of forecasting design life of turbine blades.

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