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Simulation and Experimental Study on Vibration Characteristics of Cracked Rotor System

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Abstract: In order to study the vibration characteristics of a cracked rotor system, a finite element model of a cracked rotor system was established. The rotor experiment platform was built to verify the correctness of the finite element model, and then the influence of depth on the vibration characteristics of the rotor system was studied. The results show that with the increase of the crack depth ratio, the vibration response of the rotor system becomes stronger in both directions, the frequency domain curve has higher frequency multiplication, and the axis center trajectory becomes larger. If the crack depth ratio is further increased, the rotor system vibration may be lost steady.

1. Introduction

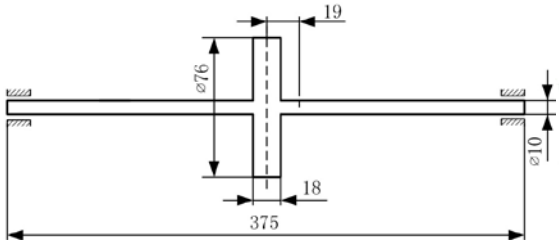
Rotary machinery is a mechanical device whose main body is the rotor system, such as large-scale turbo-generators, hydroelectric generators, nuclear power units, aerospace engines, high-speed compressors, centrifuges, fans, water pumps, centrifugal pumps, and high-precision machine tools. All belong to the typical rotating machinery. It is the most important power machinery in modern industry. It has a wide range of applications in various industrial sectors such as national defense, energy, power, petrochemical, metallurgy, transportation, machinery, chemical, aviation, aerospace, military, mining and other industries. And play an important role [1-3].

In recent years, catastrophic accidents caused by rotor cracking faults have occurred frequently, and fatigue propagation cracks due to overtime service operation have been the most harmful.[4] There have been many serious accidents caused by cracks in engine rotor system all over the world. The forced cooling of a US nuclear reactor cooling pump was due to severe shafting cracks [5]; the domestic An-24 plane crashed and was found to be due to fatigue fracture of the engine's high-pressure fuel pump transmission shaft [6]. There are countless similar cases mentioned above. Therefore, we urgently need to conduct an in-depth study of the dynamic characteristics of the cracked rotor system, systematically analyze the vibration response of the cracked rotor and make a performance evaluation to take corresponding measures to ensure the normal operation of the rotor system. Lin Yanli [7] studied the effects of parameters such as rotor speed, eccentricity, and crack depth on the system response, and discussed in detail the stiffness calculation methods of different crack rotor systems. However, the paper lacks simulation to perform intuitive simulation and verification in many aspects. Chen Tiefeng [8] used simulation software to build a cracked rotor finite element model, designed the rotor test bed to verify the simulation results, but the article did not analyze different crack angles.

In this paper, according to the type of crack, using the extended finite element method to set the crack, using reasonable fracture criteria and material damage and failure criteria, the finite element model of the cracked rotor system was established, the rotor experimental platform was built, the correctness of finite element model was verified , and based on the finite element model, studies the influence of depth and speed on the vibration characteristics of the rotor system. The research methods and conclusions can provide references for the vibration characteristics of the cracked rotor system.

2. Finite Element Modeling

The ABAQUS software was used to establish the finite element simulation model of the rotor system and study the dynamic characteristics. The model consists of a rotating shaft and a turntable. The design dimensions of the finite element analysis model are shown in Figure 1. The total length of the rotor is l=375mm, the diameter of the rotating shaft is d=10mm, the thickness of the disk in the rotor system is h=18mm, the diameter is dp=76mm, and the crack length It is 5mm. Both ends of the rotor are rigidly supported; the material parameters of the rotor system model are referred to [10].



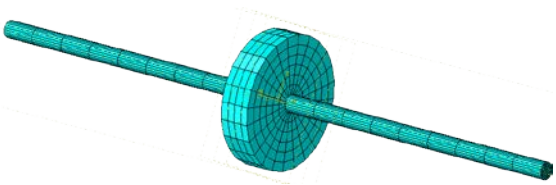
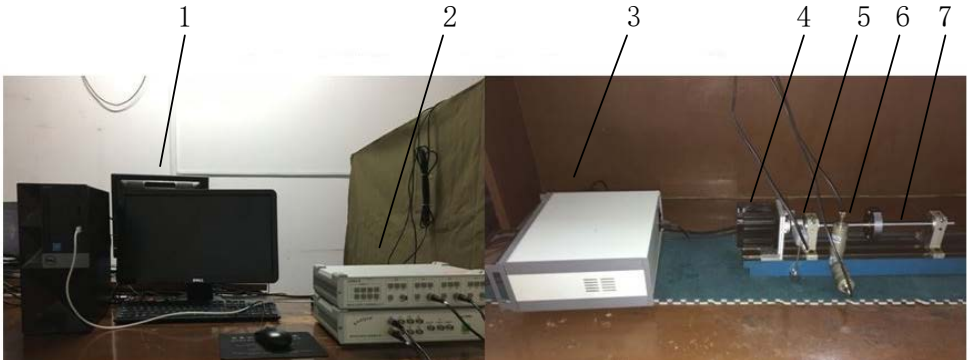


