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The Study on Vibration Characteristics of Rub-impact Rotor Based on Virtual Prototype Technology and Experiments

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Key Words : Rub Fault; Virtual Prototype; Torsional Vibration

ABSTRACT

A virtual prototype (VP) model of the rotor-to-stator rub of the rotor system is established to study the nonlinear vibration characteristics. The non-linear bearing stiffness is considered to approximate to an actual system in the model. In order to validate the effectiveness of the proposed approach, a special structure of stator is designed to simulate different kinds of rub condition. The results of experiment are well consistent with the results of simulation by VP. The vibration characteristics of rub-impact are well observed by VP model under different conditions. Based on the validated model, the torsional vibration of rub-impact is discussed. The contribution of this paper is to provide one new approach to study rub-impact problem. Based on the validated VP model, the more research can be done for incident fault identification.

symbol

O_1: the center of the stator
O_2: rotor mass eccentricity
O_3: the rotor center
Φ: the rotation angle of the rotor
R: the centroid distance of rotor and stator
C_2: the clearance circle radius
(X_0, Y_0): $x-o_1-y$: the fixed coordinate system coordinates of rotor initial center relative stator center
F_N: the Normal force
F_τ: the tangential force
μ: the Coulomb friction coefficient
M: the equivalent rotor quality
C: equivalent damping
K_c: the equivalent stiffness of the stator
E : mass eccentricity
Ω : rotor angular velocity

1. Introduction

Rotor system is the key components of rotating machinery, including generator sets, industrial turbomachinery, and aircraft gas turbine engines. Rotating machinery is becoming faster and lightweight due to the advanced technologies made in engineering and materials sciences. It is very important for the evaluation of the rotating machines' condition and the early prediction of the rub-impact.

The rotor-to-stator rub is one of the malfunctions occurring often in rotating machinery. It is usually a secondary phenomenon resulting from other faults. When the rub occurs, partial rub can be observed at first. During one complete period, rotor and stator have rub and impact interaction once or a fewer times. Alternately changed stress is formed in the shaft and the system can exhibit complicated vibration phenomena. Chaotic vibration can be found under some circumstances. Gradual aggravation of the partial rub will lead to full rub and severe vibration makes the normal operation of the machine impossible. Mathematically, the rotor system with rotor-to-stator rub is a nonlinear vibrating system with piecewise linear stiffness. There have been many publications on this problem and relevant topics [1].

The research on rub-impact rotor has obtained many achievements over the past decades. However, most of work is based on theoretical analysis and numerical simulation with part simplification, which results in a large gap between the actual equipment performances.

VP technique is a newly produced technique, which is still in the development stage. There are different definitions in different application areas. The common concept of the VP technology in the field of modeling and simulation is defined by the U.S. Department of Defense Modeling and Simulation Office (DMSO). The definition of VP technology is that a VP makes use of a digital model with functional similarity instead of a physical prototype, for testing and evaluation of specific characteristics of a product or a manufacturing process in a computational environment.

VP involves the entire life of equipment from design to application. In 1996, American engineering association applied the virtual reality technique into maintenance analysis and maintenance training as frontier research. In 2000, American Wright-Patterson Air Force Base, GE company and Lockheed Martin Company sponsored a three-year project: Service Manual Generation. The objective of this research was to enable the automatic generation of verified maintenance instructions. Recently, VP has been introduced into military equipment maintenance in China. Dr. Jia Changzhi from Shijiazhuang Mechanical Engineering College introduced VP into simulation fields of armament. The typical faults model of recoil mechanisms is established and the performances under faulty conditions are simulated with VP [2].Wang Zongchuan etc. built the virtual prototyping of armament equipment based on the mechanical system simulation software of ADAMS. They applied fuzzy evaluation and virtual prototyping technology to the field of armament equipment fault simulation [3]. Bai Xin etc. built the parameterized model of a single cylinder engine with Pro/E software, and simulated the performance of the piston pin under different working conditions by ADAMS to obtain fault diagnosis system [4].

