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On real-time fatigue damage prediction for steam turbine

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Abstract: This paper presents a real-time prediction method for fatigue damage of steam turbine. The temperature data and thermal stress data of the key parts are extracted by calculating the temperature field and the stress field. The composite stress is calculated according to the fourth strength theory, and the measured stress data are normalized. Support vector regression model is established, input and output data are trained and predicted. The relationship between stress and damage function is analyzed and fitted, and the framework of the real time fatigue damage prediction system is established. In the end, the effectiveness of the method is verified by simulation experiment.

Keywords: finite element model, fatigue damage, thermal stress, support vector regression model, on real-time calculation method

1. INTRODUCTION

Turbine rotor is one of the important parts of turbine unit. And the damage of the metal materials will have great influence on the stable operation of the equipment[1]. Because the turbine rotor has been in the harsh working environment of high temperature, high pressure and variable working conditions for a long time, the stress situation is very complex, and the rotor metal is easy to produce low cycle fatigue. According to the engineering experience and the existing experimental results, it can be determined that the ratio of low cycle fatigue damage is about 80%[2]. Therefore, in order to prevent the safety problems caused by the fatigue damage of turbine rotor, real-time calculation of fatigue damage is very important.

At present, the calculation methods of rotor low-cycle fatigue mainly includes analytical method and numerical method. The analytical method reduces the dimension of the rotor model to a wireless long cylinder. The analysis method is based on the unstable thermal differential equation and integral equation to calculate the temperature field, and then the thermal stress is calculated according to the average temperature difference. The analytical method is very fast, and it is suitable for real time calculation. According to the structural characteristics of the rotor, material physical parameters, boundary conditions and initial conditions, the analytical method is used to calculate the maximum stress of the rotor where the crack is most likely to occur[3]. The analytical method ignores the effects of heat flow and simplifies the model. Because it only considers the radial temperature difference, its calculation accuracy is not high. But the numerical analysis method does not reduce the dimension of the model. On the basis of two-dimensional model or three-dimensional model, the geometric continuum is discretized by numerical method. The numerical method considers factors such as convective heat transfer coefficient and material physical properties with space and time, and it has high calculation accuracy. However, the disadvantage of the numerical method is that the amount of calculation is too large, and it is difficult to implement real time calculation.

Sun proposed a new method for evaluating the low cycle fatigue life of a 300 MW turbine rotor through a nonlinear model[4]. The nonlinear model can accurately describe the damage accumulation process and it was consistent with the actual test data. Sun used the method of finite element analysis to evaluate the low cycle fatigue damage of steam turbine[5]. The damage was monitored on line and the correctness of the finite element analysis method was verified by experiments. Banaszkiewicz used finite element method to study the applicability of Neuber and glinka-molski rules with ideal elastic and bilinear material models in the estimation of elastoplastic strain in rotor slots[6]. For considering the groove geometry, the most accurate strain prediction can be obtained by using Neuber rule of bilinear material model. Banaszkiewicz proposed a multi-level method for turbine life assessment based on damage calculation, probability analysis and fracture mechanics considerations[7]. Based on LCF test, Sun put forward a new reliable life prediction method, which takes both fatigue and creep damage into account[8].

Based on the equivalent variable-energy density law of notched stress-strain analysis proposed by molski and Glinka, Banaszkiewicz proposed a method of monitoring the low-cycle fatigue life of steam turbine rotor by analyzing the non-isothermal low-cycle fatigue condition of turbine rotor[9]. By studying the transient equivalent stress, a new type of tie rod structure is proposed by Liu to reduce the equivalent stress[10]. Zhu studied the rotor