Figure 1 Rotor system 3D model size parameters. Figure 2 Rotor system FE model.

In this paper, XFEM is used to simulate the crack, and the failure criterion of the maximum principal stress is selected as the damage criterion. The energy evolution, linear softening, and mixed mode exponential damage evolution rules are selected for the damage evolution. The fracture toughness data of the material according to [9] is obtained. The location of the crack can be unaffected by the shape of the model and the element, such as setting the crack 19mm from the center of the axis, creating XFEM and contact, and keeping the other conditions constant, as shown in Figure 2.

3. Rotor experimental platform

Experimental principle: The rotor is supported by a sliding bearing. One end of the rotor is connected to the motor via a rigid coupling. The speed of the motor is adjusted by the rotor test bed controller. The motor directly drives the rotor via the coupling. The vibration speed sensor and the laser sensor both pass through the bottom. The magnets are adsorbed on the experimental bench, and the measured vibration speed and speed signals are transmitted to a data acquisition instrument and sent to a computer for monitoring and diagnosis. The experimental device is shown in Figure 3.



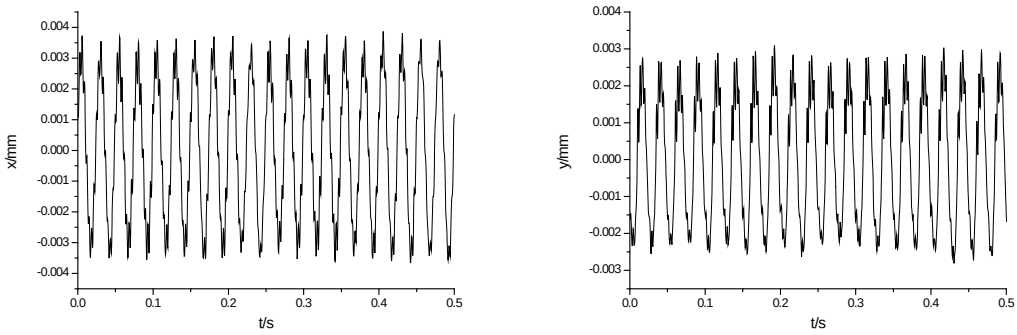
1. Computer experiment 2. Data acquisition instrument 3. Rotor controller bearing 4. Motor 5. Laser sensor 6. Vibration speed sensor
7. Rotor

Figure 3 Rotary bench.

4. Experimental verification of the finite element model

The time domain simulation and experimental curves of the rotor system in the horizontal and vertical directions are shown in Figure 4 and Figure5. Due to the influence of the surrounding

environment of the experiment, installation error, and the sensor indirectly derives the vibration response of the rotor system through the vibration of the base, many burrs and clutters appear in the experimental curve, but the simulation and experimental curves are compared in the vibration response characteristics. It is consistent and the error is within a reasonable range, which verifies the correctness of the finite element model established in this paper.



(a) Simulation curve (b) Experiment curve

Figure 4 Time domain diagram of the rotor in the horizontal direction.

5. Analysis of Influence of Crack Depth on Vibration Characteristics

The finite element model of the crack rotor with different crack depths was established. The displacement response of the center of the turntable in two directions was calculated by ABAQUS software. Figure 5 - Figure 9 shows the position of the straight crack on the rotor shaft. By changing the crack depth ratio of the straight crack, the time domain curves of the center of the rotor disk in the x-direction and y-direction in four cases are obtained. The frequency domain diagram and the axis center trajectory.

From Figure 5 to Figure 9, it can be seen that the frequency domain curves of the straight cracked rotor system have 1×, 2×, 3× frequency multiplication components which are obvious; with the crack depth ratio increasing, the straight crack rotor system vibrates more violently and the range is larger, and the amplitudes of the frequency multiplication in both directions are improved. Other high frequency components appear. The 1x amplitude is the largest, 2x is the second, and 3x is the smallest. The nonlinearity of the rotor system is relatively strong, and the lateral response high frequency component is more. Therefore, when the cracked rotor system is running at low speed, the change of the direct crack depth ratio can be detected according to the amplitude change of the vibration response.

