Study on the Effect of Temperature on Dynamic Characteristics of Rotor System with Straight Crack

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Abstract. The effect of temperature on the dynamic characteristics of cracked rotor is studied in this paper. The crack is simulated by the extended finite element method (XFEM). Based on the theory of fracture mechanics, appropriate fracture criteria are selected, and the damage and failure criteria of materials are set up, and the finite element simulation analysis is carried out. The results show that with the increase of temperature, the amplitude of 3X in frequency domain increases most obviously, and the deformation degree of axis trajectory is high. The research results have important reference value and scientific significance for the study of dynamic characteristics of cracked rotor system under high temperature environment.

1. Introduction
Rotor system is the core component of rotating machine, but many rotor systems often operate in harsh environment. It is essential for the effect of temperature factors on the rotor system. In the fields of aviation, aerospace and military industry, there are a large number of harsh environments with strong temperature change. For example, the design speed of turbofan engines is between 10,000 and 20,000 revolutions per minute, and the number of revolutions of turbojet engines is even higher. In the working process of this kind of rotor system, the gas temperature is generally above 2000 °C, and the highest temperature can be up to 3500 °C. The rotor system is subjected to a strong temperature variation of several thousand degrees per second. It can be said that it is a kind of typical rotor system which works under strong temperature variation. The working environment of aeroplane is very bad and it runs under high temperature for a long time, which leads to the thermal bending and deformation of the components such as the rotor inside the aeroplane. These problems usually cause larger vibration of the system [1]. It can be seen that the aeroplane under high temperature environment is prone to vibration failure.[2]. Although the effect of temperature on rotor system is considered in the current literature, the effect of temperature on the dynamic characteristics of cracked rotor system is ignored. In reality, many large engines have cracks. But the crack does not affect the normal operation. This kind of engine has always been in high-intensity operation, and there will be unexpected hidden danger of safety. Li Jiukai of Sichuan University studied the influence of temperature and high cycle fatigue behavior on fatigue life of supercritical steam turbine rotor steel[3]. Wang Kun of Huazhong University of Science and Technology studied fatigue damage assessment caused by high temperature and low cycle according to energy theory and process fictitious [4-5]; Zhao Mei of Shanghai Jiaotong University analyzed the diagnostic method of cracked rotor in rotating...
machinery theoretically and verified it by experiment, but the effect of temperature field on rotor system was not considered in this study [6]. The crack is simulated based on the extended finite element method (XFEM). According to the theory of fracture mechanics, the appropriate fracture criteria are selected, and the damage and failure criteria of materials are set up, and the finite element simulation analysis is carried out. The results have important reference value and scientific significance for the study of dynamic characteristics of cracked rotor system under high temperature environment. It is of great academic value and scientific significance to study the dynamic characteristics of cracked rotor system in high temperature environment.

2. Establishment of finite element model for cracked rotor system

2.1 Simulation of cracks
In this paper, the extended finite element method (XFEM) [7] is used to simulate the crack. The finite element simulation of the cracked rotor system is completed by selecting the appropriate fracture criterion, setting up the damage and failure criterion of the material and reasonable mesh division.

2.1.1 Fracture criteria for cracks
Combined with the actual crack analysis problem and the crack body structure, the maximum energy release rate criterion is chosen as the crack fracture criterion of the simulation model in this paper [8-9]. In practical engineering applications, the loads of mechanical members are usually composite loads under the combined action of multiple loads, and the composite loads can be divided into three kinds of typical crack forms in the case of small deformation [10]. In general, the energy release rate of the composite crack can be expressed by the superposition of the energy release rate of three typical crack forms. The expression for the energy release rate of the crack in the composite form is as follows:

$$G = G_1 + G_\text{II} + G_\text{III} = \frac{(1 - \nu^2)}{2E} K_1^\nu + \frac{(1 - \nu^2)}{2E} K_\text{II}^\nu + \frac{(1 + \nu)}{2E} K_\text{III}^\nu$$

(1)

2.1.2 damage and failure criteria for materials
The damage and failure criterion of mechanical structure material determines the failure form and degradation law of material. Therefore, the finite element simulation analysis in this paper needs to pre-set the damage and failure criterion of material [11].

