Dynamic Responses of Rotor Drops onto Double-Decker Catcher Bearing

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Abstract

In an active magnetic bearing (AMB) system, the catcher bearings (CBs) are indispensable to protect the rotor and stator in case the magnetic bearings fail. Most of the former researches associated with CBs are mainly focused on the dynamic responses of the rotor drops onto traditional single-decker catcher bearings (SDCBs). Based on the analysis of the disadvantages of SDCBs, a new type of double-decker catcher bearings (DDCBs) is proposed to enhance the CB work performance in AMB system. Detailed simulation models containing rigid rotor model, contact model between rotor and inner race, DDCB model as well as SDCB model after rotor drop are established using Multi-body dynamics simulation software MSC.ADAMS. Then, using those established models the dynamic responses of rotor drops onto DDCBs and SDCBs are respectively simulated. The rotor orbits, contact forces and spin speeds of various parts after AMB failure are mainly analyzed. The simulation result shows that DDCBs can effectively improve reduce the following vibrations and impacts. Finally, rotor drop experiments choosing different types of CBs are carried out on the established AMB test bench. Rotor orbits and the rotating speeds of both inner race and intermediate races after rotor drop are synchronously measured. The experiment results verify the advantages of DDCB and the correctness of simulation analysis. The studies provide certain theoretical and experimental references for the application of DDCBs in AMB system.

1 Introduction

Active magnetic bearings (AMBs) have many advantages over conventional mechanical bearings. In addition to supporting the high-speed rotor without any mechanical friction and lubrication, they enable rotor position and induced vibration to be monitored and controlled by adjusting support stiffness and damping. However, the CBs are necessary to protect the AMBs assembly from direct contact with the rotor. They prevent damages during the maintenance and destruction of the system after a possible AMBs failure.

Kirk et al. [1-2] studied the effect of the support stiffness and damping by evaluation of forced response for numerous rotor-support system parameters and showed an optimum damping. Swanson et al. [3] provided the test results of rotor drops with varying rotor speed, unbalance amplitude and location for the 5 CB configurations. Chen et al. [4] proposed the zero clearance auxiliary bearing and presented its performance over conventional CBs. Xie and Flowers [5] numerically investigated the steady-stator behavior of a rotor on CB studied the effects of various parametric configurations: rotor imbalance, support stiffness and damping. Cole et al. [6] developed a deep groove CB model with the elastic deformation of the inner race, which was modeled as a series of flexible beams and studied parametric effects of impact force, bearing width and inner race speed on ball load distributions. However, a rotor drop simulation was not conducted. Wang and Noah [7] analyzed the steady-state response of a rigid rotor in a positive clearance bush using the fixed-point algorithm and predicted a chaotic whirling of the rotor depending on excitation frequency.

However, most of those researches focused on the CBs support stiffness and damping. For it is hard to modify the bearing stiffness and damping to satisfy the optimum simulation results, a new type DDCB which has two separate rolling element series is proposed in this paper. On one hand, because of the share speed of the intermediate

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race, the limit speed of this new type CB is improved, so it can withstand higher rotor initial rotating speed. On the other hand, for another bearing is added to the traditional CB, it can to some extent buffer rotor vibrations after rotor drop. The advantages of the DDCB are verified by both simulation and experiments.

2 Simulation

2.1 Structure of AMB

Figure 1 shows the studied structure of a motor drive system equipped with magnetic bearings. The motor is located between the two radial magnetic bearings. Each radial magnetic bearing generates radial forces in two perpendicular radial axes. Thrust magnetic bearings regulate the axial forces in the shaft direction. All the magnetic forces are controlled by negative feedback control systems so that the rotor is regulated to the center of the stator bore. Besides those magnetic bearings, two catcher bearings are located in the two ends of the structure respectively to prevent damages in the event of a component, power or a control loop failure. The air gap between the catcher bearing inner race and the rotor is half the air gap of AMB. The outer rings of the catcher bearings are rigidly mounted to the bearing housings which are also rigidly mounted to the ground.

