Auto-eliminating Clearance Auxiliary Bearings for Active Magnetic Bearing Systems

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Abstract

An auto-eliminating clearance auxiliary bearing (ACAB) for Active Magnetic Bearing systems (AMBs) has been conceived and a prototype system tested. In the ACAB, a ball bearing is directly mounted on a rotor, and the outer race of the ball bearing is surrounded by a series of interconnected supporters. In the open position, a clearance exists between the outer race and the ACAB supporters. When the rotor mounted with ball bearing drop on ACAB supporter(s) due to either an AMB system failure or transient shock, the generated friction between the outer race and supporter(s) will rotate the supporters circumferentially to eliminate the clearance and re-center the ball bearing and rotor. Since the clearance is eliminated, the impact force between the outer race and supporters is reduced and the possibility of backward whirl is eliminated. This paper presents the design methodology of those supporters. And a preliminary feasibility prototype experimental rig was established under the situation of simulated AMB system failure. Experimental results demonstrate feasibility of the ACAB.

1 Introduction

The major advantages AMBs have over conventional oil-film bearings include free friction, low noise, low power consumption, without lubrication and adjustable stiffness and damping. Therefore, AMB is well suited to the needs of some special applications, such as high speed, high precision, small volume, vacuum, high specific output power and so on[1-2]. Experience has shown that an AMB-suspended rotor can support large static loads or slowly varying loads, however its capacity of bearing transient external shock is weak[3]. Consequently, the AMB-supported rotors require an auxiliary bearing system to assure the safety of AMB system and support continuous and reliable operation under transient conditions even the AMB system power-down events.

Most conventional auxiliary bearing designs use rolling element or bushing type bearings with a fixed clearance of approximately one-half of the AMB air gap. While, since the fixed clearance, the generated friction between them during the high rotating speed rotor drop on these auxiliary bearings would susceptible induces backward whirl and generates large dynamic forces after AMB system stop operating. And those large dynamic

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forces are the main reason of auxiliary bearings damages[4-6]. Some new type auxiliary bearings were also studied by some researchers. The most creative design is Zero Clearance Auxiliary Bearing(ZCAB) presented by Mohawk Innovative Technology, Inc.(MiTi), which could eliminate the clearance between rotor and ZCAB by a series of movable ball bearings surround the rotor and move circumferentially and radially inward[7-8]. However the rotating speed of those ball bearings would be several folds more than rotor's due to the diameter of each ball bearing was smaller than the rotor, and that speed may exceed the limited speed of those ball bearings. Some scholars have advised to use a hydrodynamic foil gas bearing as auxiliary bearing of AMB[9-10], but the gas bearing was difficult to bear the static and dynamic loads during the rotor drop due to its small load capacity. And a device with active electromagnet was used as auxiliary bearing by some other scholars[11], it could eliminate the clearance between the device and rotor by electromagnet release the device under the power-down or AMB stop working conditions while which could not work for over-load conditions. To cope with these issues, a kind of Auto-eliminating Clearance Auxiliary Bearing has been conceived, built and tested.

2 ACAB Structure and Operating Mechanism

2.1 ACAB Structure

As seen in Figure 1, each ACAB uses a series of interconnected supporters surrounding the outer race of a ball bearing which is directly mounted on a rotor (the rotor with the ball bearing is called as rotating part hereinafter). Each of these supporters is connected to the support plate by support pin and is also interconnected by a drive ring. The co-ordination between each support pin and supporter only allows supporter rotation but not translation. Two springs with length adjustable are mounted oppositely at the tail of one or several supporter(s).

