A NOVEL CONTROLLABLE BACK-UP BEARING FOR ACTIVE MAGNETIC BEARINGS*

Zhu Changsheng
College of Electrical Engineering, Zhejiang University, Hangzhou Zhejiang 310027 China
cszhu@hotmail.com

ABSTRACT
All high performances of active magnetic bearings (AMBs) greatly depend on the reliability of the AMBs in normal and emergency conditions. Since the loading capability of the AMBs is limited and the rotating rotor will drop to the stator when the current of the coils is suddenly cut off or some parts of the AMBs, such as sensor, control system, power amplifiers, fail. In order to improve the reliability of the AMBs, a parallel back-up support system, as part of the AMBs design, should be used. Therefore, the back-up bearing is one of key elements to use successfully the AMBs in the rotating machinery and to improve the reliability of the AMBs. In order to develop a good performance back-up bearing for the AMBs, a novel controllable back-up bearing consisted of a general back-up bearing and a controllable flexible support which is based on eddy-current principle is presented in this paper. After shown the basic structure and principle of the novel controllable back-up bearing, the dynamic behaviors of the controllable back-up bearing with a fixed clearance ball bearing to improve the dropping dynamics after the AMBs failure are experimentally investigated, and the effectiveness of the novel controllable back-up bearing in controlling the transient vibration during rotor dropping is validated. It is shown that the dynamic behaviors of the novel controllable back-up bearing can be controlled and the novel controllable back-up bearing can greatly suppress the transient vibration during rotor dropping.

INTRODUCTION

Active magnetic bearings (AMBs), unlike the conventional fluid-lubricated bearings, utilize a magnetic field to levitate and support a rotating shaft without mechanical contract. Not only have the AMBs the advantages of no-oil lubrication, high performance, high surface velocity, and low rotating friction loss etc., but also it has the additional capability for actively controlling the rotor system vibration and improving the stability of the rotor system on-line. However, the loading capability of the AMBs is limited due to magnetic saturation and the rotating rotor will drop to the stator when the current of the coils is suddenly cut off. In order to improve the reliability of the AMBs, a parallel back-up support which is generally also called back-up bearing, auxiliary bearing, touch-down bearing, load-sharing bearing, retainer bearings, and emergency bearing, as part of AMBs design should be installed.

The basic functions of the back-up bearing are to support the rotor when the magnetic bearings don't work at initial stage, to shear temporarily the load of the rotor system when the AMBs are overload, or to support the rotor system during the shut-down when the coil current of the AMBs are cut off during operation for some reasons. Therefore, the back-up bearing is one of key elements to use successfully the AMBs in the rotational machinery and to improve the reliability of the AMBs.

The back-up bearings consisting of a rolling-element bearing with a fixed clearance are often used in the AMB systems[1-13]. Furthermore, solid bronze bushing bearing[1,4-8], plain bearings[14], planetary bearings[15], zero-clearance back-up bearing[15], foil bearings[16], eventually graphite bearings, and deformable gliding rings with damping properties, etc have been studied. However, there are some disadvantages for above mentioned back-up bearings, such as the uncontrollable dynamic characteristics, complex structure, adding oil in a no-oil system etc. In order to develop a high performance back-up bearing for the AMBs, this paper presents a novel controllable back-up bearing in which a controllable flexible support based on eddy-current principle is combined with any type of the back-up bearing mentioned above in series [17]. The main objectives of this paper are to investigate experimentally the dynamic behavior of the

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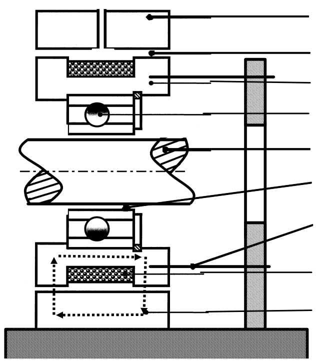
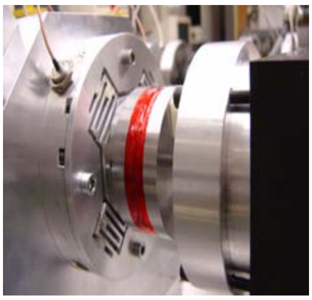
novel controllable back-up bearing with a fixed clearance ball bearing, and to determine the effectiveness of the novel controllable back-up bearing in controlling the transient vibrations during rotor dropping.