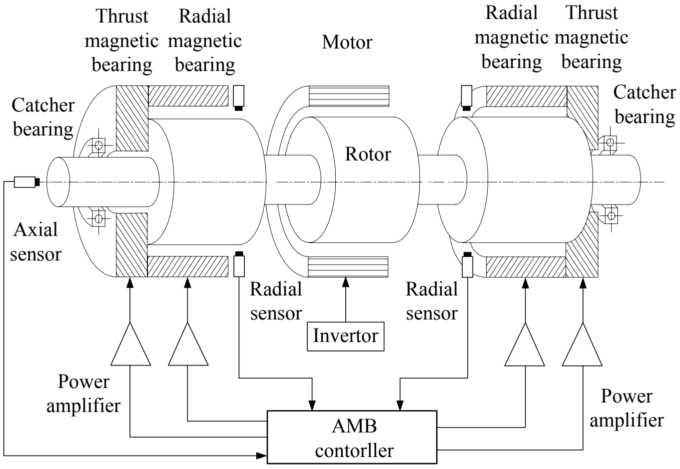
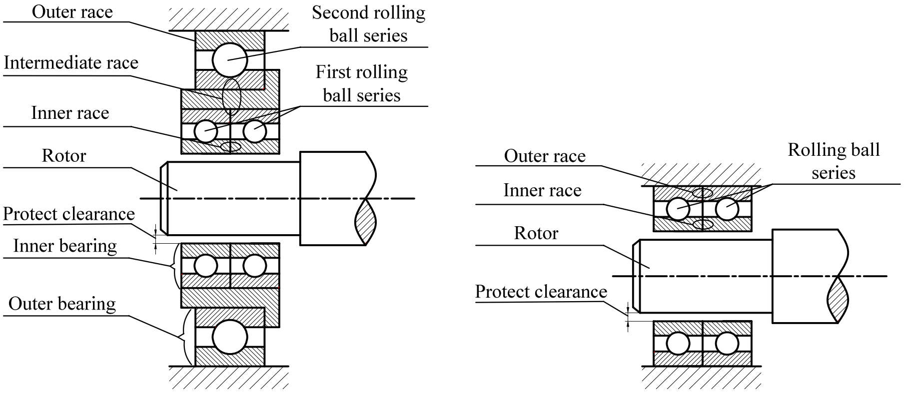


Figure 1: Structure of AMB system

2.2 Structure of CBs

In order to improve the rotational speed of the intermediate race, two deep groove ball bearings (61801) are mounted together to constitute the first layer of DDCB, while an deep groove ball bearing (61805) act as the second layer that is mounted in the bearing housing. The new type DDCB is the combination of those three bearings. The formed three races are denoted as inner race, intermediate race and outer race, respectively. The detailed structure of DDCB is shown in Figure 2(a). The structure of SDCB is also shown in Figure 2(b).



(a) (b)

Figure 2: Structure of DDCB and SDCB

2.3 MSC.ADAMS model

Multi-body dynamics simulation software MSC.ADAMS is used to simulate the rotor drop process [8]. Impact function and recovery coefficient are the two main methods to define the contact in ADAMS. Contact stiffness *k* and damping *c* are used to calculate the crash force in this rotor drop model.

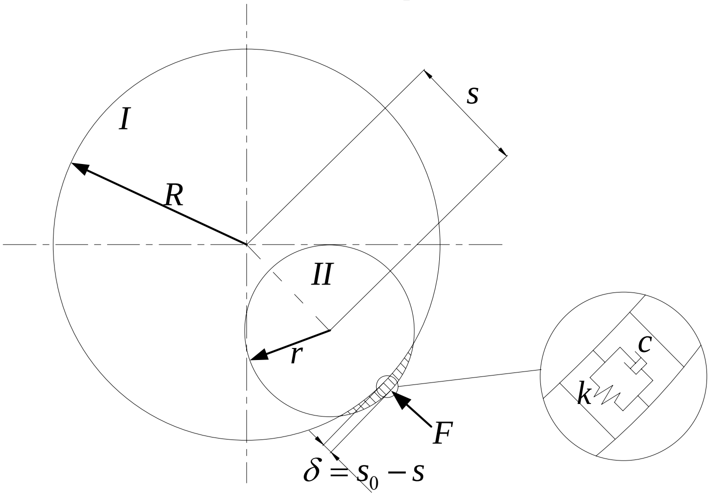


Figure 3: Contact model between rotor and inner race

Figure 3 shows the contact model between rotor and inner race, and the impact function can be expressed as a subsection function:

$$F = \begin{cases} 0 & s \le s_0 \\ k(s - s_0)^e + c\dot{s} * STEP(s, s_0 - d, 1, s_0, 0) & s > s_0 \end{cases} \tag{1}$$

Where $k = 2.4 \times 10^9 \mathrm{N/m}^{10/9}$, $e = 10/9$, $c = 1000\mathrm{N \cdot s/m}$, the contact deepness $s_0 = R - r$; here *R* is the bore radius of inner race, and *r* is the radius of rotor. The *STEP* function is used to prevent the calculation results not converge because of the contact damping mutation, here the punishment depth *d* equals 0.01 mm.

Stiffness-damping contact model is also adopted to define the catcher bearing internal contacts. Based on Hertz theory [9], the contact stiffness between ball and race can be calculated using the bearing geometrical and material parameters. As there is no reliable theoretical method to calculate the bearing damping, empirical values are chosen in this paper.

Parameters	Inner bearing (61801)	Outer bearing (61805)
Contact stiffness between ball and inner race (N·mm-3/2)	4.9×10^5	5.98×10^5
Contact stiffness between ball and outer race (N·mm-3/2)	4.3×10^5	5.18×10^5
Contact damping (N·s/m)	800	1000
Contact parameter	3/2	3/2

Table 1: Relevant parameter of double-decker catcher bearing

In order to simplify the modeling process, two separate models of inner and outer bearing are merged together in ADAMS as shown in Figure 4. The use of this method realizes the model establishments of rotor drops onto DDCB and SDCB synchronously.

