The 19th International Symposium on Magnetic Bearings
ISMB19

Development of a Compact Magnetic Bearing Controller

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Abstract
This paper is about the development of a magnetic bearing controller, which is on a single printed circuit board of 80×125 mm^2, and includes all the electronics for a five-axis magnetic bearing with five pairs of dc-biased electromagnets and five channels of displacement sensing. We explain our techniques, describe the controller, and show verification/test. We use voltage bias and voltage control, and our first technique is for building a thermally stable voltage bias with no extra electronics. The second is about power electronics. We let the four electromagnets of a radial bearing be wired as a square, and let each corner of the square be connected to a half bridge, so that four half bridges are enough for a radial bearing. The third is about sensor electronics. We let an eddy-current or inductive sensor probe be driven by a square wave voltage. Then, the current drawn from a dc power supply by the driving circuit is a baseband displacement signal. This gives a way for sensor electronics design, and what is designed turns out to be simple and capable of good performances.

Keywords : magnetic bearing, magnetic bearing controller, power amplifier, displacement sensor

1. Introduction

A magnetic bearing controller (MBC) is the collection of all the electronics and the associated firmware (if there is any) for a magnetic bearing. In this paper we only discuss the electronics. Development of the electronics is dependent on magnetic bearing arrangement (number of axes, type of displacement sensing, using permanent magnets or not, and so on). Our development is for five-axis magnetic bearings using five pairs of dc-biased electromagnets (no permanent magnets) and five channels of eddy-current or inductive displacement sensing. Magnetic bearings of such arrangements have been the most applied. Application targets include turbomolecular pumps, machine tool spindles, energy storage flywheels, and centrifugal blowers/compressors.

An MBC may need to be attached to the machine that is equipped with a magnetic bearing, thus compactness of the MBC is important, especially when the machine itself is small. The turbomolecular pump is an example, which has an overall size of 100 ~ 400 mm, and the MBC may need to be attached to the pump body. Being compact is also helpful for EMI/EMC performances since electromagnetic radiation and pickup take place on smaller surface areas. Besides, in achieving compactness an MBC must be designed to have as fewer as possible electronic components, which helps to reduce cost and enhance reliability.

2. Bias and control configurations

The electromagnets of a magnetic bearing are driven by voltages. Currents come as consequences. Configuration is about how the currents are used: all, some, or none of them may be sensed and used as feedback signals, giving rise to different bias and control configurations. To explain in more detail, consider a single-axis magnetic bearing as shown in Fig. 1, where M1 and M2 are electromagnets, u_1 and u_2 are voltages applied, i_1 and i_2 are currents produced. For clarity, let the variables be transformed as $u_0 = (u_1 + u_2)/2$, $i_0 = (i_1 + i_2)/2$, $u = (u_2 - u_1)/2$, and $i = (i_2 - i_1)/2$, where u_0, i_0, u, and i are known as, respectively, bias voltage, bias current, control voltage, and control current. Then the configurations are easily explained: current bias — u_0 is controlled such that i_0 is constant; voltage bias — u_0 is kept constant; current control — u is controlled such that i follows a control signal for rotor suspension; voltage control — u is used as the control signal for rotor suspension. For a particular magnetic bearing any of the bias configurations can be combined with any of the control configurations. For our MBC we use a thermally stabilized voltage bias (explained below) and voltage control.

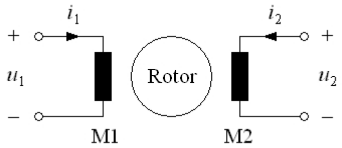


Fig. 1 Schematic diagram of a single-axis magnetic bearing.