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system by using the equivalence principle and axiality, and established the three-dimensional structure model of the rotor system[11]. The finite element method (FEM) was used to analyze the temperature field and thermal stress field under the condition of starting and ending. The low boundary steam temperature and convective heat transfer coefficient are calculated by using thermodynamic theory. Dominiczak established a finite element rotor model to obtain a neural network for locating critical stress and temperature points in the turbine during transient state[12]. Wang analyzed the creep fatigue interaction behavior of turbine rotor under ideal cyclic thermophysical load and simulated the multi-axial stress-strain behavior of rotor using the material constitutive model based on Chaboche model[13]. In order to study the influence of residence time on creep fatigue behavior, wang proposed a viscoplastic constitutive model of damage to describe the creep fatigue behavior by selecting the fixed iteration of the operation closure process to change the residence time in the operation phase[14]. The fluctuation of steam temperature during steady state operation may lead to stress oscillation, which may cause fatigue damage to the turbine rotor. Mashayekhi studied this by using the linear matching method (LMM) and based on the newly developed creep fatigue and creep fracture assessment program[15]. Zhu studied the creep fatigue interaction damage and creep fracture limit of steam turbine rotor under the coupling effect of phase change and phase change cycle thermodynamic and mechanical forces[16].

In this paper, finite element method and support vector regression method are used to study the fatigue damage of steam turbine. And it is mainly composed of the four sections. The first section is introduction of recent research results, the second section presents the mechanism of real-time fatigue damage prediction. In the third section, a numerical simulation experiment is designed and carried out to verify the effectiveness of this novel approach. Finally, a conclusion is made in the fourth section. The method design section is further divided into eight parts, the first part is the calculation of the temperature and the stress field, the second part is the extraction of temperature data and thermal stress data, the third part is the calculation of the combined stress, the fourth part is the normalization of the data, and part 5 is the establishment of support vector regression model, part 6 is analysis and fitting of stress damage function relationship, part 7 is real-time fatigue damage prediction system, the last part is the process scheme for real-time prediction of fatigue damage.

2. MECHANISM DESIGN

In view of the above shortcomings of analytic method modeling and numerical method modeling, this paper proposes a real-time fatigue damage prediction for steam turbine. This method is used to solve the problem that it is difficult to integrate real time calculation and high-precision calculation of rotor low-cycle fatigue damage in the existing technology. In this paper, the finite element software ADINA is used to model the turbine rotor. Firstly, the temperature data and thermal stress data of the key parts are extracted by calculating the temperature field and the stress field. Then, the combined stress is calculated according to the fourth strength theory, and the measured stress data are normalized. Support vector regression model is established, input and output data are trained and predicted. In the end, the relationship between stress and damage function is analyzed and fitted, and the framework of the real time fatigue damage prediction system is established.

2.1 Calculation of The Temperature and Stress Field

By calculating temperature field and stress field, the temperature data and thermal stress data of key parts are extracted. When calculating the unsteady temperature field of the turbine rotor, the boundary condition of the outer surface of the rotor is determined by the heat transfer speed of the steam to the rotor surface. This boundary condition belongs to the third boundary condition in heat transfer:

$$-\lambda \frac{\partial T}{\partial \bar{n}} = \alpha (T - T_f). \tag{1}$$

where, λ — thermal conductivity of turbine rotor, T_f — temperature of contact with the surface of the rotor. α — the heat release coefficient of steam and rotor surface.

2.2 Extraction of Temperature Data and Thermal Stress Data

The temperature data and thermal stress data of the key parts are extracted. In the calculation of fatigue damage about metal materials, the area of stress concentration will be presented. Such as, the root of turbine rotor regulator, the root of the high pressure stage, and the bottom of the elastic force groove. Fatigue damage generally occurs first from the maximum local strain at the location where the strain is concentrated. Before the crack initiation, a certain plastic strain will be generated and accumulated. Therefore, when extracting the measured stress data, the corresponding thermal stress data is usually extracted at the root of the adjustment stage according to engineering experience.

2.3 Calculation of Combined Stress

The combined stress is calculated according to the fourth strength theory. In the numerical calculation method, in order to ensure the calculation accuracy, the effects of various stresses cannot be simply ignored, so it is necessary to calculate the effective stress according to the fourth strength theory. The formula is as follows:

$$\sigma_m = \frac{\sqrt{2}}{2} \sqrt{(\sigma_y - \sigma_r)^2 + (\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_y)^2 + 3\tau_{ry}^2}. \tag{2}$$

where, σ_m — resultant stress, y, θ, r — represent axial direction, tangential direction and radial direction respectively, τ_{ry} — shear stress.

