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Modeling of Thermal Stress and Control for Steam Turbine

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ABSTRACT

In this paper, the method of system identification and predictive control is used to control the stress of steam turbine rotor. Firstly, the three-dimensional model of turbine rotor is established by using finite element simulation software, and then the results are identified by using ANSYS finite element analysis software. The transfer function is obtained. Firstly, the temperature model is identified with an accuracy of 99.73%, and then the stress model is identified with an accuracy of 98.2%. Then the transfer function is discretized, and the data is input into the discrete transfer function to verify the accuracy of system identification. After the accurate verification of the transfer function, the transfer function is transformed into the dynamic matrix control model, and then the stress feedback controller is designed to realize the model predictive control (MPC) of the rotor stress. At the same time, the output response of the system before and after the addition of the controller is compared. Finally, the rationality of the control model is verified. Further research will be conducted on the impact of various environmental factors such as temperature, load and rotational speed on the stress of turbine rotor in future work.

Keywords: steam turbine, finite element, stress, model predictive control

Introduction

In today's society, people's demand for electricity is higher and higher [1]. In order to ensure people's power demand, it is necessary to improve the operation efficiency of steam turbine unit, which means that the start-up time of the unit needs to be shortened. However, with the shortening of the start-up time of the steam turbine, the safety of the unit will also be reduced [2]. Therefore, through establish the temperature distribution of the steam turbine rotor in the start-up process through the actual data. The safety of the model after adjusting parameters is analyzed by model predictive control method [3]. The needs of today's society should be met, so it is necessary and very important to study the rapid start-up process. The start and stop of steam turbine depends on how long it can be used, which means that it directly affects the life of the unit. After a detailed study of the start and stop of the steam turbine unit, a curve of start-up is given and used to guide the unit, which can improves security and economy at the same time. In brief, the start-up optimization of steam turbine is to optimize a function. At the same time, this function has constraint conditions. Generally speaking, the start-up time is the shortest and the stress is within a reasonable range [4].

The stress control of steam turbine rotor is mainly to ensure the safety of the unit in more efficient operation. In the unit, the rotor of steam turbine is an important part, which carries the energy and torque. The safety of steam turbine unit is mainly determined by the quality of turbine rotor. It is a decisive factor to reduce the unit start-up time while ensuring that the stress value of the turbine rotor is less than the yield limit value of the rotor material. From a few years ago to now, the quality of life has improved significantly, the grid capacity has increased significantly, so the peak value of the grid has been increasing [5]. Frequent peak shaving operation means frequent start-up and shutdown of the steam turbine unit. The change of working condition of steam turbine unit will cause the damage of rotor material, thus shortening the life of the unit. The parameters of steam turbine will change greatly during start-up. Among them, the change of temperature parameter is the most important. It will make the rotor produce a force, which is called thermal stress. At the same time, it will make the metal material deform, mainly in the form of expansion deformation. Once the thermal stress exceeds the yield limit of the rotor material, the high-temperature components, mainly the turbine rotor, will produce certain damage, which will eventually bring some security risks [6].

Among the existing control technologies, predictive control is a kind of control technology which does not require high model of the whole system. In the current research of this problem, the strategy of system identification combined with adaptive control theory is widely used. MPC has a double-layer control structure [7]. On the one hand, it controls the optimization of the steady-state part of the whole system, and the other part is responsible for the dynamic optimization of the system. At the same time, the model predictive control has the function of global optimization and teacher tracking [8]. However, due to the change of operating conditions and various disturbances, the speed of the whole operation control will be reduced. In this paper, the output error model is used dynamic matrix control is actually the representative method of MPC method. Dynamic matrix control uses the step response curve of the model, which can well solve the control problem with constraints. Model predictive control combines linear programming and control problem, and solves the constraint problem and static optimal solution problem at the same time. The premise of using predictive control is that a mathematical model is needed [9]. In the establishment of steam turbine system model, neural network modeling method is commonly used, that is, neural network is used to train the collected data, train a neural network model, and then carry out predictive control on the model [10]. Jianxi Yu and others used the collected data when establishing steam turbine rotor system model a hybrid modeling method based on data and first principle mechanism is proposed and verified [11]. S. Dettori and others used fuzzy PID control algorithm in the control phase, and compared with the traditional PID algorithm [12]. In the control of steam turbine system, PID control is the most widely used at present, because the control method is very mature, and it is very convenient to use. In this paper, MPC control algorithm is used, which can make the efficiency faster and more accurate [13]. Hugo A. et al. considered the constraint problem when using adaptive MPC [14]. Yan Z. et al. proposed a stochastic model predictive control architecture [15]. Shifan W. and others proposed a model predictive control (MPC) method to regulate the grid connected microgrid system [16]. Soroush R. et al. analyzed the advantages and disadvantages of MPC method applied to nonlinear systems [17]. Luwei Y. et al. proposed a multi cell model predictive control theory, which was solved by a peer-to-peer communication algorithm based on distributed projection [18]. Morteza M. et al. introduced the design, hardware implementation and hardware in the loop simulation of MPC algorithm for turbofan engine control. In addition, the feedback correction technique is used to compensate the effect of model mismatch [19]. Various control methods, such as fuzzy control and neural network control, can be utilized to regulate stress in the turbine rotor. This paper presents a model predictive control approach for managing stress feedback. This control approach displays superior real-time performance and control accuracy compared to other techniques. The paper also provides in-depth discussions on how to apply this approach in practical engineering scenarios along with guidance on performing model validation and control experiments. These aspects present additional knowledge that this paper provides. This study aims to investigate the utilization of system identification and model predictive control as a method to address the issue of stress control for steam turbine rotors. Furthermore, it seeks to narrow the divide between theoretical exploration and practical implementation by proposing innovative ideas and approaches in order to alleviate the problems encountered in stress control for thermal engineering applications.