Current bias uses current loops, and the associated electronics has considerable complexity. Voltage bias has simple electronics, and is better than current bias in rejection of external disturbance forces on the rotor (Li, 1999). But voltage bias is open loop and has poor thermal stability. Our practice is to let the bias voltages be slightly adjusted once a few seconds such that the bias currents are thermally stable. This needs current sensing but no extra electronics. PWM drive allows the electromagnets to be connected through semiconductor switches to a dc power supply. The switches can be controlled such that the current of the dc power supply, which is sensed for other purposes, is a bias current. This needs to happen for a couple of microseconds in acquisition of a bias current, and happens once a few seconds. So influence on rotor suspension is expected to be negligible. Indeed, influence is almost unnoticeable in our test. Note that with this modification the bias is still a voltage bias, and may be referred to as thermally stabilized voltage bias.

We choose voltage control because it does not need any current loops and has been shown to be capable of better performances. For example, under voltage control the mechanical vibration caused by rotor imbalance is removed more effectively (Zhong and Li, 2011). For another example, with voltage control the open-loop positive poles of a magnetic bearing model have smaller magnitudes (Zhou and Li, 2013), giving greater flexibility in control algorithm design. For yet another example, voltage control is less sensitive to eddy current in magnetic cores (Zhou and Li, 2015), allowing for better performances when solid cores are used.

With voltage control, modeling and stabilization of a magnetic bearing are more complex. The PID control is not enough. A higher order control algorithm has to be used. Besides, dc resistance thermal drift of electromagnet coils has to be taken into account in control algorithm design. The dc resistance, which is not present in mathematical models of current-controlled magnetic bearings, is present in mathematical models of voltage-controlled magnetic bearings. When voltage control is chosen, these complexities are inevitable, but not intractable.

3. Wiring of electromagnets

To drive the four electromagnets of a radial magnetic bearing, usually eight half bridges are used. In current control the number of half bridges can be reduced to four by wiring the four electromagnets as a star (Buhler, 2005). In voltage control four half bridges also suffice: we connect the four electromagnets as a square and apply at each corner a voltage using a half bridge. This is shown in Fig. 2, where M1 and M2 are electromagnets of one axis (X-axis), M3 and M4 are electromagnets of the other axis (Y-axis), and applied at the four corners are u_0 (bias voltage), u_X (control voltage for X-axis), u_Y (control voltage for Y-axis), and $u_0 + u_X + u_Y$ (sum of the foregoing three voltages).

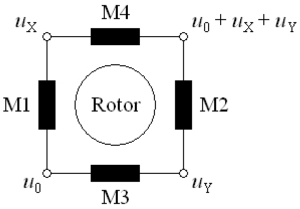


Fig. 2 Wiring of electromagnets of a radial magnetic bearing for voltage control.

It is seen that voltages applied across M1 ~ M4 are, respectively, $u_0 - u_X$, $u_0 + u_X$, $u_0 - u_Y$, and $u_0 + u_Y$, which is exactly what is needed for a radial bearing. In real-time control, voltages applied at the four corners may be out of the range of the half bridges, and need to be increased or decreased (four voltages by the same amount) to fit the range. But this is not always possible. This is possible if and only if the following condition is satisfied:

$$\max\{u_0, u_X, u_Y, u_0 + u_X + u_Y\} - \min\{u_0, u_X, u_Y, u_0 + u_X + u_Y\} \leq u_H - u_L$$

where u_H and u_L are, respectively, the highest and lowest voltages the half bridges are capable of. It is not hard to find out that this condition is satisfied if and only if the point (u_X, u_Y) on the $u_X u_Y$ plane is on or inside the octagon as shown in Fig. 3, where the octagon is symmetrical about u_X and u_Y axis, and u_0 is assumed to satisfy $0 < u_0 < (u_H - u_L)/2$. Thus the octagon defines the saturation threshold: if (u_X, u_Y) is outside the octagon then u_X or u_Y or both should be modified such that (u_X, u_Y) is moved onto the octagon.

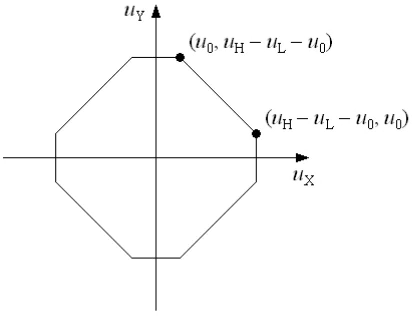


Fig. 3 Area on the $u_X u_Y$ plane in which there is no saturation.