The VP of rub-impact rotor system is established by multi-body dynamics software ADAMS. In order to validate the effectiveness of the proposed approach, a special structure of stator is designed to simulate different kinds of rub condition. The results of experiment are well consistent with the results of simulation by VP. Based on the validated model, the torsional vibration of rub-impact is discussed. The contribution of this paper is to provide one new approach to analyze the rub-impact fault.

2. A VP Model of rub - impact rotor syste m

The theory of rub-impact rotor has been published by many researchers. In this paper, the theory does not describe in detail. A schematic of a rotating flexible shaft-rigid disk system is shown in Fig. 1.

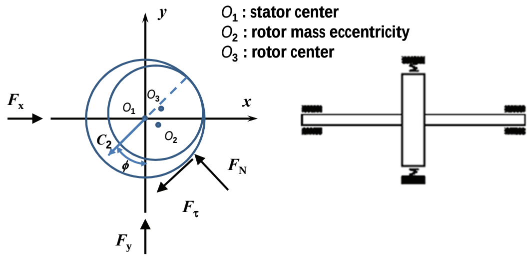


Fig 1 Jeffcott rotor model of rub-impact

The radial impact force equation based on rub-impact force model can be written as:

$$F_N = \begin{cases} 0 & R < C_2 \\ K_c(R - C_2) & R \geq C_2 \end{cases} \tag{1}$$

According to the Coulomb law of friction:

$$F_\tau = \mu F_N \tag{2}$$

Thus, the horizontal and vertical directions rub-impact force that the rotor suffered can be obtained:

$$\begin{cases} F_x = -F_\tau \cos\phi - F_N \sin\phi \\ F_y = -F_N \cos\phi - F_\tau \sin\phi \end{cases} \tag{3}$$

$$\sin\phi = \frac{X}{R} \qquad \cos\phi = \frac{Y_0 - Y}{R} \tag{4}$$

For the convenience of calculation, the rub-impact forces can also be written as followings:

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = H(R - C_2)\frac{(R - C_2)K_c}{R}\begin{bmatrix} -1 & \mu \\ -\mu & -1 \end{bmatrix}\begin{bmatrix} X \\ Y - Y_0 \end{bmatrix} \tag{5}$$

According to the above equation, the stiffness of the rotor system is a function of the position of the rotor centroid. Rubbing rotor system is a typical non-linear system since the stiffness changes enormously when the impact happens.

For the Jeffcott rotor, the influence of gravity can be ignored. The Rubbing forces equation can be expressed as:

$$M\ddot{X}+C\dot{X}+KX=F_x+ME\Omega^2\cos(\Omega t) \quad (6)$$
$$M\ddot{Y}+C\dot{Y}+KY=F_y+ME\Omega^2\sin(\Omega t)$$

Where:

$$\begin{bmatrix}F_x\\F_y\end{bmatrix}=H(R-C_2)\frac{(R-C_2)K_c}{R}\begin{bmatrix}-1&\mu\\-\mu&-1\end{bmatrix}\begin{bmatrix}X\\Y-Y_0\end{bmatrix}$$
$$H(X)=\begin{cases}0 & x\le 0\\1 & x>0\end{cases}$$
$$R=\sqrt{X^2+(Y-Y_0)^2}$$

The VP model of the impact-rub rotor system is established by ADAMS omitting the bearing houses, shown in Fig. 2. In order to simulate rubbing phenomena, the shaft is considered as a flexible body that can be generated by ANSYS Modal Neutral File. There are four Interface Points of flexible link, which are arranged at bearing inner ring and disc on both ends, respectively. The contact between disk and rotor is Hertz contact, rotor for steel, stator for aluminum. Contact parameters are as shown in Table 1.