STRUCTURE AND PRINCIPLE OF NOVEL CONTROLLABLE BACK-UP BEARING

The basic structure of the novel controllable back-up bearing under study is shown in Figure 1(a) and picture of the back-up bearing used in test is shown in Figure 1(b). Where a ball bearing with a fixed clearance is taken as an example of the back-up bearing. In fact, the novel controllable back-up bearing is a combination of any type of back-up bearing mentioned above and a controllable flexible support in series. For the ball bearing, the inner surface of the inner ring and the outer surface of the shaft is formed a fixed radial clearance back-up bearing. The fixed radial clearance is named back-up bearing radial contact clearance. In addition to the ball bearing, the other types of the general back-up bearing, such as solid bronze bushing bearing, plain bearing, planetary bearing, gliding ring, and graphite bearing etc can also be used.



(a) Schemic of novel controllable back-up bearing



(b) Picture of the back-up bearing used in test

FIGURE 1: Structure of novel controllable back-up bearing

The controllable flexible support is very similar to that of the conventional squeeze film damper but no fluid is filled in the annular clearance between the outer ring and the inner ring, and a coil wound circumferentially in the inner ring rigidly mounted on the outer race of the ball bearing is installed. The annular clearance is named back-up radial magnetic clearance, the coil as back-up bearing coil. Of course, the circumferential coil can be wound in the outer ring, but the isolating magnetic element should be used in order to setup a required magnetic field in the radial magnetic clearance. In the novel controllable back-up bearing, there are two radial clearances, i.e., radial magnetic clearance and back-up bearing contact clearance, the sum of them should less than the radial contact clearance of the AMBs.

The centralizing spring can be any type, such as squirrel cage, flexible bars, and curved beam. Its functions are to centralize the ball bearing in the steady state, to prevent rotating of the outer race of the ball bearing, and to provide an initial stiffness for the back-up bearing.

When a DC voltage is applied in the coil of the back-up bearing, the magnetic flux density in the radial magnetic clearance will produce. When the rotor drops in the ball bearing after the failure of AMBs, the inner ring moves with the ball bearing in the magnetic field, the two forces will be produced in the inner ring if the inner and outer rings are made of magnetic materials, one is radial unbalanced magnetic pull force due to the magnetic field un-uniform in the circumferential direction, the other is eddy current force which is proportional to the velocity of the inner ring and in opposite to the velocity of the inner ring. Only the eddy current force is formed if one of the inner and outer rings is made of no-magnetic material. If the current of the back-up bearing coil is changed, the dynamic characteristics of the controllable flexible support or novel controllable back-up bearing will be controlled in a simple manner.

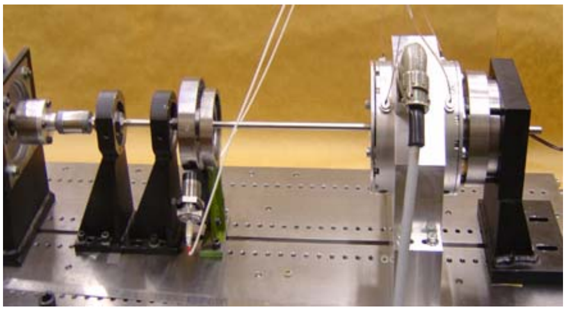
TEST RIG OF THE AMB WITH THE BACK-UP BEARING

