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MODELLING OF THERMO-MECHANICAL FATIGUE ON ENGINE GENERATOR TURBINE

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Abstract: *Presented paper is dealt with thermo-mechanical fatigue analysis of the generator turbine. Only elastic stress and temperature field are taken from FEM analysis. Elasto-plastic stress and strain are calculated with temperature dependent hysteresis model of stabilized stress-strain relation. Generalized Prandtl-Ishlinskii model is used for this purpose. For every point in loading history is found closed hysteresis loop. Damage for damage parameter corresponding to current hysteresis loop is evaluated by using Prandtl-Ishlinskii model. This procedure was implemented and applied to the generator turbine.*

Keywords: thermo-mechanical fatigue, hysteresis modeling, Prandtl-Ishlinskii model, damage prediction, turbine engine

1. Introduction

Rotating parts are crucial parts in the every aspect of turbine engine. During the service of an engine, a multitude of material damage such as foreign object damage, erosion, high cycle fatigue, low cycle fatigue, fretting, hot corrosion/oxidation, creep, and thermo-mechanical fatigue (TMF) is induced in these parts. The mechanical loading and effects based on the temperature gradient were stated as the most important factors in operational life. A common engineering practice in the fatigue analysis is based on the isothermal fatigue. This approximation is very raw estimation of complex loading state of working engine.

A promising concept for analysis of TMF is proposed by Nagode, et al. (2010). Actual damage is calculated in every step of loading history. Evolution of damage can be calculated cheap and very quickly using widely available isothermal fatigue curves. Proposed concept overcame hysteresis loop closure problems; loop's end can't intersect starting point in the case of changing temperature during the cycle. The closure problem is solved by identification of origin of hysteresis loop to current analyzing point. Temperature dependent damage is based on interpolation of experimental fatigue data for the current temperature. Actual damage is evaluated with damage operator. Prandtl-Ishlinskii model of hysteresis is applied on interpolated iso-thermal fatigue curves fur current temperature.

Objective of this paper is a demonstration of this approach in the case of real engine part. Theoretical background is introduced at first. An application of damage operator approach to the calculation of TMF on generator turbine loaded by simplified rotation speed spectrum follows.

2. Hysteresis modeling

Modelled stress and strain in actual time step are controlled with stabilized cyclic stress-strain curves corresponding to actual temperature. According Nagode, et al. (2010) stress input is suggested to be used from elastic FEM analysis. Elastoplastic behavior is modeled with generalized Prandtl-Ishlinskii model of hysteresis. Similar to the stress and strain, same hysteresis modeling approach is used in the case of damage.

2.1. Prandtl-Ishlinskii model of stress-strain relation

Brief theoretical background of hysteresis modeling is introduced in this paragraph. An example of stress modeling from stress input is described. Prandtl-Ishlinskii model is based on two fundamental models: Prandtl's and Prager's model.

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Prandtl model of elasto-plasticity, also named stop, is based on simple rheological spring-slider model. There are two parts; linear elastic element is coupled in series with rigid perfectly plastic element, see Fig. 1. Further, Prager's model of perfect plasticity, called play, is dual model of the stop, see Fig. 2. There is linear elastic element coupled in parallel with perfectly plastic part. Despite Prandtl's model, Prager's model can account for rigid plasticity with the strain hardening. Mathematical expressions of abovementioned models can be found in Bertotti, et al. (2006).