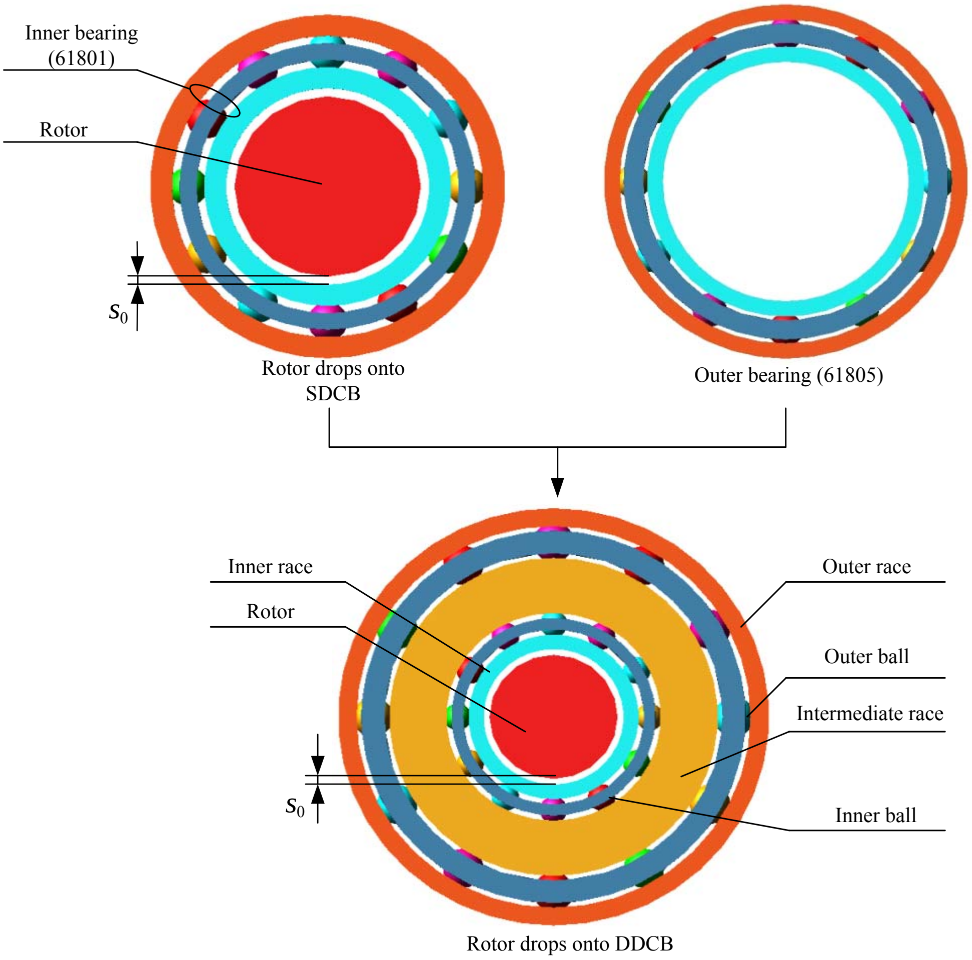
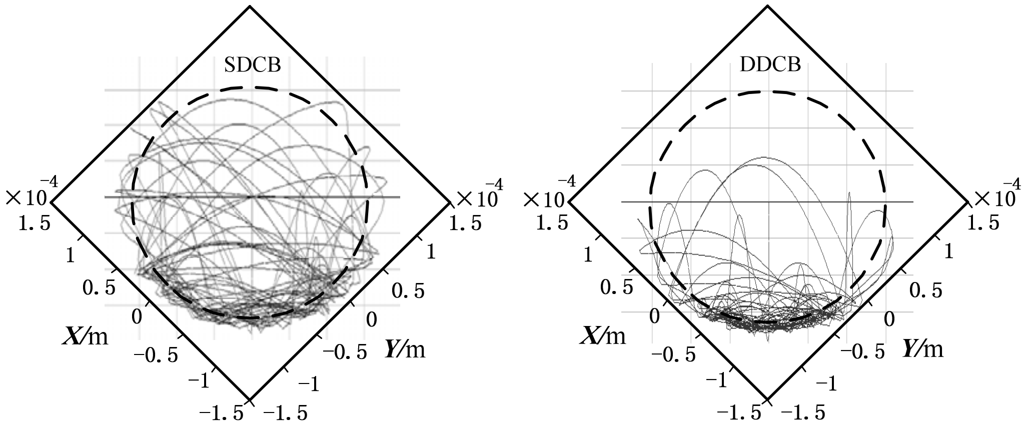


Figure 4: Model of rotor drop in catcher bearings

Using the AMB support characteristics which can be calculated using the relative AMB parameters, the model during normal operation not presented in this paper is also established to get the rotor initial motion state before rotor drop.

2.4 Simulation results

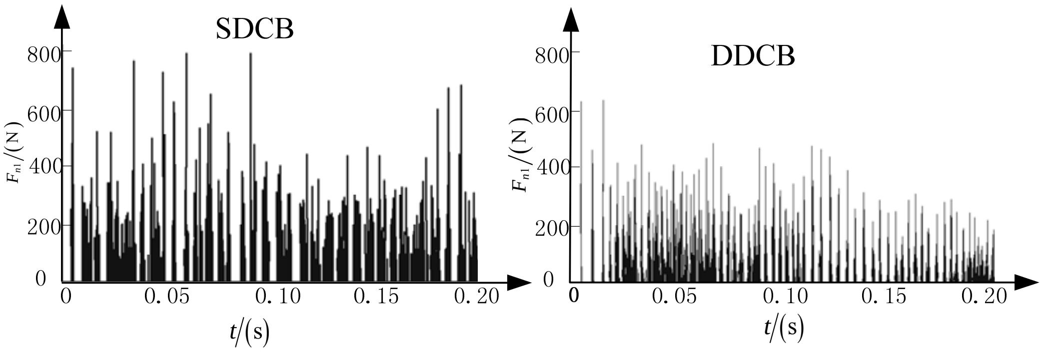
Figure 5 shows the orbits of the left journal for different CB types from 0 to 0.2 seconds after rotor drop obtained by simulation. The nominal catcher bearing clearance circle is also shown with the orbit plots. It can be seen from the figure that, the angular range of the rotor vibration using DDCBs is significantly smaller than the range using SDCBs. And the use of DDCBs helps to decrease the amplitudes of rotor vibration at least 30% after rotor drop.



