OPTIMIZATION ON START-UP PROCESS OF HIGH-PRESSURE ROTOR FOR LARGE POWER STEAM TURBINE

by

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This paper combines thermal-structure coupling technique and pattern search optimization algorithm to establish an optimization system for the start-up process of a turbine unit. Firstly, a finite element model for thermal-structure coupling calculation is established to accurately analyze the transient temperature field and thermal stress field, which can obtain the thermal stress distribution during start-up process. Afterwards, a program of optimization on rotor start-up process is exploited to improve the time allocation in each operating stage of start-up process, which minimizes the maximum equivalent stress of rotor. The maximum equivalent stress has reduced 25.7% after the optimization, which reveals obvious effect.

Key words: *finite element method, steam turbine start-up, rotor, thermal stress, optimization design, pattern search method*

Introduction

Since the 21st century, with the rapid development of economy, the demand of electric power has substantially increased and thermal power generation will be the dominating form in the long term [1]. Following the incessant growing of electricity consumption in market, the peak modulation task of electric system has been increasingly severely [2]. During the process of unit peak modulation, large thermal stress is existed, which decreases the security and reliability of a thermal power unit to a great extent and causes a prominent problem.

Among both domestic and foreign related research, the thermal stress of steam turbine rotor has been further investigated by many scholars and optimization strategy of corresponding unit has been proposed. In 1976, Schmerling *et al.* [3] revealed the rupture accident of the low pressure rotor in certain generator set in the US publicly, which drew extensive attention to security problems of rotor operation internationally. Bhaumik *et al.* [4] analyzed the invalidation problem of the integral rotor disc in an aircraft engine. A theoretical analysis was conducted that the main reason of fatigue failure is the partial microstructure on rotor and the high operation temperature. Wang [5] put forward a high precision on-line monitoring model of steam turbine rotor stress taking plastic deformation into account and several prioritization schemes to ameliorate rotor safety. Liu [6] adopted finite element method to particularly analyze the rotor's transient temperature and stress field during cold start-up while optimized the existing start-up curve to reduce thermal shock damage of the rotor. Zhang [7] employed

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ANSYS to run a numerical simulation of the rotor's transient temperature and stress field in several transient operating conditions and applied fatigue analysis software to provide theoretical foundation of rotor life optimization management. Bai [8] adopted finite element software ALGOR to analyze the transient temperature and stress distribution of a 600 MW steam turbine rotor in four transient operating conditions, presented the optimal economic start-up and shutdown curve in the promise of life expenditure. Barella *et al.* [9] studied the rotor life of a 60 MW unit. They adopted different methods to recover fatigue damage phenomenon of the rotor and concluded that the major reason of low cycle fatigue failure was the tremendous alternating thermal stress while start-up and shutdown. Zheng [10] employed thermal-structure indirect coupling method to thoroughly analyze the stress distribution of a high pressure-intermediate pressure rotor under different start-up and shutdown conditions. The proposed APDL parametric program laid a theoretical foundation for subsequent optimization design of the rotor. Ding [11] combined numerical study with field test to research the rotor thermal stress before and after the optimization of start-up process. The optimized curve shortened the starting time and decreased low cycle fatigue life consumption. Li *et al.* [12] studied the maximum stress of the rod fastening rotor by non-linear damage mechanism model under frequent start-up conditions to obtain the damage level each time, which provided a part of theoretical foundation for rotor damage decrease. Nowak *et al.* [13] aimed at a model of ultra-supercritical steam turbine rotor and proposed a method for optimization of shape and operation curve. The result indicated that shape and operation curve of the rotor was a significant factor of rotor stress field.

Former researches only consider the effect of temperature on deformation, thus neglecting the effect of deformation on temperature during heat conduction. The temperature variation of the structure not only depends on the heat transmission of surrounding medium but also the strain rate inside the object. Consequently, the heat convection and deformation of the structure can be accurately described by two-way thermal-structure coupling model.

In this paper, the thermal stress of rotor is obtained by thermal-structure coupling method. Then a program of optimization on rotor start-up process and pattern search algorithm are exploited to improve the time allocation in each operating phase of start-up process for minimizing the maximum equivalent stress.