In all of the above studies, any work assumes that the initial temperature is horizontal, which is a common assumption since there is no temperature data at the time of turbine shutdown and the process is long. Turbine rotor is the most important bearing component, can not be installed measuring device. The initial temperature field of the turbine rotor is very different due to the different initial state of cold start. Different initial thermal states will affect the initial stress field. The optimal inlet temperature of gas turbine in cycle is discussed with reference [20]. The entire analysis step takes 1 minute to calculate the stress, thus capturing the transient characteristics during startup. In this paper, the method of system identification and predictive control is applied to the stress control of steam turbine rotor. Firstly, a 3-D model of steam turbine rotor is established by using finite element simulation software. Then, the ANSYS finite element analysis software is used to identify the results and get the transfer function. Then, a stress feedback controller is designed to realize the model predictive control of rotor stress. At the same time, the output responses of the system before and after the addition of the controller are compared. Finally, the rationality of the control model is verified.

Establishment of temperature model

The temperature mathematical model plays an important role in the stress control. Only after the temperature model of stress is established, can the stress model be established based on the results of the temperature model, so as to carry out the work of stress control. The temperature model is essentially a single input single output model.

During the whole operation process of steam turbine, the steam containing heat works on the blades of the rotor through the steam nozzle, and drives the rotor body to rotate by working on the blades of the rotor. At the same time, the steam with high temperature will cause the theme temperature of the steam turbine rotor to rise. When the material properties of the rotor are selected differently, the temperature rise rate of the rotor surface is also different from the point of view of theory, the model from steam temperature to rotor surface temperature can be regarded as a single input and single output process, which can be realized by using the output error model as shown eq.1. The equation aims to establish a model that describes the relationship between steam temperature and rotor surface temperature, with steam temperature as input, and to control the rotor surface temperature appropriately.

$$T_s(k) = \frac{B(z^{-1})}{F(z^{-1})}T(k) + e(k) \tag{1}$$

Where $T_s(k)$ represents the rotor surface temperature, $T(k)$ represents the steam temperature, and $e(k)$ represents the model error.

The system identification tool used in this paper uses the Smodel identification toolbox in MATLAB to identify the model from steam temperature to rotor surface temperature through the system identification toolbox. The data of steam temperature adopts the cold start-up curve of steamturbine under standard working conditions, as shown in Figure 1.

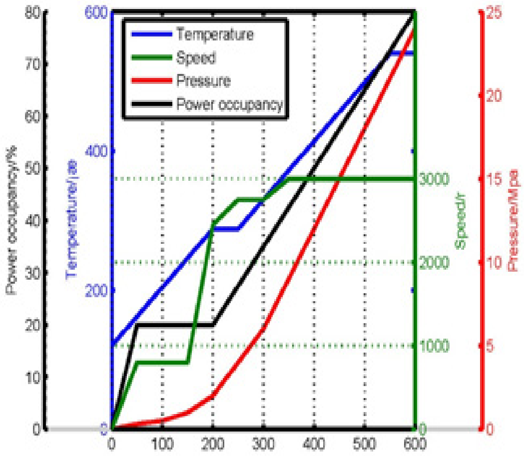

Figure 1: Start-up parameter curve of steam turbine

The temperature of the rotor surface can not be obtained directly by measurement, so the method adopted in this paper is to establish the 3-D model of the turbine rotor of ANSYS finite element analysis software, load the input data into the model, and obtain the temperature data of the rotor surface through the calculation of the finite element analysis software. The 3-D model of ANSYS is shown in Figure 2.

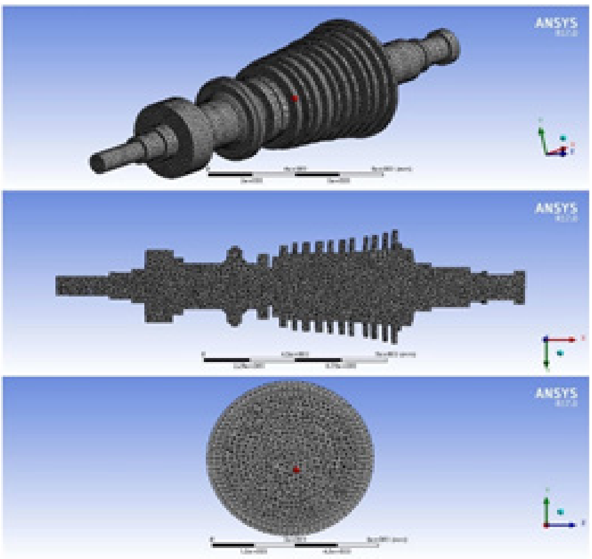

Figure 2: Finite element analysis model

By inputting the temperature data of cold start-up curve into the 3-D model of ANSYS, the temperature data of rotor surface can be obtained. The data result of steam temperature rotor surface temperature is shown in Figure 3.