The existing law of damage evolution is mainly divided into two kinds: one is based on displacement and the other is based on fracture ability, which is used to describe the law of material stiffness degradation. The evolution law of fracture ability is mainly controlled by specifying critical fracture ability and correlation coefficient. The law is divided into three kinds: POWER rule, BK rule and Reeder rule. Among them, the POWER rule:

$$\left(\frac{G_1}{G_\text{IC}}\right)^n + \left(\frac{G_\text{II}}{G_\text{IC}}\right)^n + \left(\frac{G_\text{III}}{G_\text{IC}}\right)^n = 1$$

(2)

2.1.3 mesh generation and setting near cracks
The finite element model of cracked rotor system is divided into 60320 hexahedron elements with 68341 nodes and 11000 dense meshes near the crack. Finite element model meshing is shown in Figure 1.
Figure 1. Finite element model meshing of cracked rotor

XFEM is used to simulate the straight crack, and the maximum principal stress failure criterion is selected as the damage criterion.

2.2 Establishment of simulation model for rotor with straight crack

Figure 2(a) is a straight crack section, Figure 2(b) is the size of a straight crack, and the crack shape is semicircular. The ratio of crack depth to crack depth is h=r/R. In this chapter, the depth of straight crack is r=5 mm ( h=1mm ).

Figure 2. Rotor system with straight crack

Figure 3 shows the rotor system model after adding a straight crack.

Figure 3. Model of rotor system with straight crack

3. Effect of temperature on vibration response of rotor with straight crack

The vibration response of the rotor system with a straight crack is analyzed at 20 °C, 300 °C and 500 °C. The rotational speed is 2000rpm and the crack depth ratio is 1.

Figure 4. Time-domain and frequency-domain curves of the x direction of a rotor system with a straight crack at 20 °C

Figure 5. Time-domain and frequency-domain curves of the x direction of a rotor system with a straight crack at 300 °C
Figure 6. Time-domain and frequency-domain curves of the $x$ direction of a rotor system with a straight crack at 500 °C

Figure 7. Time-domain and frequency-domain curves of the $y$ direction of a rotor system with a straight crack at 20 °C

Figure 8. Time-domain and frequency-domain curves of the $y$ direction of a rotor system with a straight crack at 300 °C

Figure 9. Time-domain and frequency-domain curves of the $y$ direction of a rotor system with a straight crack at 500 °C

Table 1. Frequency doubling amplitudes in $x$ and $y$ directions at different temperatures

| Direction | Temperature / °C | 1X amplitude / mm | 2X amplitude / mm | 3X amplitude / mm |
|-----------|------------------|-------------------|-------------------|-------------------|
| $x$       | 20               | 0.00150           | 0.00058           | 0.00061           |
|           | 300              | 0.00160           | 0.00061           | 0.00070           |
|           | 500              | 0.00180           | 0.00080           | 0.00140           |
| $y$       | 20               | 0.00180           | 0.00063           | 0.00045           |
|           | 300              | 0.00183           | 0.00063           | 0.00045           |
|           | 500              | 0.00210           | 0.00080           | 0.00093           |
Figures 4-9 shows the time-domain and frequency-domain curves of the cracked rotor system in x and y directions at different temperatures, and table 1 shows the frequency-domain frequency-doubling amplitudes of x and y directions at different temperatures.

1) At different temperatures, the waveforms of the time domain images in both directions are deformed greatly, and both of them appear synthetic vibration. The 1X amplitude is the largest.

2) With the increase of temperature, the deformation degree of time domain waveform in two directions is larger, and the vibration is more complex. In the direction of x and y, the increase rate of 3X amplitude is larger, 1X is the second, and 2X amplitude is smaller.

3) When the temperature ranges from 20 °C to 300 °C, the time domain and frequency domain curves change slightly, and the temperature ranges from 300 °C to 500 °C, the time and frequency domain curves vary greatly, and the high-frequency components in the 500 °C time-frequency domain diagram increase and the fractional frequency components appear, and the nonlinear characteristics of the rotor system become stronger. If the temperature increases gradually at 500 °C, the vibration response of the straight crack is more complicated.

Figure 10. Axis trajectory curve of rotor system with straight crack at 20 °C and 300 °C

Figure 11. Axis trajectory curve of rotor system with straight crack at 500 °C

From figures 10-11, we can see that the degree of deformation of the axis trajectory increases with the increase of temperature, and the vibration range becomes larger. At the same time, there are two grooves in the axis track. The degree of depression increases with the increase of temperature, and the figure becomes distorted. Coils appear at grooves.

4. Conclusion

(1) With the increase of temperature, the whole vibration response of the cracked rotor becomes stronger, the vibration range becomes larger, the change of 3X amplitude is the most obvious, the high frequency component increases, the fractional frequency component appears, and the nonlinear phenomenon is enhanced. The vibration response of straight crack is more complicated.

(2) The deformation degree of the axis trajectory increases with the increase of temperature, and the vibration range becomes larger. At the same time, two grooves appear in the axis locus, the degree of depression increases with the increase of temperature, and the distortion is more complicated.

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