Principle of thermal-structure coupling

Computing theory of rotor temperature field

When computing the temperature field of the rotor, the heat transfer problem can be regarded as an axisymmetric and unsteady temperature function problem without inside heat source on the basis of the homogeneous and isotropic rotor structure. In the solution domain, the temperature, T, needs to satisfy the following partial differential equation:

$$\lambda\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right)=C_\varepsilon\frac{\partial T}{\partial \tau}+\beta T_0\frac{\partial e}{\partial \tau} \tag{1}$$

where λ is the thermal conductivity of the material, T – the transient temperature of the rotor, r – the radial co-ordinate, z – the axial co-ordinate, C_ε – the specific heat capacity of the material, β – the thermal stress coefficient, T_0 – the initial rotor temperature, τ – the time, and e – the volumetric strain. An axisymmetric structure is given by:

$$e = \frac{\partial u}{\partial r} + \frac{u}{r} + \frac{\partial w}{\partial z} \tag{2}$$

where u is the radial displacement and w – the axial displacement.

The boundary condition in this problem belongs to the third and the specific heat exchange condition performs:

$$-k\left(\frac{\partial T}{\partial n}\right)_{\mathrm{w}} = \alpha(T_{\mathrm{w}} - T_f) \tag{3}$$

where T_{w} is the temperature on rotor wall, T_f – the steam temperature on rotor surface, and α – the surface heat transfer coefficient.

Adopting variation principle, then the finite element equation of temperature distribution by two-way thermal-structure coupling is written:

$$[\mathrm{M}]\frac{\partial T}{\partial \tau} + [\mathrm{T}^*]\frac{\partial \vec{\mathrm{U}}}{\partial \tau} + [\mathrm{K}]T = \vec{\mathrm{Q}} \tag{4}$$

where [M] is the thermal capacity matrix, T – the temperature, $[\mathrm{T}^*]$ – the coupling coefficient matrix, $\vec{\mathrm{U}}$ – the displacement vector, [K] – the heat conduction matrix, $\vec{\mathrm{Q}}$ – the heat flux vector.

With the application of forward difference scheme, the heat convection finite element equation of axisymmetric two-way thermal-structure coupling temperature field in recursive form then performs:

$$\begin{gathered}\left(2[\mathrm{K}] + \frac{3}{\Delta\tau}[\mathrm{M}]\right)T_\tau + \frac{3}{\Delta\tau}[\mathrm{T}^*]\vec{\mathrm{U}}_\tau = (\vec{\mathrm{Q}}_{\tau-\Delta r} + 2\vec{\mathrm{Q}}_\tau) - \\ -\left([\mathrm{K}] - \frac{3}{\Delta\tau}[\mathrm{M}]\right)T_{\tau-\Delta\tau} + \frac{3}{\Delta\tau}[\mathrm{T}^*]\vec{\mathrm{U}}_{\tau-\Delta\tau}\end{gathered} \tag{5}$$

where $\Delta\tau$ is the time step.

Computing theory of rotor stress field

The non-uniform distribution will result in a thermal stress field in the rotor. First of all, the displacement of nodes caused by the temperature field needs to be solved, and then the stress can be obtained based on the stress-strain relationship.

The axisymmetric stress balancing equation performs:

$$\left.\begin{aligned}\frac{\partial \sigma_r}{\partial r} + \frac{\partial \tau_{zr}}{\partial z} + \frac{\sigma_r - \sigma_\theta}{r} + f_r = 0 \\ \frac{\partial \sigma_z}{\partial z} + \frac{\partial \tau_{rz}}{\partial r} + \frac{\tau_{rz}}{r} + f_z = 0\end{aligned}\right\} \tag{6}$$

where, σ_r σ_θ, and σ_z are the radial normal stress, axial normal stress, and circumferential normal stress, respectively, f_r and f_z are the radial body force and axial body force, respectively.