Rotor System

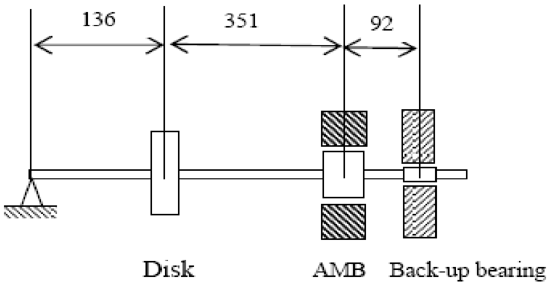
The AMB rotor test rig with the novel controllable back-up bearing is shown in Figure 2. It basically consisted of a uniform flexible shaft with a diameter 8 mm and a length 700 mm, a uniform disk located at the middle of bearing span, a novel controllable back-up bearing, a flexible coupling and a variable speed motor with a speed close-loop control. The disk with equal-space balancing holes is with a weight of 0.68 kg and a diameter of 100 mm.

The rotor system could run with a given acceleration or deceleration rate controlled by a computer or maintained any given rotational speed within 500-6000 rpm. The flexible coupling connected the shaft with the motor in order to reduce the influence of the motor vibration on the rotor system.

For simplicity, the flexible rotor was supported by a self-aligned radial ball bearing at the driven side and by the controllable back-up bearing in the non-driven side. The geometrical size of the rotor system is shown in Figure 2(a). In order to limit the shaft deformation and protect the rig from being damaged while the rotor passed through the critical speed, four safety supports are used at the sides of the disk and the AMB.



(a) Test rig system



(b) Basic size of the rotor system(dimensions are in mm)

FIGURE 2: The test rig

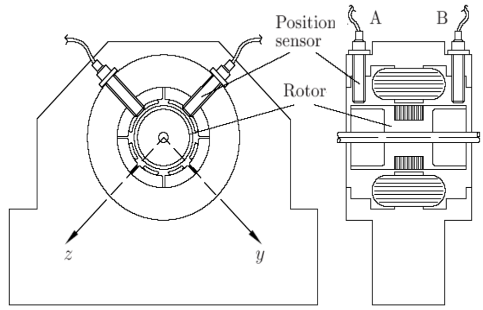
Active Magnetic Bearing

The active magnetic bearing used in test was with 8 polars, the diameter of the journal and the inner diameter of the AMB are 56 and 57.6 mm, respectively. The area of each polar is 290 mm^2, the axial length of the polar is 26 mm, the diameter of wire is 2.1 mm, the resistance is 0.35 Ω. All weight of the AMB journal is 1.061kg. The center of the magnetic polar is at 45 degree with respect to the vertical direction as shown in Figure 4(a).

A power amplifier was switching type with 8 channels and with a band of response frequency over 2 kHz, and output current of 8 A for each channel. The dynamic performance of every channel are same each other.

Measurement System

The vibrations of the rotor system in both horizontal and vertical directions at the AMB's journal and the disk positions were measured with eddy-current proximity probes in the 45 degree direction with respect to the vertical direction. Since the centre of every pair magnetic polar is also in the *z* or *y* direction, therefore, the dynamic behaviors of the AMB system in the *z* and *y* directions as shown in Figure 4(a) are same. Since it is difficult to measure directly the vibration of the AMB centre, the two pairs of eddy current proximity probes were installed at the outsides of the AMB, as shown in Figure 4(b). The signals from the two pairs of eddy current proximity probes were processed using operation amplifiers to obtain the vibration of the centre of the AMB.



(a) Coordinate system (b) Journal sensors

FIGURE 4: Method to measure the vibration of center of the AMB

Back-up Bearing

The back-up bearing in test was a ball bearing of type 6006 with a fixed radial clearance. The weight of the ball bearing is 0.106 kg. In order to study the effect of the contact material on the drop dynamics, an additional journal was mounted on the outer surface of the shaft, and a bush was installed on the inner race of the ball bearing. The journal is with outer diameter of 25.0 mm, width of 35 mm, and weight of 45 g. The inner diameter of the bush is 25.75 mm, and its width is 30 mm. The materials of both the bush and the journal are steel.

The basic parameters of novel controllable back-up bearing in test are: number of coil turns is 580, the diameter of wire is 0.56 mm, the axial total width is 35 mm, the outer diameter of the inner ring is 80 mm, the inner diameter of the outer ring is 80.8 mm, and the width of the coil is 15 mm. The weight of the inner ring and the coil is 1.20 kg. All weight of the moving part of the back-up bearing is 1.390 kg.

The DC power supply for the magnetic coil of the back-up bearing was a programmable DC voltage power with maximum output voltage 60 V and maximum output current 2.5 A.

Control System of the AMBs

The control system for the AMB and vibration measurement system was based on a d-SPACE and host PC. The basic structures of the control and measurement systems are shown in Figure 5. Since the control of the d-SPACE system is based on the MATLAB SIMULINK, a SIMULINK model in the

MATLAB should be firstly build, and then transform the SIMULINK model to the d-SPACE system to realize the required control algorithm. The SIMULINK model shown in Figure 6 is consisted of three blacks, ERROR, PID and CURRENT. The black ERROR is to obtain the error signals of the journal at the AMB. The black PID is the PID control about the error signals. The black CURRENT is to obtain the control current for each coil after considering the offset currents in every coil. In the normal operation, the control currents are directly applied into the coils after the power amplifier.

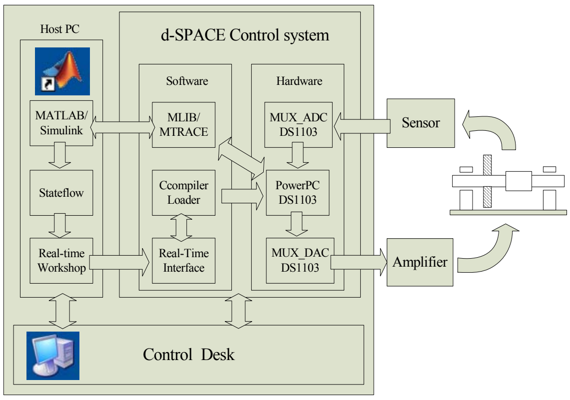


FIGURE 5: Control and measurement systems based on a d-SPACE and a host PC

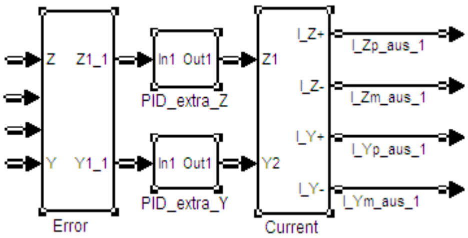


FIGURE 6: PID control

Since some tests were carried out at the super-critical speed region, in order to avoid the larger vibration during passing the critical speed after the AMB failure and to sure the dropping test repeatability, the power of the motor did not cut off after the AMB failure. Since the power of the motor is much high, so the contact of the rotating rotor with the back-up bearing does not cause any change of the rotating speed, the motor runs at the almost same rotational speed as before.

The first-two flexible critical speeds of the AMB-rotor system in which one side was supported on the self-aligned radial ball bearing at one side and on the AMB in the other side were 2190 rpm (36.5Hz) and 3570 rpm (59.5Hz), respectively.

Control Method of Rotor Dropping Position

In order to obtain the repeatable results at the same rotational speed, rotor imbalance and control parameters in different dropping tests, two basic problems should be solved in test. First is to switch the coil currents of the AMB off at the same time, second is to make the angular location of the rotor in the dropping tests be same. Many methods were tried in test, a good method was found and shows as follows.

In test, only one AMB with four coil currents should be switched off/on. In order to switch the four coil currents of the AMB off/on at the same time, the four control currents after the black CURRENT as shown in Figure 6 are transformed to a vector by Mux function in the SIMULINK, then multiple a parameter K_p, finally, the current vector is derived into four control currents by Demux function in the SIMULINK, and applied to the coils after the power amplifier. The basic structure is shown in Figure 7. The multiple vector can guarantee the every component in the vector change at the same time. If K_p is 1, the control currents do not change, if K_p is set to 0, the control currents are zero. Therefore, if K_p is set to 0 from 1, the four control currents will be zero at the same time, if K_p is set to 1 from 0, the four control currents will be reseat to the normal from zero at the same time. Since the power amplifier is with a high response frequency and every channel is same, so the change of the coil currents after the amplifier is synchronous. The measured coil currents during switching K_p show that the synchronous coil currents can be obtained.

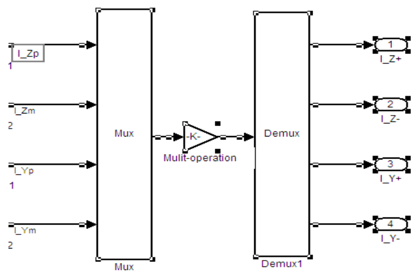


FIGURE 7: The synchronous switching method

The time of switching the parameter K_p is determined by the angular location of the rotor. The angular location of the rotor depends on the motion orbit of the rotor system. For example, if we want the rotor drop at 0 degree position in Figure 8, the vibration of the rotor in the vertical direction is taken as the reference signal, when the reference signal change from the positive to negative, we only need to set K_p be zero, the coil currents of the AMB will switch off at the time when the rotor just pass the 0 degree. The time error for different dropping tests at the steady operation conditions is very small. Therefore, the angular locations of the rotor system at different dropping tests can keep almost same. For example, when the sampling frequency is 8192 Hz, the sampling length is 1024, the difference of the angular locations is about 2.2 degree. Using the method to control the angular locations, the repeatability rate of dropping tests at the same operation conditions is more than 95% when the motion orbit of the rotor system is more regular.

The experimental process was as follows: Firstly, let the rotor run at a given rotational speed and make sure the rotor be steady state. Then the host PC sends a command to the d-SPACE to do the dropping test, the d-SPACE will find the required rotor dropping position and switch the control currents off. If the AMB is returned to the normal from the failure, another command is need to reseat the parameter K_p to 1. In this way, we can make the AMB fail or reseat easily only by means of sending a command from the host PC.

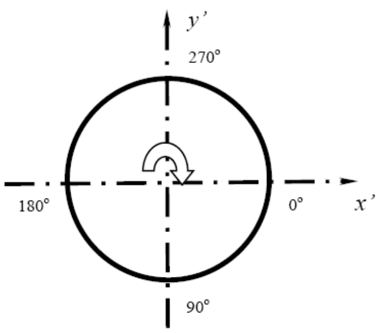


FIGURE 8: Control of rotor dropping position

RESULTS AND DISCUSSIONS

The systemically experiments on different conditions, such different rotational speeds in the sub-critical speed region and in the super-critical speed regions, different rotor imbalances, etc, were carried out.

Before the rotor dropping test, the frequency response functions of the flexible support at different back-up bearing coil currents were measured by hammer test in order to show the controllability of the flexible support. Figure 9 is the frequency response curves of the flexible support in the vertical direction at different back-up bearing coil current. It is shown that when the back-up bearing coil current is zero, the peak in the frequency response curve is highest, and the peak frequency at which the peak occurs is highest. This means that the damping of the flexible support is much low. With the increase of the back-up bearing coil current, the peak greatly decreases and the peak frequency moves towards the lower frequency. The change of the peak and the peak frequency shows that the dynamic characteristics are controllable and the damping of the flexible supported greatly increases with the coil current. In fact, the variations of the peak and the peak frequency are produced by the effects of both the magnetic pull force and the eddy current damping force. After analyzing the variation of the peak and the peaking frequency with the coil currents, it is found that the effect of the eddy current damping force is much larger than that of the magnetic pull force.

It should be noted that in the flexible support shown in Figure 1(b), the center of the contact surface of the back-up bearing with rotating rotor is not at the center of the flexible support, so the eccentricity of the inner ring with respect to the outer ring was larger, so the maximum coil current was about 0.8 A in the steady state, only about 0.5 A at the dynamic operation. If the applied current in the coil is over the maximum, the inner ring will be attracted to the outer ring. In this case, the characteristics of the flexible support can't be controlled any more. Therefore, the maximum coil current in test was 0.4A. Reducing the eccentricity can greatly increases the maximum coil current, and the effect of the flexible support on the controllable back-up bearing will more obvious.

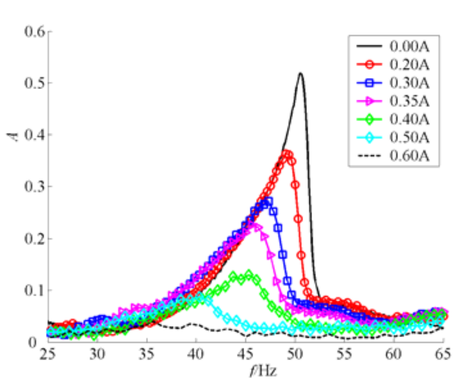


FIGURE 9: Effect of back-up bearing coil current on the frequency response function of the flexible support

Figure 10 is a transient journal motion orbit results of the rotor system in dropping with different coil current at the steady levitation state. The motion orbits in same line had the same coil current, but measured at different dropping tests. It is shown that when the rotor does not rotate, the orbit of the journal is very small, so when the currents in the AMB is de-active, the rotor will drop in the vertical direction and the journal motion after dropping is the oscillation motion back and forth with bounces in the bottom half of the clearance circle. At the same conditions, the motion orbits in dropping at the different drop tests are very similar, the results are repeatable.

Figure 11 is the journal transient motion orbits of the rotor system in dropping with different the back-up bearing coil currents after the AMB failure at the sub-critical speed region of the rotor system. It is

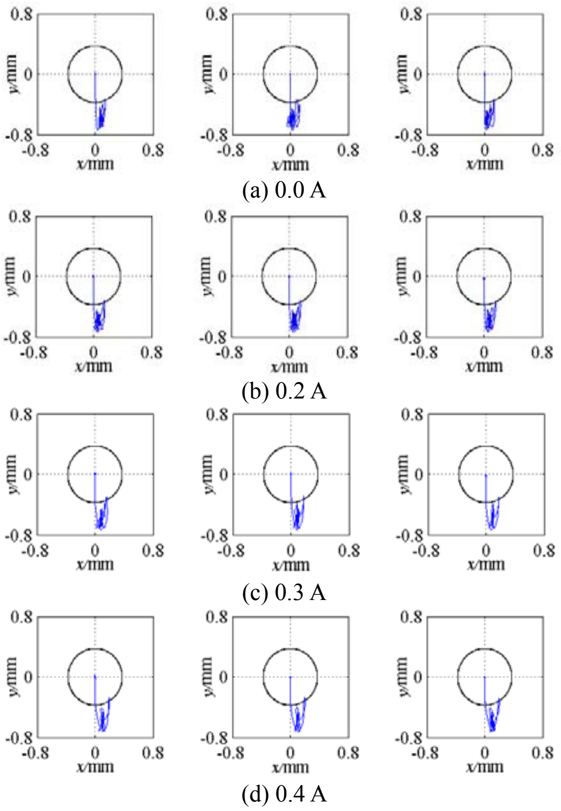


FIGURE 10: Rotor dropping motion orbits at different coil currents at the speed of 0 rpm

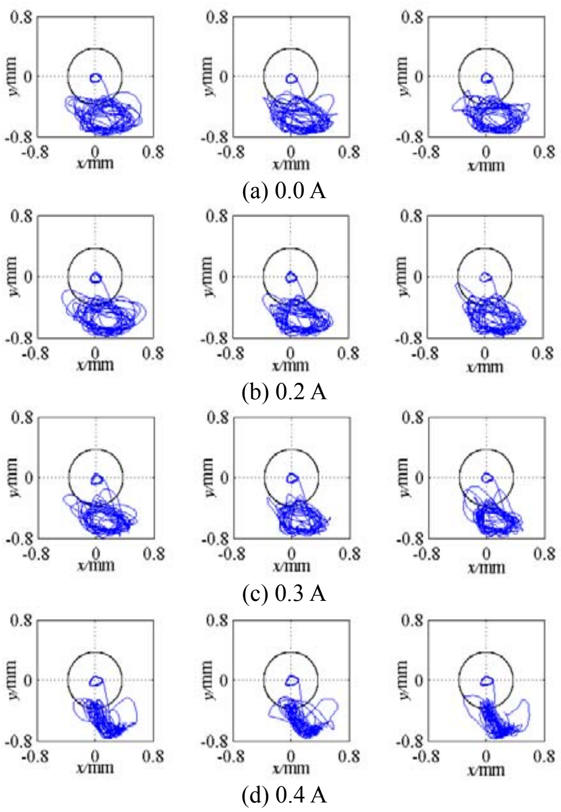


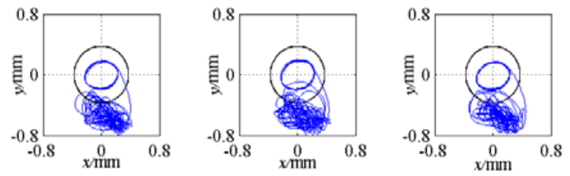
FIGURE 11: Rotor dropping motion orbits at different coil currents at the speed of 1600 rpm

shown that the basic phenomena at the same back-up bearing coil current are similar, but there are obvious differences in the different back-up bearing coil currents. When no coil current in the back-up bearing, the motion orbits in dropping are larger and the rotor takes a long time to approach the stator. If the rotor imbalance is small, the rotor motion is the oscillation motion back and forth with bounces in the bottom half of the clearance circle after the AMB failure as shown in Figure 12. If the rotor imbalance increases further, the vibration of the rotor system becomes larger, the full clearance whirl motion with impact and full clearance whirl motion without impact in dropping will occur[18], which have a greatly affect on the rotor vibration and reliability of the back-up ball bearing. When a current is applied in the back-up bearing coil, the obvious change in the rotor transient motion in dropping after the AMB failure is observed, the dropping motion orbits become small and the time to approach to the bottom of the clearance circular shortens. With the increase of the back-up bearing coil current, the motion orbits of the rotor in dropping becomes smaller and smaller and the dropping time to the bottom of the clearance greatly decreases. The results show that the novel controllable back-up bearing can effectively control the rotor motion orbits and dropping time in the rotor dropping.

Figure 12 is journal transient motion orbits of the rotor system in dropping with different back-up bearing coil currents after the AMB failure at the critical speed region of the rotor system. At the critical speed region, the steady motion orbits are larger; the rotor in dropping is still the oscillation motion back and forth with bounces in the bottom half of the clearance circle. With the increase of back-up bearing coil current, the transient motion orbits decreases.

Figure 13 is journal transient motion orbits of the rotor system in dropping with different back-up bearing coil currents after the AMB failure at the super-critical speed region of the rotor system. At the super-critical speed region, the steady motion orbits become small since the rotational speed is away from the critical speed. After the AMB failure, the rotor drops into the bottom half of the clearance circle, the oscillation motions back and forth with bounces in the bottom half of the clearance circle are much small. Even if the oscillation motion in dropping is small, the rotor motion orbits can further decrease as the back-up bearing coil current increases.