From the trajectory curve of the center axis of the disk during the operation of the rotor in Figure 9, it can be seen that the increase of the crack depth ratio has a greater influence on the trajectory of the rotor system. The crack rotor system under the action of gravity, its axis center trajectory shape with the increase of the crack depth ratio and the movement range becomes larger, the vibration is violent, the degree of deformation is larger, the top circle becomes more and more prominent.

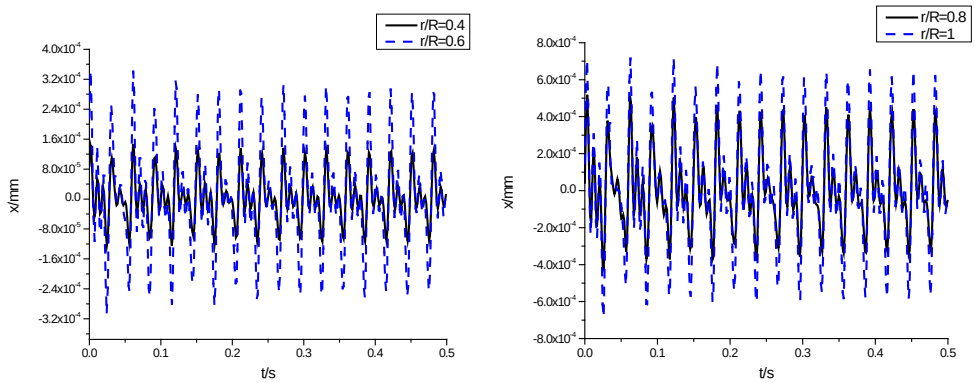


Figure 5 Time-domain curve of the center x-rotor of the rotor disk at different depths.

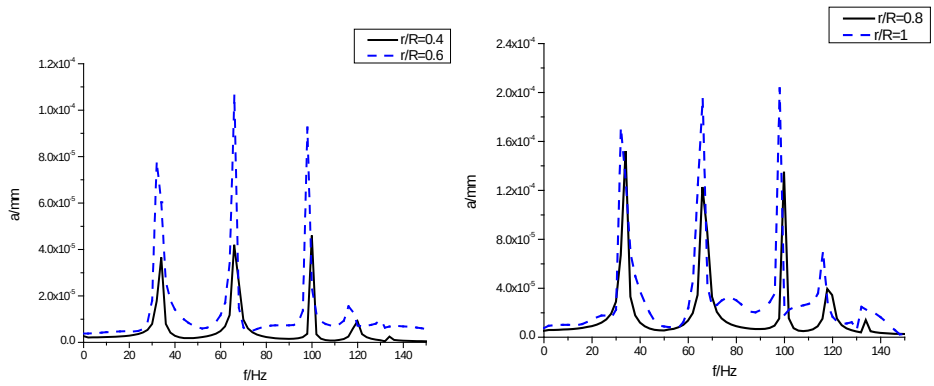


Figure 6 X-direction frequency domain curve of rotor disk at different depths.

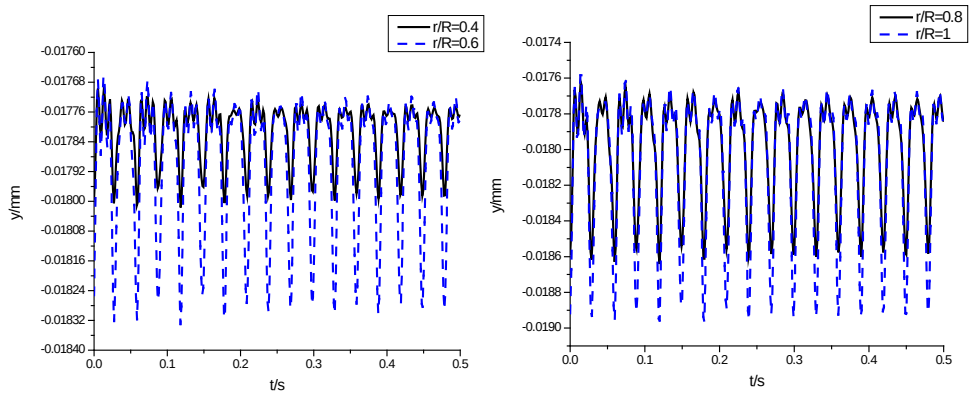


Figure 7 Time domain curve of the center y-direction of rotor disk at different depths.