2.4 Data Normalization Processing

The measured stress data are normalized. The essence of normalization is to linearize all the dimensioned numbers to obtain dimensionless numbers, and eliminate the influence of different units on the calculation unit. The raw data x is linearly transformed by normalization, and the result falls to the [0,1] interval. The conversion function is as follows:

$$x^* = \frac{x - x_{min}}{x_{max} - x_{min}}. \tag{3}$$

where, x_{min} and x_{max} are the minimum and maximum values of the original data.

2.5 Support Vector Regression Model

Support vector regression model is established, input and output data are trained and predicted. The constraint function of SVM regression model is as follows:

$$err(x_i, y_i) = \begin{cases} 0 & |y_i - \omega \cdot \varnothing(x_i) - b| \leq \varepsilon \\ |y_i - \omega \cdot \varnothing(x_i) - b| - \varepsilon & |y_i - \omega \cdot \varnothing(x_i) - b| > \varepsilon \end{cases} \tag{4}$$

Define the objective function as:

$min\frac{1}{2}\|\omega\|^2, s.t.|y_i - \omega \cdot \varnothing(x_i) - b| \leq \varepsilon(i = 1, 2, \ldots, m)$, add the relaxation variable $\varepsilon_i \geq 0$, then the constraint function of SVM regression model is as follows:

$$\begin{aligned} &min\frac{1}{2}\|\omega\|^2 + C\sum_{i=1}^{m}(\varepsilon_i^{\wedge} + \varepsilon_i^{\vee}) \\ &s.t.(\omega \cdot \varnothing(x_i) + b) - y_i \leq \varepsilon + \varepsilon_i^{\wedge} \\ &y_i - (\omega \cdot \varnothing(x_i) + b) \leq \varepsilon + \varepsilon_i^{\vee} \\ &\varepsilon_i^{\wedge} \geq 0, \varepsilon_i^{\vee} \geq 0 (i = 1, 2, \ldots, m) \end{aligned} \tag{5}$$

where, ε_i, $\varepsilon_i^{\wedge}$, $\varepsilon_i^{\vee}$ — relaxation variables, C — constant.

2.6 Analysis and Fitting of Stress Damage Function Relationship

The relationship between stress and damage function is analyzed and fitted, and the fatigue damage is calculated in real time. The cyclic stress-strain relationship is as follows:

$$\varepsilon = \frac{\sigma_{eq}}{E} + (\frac{\sigma_{eq}}{2K'})^{\frac{1}{n'}}. \tag{6}$$

where, E — Young's modulus, K' — cycle strength coefficient, n'— Cyclic strain hardening index.

The low cycle fatigue damage of rotor has the following relationship when the steam temperature is 538°C :

$$\varepsilon = 0.00332(N_f)^{-0.0697} + 0.6264(2N_f)^{-0.7553}. \tag{7}$$

where, N_f — number of cyclic cracking. Through the multi-fitting method, strain can be used as input and cyclic cracking can be used as an output. The relation between damage and strain is obtained:

$$\begin{aligned} d &= \frac{1}{2N_f} \\ &= P_1\varepsilon^7 + P_2\varepsilon^6 + P_3\varepsilon^5 \\ &+P_4\varepsilon^4 + P_5\varepsilon^3 + P_6\varepsilon^2 + P_7\varepsilon + P_8. \end{aligned} \tag{8}$$

where, $P_1 = 9.7904 \times 10^{12}$, $P_2 = -3.8943 \times 10^{11}$, $P_3 = 6.011 \times 10^9$, $P_4 = -4.6037 \times 10^7$, $P_5 = 1.8292 \times 10^5$, $P_6 = -3.3086 \times 10^2$, $P_7 = 0.27029$, $P_8 = 0$.

2.7 Real-time Fatigue Damage Prediction System

The architecture of on real time fatigue damage prediction system is established. The turbine strength of the turbine rotor is calculated by the fourth strength theory. The support vector regression model is obtained by using measured temperature, pressure and rotational speed as input and combined stress as output. The measured temperature, pressure and speed are taken as the input of the SVR model, and the combined stress of key parts of turbine rotor is calculated on real time. According to the relationship between stress and strain, and the relationship between strain and fatigue damage, the fatigue damage is calculated on real time.

