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An assessment of thermo-mechanically induced fatigue damage of a steam turbine shaft

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Abstract

The increasing demands on the flexibility of steam turbines due to the use of renewable energy sources substantially alters the fatigue strength requirements of components of these facilities. The work summarized hereafter was initiated by the effort to develop the methodology of prediction of thermo-mechanical fatigue of steam turbine rotors. A significant effort was put into local thermo-mechanical stress-strain response modelling in the shaft material. An FE model of the structure assuming 2D axisymmetry idealisation was developed and verified. In-house codes based on a variety of approaches to assess critical location and fatigue damage, including the Manson-McKnight and the Nagode methods, were created. The experimental programme aimed to investigate the material fatigue behaviour under the thermo-mechanical conditions was initiated in order to provide data for calibrating and verifying the fatigue prediction procedures. A preliminary study on thermo-mechanical fatigue behaviour was conducted and the results are summarized in the paper.

Keywords: fatigue of materials; steam turbine shaft; thermo-mechanical fatigue

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1. Introduction

Fatigue life (or fatigue damage) of steam turbine components is mainly determined by service conditions that are closely related to the current loading of the electric generator, which is due to the demand for electricity and at the same time it is given by the environmental conditions. Present trends in energy industry are mainly influenced by the EU and local government energy strategies that result in a significant support for constructing and operating power plants that use renewable energy sources, such as wind-turbine and solar plants. Unstable power supply by these sources, which is caused by unsteady environmental conditions, sets new challenges for the fossil plants. These traditional energy sources play an important role in stabilizing the electrical grids by supplying extra energy during the frequent power cuts caused by the renewable sources. Significantly increased frequency of the turbine start-ups, if compared to the service conditions from the previous years, is becoming to be the direct consequence of this state. Moreover, the grid operators set higher requirements on faster start-up to compensate for the supply of electricity. This substantially changes parameters that need to be considered in the design of steam turbines.

Another example of the increasing requirements on the steam turbine flexibility are direct steam generation solar power plants. Due to the fluctuating nature of the solar energy, multiple start-ups within a 24h period must be endured by solar steam turbines (Birnbaum et al. (2011)).

Regarding the fatigue-life design of the turbines, the following two basic service scenarios determining the fatigue load cycles have to be considered:

- *Cold-start cycle* (50-250 cycles within the turbine life assumed), i.e. start from almost zero speed and cooled state, which is due to long-term operating shutdowns caused, for instance, by inspections and repairs.
- *Hot-start cycle* (6000-8000 cycles within the turbine life assumed), i.e. starts from a pre-warmed state. These cycles are mainly due to the power supplies levelling as mentioned above. Cycling of stresses and deformations is mainly the consequence of mechanical load changes. Temperature fluctuations are, if compared to the previous scenario, quite moderate.

It is the current standard to apply the finite element method (FEM) to the design phase of mechanical structures, especially when dealing with analysis of the cyclic mechanical material response. The obtained local response is then analysed by some of the fatigue prediction technologies in order to estimate fatigue damage and lifetime.

Assessing the life of components under thermo-mechanical loading conditions is still a challenging task. The reason for this is that such conditions trigger a combination of material damaging processes, where mechanical fatigue, creep and oxidation are the most pronounced ones (Neu and Sehitoglu (1989)). Depending on time distribution of loads and environmental conditions, any of these mechanisms may be suppressed to a certain extent. Based on complex material research performed on Mar-M247 nickel-based superalloy, Neu and Sehitoglu (1989) proposed a prediction model, which handles the three mentioned mechanisms. However, identification of material parameters for this prediction procedure requires an extensive experimental programme.

Relatively frequently used in the energy industry is the Manson-McKnight model, which has several modifications (Papuga et al. (2012)). However, any of the Manson-McKnight model variants is rather suitable for predicting fatigue under isothermal fatigue conditions. The advantage of the model is that finding the material parameters requires only standard uniaxial fatigue tests.

Recently, Nagode et al. (2009) have proposed a computational framework for estimating the fatigue damage under variable mechanical and thermal loading in high and low cycle fatigue domain. It employs quite elaborate procedure for analysing the instantaneous load means and amplitudes, which are inputs to the mean stress correction and further process of the fatigue damage estimation based on a set of isothermal fatigue curves. The advantage of the model is the capability to predict fatigue under variable thermal conditions at relatively small costs for the experimental program.

The aim of the paper is to introduce the work and some of the results obtained within the initial period of the FLEXTURBINE project, namely the part dealing with the development of a fatigue damage prediction methodology applicable to steam turbine shafts. The main goal of the work was to propose an accelerated computational framework for evaluating the fatigue damage. The ANSYS FE-code was utilized to simulate thermo-mechanical material response of the selected steam turbine shaft by the assumed load scenario. The axisymmetric model of the shaft for uncoupled thermal and mechanical analyses was developed and 3D submodels for detailed modelling of the most exposed localities were created. Low-cycle fatigue tests under various temperatures were performed to identify the shaft