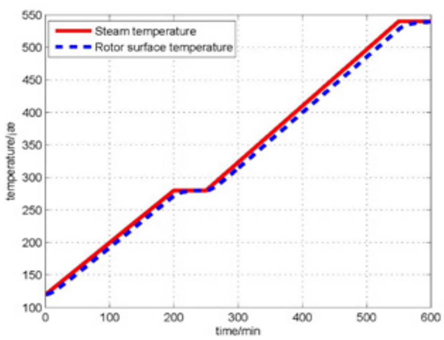

Figure 3: Rotor steam temperature and surface temperature

Calculate the slope of each stage of the start-up curve, a total of four stages, in which the slope of 2 and 4 stages is 0, and the temperature is 280^{0}C and 540^{0}C respectively. The slope of the first stage is 0.8, that is, the temperature rise rate is 0.8^{0}C/*min*, and the slope of the third stage is 0.8667, that is, the temperature rise rate is 0.8667^{0}C/*min*. Calculate the value of each minute through the slope, in fact, it is consistent with the value of start-up curve for the convenience of data fitting.

Taking the data of the start-up curve as the input and the rotor surface temperature calculated by ANSYS as the output, the system identification is used to identify the transfer function. The input and output data are presented in the form of pictures in Figure 3. Four poles and three zeros are set for the identification transfer function. Because the data difference between rotor surface temperature and actual start-up curve is not big, four poles and three zeros are selected for system identification, the identification accuracy is 98.2%, and the specific transfer function is eq.2. The identification results are shown in Figure 4.

$$G_1(s) = \frac{63.17s^3+1.433s^2+0.02318s+0.0005257}{s^4+64.45s^3+1.462s^2+0.02365s+0.0005362} \quad (2)$$

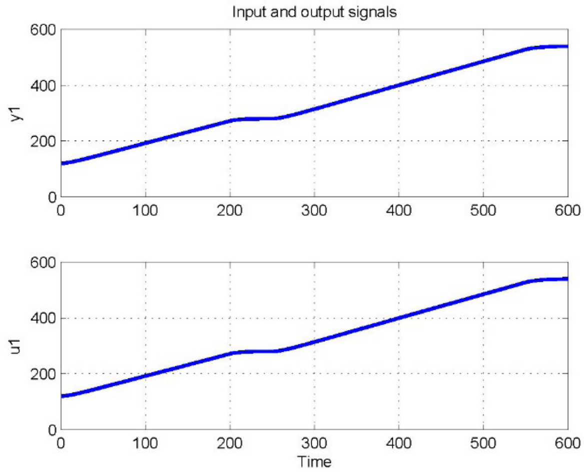

Figure 4: System identification temperature output

Discretization of temperature model

After the transfer function is established, the discrete data cannot be input into the transfer function model, but the required mathematical model must load the input data into the model for calculation, so it needs to be discretized. The discretization first is to transform the transfer function z, using the ztrans command in MATLAB to transform the transfer function z, and the discrete transfer function after the above transformation is as follows eq.3:

$$G_1(z) = \frac{0.9804z^3-1.054z^2+1.186z-0.2514}{z^4-1.075z^3+1.21z^2-0.2564z+3.243*10^{-17}} \quad (3)$$

After transforming the transfer function z, it is necessary to change the transformed transfer function into the form of difference equation, because after transforming into difference equation, the model can be analyzed directly in the form of equation [21]. The transformation rule between the transfer function and the difference equation after z transformation is as follows:

$$G(Z) = \frac{Y(z)}{X(z)} \quad (4)$$

Where *Y*(*Z*) is the z-transformed form of the output variable, and *X*(*Z*) is the z-transformed form of the input variable.

$$y(n) + a_1y(n-1)+\ldots+a_ny(n-N) = b_0x(n) + b_1x(n-1)+\ldots+b_mx(n-M) \quad (5)$$

There is formula 5 which can be obtained:

$$y(n) = \sum_{i=1}^{M} b_i x(n-i) - \sum_{n=1}^{N} a_i y(n-i) \quad (6)$$

Where a_i and b_i are the coefficients of the difference equation.

Through the above transformation, the difference equation of the model can be obtained as follows:

$$y(n) - 1.075y(n-1) + 1.21y(n-2) - 0.02564y(n-3) + 3.243 * 10^{-17} y(n-4) = 0.9804x(n-1) - 1.054x(n-2) + 1.186x(n-3) - 0.2514x(n-4) \quad (7)$$

Temperature model validation Take the above transformed difference equation as the temperature model, and input the temperature data of cold start-up curve into the model to verify the accuracy of the model. The output results are shown in Figure 5:

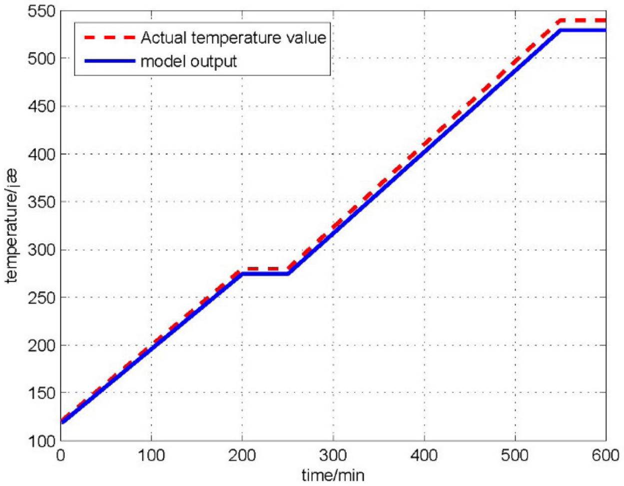

Figure 5: Comparison of actual temperature and model temperature output

The maximum error is 7.2mpa, and the maximum error between the model output data and the actual data is 1%, which indicates that the model is accurate.