2.8 The Process Scheme for Real Time Prediction of Fatigue Damage

The process scheme for on real time prediction of fatigue damage is shown in Fig. 1:

- Calculate the temperature field and the stress field. And the finite element software ADINA is used to model the turbine rotor.
- The temperature data and thermal stress data of the key parts are extracted. In the calculation of fatigue damage about metal materials, the area of stress concentration will be presented. Such as, the root of turbine rotor regulator, the root of the high pressure stage, and the bottom of the elastic force groove. Fatigue damage generally occurs first from the maximum local strain at the location where the strain is concentrated. Before the crack initiation, a certain plastic strain will be generated and accumulated. Therefore, when extracting the measured stress data, the corresponding thermal stress data is usually extracted at the root of the adjustment stage according to engineering experience.
- Calculate combined stress according to the fourth strength theory. In the numerical calculation method, in order to ensure the calculation accuracy, the effects of various stresses cannot be simply ignored, so it is necessary to calculate the stress according to the fourth strength theory.
- Normalize the measured stress data. The essence of normalization is to linearize all the dimensioned numbers to obtain dimensionless numbers, and eliminate the influence of different units on the calculation unit. The raw data x is linearly transformed by normalization, and the result falls to the [0,1] interval.
- Establish support vector regression model, input and output data are trained and predicted.
- Analyze and fit the relationship between stress and damage function, and calculate fatigue damage in real time.
- The architecture of online fatigue damage calculation system is established. Under any working condition, thermal stress, pressure and centrifugal force are obtained by ADINA simulation. The turbine strength of the turbine rotor is calculated by the fourth strength theory. The support vector regression model is obtained by using measured temperature, pressure and rotational speed as input and combined stress as output.