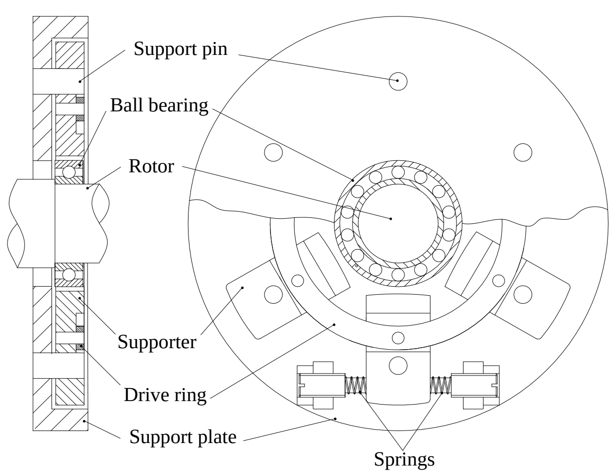


Figure 1: Auto-eliminating Clearance Auxiliary Bearing Sketch

2.2 ACAB Operating Mechanism

In normal operation, the length of the opposing springs are adjusted to keep all of the supporters at their own intermediate position to ensure a normal protective clearance between supporters and rotating part (see Figure 2). The generated normal impact force (F_n) on the supporter surface after the rotating part drops will generate a friction force (F_t) in the tangential direction of rotor's rotation. The friction force F_t will overcome the spring's restoring force (F_s) as well as other resistances, and then rotate this supporter in the same direction of rotor's rotation. Therefore, other supporters will rotate in unison at the same time since they are connected by a drive ring. With the rotation of supporters, the protective clearance will be gradually reduced if the contact surface of the supporters were chosen appropriately. And the clearance will become zero when the supporters rotate to a certain degree. The rotor will continue spinning with the inner race of the ball bearing near its original center for the supporters have pushed the outer race back. Once the AMB control system works again, all of the supporters will rotate back to their original position by the action of the springs restoring force (F_s), and the clearance between the supporters and rotating part will return back to previous size to ensure the re-worked AMB system is not disturbed.

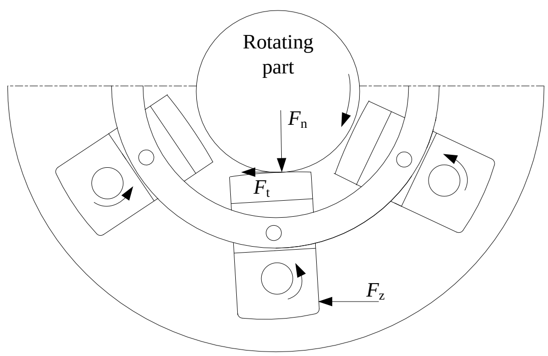


Figure 2: ACAB Operating Mechanism

3 ACAB Design Considerations

The intents of the ACAB are threefold. The first is to prevent the rotor from contacting the AMB stator during transient events or AMB failure, which is the common purpose of all auxiliary bearings. The second is to eliminate the protective clearance, reduce the vibration and improve the life and safety of auxiliary bearing. The third is to support the rotor and permit smooth continuous operation in the event of an AMB failure or system shock. In the design of ACAB, a detailed dynamic model of the rotor drops on ACAB should be established to determinate the expected loads and rotor maximum displacement in order to select an appropriate ball bearing, the strength of the support pin and the number of supporters. And the most important design is the shape of the supporter's surface which directly contacts the rotating part. Because the shape we selected will directly determines whether the supporters will rotate after the rotor drop and whether the protective clearance will be eliminated by the rotation of supporters. The following presents a brief overview of the design methodology about the shape selection.

To determine a suitable shape of supporter's surface, an analysis of supporter's surface geometrical characteristics and a mechanical model of supporter after rotating part drops are needed. Taking a cross-section of the rotating part and the supporter, assuming the cross-section shape of supporter's surface is an arc with the curvature center O_m and curvature radius R_m. As shown in Figures 3a and 3b, both concave and convex arcs are analyzed. O_r and O_r' are the center of rotor before and after dropping on supporters, ρ_0 is the initial protective clearance, l is the distance between the midpoint of the arc and O_s. l_w is the width of supporters and p is the collision point. Choosing a Cartesian coordinate system centered at the origin O_s, supposing the coordinate of the point on arc are x and y, so the equation of concave arc is:

$$x^2+\left(y-l-R_m\right)^2=R_m^2 \qquad \left(-\frac{l_w}{2}<x<\frac{l_w}{2}\right) \tag{1}$$

And the equation of convex arc is:

$$x^2+\left(y-l+R_m\right)^2=R_m^2 \qquad \left(-\frac{l_w}{2}<x<\frac{l_w}{2}\right) \tag{2}$$