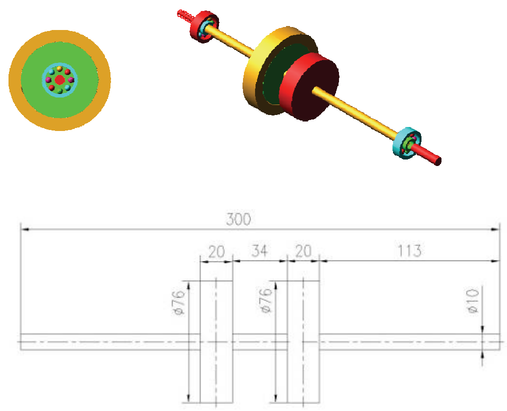


Fig. 2 The VP model of the impact-rub rotor system

Table 1 Contact parameters between rotor and stator

I t e m / U n i t	Value
stiffness/N/mm	50000
damping/N-sec/mm	50
Exponent	1.5
penetration depth/mm	0.1
static friction vel./ mm/sec	0.1
Dynamic friction vel./mm/sec	10
static friction coeff.	0.3
dynamic friction coeff.	0.25
coefficient of Restitution	0.15

Study on impact-rub rotor system with the journal bearing has been investigated. In this paper, rolling bearings are simulated to consider their variable stiffness. The corresponding adjustment has been done to the test rig.

For the ball bearing, the relationship between the contact load Fn and contact deformation can be expressed as:

$$F_N=K\cdot\delta^{3/2} \quad (7)$$

Equation 7 shows that the relationship of the contact load and deformation is non-linear. When the amplitude ΔF_N and the average amplitude F_{N0} of the variable load change little, the contact stiffness of the Loading point can be linearized and approximately expressed as

$$s=\frac{dF_N}{d\delta}\Big|_{F_{N0}}=\frac{3}{2}(K^2F_{N0})^{\frac{1}{3}} \quad (8)$$

The effect of variable stiffness is obtained by measuring displacement change of the bearing inner ring with the load angle, shown in Fig. 3. The amplitude variation is less than 7% of the overall displacement.

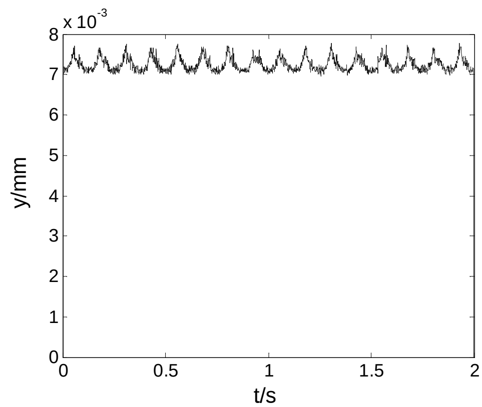


Fig.3 Displacement of the bearing inner ring with the load angle change

3. The simulation results

The advantages of VP are to obtain different system characteristics by different working conditions under virtual environment. Due to paper limit, coast-up process with frequency range from 0 to 70Hz is demonstrated with one set of parameters. The rotor's eccentric mass is 0.005Kg, the eccentricity of rotor is 30mm, the initial eccentricity is 0.13mm.

The waterfall plot of the horizontal displacement is shown in Fig.4. It describes the whole process from no rub-impact to all round rub-impact.

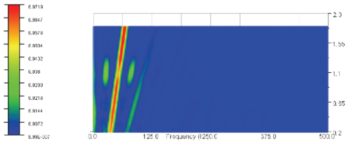
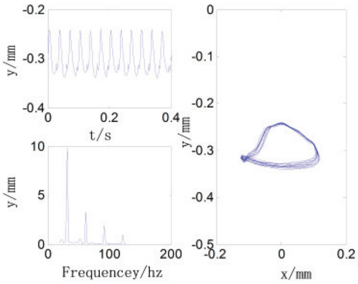
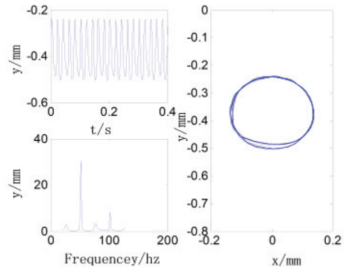