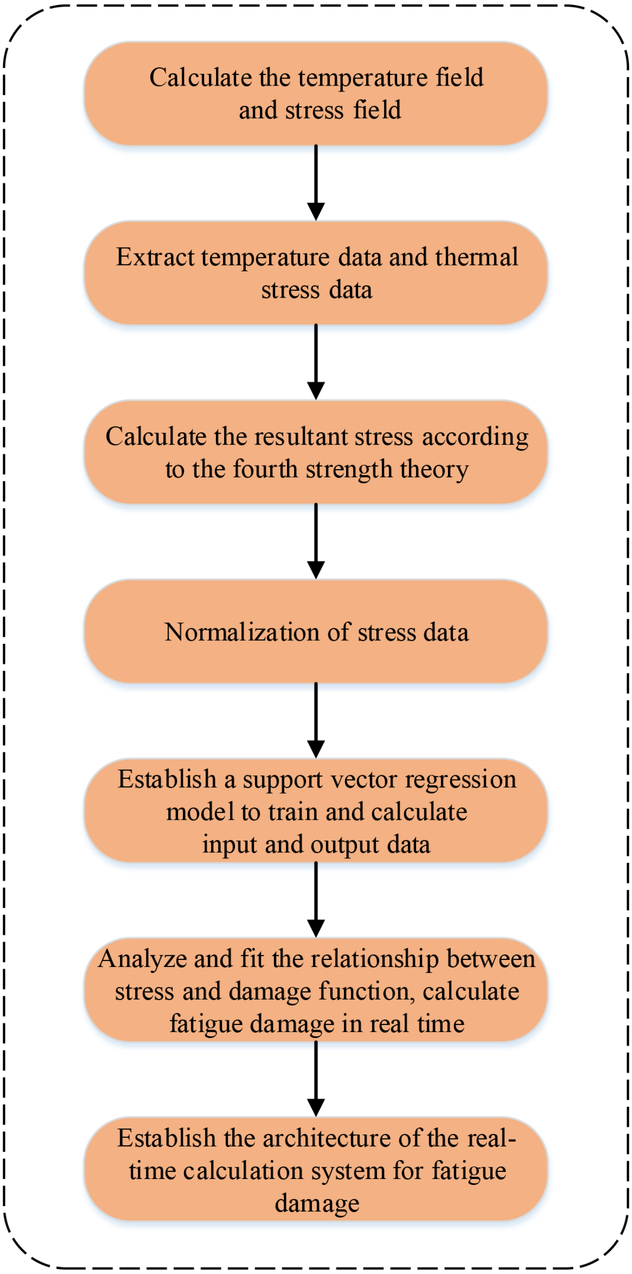

Fig. 1. Scheme of real time prediction for fatigue damage

3. SIMULATION EXPERIMENT

In the field of turbine rotor damage assessment, the calculation methods can be divided into one-dimensional analytical method and numerical analysis method. The one-dimensional analytical method is based on the simplified model of the rotor, the physical properties of the material, and the initial conditions. The calculation speed is fast and suitable for real time calculation. However, due to the simplification of the model dimension reduction, many parameters are simplified to constant, and at the same time, the complex structure of the rotor and the application of the load cannot be effectively taken into account, so the calculation accuracy is not high. On the basis of the two-dimensional or three-dimensional model of the rotor, the numerical analysis method fully considers the physical properties of the material, the temporal and spatial changes of the parameters, and the boundary conditions of the working conditions. And the numerical analysis method has high calculation accuracy and can even be close to the actual situation. However, since the numerical method is mostly solved by algebraic equations, the solving process is complicated and slow, so it is only suitable for offline calculation. In this paper, an real time calculation method for fatigue damage of steam turbine rotor based on finite element model is proposed, and the method is verified by experiments.

Then, an example is given to illustrate the simulation process. This example is mainly completed under the environment of Matlab 2014a and ADINA8.5 software. The turbine rotor used is based on the No. 1 unit of a power plant. The steam turbine is a single shaft, condensing steam turbine, and the material of the rotor is 30Cer1Mo1V. The length of the high-pressure rotor is about 4800mm, with a single row of regulating stage and a pressure stage of 11. A two-dimensional model of the rotor is established through ADINA, and the operating conditions are simulated at the regulating stage and the high-pressure stage according to the domestic 300MW steam turbine operation guidelines.

The finite element software ADINA is used to model the turbine rotor. And the temperature data and thermal stress data of the key parts are extracted by calculating the temperature field and the stress field. The rotor is symmetrical and the appropriate geometric model is established. The amount of calculation can be reduced by appropriately simplifying the model, for example, the gas seal system device is simplified into a line.

In the finite element software ADINA, the stress data of corresponding working conditions are extracted. Fatigue damage generally occurs first from the maximum local strain at the location where the strain is concentrated. Before the crack initiation, a certain plastic strain will be generated and accumulated. Therefore, as long as the local stress and strain are the same, the fatigue damage is the same. Fig. 2 shows the change of root temperature at the regulating stage of cold start, and Fig. 3 shows the change of root thermal stress at the regulating stage of cold start.

