Steam turbine start-up optimization based on finite element analysis of rotor thermoelastic stresses

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Abstract

This paper presents an optimization algorithm for steam turbine start-up calculations. The selected optimization criterion is minimization of start-up time which is ensured by saturation of stress bounds. Optimization is carried out based on the thermoelastic stress analysis performed using the finite element method. Steam mass flow to the turbine is adopted as an optimization variable Performance of the presented algorithm is shown by an example of steam turbine rotor calculations. According to the optimised start-up diagram, the calculated mass flow variation ensures saturation of stress bounds shortly after start of loading.

Keywords: steam turbine, thermoelastic stress, optimization algorithm

1. Introduction

Steam turbines designed for cyclic duty have to fulfil high requirements regarding the number of starts and start-up times. In design phase, the low-cycle fatigue theory is used for lifetime calculations of the most critical components. In order to secure the design lifetime, the turbine operating instructions include start-up diagrams which must be followed in real operation. Nowadays, the design calculations are done using the finite element method, and also start-up analysis and optimisation have to employ the same methods.

The paper presents start-up optimization methodology and its application to steam turbine rotors analysis.

2. Optimization algorithm

Optimization of turbine start-up is a problem of complex process optimization requiring unique formulation of optimization criteria. In our case they are [1]:

- economic criterion expressed as minimization of start-up time,
- safety criterion expressed as the level of component stresses

The mathematical model of process optimization includes decision variables $X = (x_1, \ldots, x_n)$, bounds φ_i and objective function V. The decision variables comprise parameters and optimization variables. Component geometry and material properties are assumed as parameters, while the optimization variable in time t_i is the increase of turbine load N

$$x_i = \frac{dN(t_i)}{dt} \tag{1}$$

The increase of steam temperature is optimized indirectly.

The form of the objective function and bounds is derived from the assumed optimization criterion. If minimization of start-up time is assumed as the criterion, then the objective function is expressed as

$$V = t_{SU} \tag{2}$$

In such a case, the permissible stress is adopted as a bound

$$\varphi_i = \sigma_i \le \sigma_{i,perm} \tag{3}$$

Minimum start-up time is thus achieved when the stress is equal to its bound, and this condition is finally used in the optimization model. No specific optimization method is applied as start-up optimization is performed by conducting iterative calculations so as to minimize the difference between current stress and its bound (ideally reaching zero).

The optimum mass flow (turbine load) is chosen such that the stress is as close as possible to the bound (saturation of stress bound close to 100%). During optimization calculations, the mass flow m for the next time step ($t+\Delta t$) is calculated as [2]:

$$m(t+\Delta t) = m(t) + f(t)\cdot u(t)\cdot m_n \tag{4}$$

where $f(t)$ is a tuning function and $u(t)$ stands for a proportional-derivative control function of error argument depending on the saturation of stress bound.

The optimization process overview is shown in Fig. 1. Calculations start with applying initial conditions and evaluating thermal boundary conditions for the first time step. Coupled thermo-mechanical finite element analysis is then performed for this time step and stress results are evaluated. Thermoelastic equivalent Huber-Mises stress is used for this purpose. Based on the saturation of stress bound, the control algorithm calculates the value of control function $u(t)$ which is then used to determine the mass flow for the next increment. The process of controlled computation is continued for the entire start-up period.

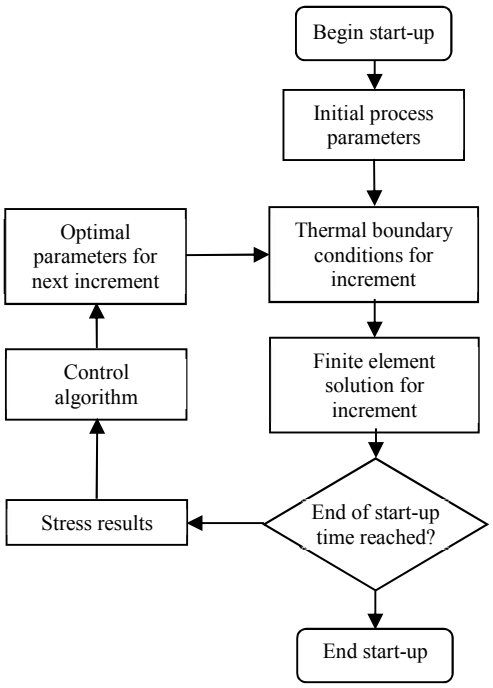

Figure 1: Start-up optimization diagram.

