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Research Paper

On-line monitoring and control of thermal stresses in steam turbine rotors

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HIGHLIGHTS

- Thermodynamic, heat transfer and solid mechanic aspects of stress control were discussed.
- On-line steam temperature calculation model was validated by turbine measurements.
- Equivalent Green's function concept was proposed for rotor stress calculations.
- Rotor groove stresses and strains were investigated by FEM and analytically.
- Neuber's rule was shown to be applicable to determining strain amplitudes in grooves.

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ABSTRACT

The requirement of high operational flexibility of utility power plants creates a need of using on-line systems for monitoring and control of damage of critical components, e.g. steam turbine rotors. Such systems make use of different measurements and mathematical models enabling calculation of thermal stresses and their continuous control. The paper presents key elements of the proposed system and discusses their use from the point of view of thermodynamics, heat transfer and solid mechanics. Thermodynamic relationships, well proven in design calculations, are applied to calculate on-line the steam temperature at critical locations using standard turbine measurements as input signals. The model predictions are compared with operational data from a real power plant during a warm start-up and show reasonably good accuracy. The effect of variable heat transfer coefficient and material properties on thermal stresses is investigated numerically by finite element method (FEM) on a cylinder model, and a concept of equivalent Green's function is introduced to account for this variability in thermal stress model based on Duhamel's integral. This approach was shown to produce accurate results for more complicated geometries by comparing thermal stresses at rotor blade groove computed using FEM and Duhamel's integral. Finally, the applicability of Neuber's and the Glinka–Molski rule with ideal elastic and bilinear material model to estimating elasto-plastic strains at the rotor groove was investigated by FEM. For the considered groove geometry, Neuber's rule with bilinear material model resulted in most accurate strain predictions.

1. Introduction

Modern energy markets put a requirement of high operational flexibility of power plant units [1,2]. Due to this, new designed units, including steam turbines, have to fulfill a series of requirements regarding the number and rate of change of specified operation states. With regard to steam turbines, the requirements concern the number and time of start-ups from different thermal conditions and the rate of load change. The above operation states generate elevated loads and stresses in turbine components leading to material damage due to thermo-mechanical fatigue [3].

The problem of thermal stress monitoring and control in steam turbines was considered already in the mid-sixties [4]. In the first thermal stress control systems, steam turbine rotors were supervised using start-up probes which were thermo-physical models of turbine rotors [5–7]. Thermal stresses were calculated based on measured temperature difference between the probe surface and its integral-averaged temperature. A better accuracy of stress calculation was achieved by replacing the measured average temperature with a mathematical model [8–10].

Further development of thermal stress supervision systems consisted in complete resignation from the temperature probe and modeling thermal stresses based on the standard process measurements of power units, which were a basis for calculating the characteristic temperature difference surface-mean [11]. Rusin et al. [12] proposed a new method of thermal stress modeling in

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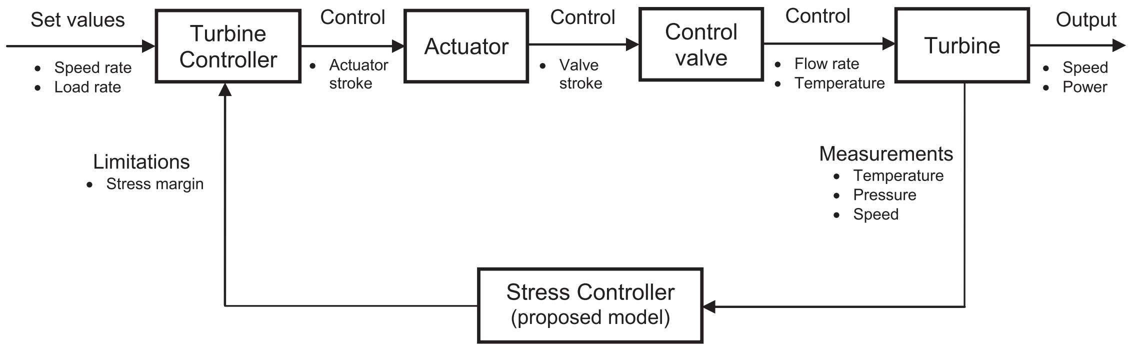