It is shown that the effects of the back-up bearing coil currents on the rotor dropping motion orbits in the sub-critical speed region, the critical speed region and the super-critical speed region are similar, i.e., with the back-up bearing coil current increases, the rotor motion orbits in dropping decrease, and the possibility for



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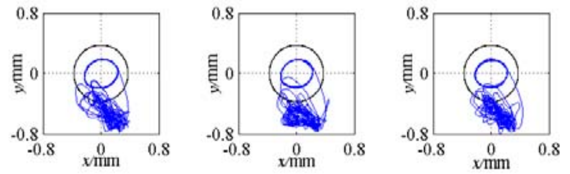
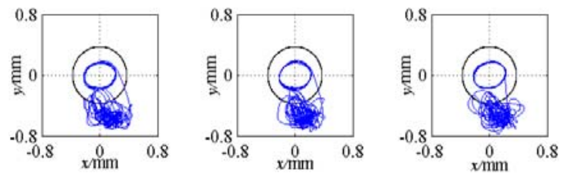


(b) 0.2 A



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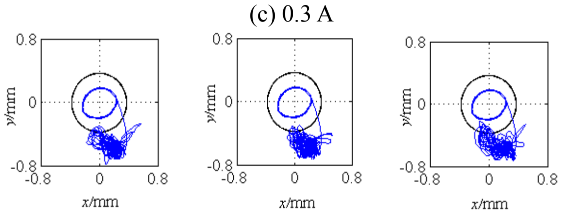
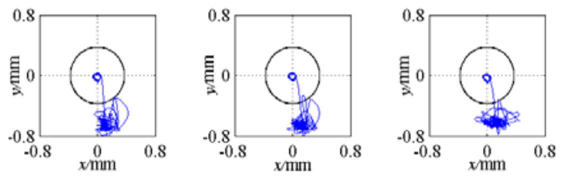


(d) 0.4 A

FIGURE 12: Rotor dropping motion orbits at different coil currents at the speed of 2100 rpm



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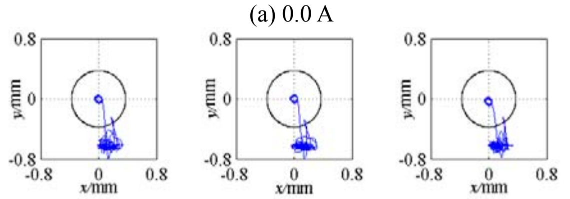

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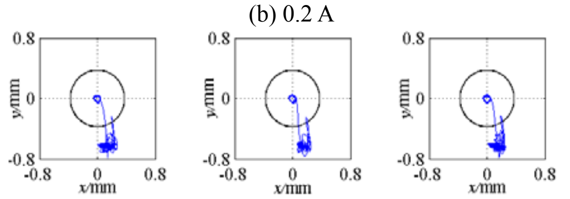

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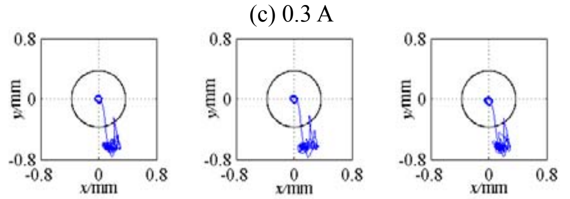

(d) 0.4 A

FIGURE 13: Rotor dropping motion orbits at different coil currents at the speed of 3000 rpm

occurring the full clearance whirl motion with impact and full clearance whirl motion without impact in dropping becomes less. If the structure of the novel controllable back-up bearing is optimized and the magnetic flux density in the radial magnetic clearance increases further, the effect of the novel controllable back-up bearing on the rotor dropping motion orbits will be more significant.

CONCULATION

A novel controllable back-up bearing, which is a combination of a general back-up bearing and a controllable flexible support based on eddy-current principle in series, is presented in this paper. After being shown the basic structure and principle of the novel controllable back-up bearing, the dynamic behaviors of the back-up bearing with a fixed clearance ball bearing to improve the dropping dynamics after the AMBs failure are experimentally investigated, and the effectiveness of the novel controllable back-up bearing in controlling the transient vibration during rotor dropping is validated. It is shown that the dynamic behaviors of the novel controllable back-up bearing can be controlled and the novel controllable back-up bearing can greatly suppress the transient vibration during rotor dropping after the AMB failure.

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