(a) SDCB (B) DDCB

Figure 5: The orbits of the left journal obtained by simulations for various CB types

The contact forces between the left journal and inner race after rotor drop are presented in Figure 6. Due to the added outer rolling bearing, the support stiffness of the DDCB is smaller, while the damping is larger. The changes of the support characteristics make the maximum contact forces drop about 20%~30% compared to the initial results using SDCBs. Because of the increase of the support damping, the contact force using DDCBs decays a little faster.



(a) SDCB (B) DDCB

Figure 6: The contact forces between the left journal and inner race obtained by simulations for various CB types

3 Experiments

Rotor drop experiments for different CB types are carried out to verify the established dynamic models and the performance of DDCB. Figure 7 shows the mechanical parts of DDCB, SDCB as well as the corresponding bearing blocks.

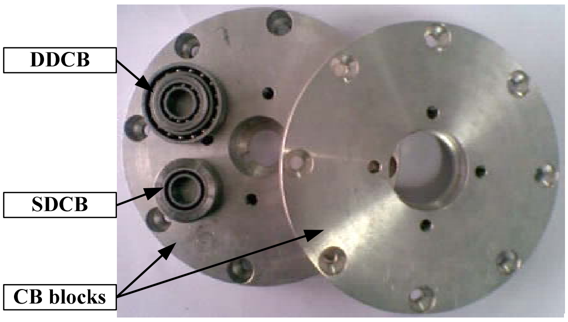


Figure 7: Photograph of the CBs and CB blocks

Figure 8 shows the experimental facilities necessary for measurement. The system adopts eddy current sensor to realize the measurement of rotor vibration displacement, which also have to be known for controlling the AMBs anyway. A fiber sensor is used to detect the black and white stripes painted on the rotor. Then the rotor spin velocity can be calculated by using the output signal of the fiber sensor collected by the Labview data acquisition (DAQ). In order to quantify the rotating speeds of the inner and intermediate races, two fiber sensors are adopted. The measurement principle is the same as that for the rotor spin velocity. Infrared thermo scope is used to measure the CB's real-time temperature after rotor drop. The data acquisition boards collect all the sensor signals except the temperature signals. For the data acquisition, three boards NI-9215 from National Instruments are chosen. A subsequent analysis of the collected data is carried out with MATLAB software.

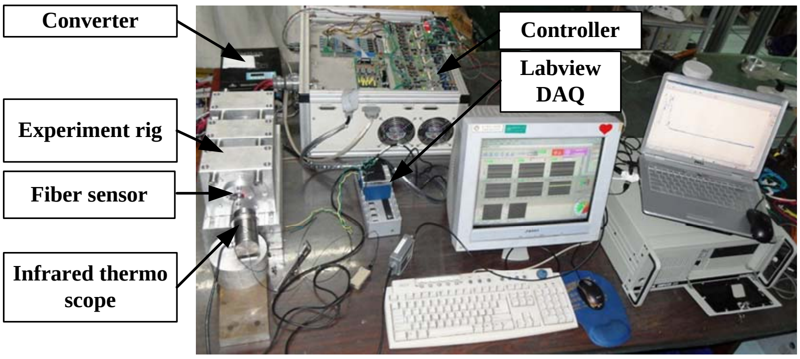
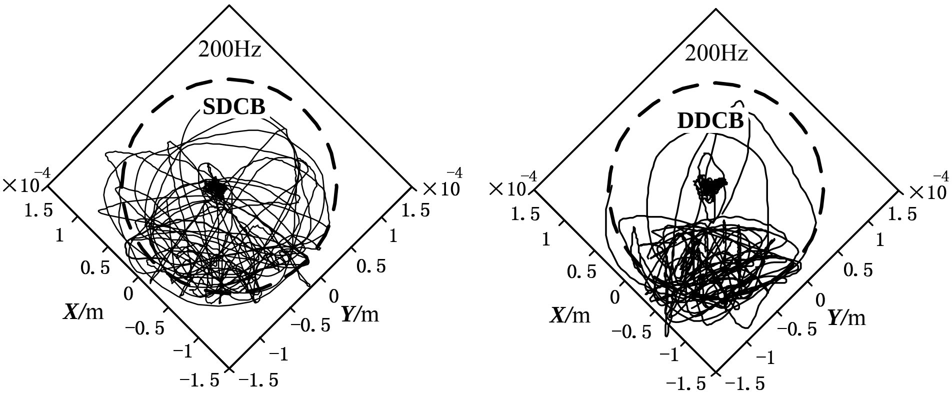


