Practical methods for online calculation of thermoelastic stresses in steam turbine components

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Abstract

This paper presents two practical methods of thermoelastic stress calculation suitable for application in online monitoring systems of steam turbines. Both methods are based on the Green function and Duhamel integral, and consider the effect of variable heat transfer coefficient and material physical properties on thermal stresses. This effect is taken into account either by using equivalent steam temperature determined with constant heat transfer coefficient or by applying an equivalent Green's function determined with variable heat transfer coefficient and physical properties. The effectiveness of both methods was shown by comparing their predictions with the results of finite element calculations of a steam turbine valve.

Keywords: thermoelastic stress, steam turbine, online calculation

1. Introduction

The flexible operation of steam turbines generates elevated loads and stresses in turbine components leading to material damage due to thermo-mechanical fatigue. In order to control the fatigue damage, thermal stresses should be computed on-line and limited to permissible values.

In power generation industry, the approach based on the Duhamel integral and the Green functions is widely used for thermal stress calculations. The major issue in using this approach is variability of material physical properties and heat transfer coefficients affecting proper evaluation of the Green functions.

The paper presents two simple methods of thermoelastic stress calculation taking into account the mentioned above variabilities. Both methods are suitable for online applications.

2. Thermoelastic stress model

It is assumed that the thermoelastic stress model used in on-line calculations is based on the Green function and Duhamel integral method. This method allows for fast calculation of thermal stresses at supervised areas for any changes of fluid temperature causing heating-up or cooling-down of an element.

Considering elastic stresses only, it is assumed based on the thermoelasticity theory, that stress distribution in an elastic body is a unique function of temperature distribution. Hence, the thermal stresses can be calculated using the Duhamel integral [1]

$$\sigma_{ij}(r,t)=\int_0^t G_{ij}(r,t-\tau)\frac{\partial T_{st}(\tau)}{\partial \tau}d\tau \quad (1)$$

where $G_{ij}(r,t)$ is a Green function for thermal stress component ij. The shape of the Green function for a given location r describes the stress response at time and depends on heat transfer coefficient and material physical properties. In real operating conditions both the heat transfer coefficient and material properties vary with time due to variable steam velocity and component temperature. In order to consider the variation of the Green function in Eqn (1), two methods are proposed:

- use of equivalent steam temperature determined with constant heat transfer coefficient
- use of an equivalent Green's function determined with variable heat transfer coefficient and physical properties

3. Equivalent steam temperature

In this method, equivalent steam temperature T_{eq} is used in Eqn (1) instead of the actual steam temperature T_{st}, together with the Green function determined with a constant heat transfer coefficient α_c. The equivalent steam temperature is obtained from the condition of surface heat flux equality [1]

$$\alpha\left(T_{surf}-T_{st}\right)=\alpha_c\left(T_{surf}-T_{eq}\right) \quad (2)$$

where T_{surf} is the current temperature of component surface. This temperature is obtained from a solution of one-dimensional (1D) Fourier-Kirchhoff equation for a simplified component geometry (e.g. cylinder, sphere, etc). A flow chart of the calculation algorithm is shown in Fig. 1. For online calculations it is proposed to use the finite volume method for solving 1D heat conduction problem. The equivalent steam temperature obtained from the condition of surface heat flux equality (Eqn (2)) is used in step 2 together with the Green function determined in finite element analysis assuming a constant heat transfer coefficient α_c. The finite element calculations are performed off-line to determine the Green function in advance. Thermoelastic stresses in the component are finally calculated using the Duhamel integral (Eqn (1)).