Fig.4 Waterfall plot of horizontal displacement

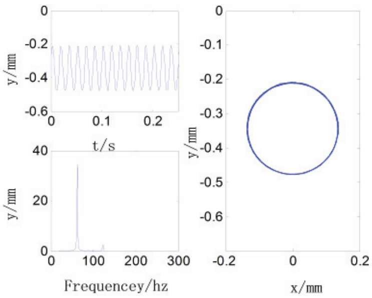
According to the waterfall plot, three typical vibration phases are selected to analyze the vibration characteristics through waveforms, spectra and orbit of the shaft center, shown in Fig. 5.



a) 25Hz slightly and locally rub-impact



b) 50Hz seriously and locally rub-impact



c) 60Hz all round rub-impact

Fig 5 Result of virtual prototyping simulation

When the rotating speed is increased to 25Hz, there is some sign of slight rubbing in the orbits. 2X component can be clearly seen from the spectrum except the 1X component. At 50Hz, not only the rub-impact but also the bifurcation phenomenon can be observed. The spectrum shows the 1/2 fractional harmonic components, such as 1/2X, 3/2X, etc. Certainly the 2X component is still big. The orbits show two circles. When the motion has passed the critical speed, the full round rub-impact happens at 60Hz. 2X component becomes smaller.

4. Experimental validation

In order to validate the simulation results, the corresponding tests are carried out. The test rig shows in Fig. 6. The original rub-impact structure does not agree with most cases of the real rotor-to-stator rub-impact. Only the point contact is available. In order to simulate the real process of the rub-impact, a special structure is designed, as shown in Fig 7. It is convenient to adjust the position of the stator.

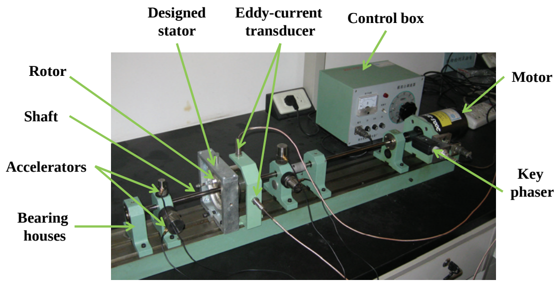


Fig. Experimental test rig

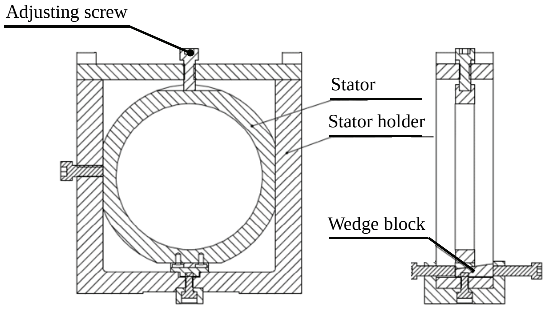
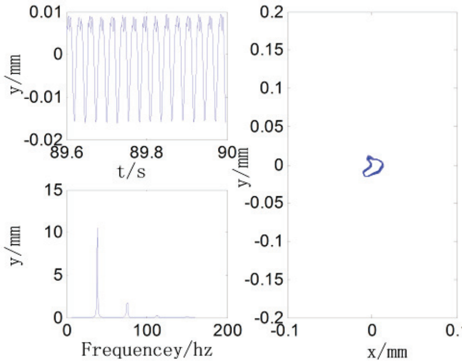
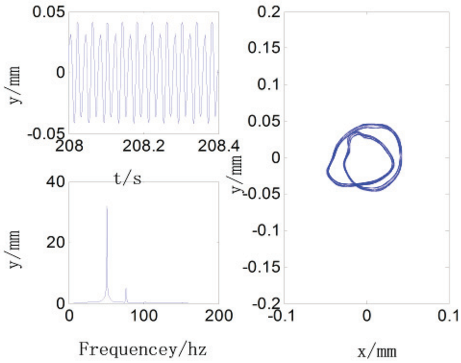