Establishment of stress output model

Before establishing the stress output model of the steam turbine rotor, the heat flux of the steam turbine rotor should be calculated first [22]. The heat flux needs to be calculated through the temperature model. During the start-up and shutdown of the steam turbine unit, the steam temperature and heat release coefficient on the rotor surface will change with time. At the same time, the values of different positions are also different, so the steam temperature can be explained and the heat release coefficient is a function of time and space. The calculation formula of heat release coefficient is given below, which is a function of rotor speed and pressure. The formula is given by Westinghouse [23]. The formula is as follows:

$$h = (0.0633678 * N - 7.71255 * 10^{-6} * N^2 + 0.00339265 * P * N) * F + 2.724 \quad (8)$$

where, is the rotation speed of the turbine rotor, is the back pressure value at the same spatial position, is the adjustment factor for adjusting the value of heat release coefficient. The values of heat release coefficient are different for different types of turbine rotors with different materials. The formula is also given by Westinghouse. The calculation formula of heat release coefficient is as follows:

$$F = \frac{0.03}{\phi} * \left[\frac{25.817 * G * (1-\gamma)}{57735 * D_{dia}}\right] \quad (9)$$

Where, ϕ is the seal clearance, in inches, G is the steam flow at the high pressure part under the maximum power working condition, D_{dia} is the diameter of the steam seal, γ is the leakage factor of the blade, and the physical parameters of the 300MW turbine rotor should be considered when selecting the value of F [24], as shown in the following table 1-table 3:

Table 1: The 30Cr1Mo1V steel chemical composition 1.

Element	C	Fe	Mo	Cr	Si	Mn	P	S	V	Ni
/	0.28	1.10	0.28	0.73	1.13	0.023	0.22	0.005	0.24	0.4

Table 2: The 30Cr1Mo1V steel chemical composition 2

Temperature	Yield strength	Ultimate strength	Elongation	Reduction of area
20	629Mpa	779Mpa	20%	60%
540	465Mpa	520Mpa	29.6%	88.5%

Table 3: The physical property of 30Cr1Mo1V steel.

Temperature	20	100	200	300	400	500	600
Young modulus	214Gpa	212Gpa	205Gpa	199Gpa	190Gpa	178Gpa	178Gpa
Poisson ratio	0.288	0.292	0.287	0.299	0.294	0.305	0.305
Thermal conductivity	48.5W/mK	47.1W/mK	44.8W/mK	42.8W/mK	40.3W/mK	37.5W/mK	35.3W/mK
Linear expansion coefficient	0	11.99	12.81	13.25	13.66	13.92	14.15
Specific heat	554J/Kg	574J/Kg	599J/Kg	624J/Kg	666J/Kg	720J/Kg	804J/Kg

After the heat release coefficient is calculated, the stress output model can be established through the temperature model calculated in the previous chapter. The specific steps are as follows:

The heat release coefficient is calculated by the process variables during the start-up of the steam turbine unit, including steam temperature, steam pressure, steam flow, rotor speed, etc.

$$h = (0.0633678 * N - 7.71255 * 10^{-6} * N^2 + 0.00339265 * P * N) * F + 2.724 \quad (10)$$

(2) After Newton's cooling law, when there is a temperature difference between the surface and the surrounding, the heat loss per unit time from the unit area is directly proportional to the temperature difference, and the proportional coefficient is called the heat transfer coefficient, the heat flow density q can be calculated as follows:

$$q = h(T - T_0) \quad (11)$$

Where, T is the input temperature of the rotor and T_0 is the actual temperature of the rotor surface. The temperature model has been found in the previous chapter. The model is a temperature model transfer function, which is transformed by z-trans command of MATLAB. The discrete function model between T and T_0 is:

$$G_2(z) = \frac{0.9804z^3 - 1.054z^2 + 1.186z - 0.2514}{z^4 - 1.075z^3 + 1.21z^2 - 0.2564z + 3.243 * 10^{-17}} \quad (12)$$

Take $G_2(Z)$ into eq.12 and get the following formula:

$$q = h(T - T_0) = h\left(\frac{0.9804z^3 - 1.054z^2 + 1.186z - 0.2514}{z^4 - 1.075z^3 + 1.21z^2 - 0.2564z + 3.243 * 10^{-17}} - 1\right)T_0 \quad (13)$$

Take the calculated value as input and the stress value as output to fit the transfer function of and stress value, and finally get the stress output model.

System Identification of Stress Model

The stress value can not be obtained by direct measurement, so the stress value is calculated by establishing a finite element 3-D model, and the cold start curve is given to the established 3-D model, according to the relationship between stress and strain, geometric equation and balance equation 25, the thermal stress distribution of rotor can be obtained.

$$\sigma_{rr} = \frac{\alpha_l E}{1-u} * \{-\frac{1}{r^2}\int_{r_i}^{r_o} tr\,dr + \frac{r^2-r_i^2}{r^2(r_o^2-r_i^2)}\int_{r_i}^{r_o} tr\,dr\} \quad (14)$$

$$\sigma_{xx} = \frac{\alpha_l E}{1-u} * \{\frac{1}{r^2}\int_{r_i}^{r_o} tr\,dr + \frac{r^2+r_i^2}{r^2(r_o^2-r_i^2)}\int_{r_i}^{r_o} tr\,dr - t\} \quad (15)$$

$$\sigma_{yy} = \frac{\alpha_l E}{1-u} * \{\frac{2}{r^2(r_o^2-r_i^2)}\int_{r_i}^{r_o} tr\,dr - t\} \quad (16)$$