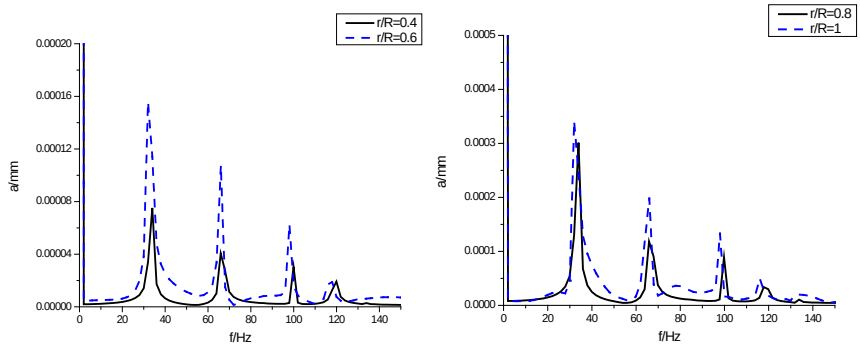


Figure 8 Curve of y-direction frequency domain of rotor disk at different depths.

6. Conclusion

(1) With the increase of the crack depth ratio, the straight crack rotor system vibrates more violently and has a larger range of motion. The amplitudes of the frequency multiplication in both directions are increased. Other high frequency components appear, and the 1x amplitude is the largest. 2x Next, 3x minimum, The nonlinearity of the rotor system gets stronger, and the lateral response high frequency component is more. Therefore, when the cracked rotor system is running at low speed, the change of the direct crack depth ratio can be detected according to the amplitude change of the vibration response.

(2) Under the action of gravity, the crack rotor system's axial trajectory shape increases with the increase of the crack depth ratio. The vibration range is large, the vibration is fierce, the degree of deformation is large, and the top circle becomes more and more prominent.

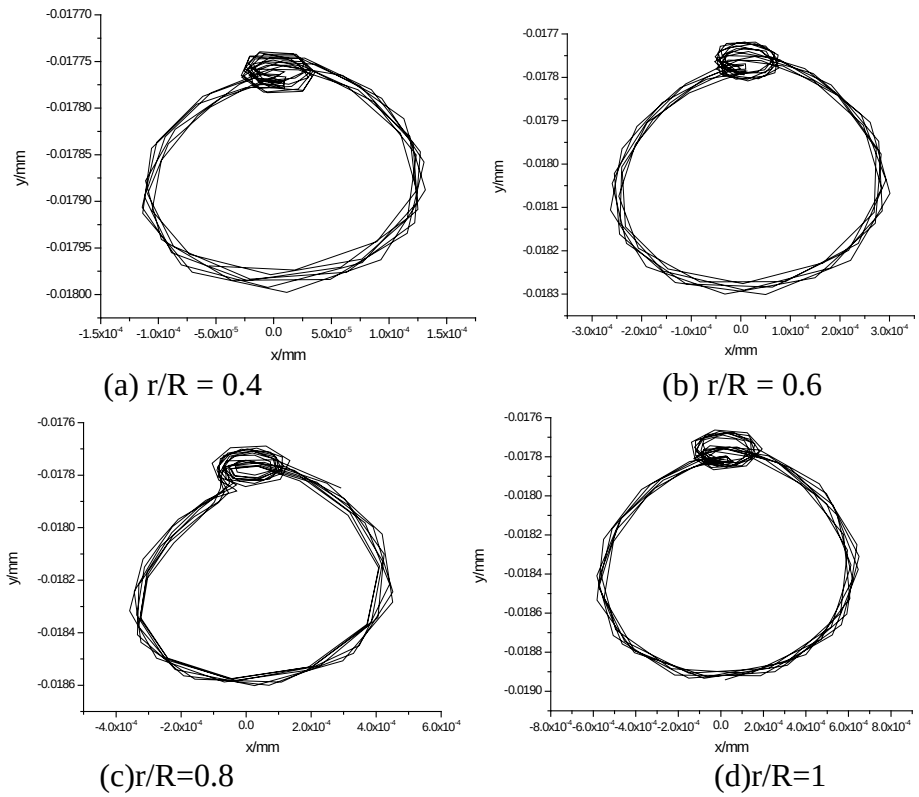


Figure 9 Axis trace of the rotor disk center at different depths.

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