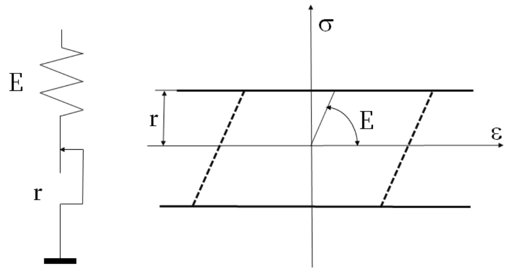

Fig. 1: Prandtl's model (stop) of elasto-plasticity

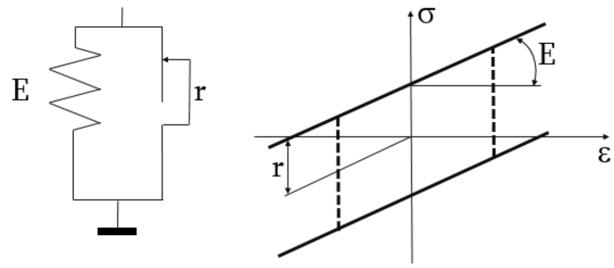

Fig. 2: Prager's model (play) of perfect plasticity

Model of elastoplasticity with strain hardening can be assembled with "stops" connected in series. Because of duality, same results can be done with construction of "plays" connected in parallel. This type of model is called Prandtl-Ishlinskii model, see Fig. 3.

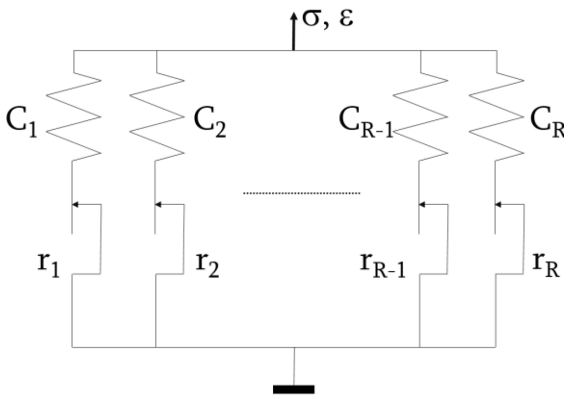

Fig. 3: Prandtl-Ishlinskii model

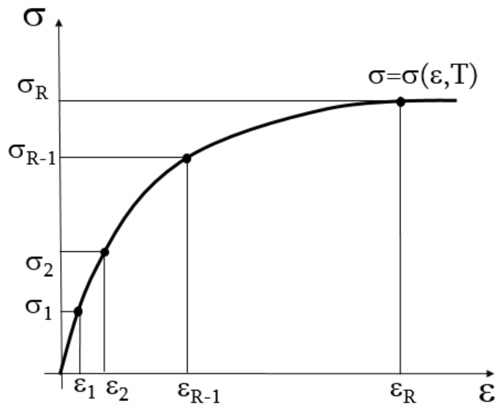

Fig. 4: Approximation of cyclic stress-strain curve

Let's assume stress controlled model loaded with stress stepwise history $\sigma = \sigma(t_i)$. Elasto-plastic stress is calculated with Neuber's approximation. Strain $\epsilon(t_i)$ in time step t_i in the Fig. 3 can be expressed as sum of elemental strain contributions from each individual spring-slider sub-models according to (1).

$$\epsilon(t_i) = \sum_{r=1}^{R} C_r(T_i) * \left(\sigma(t_i) - \sigma_r^{pl}(t_i)\right) \quad (1)$$

Instead of original procedure published in Nagode, et al. (2010), identification of parameters C_i and r_i of sub-model is used according to Grzesikiewicz, et al. (2012) and this leads to equations (2) and (3). Number of sub-models is chosen based on sufficiently approximated stabilized cyclic stress-strain curve as schematically depicted in Fig. 4.

$$C_r(T_i) = \frac{\epsilon_r - \epsilon_{r-1}}{\sigma_r - \sigma_{r-1}} - \sum_{j=r+1}^{R} C_j(T_i)$$

$$r = R-1, R-2, \ldots 2 \quad (2)$$

Play operator in r-th sub-model of eq. (1) is expressed in equation (3).

$$\sigma_r^{pl}(t_i) = max \left\{ \begin{matrix} \sigma(t_i) - r_r \\ min \left\{ \begin{matrix} \sigma(t_i) + r_r \\ \sigma_r^{pl}(t_{i-1}) \end{matrix} \right\} \end{matrix} \right\} \quad (3)$$

Aforementioned relations are expressed for temperature T_i in analyzed time step t_i. As usual, experimental stress-strain curves are available for only a few temperatures. Therefore, to obtain stress and strain at any temperature, one can interpolate from experimental available curves.