3. Calculation example

Performance of the start-up optimization algorithm is presented by an example of a steam turbine rotor calculations. Temperature and stress calculations are performed in the same analysis using coupled temperature-displacement elements [3]. Fig. 2 presents instantaneous temperature distribution in the rotor 50 minutes after beginning of start-up. The corresponding equivalent stress distribution at the same instant is shown in Fig. 3. The figure also presents detailed stress distribution in the first grooves where the stresses are highest (red colour denotes maximum, while blue stands for minimum in both figures) and determine the rate of turbine loading.

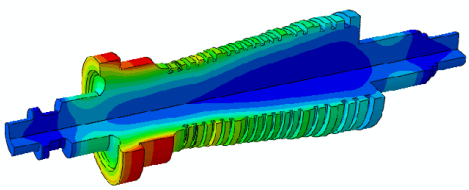

Figure 2: Transient temperature distribution during start-up.

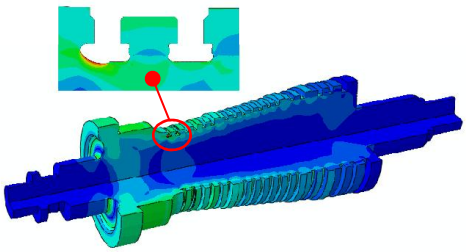

Figure 3: Transient stress distribution with detailed stress profile in front blade grooves during start-up.

The start-up process was automatically optimized using the algorithm described above and the optimized start-up diagram is shown in Fig. 4. The optimised parameters are steam temperature and turbine load (mass flow). The rotational speed is included in the diagram as the run-up phase precedes the loading phase and its end provides initial conditions for optimisation. As it was mentioned above, the saturation of stress bound was used as an optimisation criterion assuming that the minimum start-up time is achieved when the saturation equals 100%. This condition was met in the presented example as the saturation of stress bound reached 100% at c.a. 60 minute of start-up. Later on, its value was close to maximum but slightly decreasing, what results from additional constraints of steam parameters. According to the optimized start-up diagram, the full load is attained after c.a. 110 minutes with saturation of stress bound exceeding 90%.

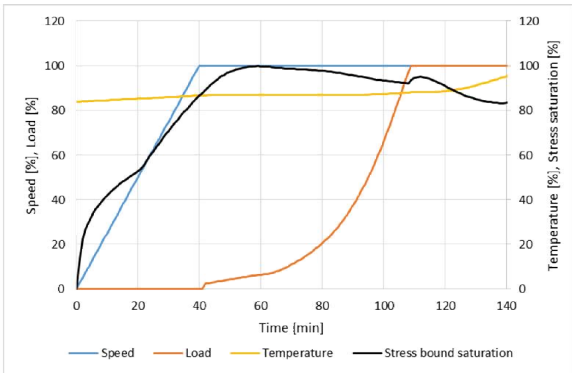

Figure 4: Optimum start-up diagram.

4. Summary

The presented method of steam turbine start-up optimization aims at minimizing start-up time by maximizing the saturation of stress bound. Steam mass flow to the turbine is adopted as the main optimization variable, while steam temperature is optimized indirectly.

The major part of the optimization algorithm is solution of the component model by means of the finite element method. Coupled temperature-displacement analysis is used in order to minimize the solution time. Thermoelastic equivalent stress is adopted for calculating saturation of stress bound.

The start-up diagram calculated for a turbine rotor predicts optimum mass flow and temperature variation which ensures maximum saturation of stress bound and minimization of the start-up time.

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