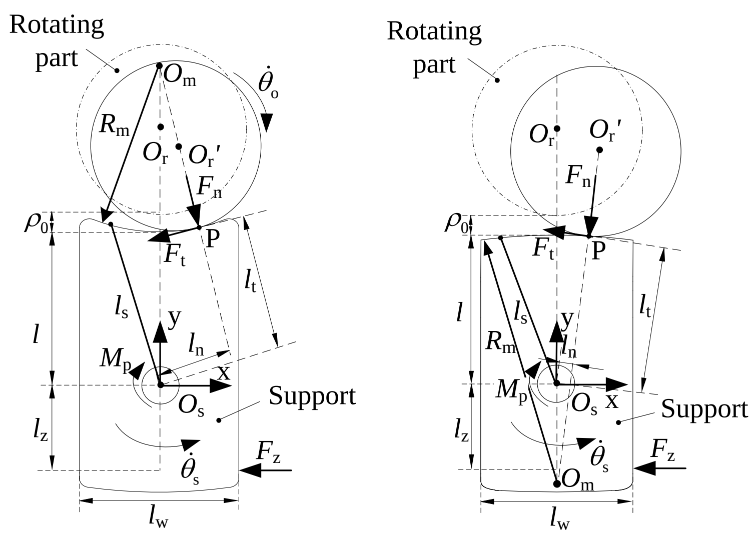


Figure 3: Supporter Mechanical Model

The supporter is symmetrical about y axis, so the positive direction of x axis is only considered. l_s is the line connects the point on arcs to O_s. In order to rotate the supporters and eliminate the protective clearance after the rotor contact supporters, two following conditions need to be satisfied:

1) $M>0$ at any collision point on arc, where M is the torque of the supporter suffered.

2) l_s increases with the increase of x and $l_s\left(x_0\right)\geq l+\rho_0$ is satisfied, where x_0 is the horizontal axis of the point on the arc.

The forces acting on the supporter after rotor drops include the normal contact force (F_n), tangential frictional force (F_t), spring restoring force (F_z) and support pin resisting moment (M_p) with the force arms relative to rotating center O_s l_n, l_t and l_z. So the total torque of supporter suffered is:

$$M = F_t l_t - F_n l_n - F_z l_z - nM_p \tag{3}$$

Where n is the number of supporters; $M_p = F_p r_p$, F_p refers to the friction force between support pin and supporter, r_p is the radius of support pin. The value of F_z is a variable by manual adjustment and r_p is usually small. Therefore, in order to get a qualitative standard of design, F_z and M_p are not considered here. So equation (3) is simplified as:

$$M = F_t l_t - F_n l_n \tag{4}$$

$$F_t = \mu^+ F_n \tag{5}$$

Where μ^+ equals to the coefficient of sliding friction μ_d when a relative sliding occurs between the rotating part and supporter(s), otherwise μ^+ equals to the coefficient of static friction μ_s.

To meet the condition (1), the following relationship between l_t and l_n can be obtained:

$$\frac{l_t}{l_n} > \frac{1}{\mu^+} \tag{6}$$

The geometric analyses of the concave and convex arcs are completed. And at the collision point (p), the l_n and l_t can be written as:

Concave:
$$\begin{cases} l_{n1} = \dfrac{R_m + l}{R_m} x_p \\ l_{t1} = \dfrac{(R_m + l)\sqrt{R_m^2 - {x_p}^2}}{R_m} - R_m \end{cases} \tag{7}$$

Convex:
$$\begin{cases} l_{n2} = \dfrac{R_m - l}{R_m} x_p \\ l_{t2} = R_m - \dfrac{(R_m - l)\sqrt{R_m^2 - x_p^2}}{R_m} \end{cases} \tag{8}$$

The relationships between l_t / l_n and R_m determined by equations (7) and (8) are presented in Figure 4. It could be clearly seen that l_{t2}/l_{n2} is always greater than l_{t1}/l_{n1} for any R_m, so the convex arc is advisable to bring supporters the largest torque. l_{t2}/l_{n2} increases with the increase of R_m, and the minimum value is close to l/x_p when R_m is close to ∞. The relationship between l and x_p is shown in the following according to equation (6) when l_{t2}/l_{n2} takes the minimum value.