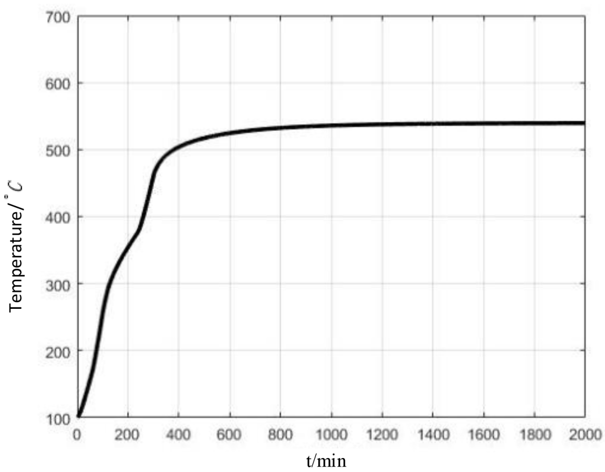

Fig. 2. Temperature at the root of regulating stage under cold start condition

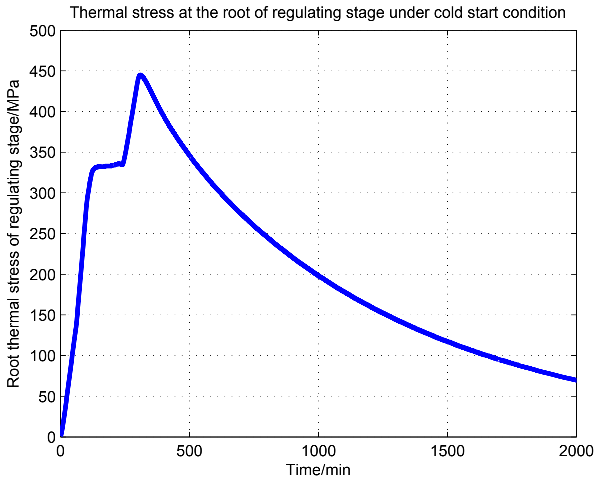

Fig. 3. Thermal stress at the root of regulating stage under cold start condition

The combined stress is calculated according to the fourth strength theory. The surface of the rotor is subjected to multiple stresses. When calculating the resultant stresses, the fourth strength theory is used for analysis. The outer surface and center hole of the rotor are subjected to tangential and axial stresses, that is, σ_r and τ_{rs} are zero, and the combined stress is calculated according to eq(1), according to eq(2) the sum of tangential stresses is calculated.

The measured stress data are normalized. For the convenience of subsequent data processing, the dimensionless number is obtained through linear normalization processing, and the influence of different units on the computing unit is eliminated. The raw data x is linearly transformed by normalization, and the result falls to the [0,1] interval. A sample data set is created, each column of data is a sample, and each row is the same dimension of multiple samples. In other words, for a matrix of $M \cdot N$, the dimension of the sample is M, and the number of samples is N.

The support vector regression model is established and input and output data are trained and predicted. Call the Matlab function to complete the read, write, training, and prediction functions. The read function is mainly used to read data, the write function saves the known data. The training function is used to train the data to build the SVR model. The prediction function and the training function use the trained model to predict the data type. The root stress training data of the adjustment stage are shown in Fig. 4, and the test data are shown in Fig. 5.

The relationship between stress and damage function is analyzed and fitted, and the fatigue damage is calculated in real time. The maximum stress is known and the low cycle fatigue damage can be calculated from the number of processes. According to eq(6), the cyclic stress-strain relationship is obtained. When the steam temperature is 538°C, the relationship of low-cycle fatigue damage of the rotor is obtained according to eq(7).

Through the multi-fitting method, the strain can be used as input and cyclic cracking can be used as an output.