The stress of rotor is related with deformation and temperature simultaneously. According to the generalized hook's law, the relationship between stress, deformation, and temperature can be expressed:

$$\left.\begin{aligned}\sigma_r &= 2G\left[\frac{1-\mu}{1-2\mu}\frac{\partial u}{\partial r}+\frac{\mu}{1-2\mu}\left(\frac{u}{r}+\frac{\partial w}{\partial z}\right)\right]-\beta T\\ \sigma_\theta &= 2G\left[\frac{1-\mu}{1-2\mu}\frac{u}{r}+\frac{\mu}{1-2\mu}\left(\frac{\partial w}{\partial z}+\frac{\partial u}{\partial r}\right)\right]-\beta T\\ \sigma_z &= 2G\left[\frac{1-\mu}{1-2\mu}\frac{\partial w}{\partial z}+\frac{\mu}{1-2\mu}\left(\frac{\partial u}{\partial r}+\frac{u}{r}\right)\right]-\beta T\\ \tau_{zr} &= G\left(\frac{\partial w}{\partial z}+\frac{\partial u}{\partial z}\right)\end{aligned}\right\} \tag{7}$$

where G is the shear elasticity and μ – the Poisson's ratio.

Based on the Hamilton's principle, the finite element formulation of thermal-structure coupling model is given by:

$$[\mathrm{D}]\vec{\mathrm{U}}-[\mathrm{H}]T-\vec{\mathrm{F}}=0 \tag{8}$$

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

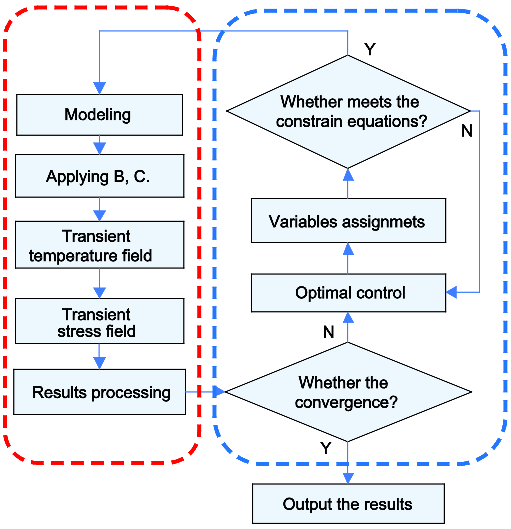

Figure 1. Flow chart of the optimization

Optimal configuration

The optimization of start-up curve is to minimize the maximum equivalent stress of rotor by adjusting the time allocation in each operating stage on the premise that the total time of the operating stage remains unchanged.

The process of optimization includes the calculation of the transient temperature field, thermal stress field and optimal control, which is illustrated in fig. 1.

The procedure of two-way thermal-structure coupling technique

The calculation of rotor thermal stress is grouped by the calculation of the transient temperature field and thermal stress field. In eqs. (5) and (8), the temperature vector, $\vec{\mathrm{T}}$, and displacement vector, $\vec{\mathrm{U}}$, are coupled and need to be solved by iteration and recurrence. Inserting the displacement $U_{\tau-\Delta\tau}$ at time $\tau-\Delta\tau$ as the displacement $U_\tau(0)$ at time τ in eq. (5), the temperature, T_τ, at time, τ, can be obtained. Then, inserting, T_τ, in eq. (8), the displacement, U_τ, at time, τ, can be obtained. Comparing the value of U_τ and $U_\tau(0)$, if $|U_\tau-U_\tau(0)|>\varepsilon$, let $U_\tau(1)=U_\tau$ while maintain $T_{\tau-\Delta\tau}$ and $U_{\tau-\Delta\tau}$. Repeating previously mentioned iteration process, the displacement $U_\tau(m)$ and temperature $T_\tau(m)$ at time, τ, will be obtained after m times of iteration. The iteration process terminates if $|U_\tau-U_\tau(m)|<\varepsilon$, where ε is the convergence tolerance.

Carrying out the iteration process from the initial moments, the temperature, displacement, and stress during the start-up process can be obtained.

The procedure of optimal control

Optimal control is to minimize the object function value by iterative control which is realized by optimization algorithm. Firstly, find a set of variable values and call the program to obtain thermal stress. If the results satisfy the convergence tolerance, then output the optimal solution. If not, find the next variable values. The pattern search algorithm is used in this paper to control the iteration process by axial movement and pattern movement.

First of all, conduct search from the initial value, x_k, of the iteration, k, along the vector $e_1, e_2, ..., e_n$ with the step size, l_m, where m is the number of searches.