$$l > \frac{1}{\mu^{+}} x_p \tag{9}$$

Therefore, the distance between the point on arc and O_s becomes:

$$l_s(x) = \sqrt{\left(\sqrt{R_m^2 - x^2} - R_m + l\right)^2 + x^2} \tag{10}$$

According to the condition (2), R_m can be determined by the following equation:

$$R_m \geq \frac{2x_0^2 l - l\rho_0^2 - 2l^2\rho_0 + \left[-\left(4l^2\rho_0^2 + 4l\rho_0^3 + \rho_0^4\right)x_0^2 + 4l^4\rho_0^2 + 12l^3\rho_0^3 + 13l^2\rho_0^4 + 6l\rho_0^5 + \rho_0^6\right]^{\frac{1}{2}}}{2\left(x_0^2 - 2l\rho_0 - \rho_0^2\right)} \tag{11}$$

Of course, x_0 should be smaller than $l_w/2$, and the length of l can be determined through combining equation (9), then the radius of curvature of supporter arc R_m is determined according to equation (11).

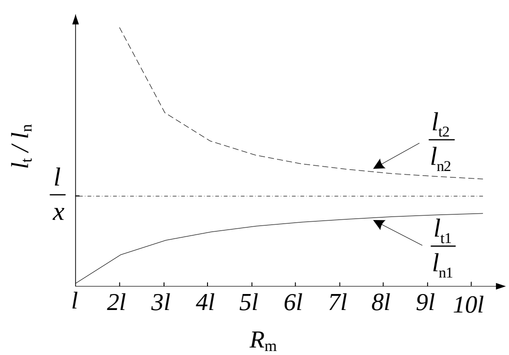


Figure 4: Relationships between l_t/l_n and R_m

4 ACAB Tests and Results

4.1 Test Setup

Using the above methods, an ACAB was designed, fabricated and installed in a test rig for feasibility testing. The test rotor was suspended by an AMB system during normal operation and rotated by the driving motor as shown in Figure. 5. A pair of angular contact bearings was used as both radial and axial auxiliary bearings at one end, while at the another end two ball bearings were mounted to the rotor, and an ACAB was tested as a radial auxiliary bearing at this end.

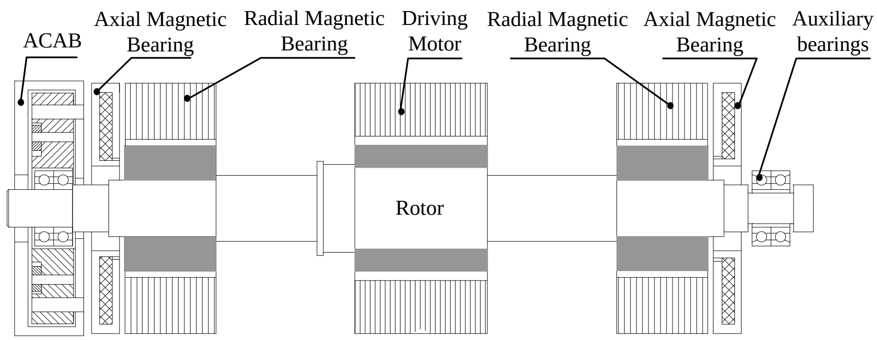


Figure 5: ACAB Test Rig

The rotor in the test rig is 35 cm long and 2.4 kg weight. The ACAB includes 6 supporters, and according to theoretical calculations, the specifications of each supporter are determined: l=40 mm, l_w=16 mm, R_m=150 mm. The diameter of the ACAB is 130 mm. The ACAB was installed in the test rig with an initial radial clearance 0.15 mm (Seen Figure 6). The radial clearance between radial magnetic bearing and rotor is 0.4 mm.