The maximum stress curve obtained by finite element analysis software is shown in Figure 6:

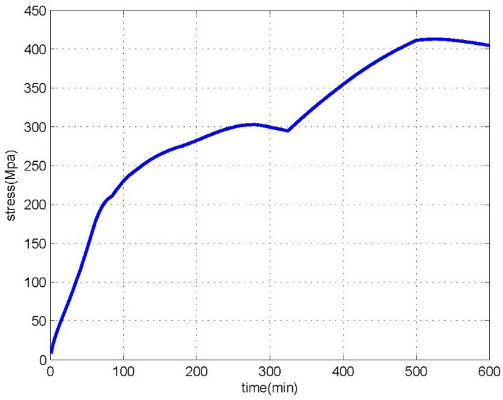

Figure 6: Maximum stress of rotor

After calculation, the size of is shown in Figure 7:

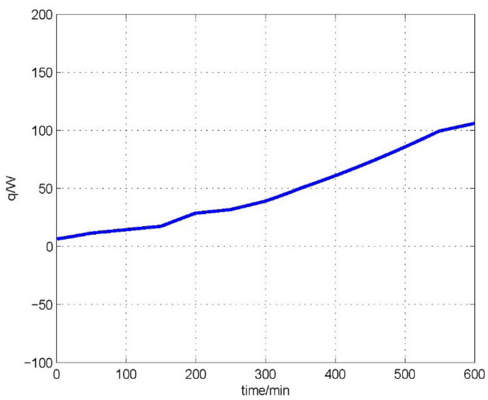

Figure 7: *q* value of heat flux

With the above figure value as the input and the stress value as the output, the data information shown in Figure 8 and the transfer function shown in formula 14 can be obtained through the system identification toolbox of MATLAB. After fitting, the accuracy of the transfer function is 98.23%.

$$G_2(s) = \frac{0.06245s^4+0.006419s^3+0.0002455s^2+0.00002362s-0.0000006247}{s^5+0.01564s^4+0.003776s^3+0.00005561s^2+0.000001003s+0.0000003642} \quad (17)$$

The above transfer function is discretized to verify the accuracy of the transfer function, use ztrans command in MATLAB to make eq.17 Z-transform:

$$G_2(z) = \frac{1.2835z^4-0.7825z^3+1.0224z^2+2.21z-0.002325}{z^5+0.45217z^4-0.08254z^3+0.23345z^2-1.2117z-0.00004214} \quad (18)$$

When the calculated *q* value is input into the discrete model as the input data, a group of stress output data can be obtained, and the data is compared with the stress value under the actual working condition, as shown in Figure 9.

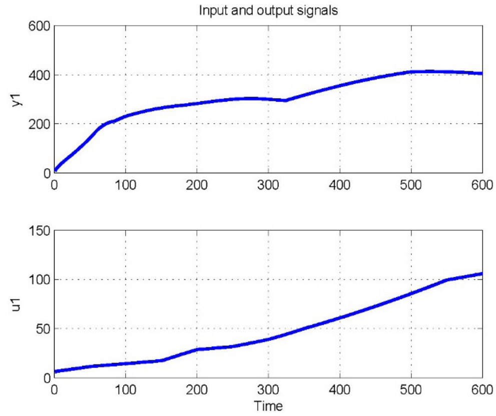

Figure 8: Input and output of stress model system identification.

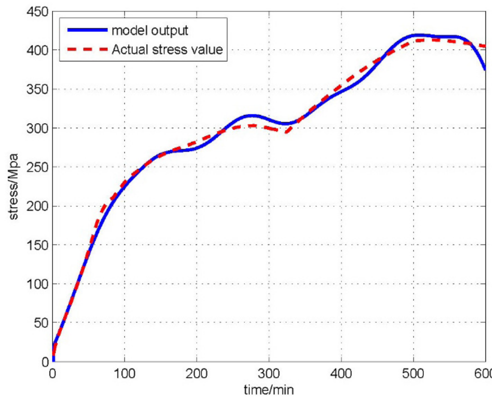

Figure 9: Comparison of actual stress value and model output

These two sets of data are continuous, it is impossible to directly take points to calculate the error, so the determination coefficient method is used to evaluate the accuracy of the model. When the determination coefficient method is used, the closer the value is to 1, the better the proof result is. The formula of the determination coefficient is as follows:

$$R^2 = \frac{\sum_{i=1}^{n}(s_i'-\bar{s}_i')^2}{\sum_{i=1}^{n}(s_i-\bar{s}_i)^2} \quad (19)$$

Where, n is the number of model output data, s_i is the actual data, s'_i is the model output data, is the mean value of the data. After calculation, the coefficient of determination R^2=0.9972, it shows that the model has very high availability.