(1) If $f(x_k + l_m e_j) < f(x_k)$, let $x_{k+1} = x_k + l_m e_j$. If not, carry out backward search.
(2) If $f(x_m - l_m e_j) < f(x_m)$, let $x_{k+1} = x_k - l_k e_j$. If not, remain the value of x_{k+1}.
(3) If $f(x_{k+1}) = f(x_k)$, carry out the search again by using the new step size $l'_m (l'_m < l_m)$.

After several times of search, we can find the descent direction of the objective function value and execute next search by treating the x_k searched this time as the new initial value.

Conduct search from x_{k+1} by the step size 1 along the direction vector $\vec{d}_k = x_{k+1} - x_k$ to obtain the new reference point $x'_{k+1} = x_{k+1} + \vec{d}_k = 2x_{k+1} - x_k$. Then, continue the axial movement from the point x'_{k+1} with the step size l_k.

Optimization design procedure

Computation model

The investigated object in this paper is a high-pressure steam turbine rotor, which comprises a governing stage blade and thirteen pressure stage blades. In order to reduce the computation amount, a 2-D axisymmetric model is established, which is shown in fig. 2. Refinement has been executed in regions where the stress concentration usually occurs in order to improve the calculation accuracy, which is shown in fig. 3.

Three monitoring areas have been selected to extract the results. The locations of these monitoring points are illustrated in fig. 4. Points A2, B2, and C2 are on the axis responding to points A1, B1 and C1, respectively.

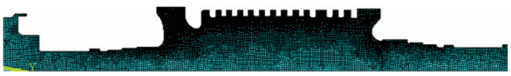

Figure 2. Finite element model of rotor

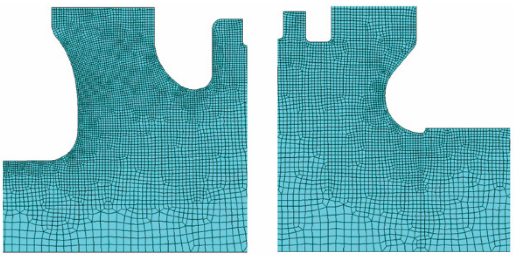

Figure 3. Finite element model of local area of rotor

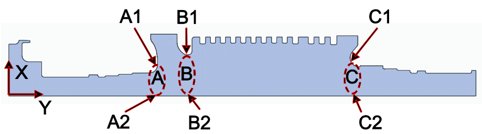

Figure 4. The locations of monitoring points

Optimization of the start-up process

Figure 5 shows the variables diagram in the optimization process. Temperature, pressure, and rotating speed have great impact on the coefficient of heat transfer and temperature ramp rate, which will influence the maximum equivalent stress of the rotor during the start-up procedure. The initial time allocation is [7, 4, 28, 10, 14, 3, 18, 15, 37, 59, 14, 41], which corresponds to the time of twelve stages.

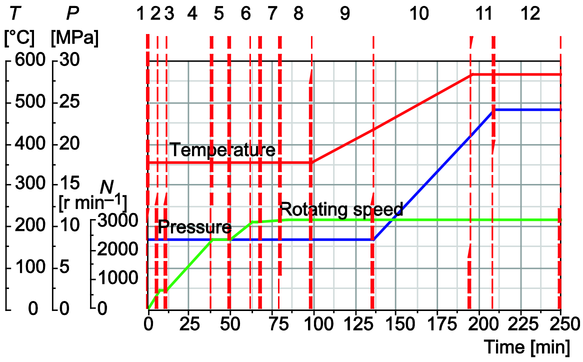

Figure 5. Variables diagram

The start-up curves before and after the optimization are shown in figs. 6 and 7. The optimized time allocation is [16.0, 6.4, 4.5, 3.6, 3.3, 3.0, 3.1, 4.3, 87.9, 110.2, 3.3, 4.3].

Figure 8 shows the temperature difference of the monitoring points before and after the optimization. We can obtain that the temperature difference at the monitoring area B is greater than the other two monitoring areas, which will result in obvious stress concentration.