2.2. Damage evaluation

Similar as strain modeling, current damage can be calculated from Prandtl-Ishlinskii model applied to description of fatigue curves. This approach was published in Nagode, et al. (2010). Current damage is calculated according to equations (4).

$$\mathrm{D_f}(t_i) = \sum_{j=1}^{i} \left| D(t_j) - D(t_{j-1}) \right| \tag{4}$$

Damage $D(t_j)$ is calculated as a sum of contributions of spring-slider models, see (5).

$$D(t_j) = \sum_{p=1}^{P} F_p(T_i) * \left(P_{SWT}(t_i) - p_p\ (t_i)\right) \tag{5}$$

Similar to Prandtl-Ishlinskii model of strain, fatigue curves (for available temperature) are approximated with number of spring-slider sub-models. For this purpose fatigue curve is expressed depending on damage level $d_f = (1/N_f)$ instead of number of cycles (reversals). In the case of low cycle fatigue, the damage parameter SWT (or generally other one) is expressed instead of $P_{SWT}=P_{SWT}(2N_f)$ as $P_{SWT}=P_{SWT}(2/d_f)$. Damage level d_f is non-decreasing value varies in range of $0 \leq d_f \leq 1$. Due to always bounded damage level, numerical difficulties are avoided in the case of $N_f \to \infty$.

Play operator $p_p\ (t_i)$ in (5) is expressed in (6). It depends on damage parameter $P_{SWT}(t_i)$ in current time.

$$p_p\ (t_i) = max \begin{Bmatrix} P_{SWT}(t_i) - r_r \\ min \begin{Bmatrix} P_{SWT}(t_i) + r_r \\ p_p\ (t_{i-1}) \end{Bmatrix} \end{Bmatrix} \tag{6}$$

Current damage parameter is calculated from closed hysteresis loop. This closed loop is created from current analyzing stress-strain point and corresponding origin in the loading history. Procedure for searching and storing these origins are published in Nagode (2014).

3. Fatigue analysis of generator turbine

Damage operator approach was applied to fatigue assessment of generator turbine. It is known from previous work, crucial point is a connection of bladed disk with other parts. Therefore, modeling approach was focused on this detail. A third section of generator turbine assembly was modeled. Cutting planes with appropriate boundary conditions were placed far from screw connection, see Fig. 5. The model and all subsequent FEM analyses were performed in commercial software ABAQUS.

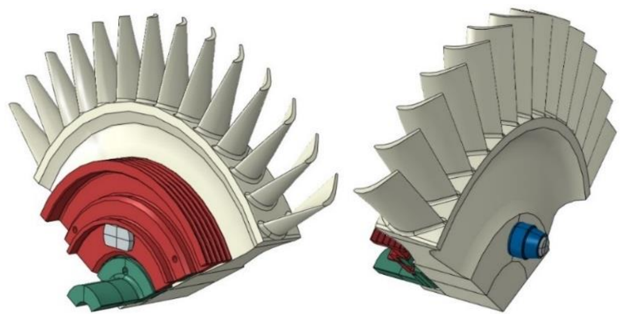

Fig. 5 Analyzed assembly of the generator turbine

Firstly, heat transport analysis was performed to solve convection and conduction of heat from gas to structural parts. Gas temperature was calculated according to the rotational speed spectrum using in-house software for calculation of thermodynamic variables in the engine. The spectrum can be seen in Fig. 6. The spectrum represents start of the engine, followed by single pre-heating cycle and subsequent 5 working cycles. A special attention was paid to the contact connection, where heat transfer condition is included in the contact definition.