State space equation of stress output system

In this paper, the control method is model predictive control, model predictive control calls the mathematical model in the form of state space equation is more convenient, so in the next use of model predictive control, the stress output model needs to be transformed into the state space format, the transformation of the two uses the SS function of Matlab. The mathematical model form of the specific state space equation is eq.20-eq.24, it is transformed from eq.17 through SS function of MATLAB:

$$\begin{cases} \frac{dx}{dt} = Ax + Bu \\ y = Cx + Du \end{cases} \quad (20)$$

$$A = \begin{bmatrix} -0.1085 & -0.0033 & -0.0002872 & -0.00000242 & -0.0000007159 & -0.000000002774 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \quad (21)$$

$$B = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (22)$$

$$C = [-0.0707; -0.0033; 0.0006738; 0.0000189; 0.000002293; 0.000000007125] \quad (23)$$

$$D=0 \quad (24)$$

The above state space model is verified by using the lsim function of MATLAB, and q is input into the model as an input variable to obtain a set of stress curves. The specific stress curves are shown in Figure 10:

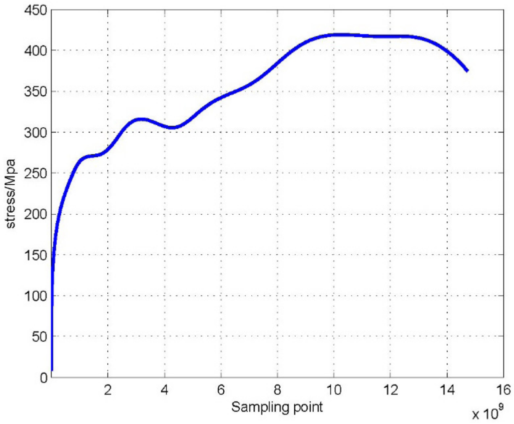

Figure 10: Stress output of state space model

It can be seen from the figure that the trend of the model in the form of state space equation is consistent with that of the discrete transfer function model, which proves that the mathematical model in the form of state space can be used.

Stress-Speed Feedback Model Predictive Control

Calculation conditions of effective stress

The stress of steam turbine rotor mainly includes two aspects, one is the thermal stress caused by the drastic change of material temperature of steam turbine rotor due to the application of temperature load during start-up, and the other is the centrifugal stress generated with the increase of speed during start-up. The thermal stress and centrifugal stress can be calculated by the fourth strength criterion eq.25. The fourth strength criterion formula of effective stress is shown in eq.25.

$$\sigma_{eq} = \sqrt{{\sigma_{th}}^2 + {\sigma_t}^2 + \sigma_{th}\sigma_t} \quad (25)$$

where, σ_{eq} is the effective stress, σ_{th} is the thermal stress and σ_t is the centrifugal stress of the rotor. The calculation formula of rotor speed and centrifugal stress [25] is shown in eq.26

$$\sigma_t = \sigma_e \frac{N}{N_e} = \sigma_e \frac{N}{3000} \quad (26)$$

where, σ_e is the value of the rated stress, N is the speed in the formula, N_e is the rated speed.

Centrifugal stress control

The centrifugal stress control of the steam turbine rotor is actually the speed control of the steam turbine rotor. By adjusting the speed, the centrifugal stress is within the required reasonable range. The speed control of steam turbine can directly affect the value of centrifugal stress caused by the change of speed. In the previous researchers, the speed model of steam turbine given is the model [26] shown in eq.27 and eq.28, which is composed of hydraulic motor and steam volume. $W(s)$ is the transfer function of hydraulic motor and $Q(s)$ is the transfer function of steam volume.

$$W(s) = \frac{1}{0.08s} \quad (27)$$

$$W(s) = \frac{1}{6.2s+1} \quad (28)$$

The speed model is simulated. Under the condition of step response as input, the speed output response of the speed model is shown in Figure 11.

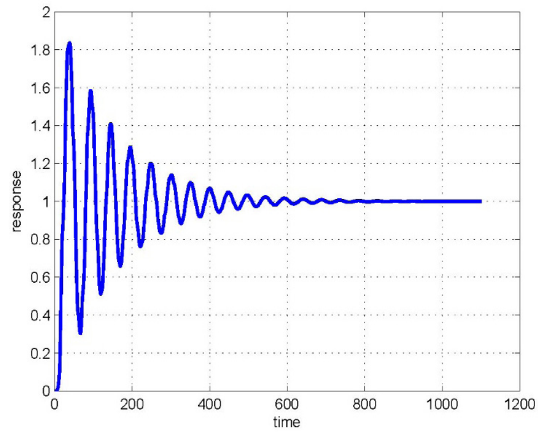

Figure 11: Step response of original speed model

It can be seen from the figure that the overshoot of the speed model is large and the stable time is long. On this basis, a PID controller is connected in series to the speed model, and the parameters of the controller are set as follows: P = 0.02967, I =7.73867, D = 0.11769. The unit step response of PID controller is shown in Figure 12.

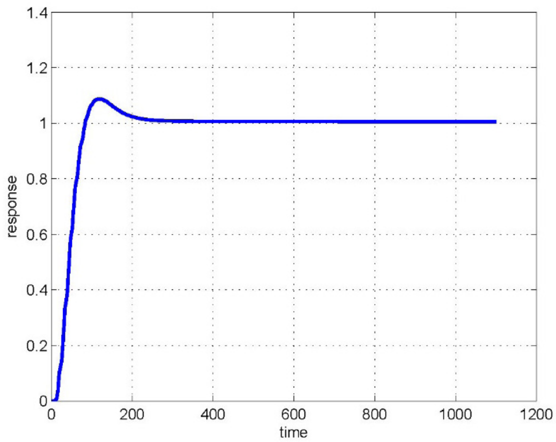

Figure 12: Speed response after adding PID controller

It can be clearly seen from the figure that the overshoot of the model is reduced and the stabilization time is shorter. Subsequent control will be studied on the basis of this model. In order to more visually see the control effect, the model output after adding the speed controller and the original speed control model are compared, as shown in Figure 13:

oad monitoring of steam turbine connected to grid

The system model used in the process of steam turbine grid connection is composed of hydraulic motor module and steam volume module as shown in eq.27 and eq.28, and reheater module and steam turbine rotor module are also used. The model of reheater module $D(s)$ and steam turbine rotor module [26] is shown in eq.29 and eq.30.