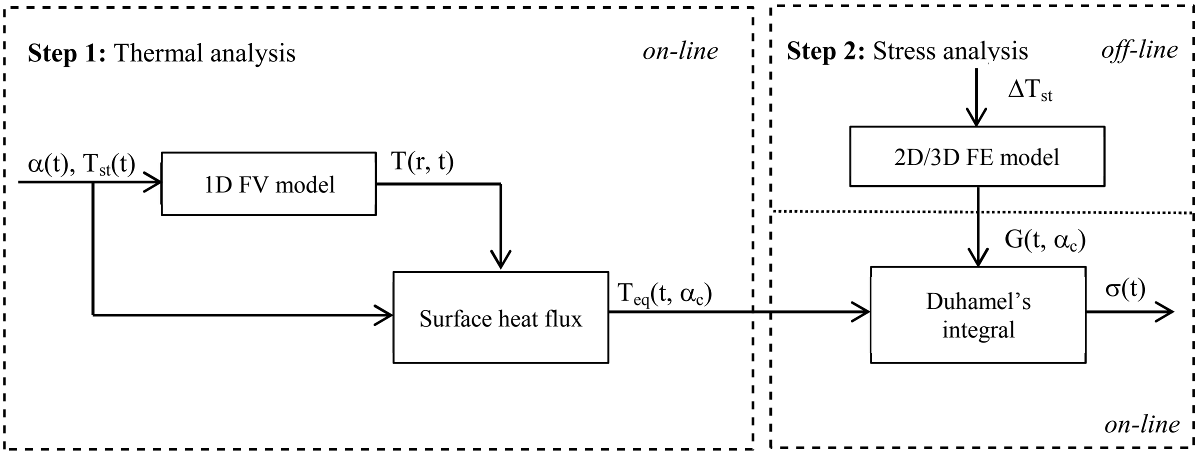

Figure 1: Flow chart of the stress calculation algorithm

4. Equivalent Green's function

The second method relies on using in Eqn (1) an equivalent Green's function determined assuming variable heat transfer coefficient and physical properties. It can be done if the variation of process parameters is known in advance and used to determine the shape of the equivalent Green's function. The is the case in steam turbines operation as steam parameters are defined in design start-up diagrams for specific types of starts and should be followed within some margins.

The equivalent Green function is evaluated by performing finite element thermal analysis with the following boundary conditions [2]:

- steam temperature step characteristic for a given start-up type
- variable heat transfer coefficient resulting from the variation in time of the steam mass flow rate characteristic for a given start-up

An example of the equivalent Green functions for axial and circumferential thermoelastic stress components on the surface and axis of externally heated cylinder is shown in Fig. 2.

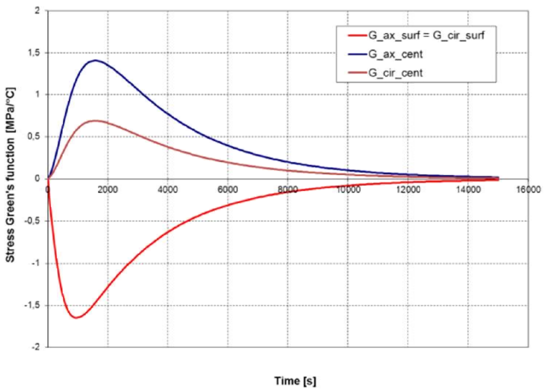

Figure 2: Equivalent Green's function for axial and circumferential stresses in externally heated cylinder.

5. Validation of methods

The proposed methods were validated by comparing their predictions with the results of finite element calculations performed for a steam turbine valve. Figure 3 presents the Huber-Mises thermoelastic stress variations in the valve critical area during turbine start-up calculated using three methods. As it is seen both proposed methods predict the stresses with good accuracy comparing with the non-linear finite element method.

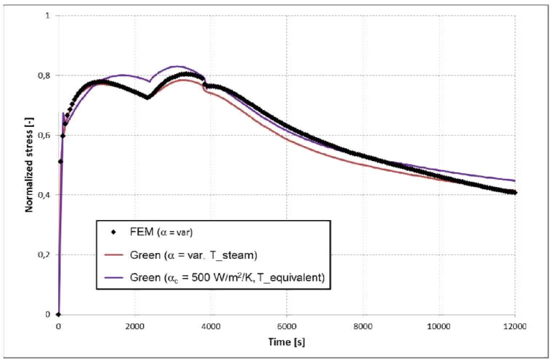

Figure 3: Normalized stress variations during turbine start-up.

6. Summary

Two simple methods of thermoelastic stress calculation suitable for online applications were presented. Both methods employ the Duhamel integral and the Green function for stress computation. The first method is based on the use of equivalent steam temperature determined with constant heat transfer coefficient, while the second one relies on the equivalent Green's function determined with variable heat transfer coefficient and physical properties.

The numerical example of turbine valve calculation showed a good agreement between the proposed methods and the non-linear finite element analysis.

References

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