Temperature field is assumed from previous heat analysis as a boundary condition in subsequent structural analysis. Furthermore, the structural model (finer mesh) is loaded by rotational speed spectrum and by aerodynamic force depending on current RPM. In general, linear analysis (elastic material) is recommended for subsequent fatigue analysis; strain is reconstructed from elasto-plastic stress calculated from Neuber‘s approximation. In the case of present contact, large plastic area with higher strain can be expected (and confirmed by analysis) and therefore Neuber's approximation isn't suitable approach. Therefore, nonlinear analysis with plasticity and included contact definition was performed.

According to Nagode, et al. (2010) FEM results (stress-strain state, temperature) in every loading increment are stored from FEM analysis as an input to damage calculation briefly described ahead. Because of considered plasticity in the structural analysis both stress and strain distribution can be used. Set of nodes inside of hole and in adjacent surface were analyzed. Fatigue analysis was implemented in MATLAB. All imported FEM entities was analyzed, a crucial one is the node with maximal damage at the end of the analyzed loading sequence. Limit number of repetitions of working cycles N can be calculated from (7). Term d_{N_i} stands for damage up to the beginning of last fifth cycle; N_i stands for number of already analyzed working cycles (N_i=4) and d_{last} is increased damage during the last fifth cycle.

$$D_{total} = 1 = d_{N_i} + (N - N_i) * d_{last} \quad (7)$$

Stress and temperature results in crucial point as well as predicted damage progression are shown in Fig. 6.

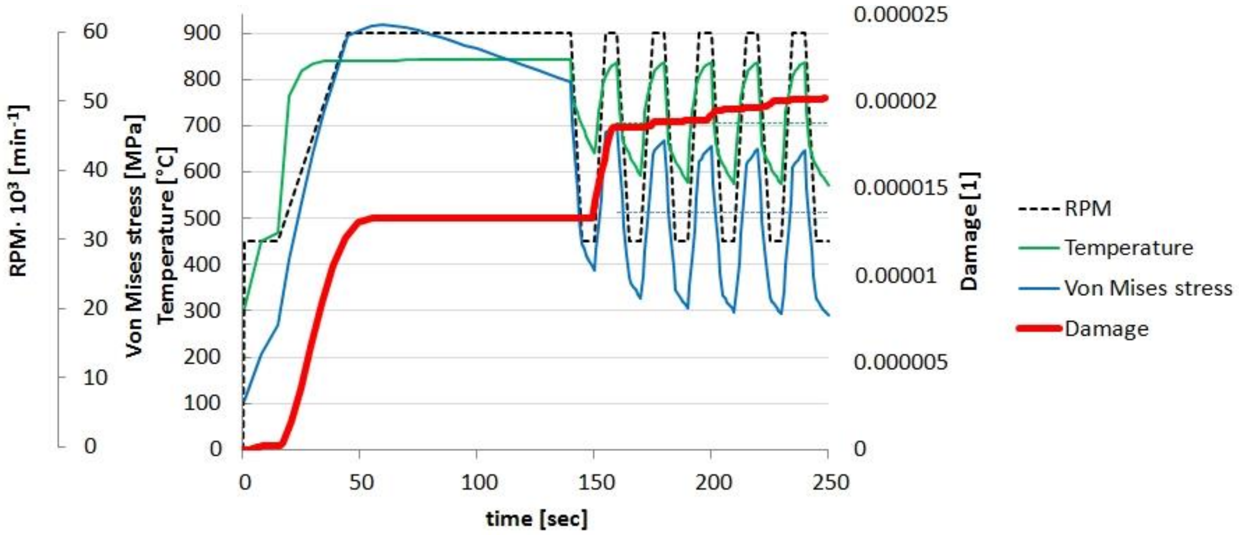

Fig. 6 Predicted damage progression and FEM results

4. Conclusions

Presented paper demonstrates continuous damage calculation during the non-isothermal loading of engine generator turbine. Duration of loading cycles is suggested long enough to enforce temperature is changing significantly. More straightforward identification procedure of parameters of spring-slider sub-model was used compare to the original paper. Verification of implemented damage calculation approach should be the inevitable next step in the future work.

Acknowledgement

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