$$D(s) = \frac{1}{0.3s+1} * \frac{1}{0.08s} \quad (29)$$

$$G_3(s) = \frac{1}{0.35s+1} * \frac{8/3s+1}{8s+1} * \frac{1}{0.2s+1} \quad (30)$$

The turbine can not be directly loaded after grid connection, and it needs to be increased step by step. This paper analyzes the corresponding speed output under the unit step input condition when the load is mounted at 30% load and 60% load. When the load is 30%, the output response of turbine speed is shown in Figure 14.

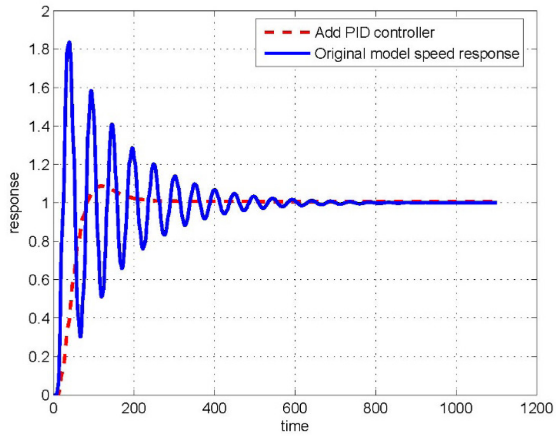

Figure 13: Speed model output comparison before and after adding controller.

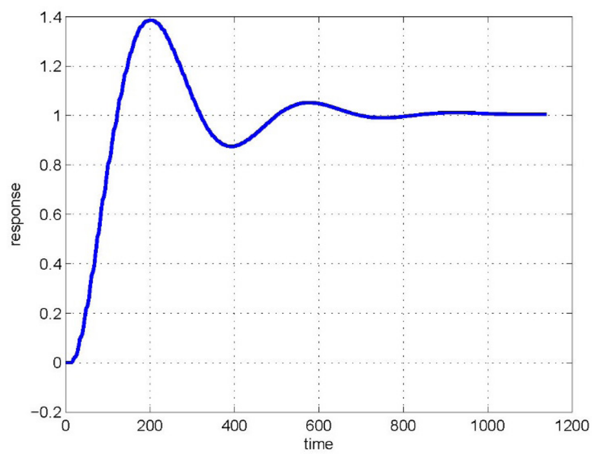

Figure 14: Speed response at 30% load.

It can be seen from the above figure that when the turbine is loaded with 30% load, the overshoot increases and the stable time increases. When the turbine is loaded with 60% load, the speed output response of the turbine is shown in Figure 15.

When the load is 60%, the turbine speed output overshoot increases and the stable time is long, which is convenient for intuitive analysis. The output response of 30% and 60% load is given, as shown in Figure 16. The system exhibits reduced overshoot and smoother curve at a 30% load.

The stress speed model predictive control in this paper is mainly aimed at the speed control of the steam turbine unit system. Through the speed control, the centrifugal stress of the steam turbine rotor is within a reasonable range. The effective stress online detection model of the steam turbine rotor has been given by previous researchers [25]. In this paper, the existing stress monitoring model is stripped out by deducing the fourth strength criterion formula in the centrifugal stress part of the effective force, the centrifugal stress is fed back to the rotor speed model through the feedback of rotor speed data. At the same time, PID controller is added to the speed model for comparison to realize the predictive control of centrifugal stress. The improved system block diagram is shown in Figure 17.

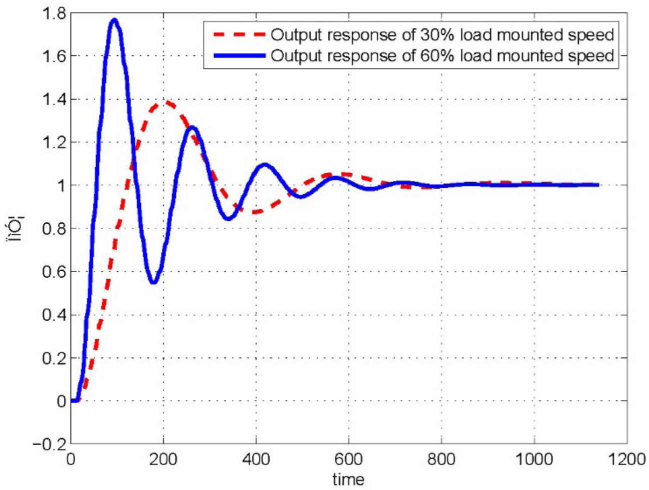

Figure 16: Speed response of 30% and 60% load respectively.

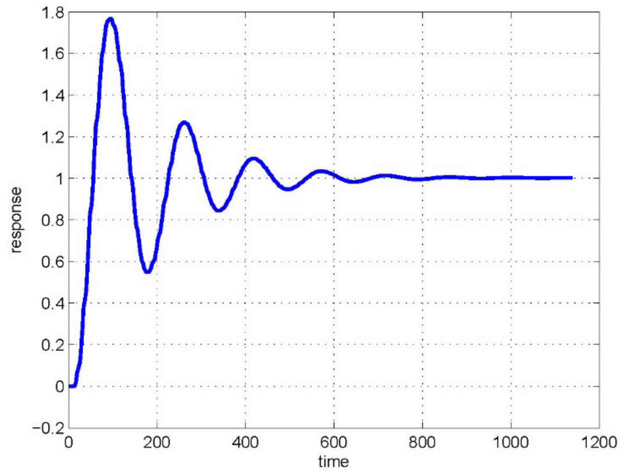

Figure 15: Speed response at 60% load.