An axial magnetic bearing has only two electromagnets. In any bias and control configurations, three half bridges are enough. See (Li, 1999) for an example. But in wiring of electromagnets, letting the two electromagnets not be wired together may be preferable. Unlike a radial magnetic bearing in which the four electromagnets are integrated as a single part, an axial magnetic bearing has its two electromagnets as two individual parts, which are manufactured, tested, and assembled one after another.

It is worth mentioning that the number of half bridges for a radial bearing cannot be fewer than four since there are three independent voltages. It is also worth mentioning that the wiring in Fig. 2 is not the only one for which four half bridges suffice. Shown in Fig. 4 is another. Note that if the bias voltages of all the axes of a magnetic bearing are of the same value then electromagnets of each axis can be wired to u_0 and $-u_0$ like M1 ~ M4, and seven half bridges will be enough for a five-axis magnetic bearing.

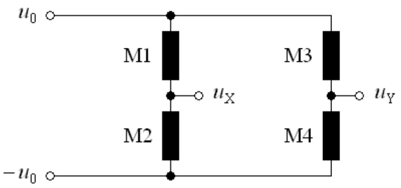


Fig. 4 Another wiring of electromagnets of a radial magnetic bearing for voltage control.

4. Sensor electronics

The most used displacement sensors for magnetic bearings are eddy-current type and inductive type. It is preferable that an MBC is capable of both types. The eddy-current displacement sensing using switching drive (Li, 2008) can be implemented by simple electronics, and is just suitable for compact MBCs. We have observed that this technique is also applicable to inductive displacement sensing. As a result, the electronics can be designed to support either eddy-current or inductive probes by selecting different parameter values for a few passive components.

To see that the switching drive is applicable to inductive displacement sensing, let an inductive probe be viewed as an ideal inductor of inductance L and be connected with a resistor of resistance R to form an LR series circuit as shown in Fig. 5, where u is a square wave voltage of amplitude U and period T, and i is the current produced by u in steady state. Then consider the average power P on the resistor. It is the average of the instantaneous power i^2R or the sum of all the items where each is the power of a harmonic component of i on the resistor. For all frequencies a higher L gives a higher impedance seen by u, thus P is a strictly monotonic function of L. Since a probe must be designed such that L is a strictly monotonic function of displacement, P is a strictly monotonic function of displacement.

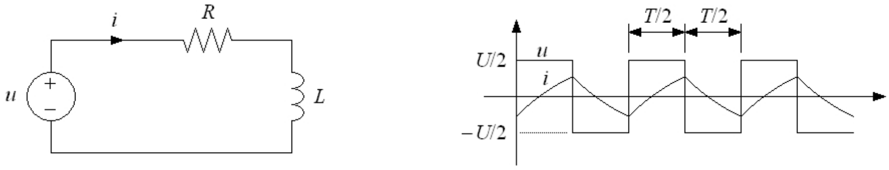


Fig. 5 An LR series circuit formed by a probe and a resistor.

Changes in P caused by changes in displacement should be significant, or sensor performances will be poor. To see that changes in P can be significant, let $L = L(x) = L_0/(1 + x/X_0)$, where x is displacement and $L_0 = 200$ µH is inductance at a probe-target distance of X_0. Then calculate P with $U = 5$ V, $T = 20$ µs, x/X_0 going from –0.5 to 0.5, and $R = 20$, 40, and 80 Ω, respectively. The results are plotted in Fig. 6. It is seen that both absolute and relative changes in P can be significant. In addition, P as a function of x/X_0 can have rich features: concave upward ($R = 20$ Ω), concave downward ($R = 80$ Ω), and almost linear ($R = 40$ Ω, giving rise to an inflection point).

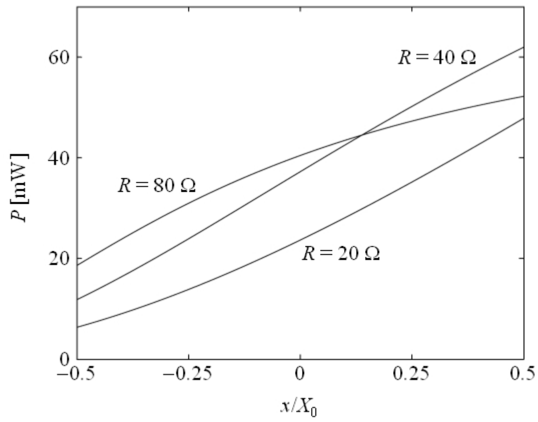


Fig. 6 Average power P versus displacement x/X_0 at different resistances R.

In real electronics a half bridge or full bridge connected to a dc power supply can be used as the final output stage for providing u, and the current drawn by the bridge from the dc power supply can be used as a displacement signal. As for dynamic performances, the electronics should be designed such that when there is a sudden change in displacement arrival of a new steady state in the circuit is as soon as acceptable.

5. Design and fabrication

A prototype is designed and fabricated (see Fig. 7 and the text wherein). All the electronics is on a single printed circuit board of 80×125 mm^2. The overall height is 20 mm. The board has four copper layers, and there are components on bottom side (only low-profile). Of the total board area, about 50% is taken by power electronics and 25% by sensor electronics. The power electronics consists of eleven half bridges (over-current and short-circuit protected). The sensor electronics is made up of functional blocks such as switching drive and low-pass filtration, and supports eleven sensor probes (ten for displacement, one for rotor speed). On the remaining area of the board are a microcontroller, an isolated

RS-232 port, five analog-to-digital converters, two dc-dc converters, and so on. The microcontroller is capable of PWM output and analog input, which saves a lot of area. Information about the design is also involved in descriptions about connectors (see Fig. 7). The isolated digital I/O is intended for communication with a motor driver (receive rotor speed signal and send emergency brake signal).