Fig. 1. Schematic diagram of turbine control system with thermal stress control.

turbine rotors employing Green's functions and Duhamel's integral, and steam temperature measurement at critical location. The Green's functions and Duhamel's integral have been for many years used for fatigue life monitoring of nuclear plants equipment by such companies like EPRI [13–15], GE [16] or EDF [17,18]. Such an approach has also been adopted for monitoring of power boilers operation by Taler et al. [19], and as shown by Lee et al. [20] can also be used for calculating stress intensity factors at transient thermal loads. Recent developments in the field are focused on the use of artificial neural networks for predicting boiler wall temperature [21] and turbine thermal stresses [22,23].

The major issue in using Green's function and Duhamel's integral method in modeling transient thermal stresses in steam turbines components is time-dependence of material physical properties and heat transfer coefficients affecting proper evaluation of Green's functions. There are known approaches assuming determination of the influence functions at constant values of these quantities [24]. The inclusion of temperature dependent physical properties proposed by Koo et al. [25] relies on determining the weight functions for steady-state and transient operating conditions. A more important, in most cases, variation of heat transfer coefficient can be taken into account by calculating the surface temperature using a reduced heat transfer model and employing Green's function to calculate a stress response to the step change of metal surface temperature [26]. However, numerical solution of a multi-dimensional heat transfer model is complicated and time-consuming, and due to this cannot be used in on-line calculations. A full inclusion of time variability of the physical properties and heat transfer coefficients proposed by Zhang et al. [27] relies on the solution of non-linear heat conduction problem by using artificial parameter method and superposition rule and replacing the time-dependent heat transfer coefficient with a constant value together with a modified fluid temperature. The effectiveness of the method has been proven by an example of a three-dimensional model of a pressure vessel of nuclear reactor.

The present paper deals with the problems of modeling steam temperature and thermal stresses for on-line supervision of low-cycle fatigue life. A control system is proposed and its main elements are:

1. thermodynamic model enabling fast calculation of steam temperature at critical location
2. thermal stress model for on-line calculation of rotor thermal stresses
3. relationship between elastic stress amplitude and total strain amplitude allowing to determine permissible stresses for a given number of starts

The models have been validated by comparing the results of numerical calculations with real turbine measurements and more accurate 3D simulations.

2. Thermal stress control system

Thermal stress control systems of steam turbine rotors are currently a commonly used measure of protecting the design fatigue life of high- and inter-mediate pressure turbine rotors. These systems are very important elements of turbine control and protection systems and operate in closed-loop control. A schematic diagram of turbine control system including a module responsible for thermal stress control is shown in Fig. 1. Based on turbine measurements (e.g. temperature, pressure, speed), the stress controller calculates stresses and load fraction and outputs to the turbine controller a signal of stress margin which reduces the set values of speed or load rates. The turbine controller positions, with the help of actuator, the control valve head controlling in this way the steam flow rate and temperature upstream the turbine blading. These two parameters have impact on the rotor temperature and the resulting thermal stresses.

The thermal stress controller calculates stresses at rotor critical locations on the basis of measurement signals and compares them with the permissible stresses. On the basis of these two stresses, a load fraction *LF* is calculated using the formula:

$$LF = \frac{\sigma_{eq}}{\sigma_{perm}} \quad (1)$$

The equivalent stress σ_{eq} is computed based on the measured temperature, pressure, rotational speed and using a mathematical model of temperature (if it is not measured directly) and thermal stresses. The permissible stress σ_{perm} is derived from the material fatigue characteristics knowing the required number of cycles and assuming a material model.

Thus, the key elements of the considered thermal stress control system are:

1. thermodynamic model allowing for steam temperature calculation at critical regions
2. thermal stress model for on-line stress calculation
3. relationship between elastic stress and total strain allowing for the calculation of permissible stresses for a given number of start-ups

3. Thermodynamic model

3.1. Model formulation

In order to calculate thermal stresses at rotor critical locations, it is necessary to know the steam temperature at these locations, which is an input signal to the stress calculation algorithm. Steam temperature can be evaluated in two ways, namely: