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ANALYSIS AND OPTIMIZATION ON THERMAL STRESS OF CENTRIFUGE SPINDLE

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Abstract

The high-speed centrifuge rotor will produce large thermal stress in the process of quick starting, which will affect the thermal fatigue life of the rotor. Combining the genetic algorithm with the thermal analysis of the rotor structure, the temperature rise control curve in the process of quick starting of the rotor is optimized. The optimization process takes the maximum thermal stress of the rotor as the objective function, calculates and searches the optimal solution, and studies the influence of temperature rise control curve on the maximum thermal stress of the rotor. The results show that the optimized temperature rise control curve can effectively reduce the maximum thermal stress of the rotor and shorten the quick start time. At the same time, in order to verify the effectiveness of the proposed optimal design method for the temperature rise curve of the quick start of the rotor, a test rig for measuring the thermal shock stress of the rotor is built. The theoretical analysis results are verified by comparing the maximum thermal stress of the rotor under the temperature rise curve before and after optimization.

Keywords: thermodynamic, numerical simulation, thermal-solid coupling, fluid-solid coupling, brake disc

INTRODUCTION

When a high-speed centrifuge works, there will be a large temperature gradient in the rotor for a long time. Thermal shock makes the surface of the rotor change dramatically in tension and compression stresses [1], resulting in huge transient thermal stresses [2]. It is pointed out that the transient thermal stress of the rotor is the most important parameter for evaluating the thermal fatigue life in the process of quick starting and changing working conditions. Because of the large thermal inertia of the centrifuge rotor, the temperature rise of the structure is slow. Under the impact of high temperature airflow, the surface temperature of the rotor rises rapidly due to heat conduction, and it takes some time for the interior of the rotor to reach the designed temperature. During the start-up process, there is a large temperature difference on the turbine rotor, and the thermal stress is formed due to the uneven thermal expansion of the material. Rotor structure and heat transfer process are the two main causes of transient thermal stress, which occur in the stress concentration area.

At present, the research on the thermal stress of centrifuge rotor during starting process is only to carry out the thermal analysis of specific structure or to optimize the results of a certain thermal analysis. There is no research on the optimization of starting process combined with thermal analysis and optimization methods at the same time. Therefore, it is necessary to find an optimal design method for the control curve of quick start, which is not affected by thermal stress lag. By using the optimized control curve, the thermal stress of the rotor in the process of quick start can be reduced, and the starting time can be shortened while the thermal fatigue life can be guaranteed. This optimization method can obtain the maximum thermal stress caused by the quick start process, avoid the serious thermal stress lag phenomenon and improve the optimization efficiency. It can reduce the thermal stress of the rotor in the quick start process, and shorten the start time on the premise of ensuring the thermal fatigue life.

PRINCIPLE OF PARAMETRIC CURVE OPTIMIZATION

The optimum object is the maximum thermal stress of the centrifuge rotor in the process of quick starting. Because the total stress of the rotor is linearly superposed with the thermal stress and centrifugal stress [3], and the centrifugal stress is only linearly related to the speed of the rotor, and is not affected by the temperature rise curve. Therefore, this paper only considers the influence of temperature rise curve on the maximum thermal stress optimization results during quick start.

Temperature rise curve can be expressed by fitting function, the value of which is usually the air temperature at each time. Dividing the airflow temperature in the starting process by the corresponding airflow temperature in the rated working condition, the dimension one obtained has the same value as the valve opening of the intake valve, so that the temperature rise curve can control the airflow parameters flowing through the rotor surface by controlling the valve opening at each time during the starting process. After discretizing the temperature rise curve, the coordinates of the points crossed by the curve can be described by polynomial fitting. These points also correspond to the temperature values at each time during the start-up of the centrifuge. The more points the curve is described, the more curves it can represent, and the more likely it is to find the best curve in such a curve. When the specific values of these variables are given, the form of the curve is uniquely determined, which can be monotonic or non-monotonic. Through the discretization of the curve and the fitting of Lagrange interpolation function, the curve is connected with variables, and the optimal curve is found to determine the corresponding variables of the curve. The optimization of curves is parameterized into a multi-variable optimization problem, which can be realized by genetic algorithm optimization.

The genetic algorithm can be used to solve the multi-parameter optimization problem after the curve is discretized. In this paper, SGA (Simple genetic algorithms) standard algorithm is used, and its basic flow chart is shown in Figure 1. The natural binary encoding is used to encode four variables in each group of solutions into corresponding binary numbers, and the corresponding binary encoding symbol string of the individual solution is formed. The objective function is set to the maximum thermal stress corresponding to the individual, and the optimization program can be automatically calculated by the secondary development of the finite element software.

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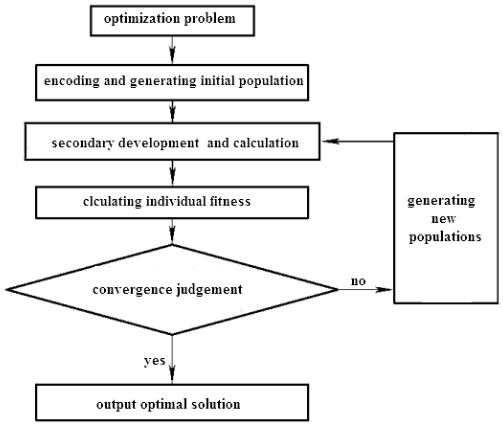


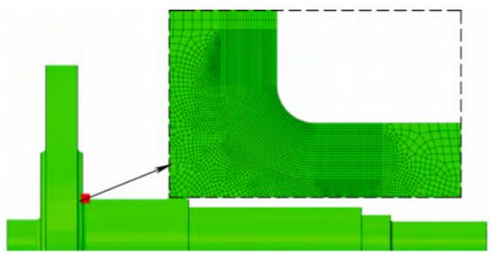
According to the fitness of individuals, the genetic operation of population can be realized, that is, the evolutionary process of survival of the fittest can be completed, and the individual can be optimized generation by generation, and finally the optimal solution can be approached. In this case, the number of individuals in each generation was 10, and the selection rate was 0.9. Nine individuals will be selected for crossover and mutation in each generation, and nine new individuals will be generated. Ten individuals of the new generation will be composed of the best two individuals in the original population. Single-point crossover is used in the optimization, and the initial crossover probability is 0.7. Considering that the excessive crossover probability may cause the optimization results to oscillate near the optimal solution and cannot obtain the optimal solution, the crossover probability is reduced by 0.5 when the genetic algebra is greater than 50. The mutation probability is 0.05 in order to increase the ability of the algorithm to find the optimal solution locally. Finally, genetic algebra is used as the stopping criterion. When the optimization is carried out for 100 generations, it stops and outputs the optimal solution.

ANALYSIS OF THERMO-MECHANICAL COUPLING MODEL

Model establishment

In this paper, the rotor of high-speed industrial centrifuge is taken as the research object. The rotor has a first-stage turbine disk, a gas intake end and a thrust disk on the left side. The radial bearing supports the rotor on the bearing seat. The initial temperature of the rotor is ambient temperature [4]. Because of the low heat flux at both ends of the rotor, it can be used as adiabatic heat treatment. The external surface of the rotor is in the convective heat transfer environment with the air flow. The empirical formulas for the surface heat transfer coefficients on both sides of the optical axis and impeller can be found in Ref [5].

The two-dimensional axisymmetric thermo-mechanical coupling analysis model of the rotor is established, as shown in Figure 2 and the blade structure in the rotor model is simplified to ensure the accuracy of the solution and calculation time [6, 7], and to improve the optimization efficiency. In this paper, the grid of dangerous area is refined and the grid independence test is carried out (the stress error is less than 3% after the grid is doubled). Through thermal stress finite element simulation, the maximum thermal stress appears after the rotor is subjected to thermal shock in the process of quick starting. The stress distribution nephogram of the rotor is shown in Figure 3. In the process of quick starting, the temperature gradient of the rotor is large both in radial and axial direction, which results in uneven expansion of each position of the rotor. Because the temperature of impeller is higher and the temperature gradient is bigger, the maximum thermal stress of the wheel disk is produced, while the stress value of other parts is not high because of the lower temperature.



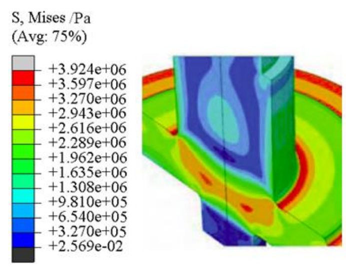


Figure.2 Schematic diagram of mesh generation **Figure.3** Distribution of maximum thermal stress (120th second)

Convergence Verification of Computation

The objective of this paper is to optimize the four variables that constitute the starting curve. Figure 4 shows the distribution of the initial population generated randomly in the genetic algorithm, and the four variables that optimize the solutions in the population of 25, 50, 75 and 100 generations. After 25 generations of optimization, the curve approximates to the optimal solution. There is little difference between the results of 100 generations and 75 generations, which indicates that the optimal solution is very close to the optimal solution. This optimization method has notable convergence [8] for the optimization of the temperature rise curve of the quick starting rotor.

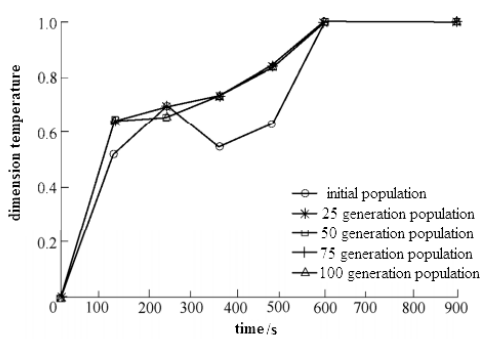


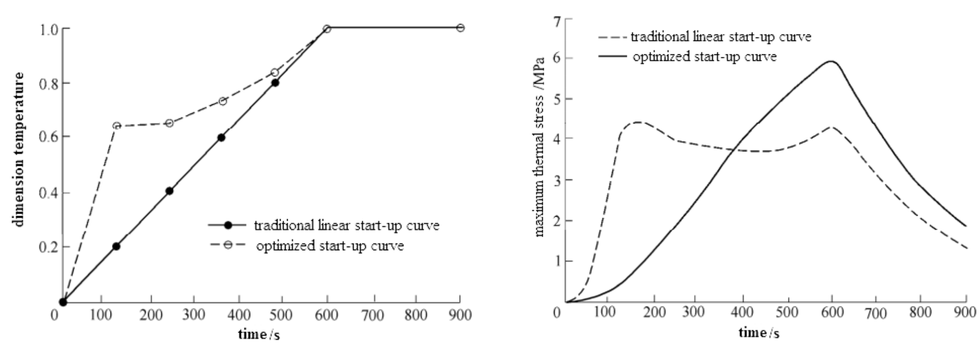
Figure.4 Contrast charts of optimal curves for each generation

Thermal Stress Optimization of Quick Starting of Rotor

Quick start optimization based on minimum thermal stress

Using the above optimization method, the temperature rise curve of the modeled rotor is optimized within 10 minutes of the specified starting time, and the curve of the minimum thermal stress of the rotor is sought. The optimized starting process is compared with the traditional starting process as shown in Figure 5(a). It can be seen that, compared with the traditional starting process, the optimized starting process is not monotonous temperature rise, and the temperature rise rate is very high at the initial time, then it keeps for 2 minutes at a higher airflow parameter position, and then rises slowly to the rated condition and remains unchanged.

The variation of maximum stress with time during starting is shown in Figure 5(b). Compared with the traditional starting, the maximum stress of the optimized starting process is reduced by 25.59%, while the starting time remains unchanged. It can be seen that the optimization method in this paper can effectively reduce the maximum thermal stress in the starting process under the same starting time.

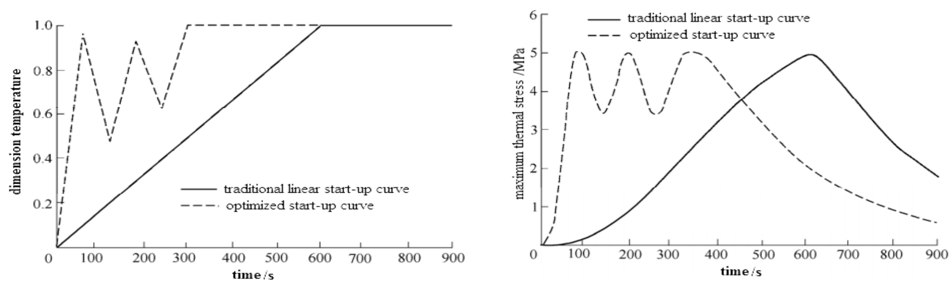


(a) Dimensional temperature-time (b) Maximum thermal stress-time

Figure.5 Traditional and optimized start control curve

Quick start optimization based on shortening time

Based on the same optimization method, the starting time is shortened with the maximum thermal stress unchanged. The starting time is set to 5 minutes, and the optimization goal is to find a 5-minute quick starting curve with the same maximum thermal stress value as the traditional 10-minute starting. The optimized results are shown in Figure 6. The maximum thermal stress of the rotor in the traditional 10-minute starting process is basically the same as that in the optimized starting process, but the starting time is shortened by 5 minutes. It can be seen that the optimization method can effectively shorten the starting time under the premise that the maximum thermal stress remains unchanged.



(a) Dimensional temperature-time (b) Maximum thermal stress-time

Figure.6 Traditional and optimized start control curve

Thermal shock analysis

On the basis of optimization design and simulation, combined with the optimization results of thermal shock curves of modeled rotors, a test platform for thermal shock of rotors was built to carry out thermal shock tests under different temperature rise curves. The effectiveness of theoretical analysis model and optimization design method is verified by comparing the results of theoretical simulation research. Based on the results of thermal analysis, the location of the maximum thermal stress of the model rotor in the thermal shock process is determined near the chamfer corner at the junction of the turbine disk and the spindle. Because of the restriction of the structure, strain gauges cannot be arranged there. Instead, the stress values at the principal axis near the chamfer corner are examined to reflect the maximum stress level of the modeled rotor. Combined with the thermal shock process, the strain on the surface of the specimen is transformed into the resistance change of the strain gauge, and then the strain value is obtained by the strain analyzer.

The test results will be affected by strain analyzer and platinum resistance sensitivity. For this reason, a number of groups of measurements have been carried out to eliminate the large fluctuation range of strain measurement results by means of averaging method. In addition, the experiment is limited by the temperature rise rate of the thermostat, and the actual temperature rise rate is different from the theoretical simulation conditions, which also affects the optimization effect to a certain extent. After many tests and taking the average value, the thermal stress test results of the thermal shock curve before and after optimization are finally obtained, and compared with the theoretical simulation results, as shown in Figure 7.

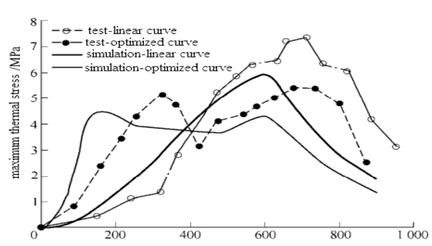


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Figure.7 Comparison of simulation and test results before and after optimization

Conclusions

In view of the influence of temperature rise curve on the thermal stress of centrifuge rotor during quick start-up, a multi-parameter temperature rise control curve with non-monotonic characteristics is proposed by combining genetic algorithm with thermal analysis, and multi-parameter optimization is carried out. The results show that the maximum thermal stress of the rotor can be reduced and the quick start time can be shortened. At the same time, the thermal shock test was carried out to verify the effectiveness of the optimization method and the accuracy of the analysis model. It is proved that the optimization method presented in this paper can be used as an effective means to reduce the maximum thermal stress and start-up time of the turbine rotor in the process of quick start-up, and it has reference significance for the scheme demonstration in the initial stage of turbine design.

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