A PREDICTION METHOD OF TEMPERATURE DISTRIBUTION AND THERMAL STRESS FOR THE THROTTLE TURBINE ROTOR AND ITS APPLICATION

by

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In this paper, a prediction method of the temperature distribution for the thermal stress for the throttle-regulated steam turbine rotor is proposed. The rotor thermal stress curve can be calculated according to the preset power requirement, the operation mode and the predicted critical parameters. The results of the 660 MW throttle turbine rotor show that the operators are able to predict the operation results and to adjust the operation parameters in advance with the help of the inertial element method. Meanwhile, it can also raise the operation level, thus providing the technical guarantee for the thermal stress optimization control and the safety of the steam turbine rotor under the variable load operation.

Key words: *steam turbine rotor, temperature distribution, thermal stress, inertial element method*

Introduction

The steam temperature of rotor surface changes greatly during the start, shutdown and load change of steam turbine operation process [1]. However, the temperature inside the rotor changes slightly due to heat resistance [2]. The temperature difference between rotor surface and volume average temperatures is large. As a result, the thermal stress of rotor surface is high and the rotor life damage is serious [3]. The temperature distribution and thermal stress of steam turbine rotor has been further studied by many scholars and optimization strategy of corresponding unit has been proposed. Bhaumik *et al.* [4] analyzed the invalidation problem of the integral rotor disc in an aero engine. It was concluded that the main reason of fatigue failure was the partial micro-structure on rotor and the high operation temperature. Zhang [5] employed ANSYS to run a numerical simulation of transient temperature and stress field in several transient operating conditions. The result was applied to provide theoretical foundation of rotor life optimization management. Nowak and Rusin [6] aimed at a model of ultra-supercritical steam turbine rotor and proposed a method for optimization of shape and operation curve. The shape and operation curve of the rotor was a significant factor of rotor stress field. It is obvious that keeping the temperature difference in a certain range can retain the rotor thermal stress to be low enough, thus making the rotor life damage reduced. Before load dispatching or load regulation, the suitable operation mode and operation parameters should be determined to help

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the operators to operate reasonably [7]. Usually, it can be finished according to peak modulation capacity, operation characteristics and thermal stress characteristics, especially variation curves of the power, main steam temperature, main steam pressure, reheat steam temperature, and reheat steam pressure [8].

The aim of this paper is to present a new approach for predicting thermal stress of the throttle-regulated steam turbine rotor. The predicted thermal stress curve can be calculated according to the preset power requirement, the operation mode, and the predicted critical parameters. It can be concluded that the operators can predict the operation results, adjust the operation parameters in advance using the present method and raise the operation level, fig. 1.

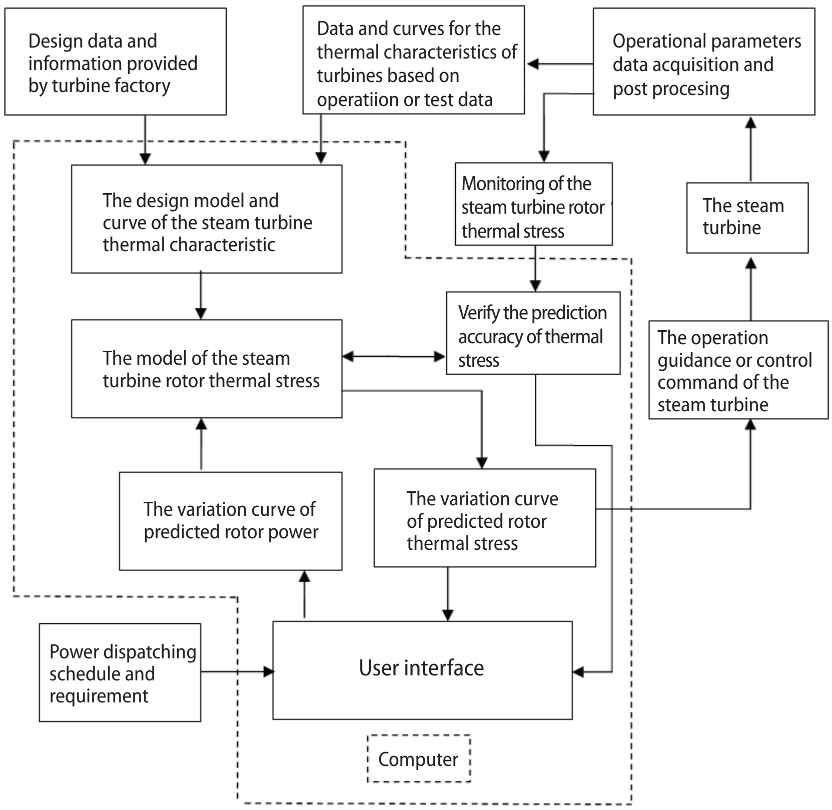

Figure 1. The schematic diagram of thermal stress prediction method for throttle-type steam turbines

Temperature prediction of turbine rotor

Identify the current state of the turbine

The current state of turbine can be identified according to the collection of the current and the first one-hour of the critical parameters of the turbine. To be concrete, it includes the outer surface temperature, the volume average temperature, the turbine inner surface (or the axis) temperature at the monitoring positions, the main steam temperature, the main steam pressure, the reheat steam temperature, the reheat steam pressure, the condenser pressure, the turbine speed, and the generator load. The turbine can be in the process of outage, start-up, steady operation, load increased, and power decreased or stop-down.

Formulate critical steam parameters and steam turbine power curve

Based on the requirements of load dispatching, the default change curves of the critical parameters are established, such as turbine load, flow, the main steam pressure, the main steam temperature, the reheat steam pressure, and the reheat steam temperature.

In general, the curves can be calculated according to the thermal characteristic data. For each load on the time-varying load profile, the main steam flow can be calculated according to the main steam flow *vs.* load graph, thus making the change curve of the main steam flow. For each main steam flow on the time-varying curve, the main steam pressure can be calculated based on the sliding pressure operation curve of the main steam pressure and the main steam flow, thus establishing the main steam pressure curve. In the same way, the main steam temperature, reheat steam pressure, reheat steam temperature, and other changing curves are formulated.

The thermal data and curves can be obtained based on the design data and curves provided by turbine manufactory or the turbine running and testing data provided by the power plant. Furthermore, the curves of main steam flow *vs.* load, main steam pressure *vs.* main steam flow, main steam temperature *vs.* main steam flow, reheat steam temperature *vs.* main steam flow are obtained. Relatively, the use of steam turbine running and testing data will be more accurate if the data is more realistic.

Formulate the change curve of steam parameters at turbine monitoring positions

According to the preset curves of turbine flow, the main steam pressure, the main steam temperature and the reheat steam temperature, the steam parameters of turbine rotor thermal stress monitoring positions can be calculated. They are obtained by available technology such as thermal characteristic data method. The default change curve of the steam flow, steam pressure, steam temperature at the turbine thermal stress-monitoring positions can be accessed.

Let us take the thermal characteristic data and curve method for instance. For each main steam flow on the time-varying main steam flow profile, the pressure after the first stage of high pressure cylinder can be calculated based on the pressure after first stage of high pressure cylinder *vs.* the main steam flow graph. Thus, the curves of the pressures after the first stage of high pressure cylinder varying with time are obtained. By the same way, the temperature after the first stage of high pressure cylinder curve can be established.

The thermal data and curves can be obtained based on the design data and curves provided by turbine manufactory or the turbine running and testing data provided by the power plant. Furthermore, the curves of the pressure after first stage of high pressure cylinder *vs.* the main steam flow, the temperature after first stage of high pressure cylinder *vs.* the main steam flow are obtained.

Formulate the change curve of turbine outer surface temperature

According to the default curves of steam flow, steam pressure, and steam temperature, the heat transfer coefficient of turbine outer surface at the thermal stress monitoring positions can be easily obtained. Furthermore, the changing curves of the default turbine rotor outer surface temperature at the thermal stress monitoring positions can be established.

Besides, the curves of rotor outer surface temperature heat transfer coefficient, steam flow, steam pressure, and steam temperature can be fitted according to the accumulated turbine operating and testing data, and then the rotor outer surface temperature at the thermal stress monitoring positions can be calculated [9-11].

Formulate the change curve of turbine volume average temperature and inner surface temperature

A large number of scholars at home and abroad carried out the simulation of the rotor temperature field [12-17]. In the paper, the inertial element method is executed to calculate turbine rotor temperature field and plot the default turbine rotor volume average temperature and inner surface (or the axis) temperature curves.

The inertial element method is applied n-juxtaposed inertial elements, $k_1 + k_2 + \cdots + k_n$, in which k_1 is the weight coefficient of the first inertial element, k_2 is the weight coefficient of the second inertial element, … , k_n is the weight coefficient of the nth inertial element, thus the iteration equation of the i^{th} inertial element is:

$$y_i = y_{i-1} + \frac{\tau_a}{T}\left(x_i - y_{i-1}\right) \tag{1}$$

where y_i is the response of the i^{th} inertial element, x_i – the motivation of the i^{th} inertial element, y_{i-1} – the response of the $(i$-1$)^{\text{th}}$ inertial element, τ_a – the time step, and T – the time constant of inertial elements.

According to the default volume average temperature of the turbine rotor, inner surface (or the axis) temperature and outer surface temperature varying curves, the turbine rotor temperature difference and thermal stress are calculated and the variation curves are plotted.

Thermal stress prediction of turbine rotor

Formulate the change curves of turbine thermal stress

The irregularity of temperature field leads to the different expansion and contraction of different parts, or makes the deformation of certain area limited, thus the thermal stress field of rotor inner comes into being. To solve stress field, the node displacement under the temperature field should be solved firstly, and then the element internal stress can be calculated based on the stress-strain relationship.

The stress equilibrium equations in axisymmetric form can be expressed as [18, 19]:

$$\begin{cases} \dfrac{\partial \sigma_r}{\partial r} + \dfrac{\partial \tau_{zr}}{\partial z} + \dfrac{\sigma_r - \sigma_\theta}{r} + f_r = 0 \\ \dfrac{\partial \sigma_z}{\partial z} + \dfrac{\partial \tau_{rz}}{\partial r} + \dfrac{\tau_{rz}}{r} + f_z = 0 \end{cases} \tag{2}$$

where σ_r, σ_θ, and σ_z are radial, circumferential and axial normal stress, respectively, τ_{zr} is shear stress, and f_r and f_z are radial and axial body force, respectively.

The stress in the rotor is related to both deformation and temperature. According to the generalized Hooke's law, the relationship between stress and displacement, temperature can be expressed:

$$\begin{cases} \sigma_r = 2G\left[\dfrac{1-\mu}{1-2\mu}\dfrac{\partial u}{\partial r} + \dfrac{\mu}{1-2\mu}\left(\dfrac{u}{r} + \dfrac{\partial w}{\partial z}\right)\right] - \beta T, \quad \sigma_\theta = 2G\left[\dfrac{1-\mu}{1-2\mu}\dfrac{u}{r} + \dfrac{\mu}{1-2\mu}\left(\dfrac{\partial w}{\partial z} + \dfrac{\partial u}{\partial r}\right)\right] - \beta T \\ \sigma_z = 2G\left[\dfrac{1-\mu}{1-2\mu}\dfrac{\partial w}{\partial z} + \dfrac{\mu}{1-2\mu}\left(\dfrac{\partial u}{\partial r} + \dfrac{u}{r}\right)\right] - \beta T, \quad \tau_{zr} = G\left(\dfrac{\partial w}{\partial z} + \dfrac{\partial u}{\partial z}\right) \end{cases} \tag{3}$$

where G is the shear modulus and μ is Poisson ratio.

According to the Hamilton principle, the finite element equation of bidirectional coupling stress field at any time can be written:

$$[D]U-[H]\vec{T}-\vec{F}=0 \tag{4}$$

where [D] is the stiffness matrix, [H] – the thermal stress coefficient matrix, and $\vec{F}$ – the body force vector.

The analysis theory of fluid-solid coupling

The thermo structure bidirectional coupling model [20] for rotor thermal stress calculation concludes the calculation of temperature field and stress field, the wanted temperature vector, $\vec{T}$, and displacement vector, $\vec{U}$, are coupled with each other, therefore the solution should be done with iteration and recursion. The specific process of iteration and recursion is as follows.

– Take the displacement $U_{\tau-\Delta\tau}$ at time $\tau-\Delta\tau$ as the initial value of the iteration displacement $U_\tau^{(0)}$ at the time, τ, to get the temperature value, T_τ, at the time, τ.
– Take T_τ as the boundary condition at the time, τ, to get the displacement value, U_τ, at the time, τ.
– Compare the U_τ with $U_\tau^{(0)}$, if:

$$\left|U_\tau-U_\tau^{(0)}\right|>\varepsilon \tag{5}$$

Then make $U_\tau^{(1)}=U_\tau$, maintain $T_{\tau-\Delta\tau}$ and $U_{\tau-\Delta\tau}$, the displacement $U_\tau^{(m)}$ and temperature, $T_\tau^{(m)}$, at the time, τ, are obtained after repeating the iteration for m time.
– The calculation is completed if the convergence condition satisfies:

$$\left|U_\tau-U_\tau^{(m)}\right|<\varepsilon \tag{6}$$

where m is the number of iterations and ε – the set error allowed value.

Start from the beginning, then repeat the previous iterations in order. The values of temperature, displacement and stress in each node during the whole start process can be calculated by recursion by step.

Verify and plot the change curves of critical parameters

The rotor thermal stress change curve is compared with the thermal stress allowable value of related criteria for the life loss of the steam turbine. When the verification is overrun, the alarm is given to the overrun section [21, 22]. If the thermal stress level is relatively low for some section, the operator will be promoted to adjust the appropriate adjustments.

Application to the 660 MW class throttling turbine

For some 660 MW throttling regulator steam turbines, the main steam pressure is 27 MPa, the main steam temperature is 600 °C, and the reheat steam temperature is 620 °C . Based on the steam turbine characteristic curves, the inertia element method shown in fig. 2 (k_1 , k_2 , k_3 , k_n , E_2 , E_3 , E_n is constant, PT1 is the inertia element), regarding the default steam turbine load curve shown in fig. 3, the estimated thermal stress curve of the turbine rotor shown in fig. 2 is formulated. It provides technical guarantee for the thermal stress optimal control of steam turbine rotor and the safety of steam turbine variable load operation.

Firstly, according to the collection of the current and the first one-hour of the critical parameters of the turbine, especially for the power curve, it is recognized whether the current state of turbine is in a stable running state. Secondly, the operator formulates the default change

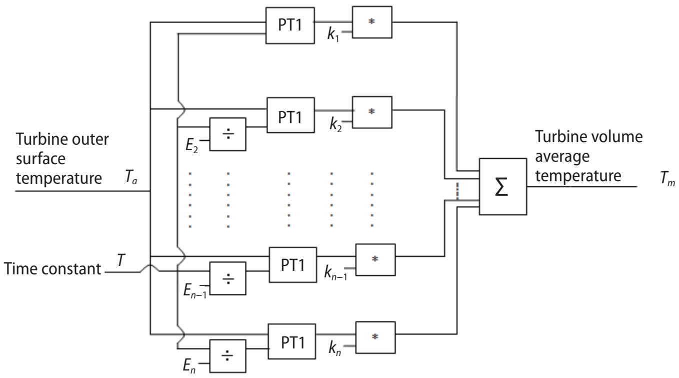

Figure 2. Rotor volume average temperature inertia link calculation structure diagram

curves of the turbine power as shown in fig. 3, based on the requirements of power dispatching.

Utilize the thermal data and curves, for each power on the time-varying power profile, the main steam flow can be calculated according to the main steam flow *vs.* power graph. Hence, the changing curve of the main steam flow is obtained. The main steam pressure and temperature can be calculated according to the main steam pressure and temperature *vs.* the main steam flow graph, thus the changing curve of the main steam pressure and temperature is obtained. By the same way, the changing curve of reheat steam pressure, reheat steam temperature can be obtained.

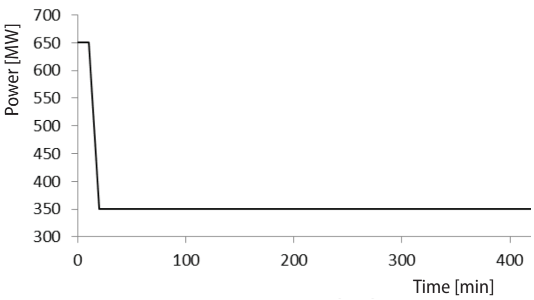

Figure 3. Preset power *vs.* time curve

Thirdly, based on the estimated curves of the turbine flow, the main steam pressure, the main steam temperature, reheat steam pressure and reheat steam temperature, the changing curve of the steam parameters at the turbine monitoring positions is formulated.

Utilize the thermal data and curves, for each main steam on the time-varying power profile. The pressure and temperature after the first stage of high pressure cylinder can be calculated based on the pressure and temperature after the first stage of high pressure cylinder *vs.* the main steam flow graph. Thus, the curve of the pressure and temperature after the first stage of high pressure cylinder varying with time is obtained as shown in fig. 4.

Fourthly, formulate the changing curve of turbine outer surface temperature. According to the default curves of steam flow, steam pressure and steam temperature, the heat transfer coefficient of turbine outer surface at the thermal stress monitoring positions is accessed by empirical formula. It is considered that the temperature of turbine outer surface at the thermal stress monitoring positions equals to the steam temperature at the site when the heat transfer coefficient is big enough. The estimated temperature curve of turbine outer surface at the thermal

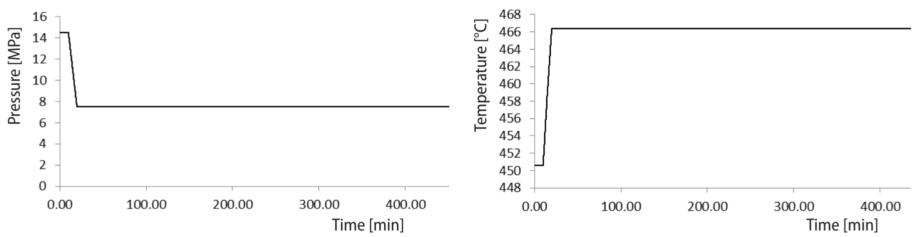

Figure 4. Preset steam pressure and temperature curve at the monitoring positions

stress monitoring positions is formulated as shown in fig. 5.

Fifthly, the temperature field of turbine rotor is calculated with the inertial element method. The default turbine rotor volume average temperature and inner surface (or the axis) temperature curves are formulated as shown in fig. 5.

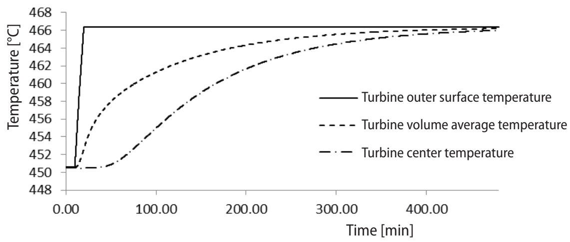

Figure 5. Preset rotor temperature curve at monitoring positions

In this application, the inertial element method applies four juxtaposed inertial elements, in which k_1, k_2, k_3, k_4 is the weight coefficient of the first, second, third, fourth inertial element, respectively. The sum of four weight coefficients equals to 1.

Lastly, formulate the changing curves of turbine temperature difference and thermal stress: According to the default turbine rotor volume average temperature, inner surface (or the axis) temperature and outer surface temperature varying curves, the turbine rotor temperature difference and thermal stress are calculated. The variation curve is formulated as shown in fig. 6.

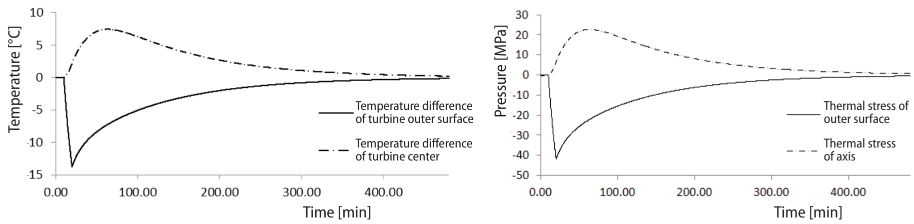

Figure 6. Preset rotor temperature difference and thermal stress curve at monitoring positions

Conclusions

In the thermal stress prediction method proposed in this paper, the thermal stress curve can be calculated according to the preset power requirement, operation mode and the predicted critical parameters curves. The accuracy of the relevant calculation, on the one hand depends on the design data obtained. On the other hand, it can use intelligent algorithms to improve through the power plant site monitoring data.

It is concluded that the operators predict the operation results, adjust the operation parameters in advance and raise the operation level, thus providing a technical guarantee for the thermal stress optimization control and the safety of the steam turbine rotor variable load operation.

Nomenclature

f_r – axial body force, [Nm^{-3}]
f_z – radial body force, [Nm^{-3}]
G – shear modulus, [Pa]
T – temperature, [K]

Greek symbols

μ – Poisson ratio, [–]
τ_{zr} – shear stress, [Pa]
σ_r – radial stress, [Pa]
σ_z – axial normal stress, [Pa]
σ_θ – circumferential stress, [Pa]

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