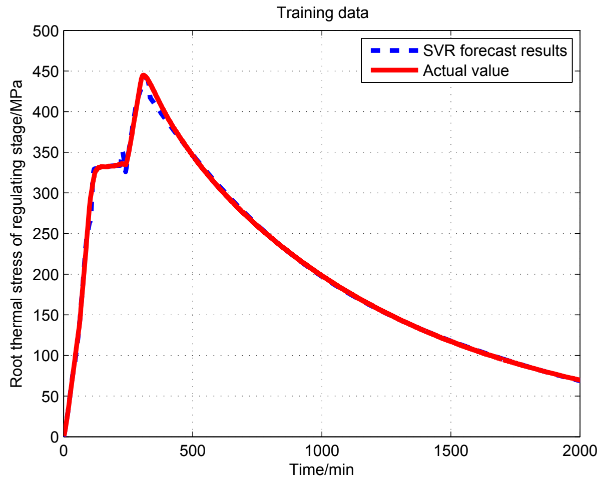

Fig. 4. Root stress training data of regulating stage under cold start condition

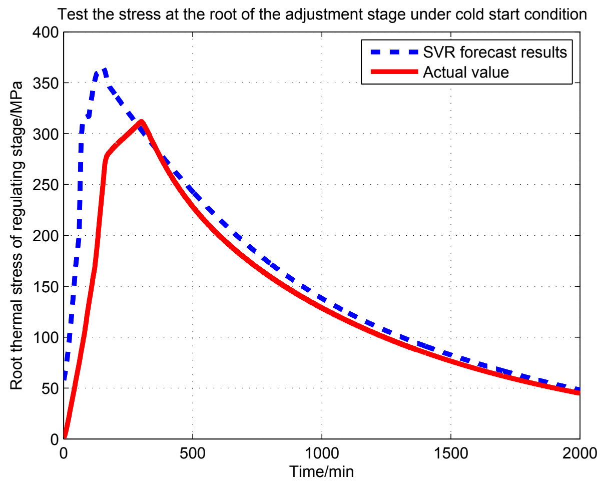

Fig. 5. Root stress test data of regulating stage under cold start condition

According to the eq(8) the relation between damage and strain is obtained. The calculation results are shown in Fig. 6.

The architecture of on real-time fatigue damage calculation system is established. Under any working condition, thermal stress, pressure and centrifugal force are obtained by ADINA simulation. The turbine strength of the turbine rotor is calculated by the fourth strength theory. The support vector regression model is obtained by using measured temperature, pressure and rotational speed as input and combined stress as output. The measured temperature, pressure and speed are taken as the input of the SVR model, and the combined stress of key parts of turbine rotor is calculated in real-time. According to the relationship between stress and strain, and the relationship between strain and fatigue damage, the fatigue damage is calculated in real-time.

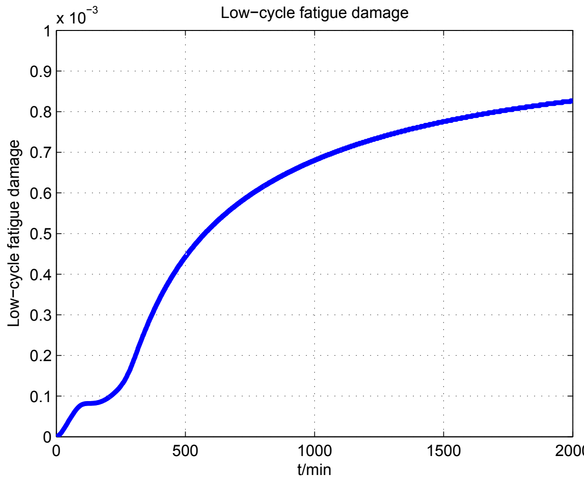

Fig. 6. Low cycle fatigue damage of rotor under cold start condition

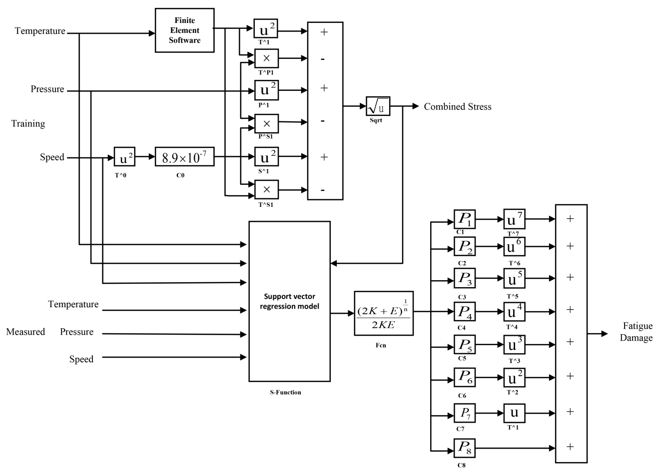

Fig. 7. Scheme diagram of real time prediction system for low cycle fatigue damage of turbine rotor

4. CONCLUSION

In this paper, a real-time fatigue damage prediction for steam turbine based on finite element model is proposed for fatigue damage. The temperature data and thermal stress data of the key parts are extracted by calculating the temperature field and the stress field. Then, the combined stress is calculated according to the fourth strength theory, and the measured stress data are normalized. Support vector regression model is established, input and output data are trained and predicted. In the end, the relationship between stress and damage function is analyzed and fitted, and the framework of the on real-time fatigue damage prediction system is established. According to the relationship between stress and strain, and the relationship between strain and fatigue damage, the fatigue damage is calculated in real-time.

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