Auto-eliminating Clearance Auxiliary Bearing

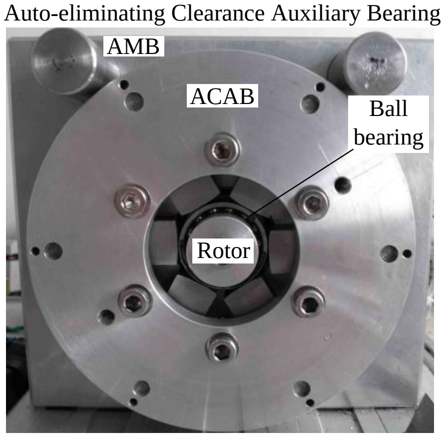
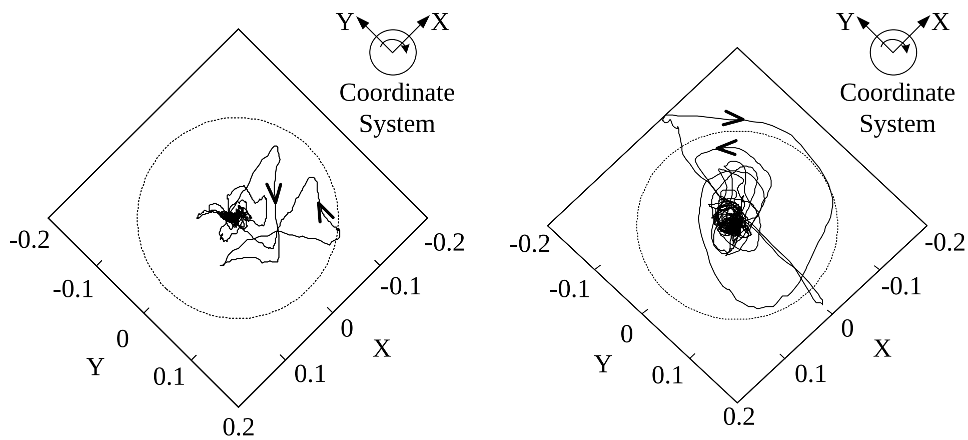


Figure 6: ACAB installed in test rig

4.2 Test Results

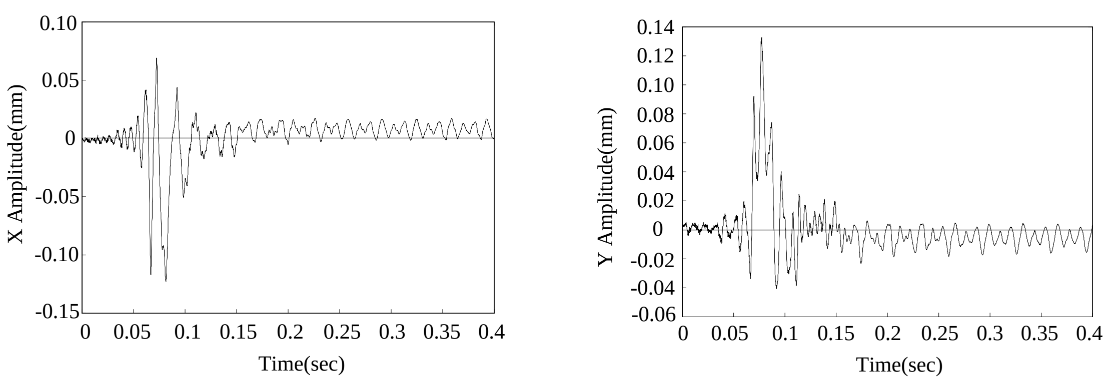
The situation of AMB system failure was simulated by cutting off the AMB power when the high speed rotor was suspended by magnetic bearings. The spring restoring force was not considered in the theoretical calculation, so in order to verify the correctness of theory in the previous section and the feasibility of the ACAB, the springs in the tested ACAB were not used. Instead of the springs, manual adjustment was used to adjust the supporters and keep a normal clearance between supporters and the outer race of the two ball bearings at the beginning of each test.

The rotor orbits dropped on the ACAB at speed 6,000 rpm and 12,000 rpm were presented respectively in Figures 7a and 7b. The directions of X and Y axis are consistent with the magnetic poles of magnetic bearing, which are equivalent to the horizontal and vertical directions rotate 45 degree along the counterclockwise. The rotor orbits show that the rotor was quickly pushed back to nearly the original center of AMB after several impacts. Figures 8a, 8b and Figures 9a, 9b show the detailed vibration displacement for the X and Y directions.