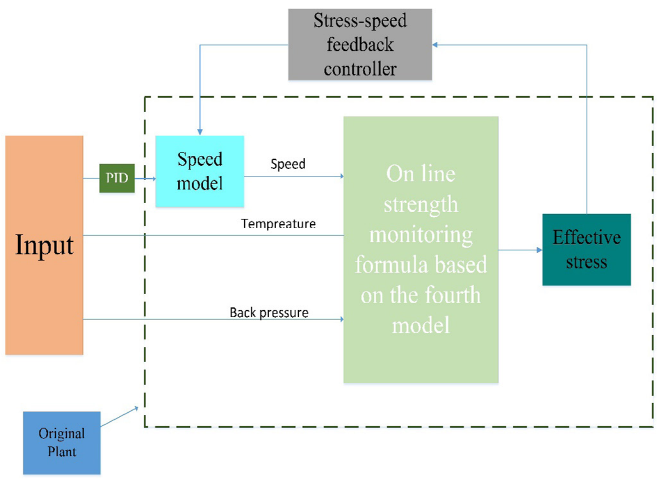

Figure 17: Structure diagram of stress-speed feedback control model.

The stress speed controller is mainly deduced by the fourth strength criterion formula shown in eq.25, which makes the centrifugal stress as shown in eq.31.

$$\sigma_t = \frac{-\sigma_{th} + \sqrt{-3\sigma_{th}^2 - \sigma_{eq}^2}}{2} \quad (31)$$

When there is no stress speed feedback controller, the stress output response of steam turbine rotor is shown in Figure 18. In Figure 18, the overshoot reaches 1.6.

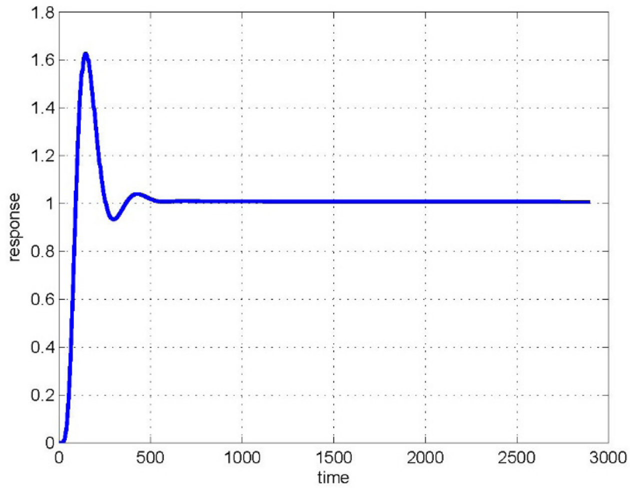

Figure 18: Stress output response without feedback controller.

In order to facilitate comparison, the output response without feedback controller is compared with the stress output with feedback controller, as shown in Figure 19.

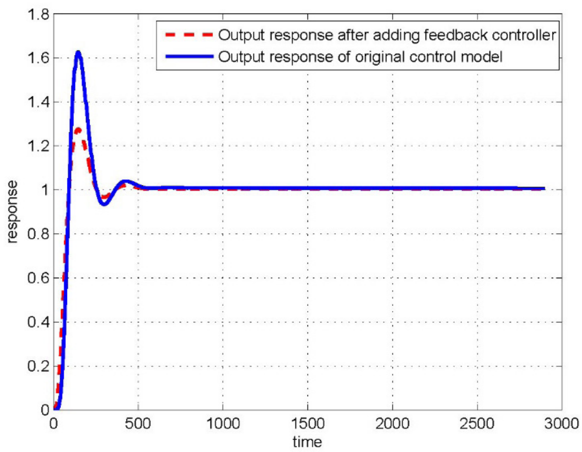

Figure 19: Stress output response with feedback controller.

As shown in Figure 19, after adding the feedback controller, the overshoot is reduced by nearly 23%, and the start-up time is shortened by nearly 7%, which indicates that the response speed and stability of the system are better than the original system after adding the feedback controller.

Conclusion

In this paper, stress control problem of steam turbine rotor is solved by the model identification and predictive control. Firstly, a three-dimensional model of steam turbine rotor is established using finite element technology. Combined with the working condition, then the simulation data is obtained and identified to get the transfer function. Parameters of this transfer function are determined according to the working condition and simulation results. After discretization the transfer function can be converted to dynamic matrix control model, and then the stress-feedback controller is designed. Structure diagram of stress-speed feedback control model is drawn to realize the stress of rotor model predictive control (MPC), at the same time, it is compared with original controller system. Comparison of actual stress value and model output are conducted. Speed response by adding PID controller improves the results greatly. On basis of the speed model, the speed response of 30\% and 60% are given respectively, and the stress output response without feed back controller and the stress output response with feedback controller are obtained and compared. Finally, the feasibility of this control scheme is verified. This work supplies a new view to solve the stress control problem in thermal engineering, and the gap between the theory and engineering may be overcome.

Author Declarations

The author has no relevant financial or non-financial interests that need to be disclosed, and no competitive interests related to this article.

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