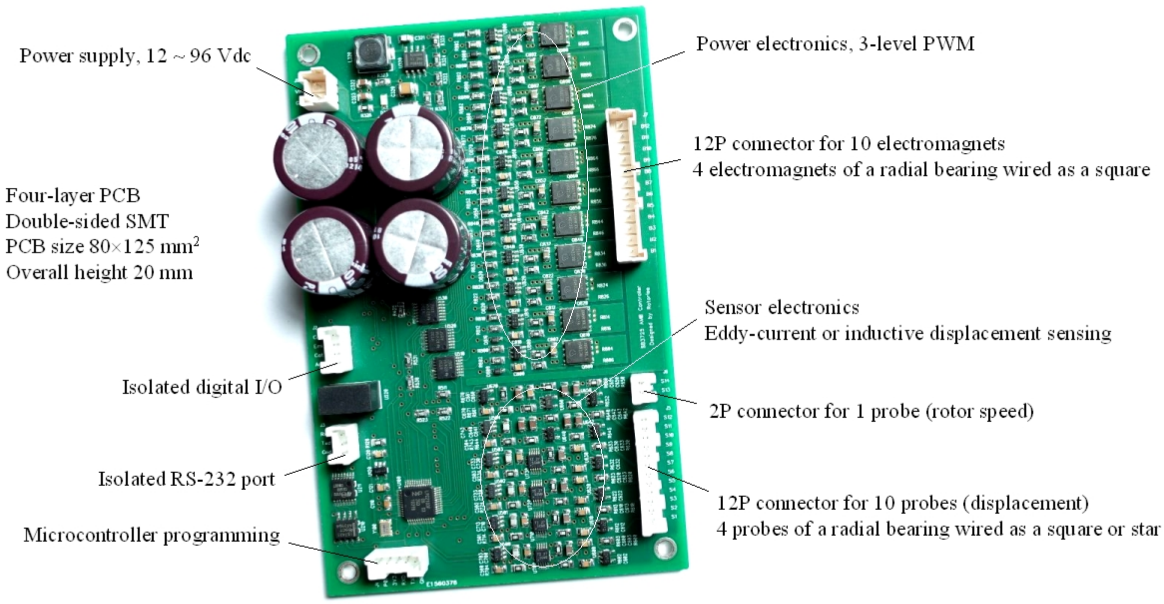
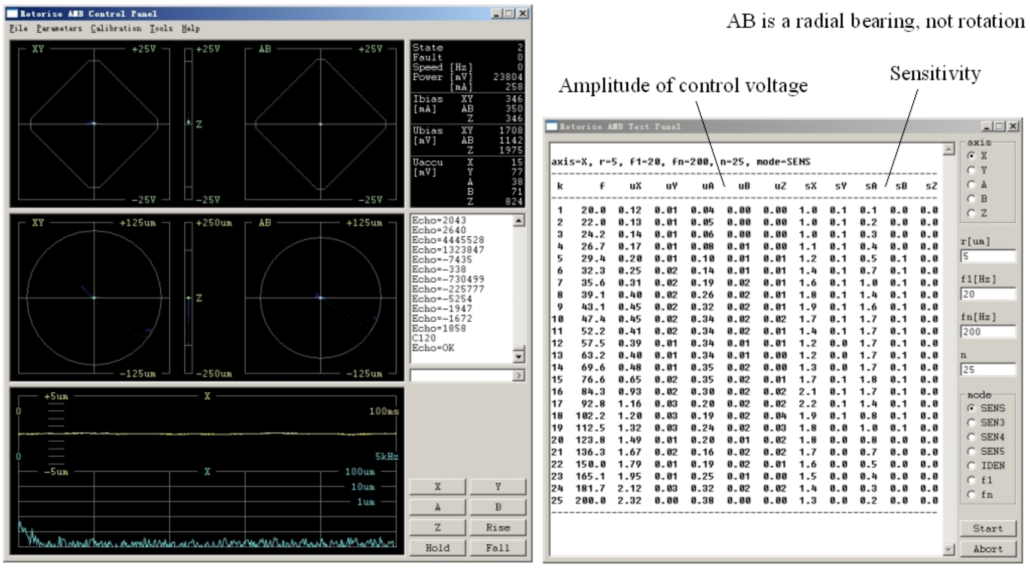


Fig. 7 Prototype of a compact magnetic bearing controller.

6. Verification and test

The thermally stabilized voltage bias, wiring of electromagnets as a square for voltage control, and switching drive for inductive displacement sensing are all verified to be effective. In the meantime, the prototype itself is verified and revised as well. Verification is carried out on a magnetic bearing and assisted by a PC software communicating with the prototype. Shown in Fig. 8 is a screen shot. On the left is the main window for real-time information. On the right is a pop-up window showing a finished sensitivity test. Note that AB is a radial bearing, not rotation.



```
State              2
Fault              0
Speed [Hz]         0
Power [mV]     23804
      [mA]       258
Ibias    XY      346
[mA]     AB      350
          Z      346
Ubias    XY     1708
[mV]     AB     1142
          Z     1975
Uaccu     X       15
[mV]      Y       77
          A       38
          B       71
          Z      824
```

```
Echo=2043
Echo=2640
Echo=4445528
Echo=1323847
Echo=-7435
Echo=-338
Echo=-730499
Echo=-225777
Echo=-5254
Echo=-1947
Echo=-1672
Echo=1858
C120
Echo=OK
```