Fig. 7 Self-designed rub-impact components

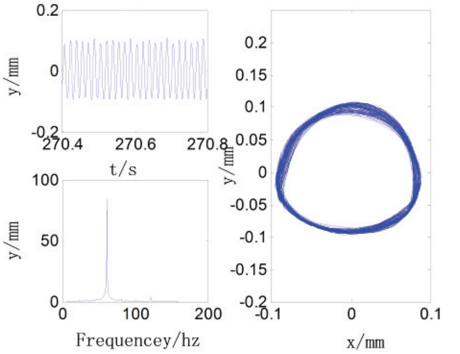
Through adjusting the stator structure and control box, the similar condition of the simulation is obtained. The corresponding experimental results are shown in Fig. 8.



a) 33.1Hz slightly and locally rub-impact



b) 50.6Hz seriously and locally rub-impact



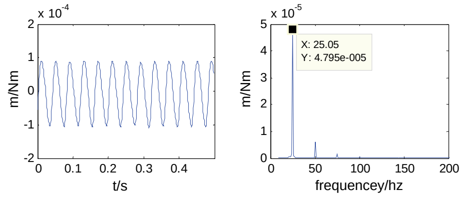
c) 59.4Hz all round rub-impact

Fig. 8 Experimental results

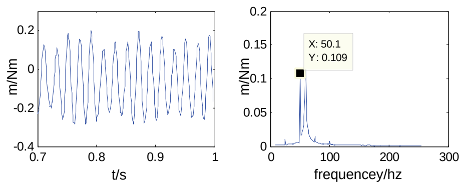
The results of simulation by VP are well consistent with the results of experiment. Also, the results of this paper are similar to the published papers.[5-8]

5. Torque change of rub - impact rotor

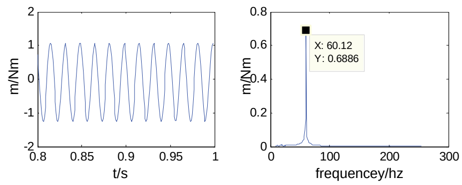
Due to the existence of nonlinear rub-impact force, torque will change when rotor and stator collides. By measuring the torque of the torsion spring in the VP, we can observe its change law.



a) 25Hz slightly and locally rub-impact



b) 50Hz seriously and locally rub-impact



c) 60Hz all-round rub-impact

Fig 9 Torque time-frequency diagram of typical rub-impact fault

Fig.9 is the time-frequency diagram of torque change corresponding to the conditions in figure 4.

Fig.9 (a) is torque change in slightly and locally rub-impact, its frequency change is similar to the amplitude spectrum characteristics in figure 4(a), the frequency-doubled component is obvious.

Fig.9 (b) shows the time-frequency diagram of the torque change in seriously and locally rub-impact, the n/2 sub-harmonic frequency and the resonance frequency appear in the torque spectrum, while the frequency peak is power frequency.

Fig.9 (c) shows the time-frequency diagram of the torque in all round rub-impact, torque spectrum appears the power frequency and the resonance frequency, the highest peak is the power frequency.

The frequency spectrum changes of torque in rub-impact of different degree can be used as a judgment for rub-impact fault.

Conclusion

Based on the VP technology, a rub-impact rotor model system is established to investigate vibration characteristics considering the influence of variable stiffness of rolling bearing. The simulation results are consistent with experiment ones and the published papers.

By VP simulation and test, we can draw the following conclusions:

1) The displacement spectrum of rotor is mainly the power frequency and frequency-doubled when the rotor is in slightly local rub-impact and the axis orbit appears a closed loop.

2) The n/2 sub-harmonic frequency and the resonance frequency appear in the displacement spectrum when the rotor is in severe local rub-impact and the axis orbit appears two circles.

3) When rotor is in severe full annular rub, its axis orbit appears a circle, but the power frequency, minor frequency-doubled components and the n/3 frequency components appear in the displacement spectrum of rotor.

4) By the VP simulation of rub fault, we can observe the torque has power frequency, multiplier and the resonance frequency in the different rub state. It can be regarded as the characteristic sign of rub fault, and applied to the state detection of rub fault and early diagnosis.

Acknowledge

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