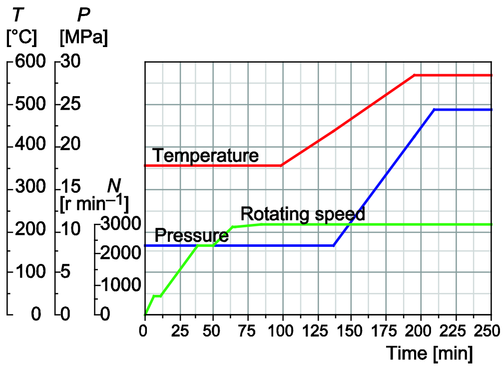

Figure 6. The original start-up curves

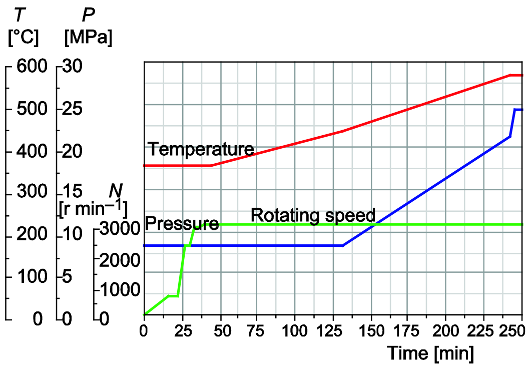

Figure 7. The optimized start-up curves

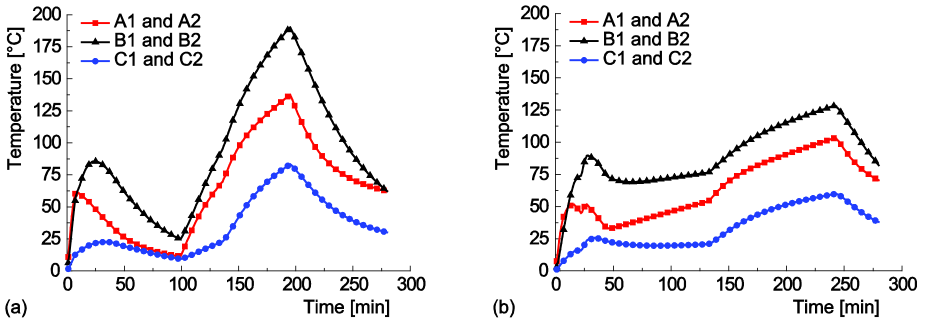

Figure 8. Temperature difference curves before (a) and after (b) the optimization

Table 1. The maximum equivalent stress

Monitoring points	Original [MPa]	Optimized [MPa]	Percentage decline [%]
A1	291	194	33.3
B1	595	442	25.7
C1	248	157	36.7

The maximum equivalent stresses at different monitoring areas before and after the optimization are in tab. 1. On the premise that the total time of the operating stage is unchanged, changing the time allocation in every operating stage reduces the maximum equivalent stress of the rotor. The maximum equivalent stresses of the three areas are reduced by the reduction 33.3%, 25.7%, and 36.7%, respectively.

Conclusions

This paper combines thermal-structure coupling technique and pattern search optimization algorithm to establish an optimization system to minimize the maximum equivalent stress of the turbine rotor. The main conclusions are as following.

- Considering the interaction effect of the temperature field and the stress field, a thermal-structure coupling model is established to analyze the transient temperature field and transient stress field.
- On the premise that the total time of the operating stage remains unchanged, the maximum equivalent stress of rotor has reduced 25.7% by changing the time allocation in each operating stage.
- The optimization system in this paper to minimize the maximum equivalent stress has been proved to be effective, which can provide reference for designing the optimal start-up curves.

Nomenclature

C_ε – specific heat, [$Jkg^{-1}K^{-1}$]
[D] – stiffness matrix, [–]
e – volumetric strain, [–]
$\vec{F}$ – body force vector, [N]
G – shear elasticity, [Pa]
[H] – thermal stress coefficient matrix, [–]
[K] – heat conduction matrix, [–]
k – heat conduction coefficient, [$WK^{-1}m^{-1}$]
[M] – thermal capacity matrix, [–]
$\vec{Q}$ – heat flux vector, [–]
T – temperature, [K]
T_f – steam temperature on the surface, [K]
T_w – temperature on the wall, [K]
[T^*] – coupling coefficient matrix, [–]
$\vec{U}$ – displacement vector, [–]

Greek symbols

α – surface heat transfer coefficient, [$Wm^{-1}K^{-1}$]
β – thermal stress coefficient, [$Jkg^{-1}K^{-1}$]
λ – thermal conductivity [$Wm^{-1}K^{-1}$]
μ – Poisson's ratio, [–]
σ – normal stress, [Pa]

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