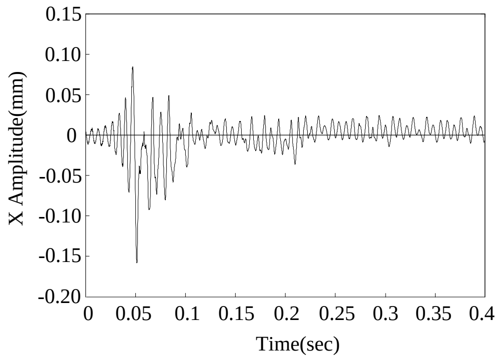
(a) 6,000 rpm (b) 12,000 rpm

Figure 7: The orbits of dropping rotor onto ACAB

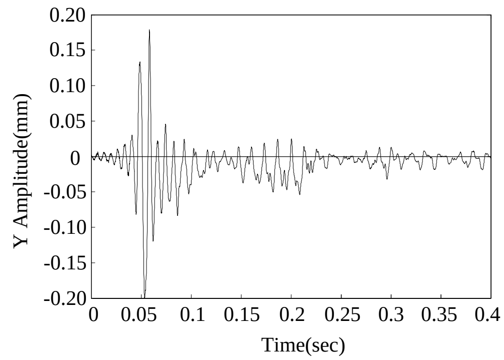


(a) X Rotor Displacement (b) Y Rotor Displacement

Figure 8: Rotor Displacement at 6,000rpm



(a) X Rotor Displacement



(b) Y Rotor Displacement

Figure 9: Rotor Displacement at 12,000rpm

As seen in Figure 8 and Figure 9, after about 0.05 second, the ACAB was closed and the rotor was brought to the center which is slightly higher in X direction and slightly lower in Y direction than the original AMB center. This may be caused by the misalignment between the ACAB and the AMB. The clearance between supporters and the rotating part is not equally everywhere due to the supporter arcs are not concentric circles with the rotating part as seen in Figure 1 in Section 2.1. The minimum clearance is the protective clearance, and the displacement of the rotor will be bigger than that clearance if the rotating part drops on the mid position between two supporters. As shown in Figure 9b, the maximum displacement reaches 0.2 mm, which is larger than the protective clearance 0.15 mm but remains smaller than the electromagnet air gap. Because there are no springs in the ACAB, the supporters can not automatically reset to their original positions after they catch the rotating part.

In a comparative test a bearing housing with a 0.15 mm fixed clearance between this bearing housing and the outer race of the two ball bearings was completed. The rotor mounted with the two ball bearings immediately entered backward whirl in the full clearance after AMB failure at the rotor initial rotating speed of 12,000 rpm. A 70 msec orbit time trace is presented in Figure 10.

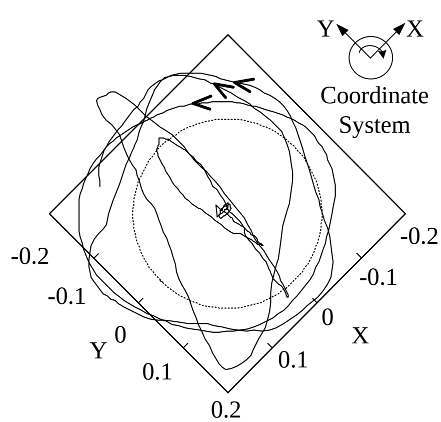


Figure 10: The orbits of dropping rotor onto bearing housing

5 Conclusions

The ACAB concept has been experimentally tested under AMB fail conditions at the speed of 6,000rpm and 12,000rpm respectively. The test results showed that the ACAB not only limits the rotor transient displacement to protect the AMB, but also moves the rotor nearly to its original AMB center in very short time once it is engaged. Because of the clearance elimination, the possibility of backward whirl in the full clearance is reduced. The feasibility of the ACAB is presented in this paper. In order to optimize the ACAB, more factors should be considered later, such as the lubrication and thermal design issues of the ball bearing, the restoring force of springs, the supporter pin resistance and so on. And more experimentally tests are being carried out to assure long-life steady-state operation in case of AMB failure.

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