Figure 8: Photograph of the experimental facilities

Figure 9(a)-(b) present the orbits of the left journal after rotor drop at the rotor initial rotating frequency 200Hz obtained by experiments. Comparing Figure 6 and Figure 9, the experimental results are basically correspondent with the simulation results.



(a) SDCB (b) DDCB

Figure 9: The orbits of the left journal obtained by experiments

To gain a better understanding of the dynamical behavior of DDCB, The frequencies of different rotating parts obtained by rotor drop experiments are shown in Figure 10. The inner race is accelerated very quickly up to the maximum velocity. At the time $t_{\mathrm{bi1}} \approx 0.04$ s, inner race and rotor have the same tangential velocity, but different rotational frequencies for the various radiuses. After the inner race reaches the maximum speed, it enters a state of acceleration and deceleration process. Because of the smaller drive torque and larger polar moment of inertia (MOI) of intermediate race, the acceleration time of the intermediate race t_{bo1} is a little longer than t_{bi1}. After the time $t_{\mathrm{bo1}} \approx 0.15$ s the spin speed of intermediate race has very small fluctuation and keeps about 17% of the inner race speed. As a part of the rotor energy is transferred to heat and DDCBs kinetic energy, the rotor spin speed keep reducing during the presented time.

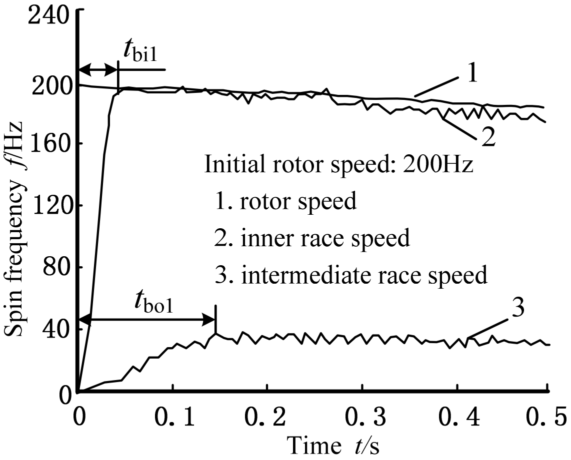


Figure 10: Experiment results of the rotor, inner race and intermediate race spin frequencies

4 Conclusion

In this paper, DDCBs are proposed to be used as CBs in AMB system. Both of the dynamic responses of the rotor drops onto DDCBs and SDCBs respectively are simulated on the platform of ADAMS. Finally, rotor drop experiments are carried out to validate the simulation results. The following conclusions can be obtained from the above researches:

(1) Use of DDCBs helps to reduce the rotor vibration amplitudes and contact forces after rotor drop.

(2) The angular acceleration of the intermediate race is a little smaller than that of the inner race. After the acceleration time, the speed of the intermediate race keeps about 17% of the rotating inner race speed.

In a word, except for the higher limit speed, taking the rotor vibration amplitudes and contact forces after rotor drop in view, DDCBs are more suitable for CBs used in AMB system.

Acknowledgment

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (Grant No. 50975134).

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