axis: ● X ○ Y ○ A ○ B ○ Z

r[um]: 5

f1[Hz]: 20

fn[Hz]: 200

n: 25

mode: ● SENS ○ SEN3 ○ SEN4 ○ SEN5 ○ IDEN ○ f1 ○ fn

```
axis=X, r=5, f1=20, fn=200, n=25, mode=SENS
-----------------------------------------------------------------------
 k      f     uX     uY     uA     uB     uZ    sX    sY    sA    sB    sZ
-----------------------------------------------------------------------
 1   20.0   0.12   0.01   0.04   0.00   0.00   1.0   0.1   0.1   0.0   0.0
 2   22.0   0.13   0.01   0.05   0.00   0.00   1.0   0.1   0.2   0.0   0.0
 3   24.2   0.14   0.01   0.06   0.00   0.00   1.0   0.1   0.3   0.0   0.0
 4   26.7   0.17   0.01   0.08   0.01   0.00   1.1   0.1   0.4   0.0   0.0
 5   29.4   0.20   0.01   0.10   0.01   0.01   1.2   0.1   0.5   0.1   0.0
 6   32.3   0.25   0.02   0.14   0.01   0.01   1.4   0.1   0.7   0.1   0.0
 7   35.6   0.31   0.02   0.19   0.02   0.01   1.6   0.1   1.0   0.1   0.0
 8   39.1   0.40   0.02   0.26   0.02   0.01   1.8   0.1   1.4   0.1   0.0
 9   43.1   0.45   0.02   0.32   0.02   0.01   1.9   0.1   1.6   0.1   0.0
10   47.4   0.45   0.02   0.34   0.02   0.02   1.7   0.1   1.7   0.1   0.0
11   52.2   0.41   0.02   0.34   0.02   0.01   1.4   0.1   1.7   0.1   0.0
12   57.5   0.39   0.01   0.34   0.01   0.01   1.2   0.0   1.7   0.1   0.0
13   63.2   0.40   0.01   0.34   0.01   0.00   1.2   0.0   1.7   0.1   0.0
14   69.6   0.48   0.01   0.35   0.02   0.00   1.3   0.0   1.7   0.1   0.0
15   76.6   0.65   0.02   0.35   0.02   0.01   1.7   0.1   1.8   0.1   0.0
16   84.3   0.93   0.02   0.30   0.02   0.02   2.1   0.1   1.7   0.1   0.0
17   92.8   1.16   0.03   0.20   0.02   0.02   2.2   0.1   1.4   0.1   0.0
18  102.2   1.20   0.03   0.19   0.02   0.04   1.9   0.1   0.8   0.1   0.0
19  112.5   1.32   0.03   0.24   0.02   0.03   1.8   0.0   1.0   0.1   0.0
20  123.8   1.49   0.01   0.20   0.01   0.02   1.8   0.0   0.8   0.0   0.0
21  136.3   1.67   0.02   0.16   0.02   0.02   1.7   0.0   0.7   0.0   0.0
22  150.0   1.79   0.01   0.19   0.02   0.01   1.6   0.0   0.5   0.0   0.0
23  165.1   1.95   0.01   0.25   0.01   0.00   1.5   0.0   0.4   0.0   0.0
24  181.7   2.12   0.03   0.32   0.02   0.02   1.4   0.0   0.3   0.0   0.0
25  200.0   2.32   0.00   0.38   0.00   0.00   1.3   0.0   0.2   0.0   0.0
-----------------------------------------------------------------------
```

Fig. 8 Screen shot of a PC software communicating with the prototype.

The prototype is actually a platform, and functionality seems unlimited when it comes to the firmware. Presently it accepts about 60 commands and 100 user-settable parameters, making it easy to carry out a test. Indeed, the prototype is tested on a turbomolecular pump with great ease (as compared to verification). The pump has an overall size of 320 mm and runs on a five-axis magnetic bearing. Control of the magnetic bearing is not a trivial task because the rotor is highly gyroscopic, the two radial bearings are close together, and the rotor blades cause a lot of rotor-speed-dependent vibration modes. After all, up to standard performances are obtained. In particular, sufficiently small sensitivity values are obtained for all control axes and at all rotor speeds (from zero, with a step of 300 rpm, to rated speed).

7. Conclusions

Using voltage control and the thermally stabilized voltage bias, and wiring the electromagnets of a radial bearing as a square, the power electronics can be greatly simplified. With simplified power electronics, fewer channels of PWM signals may be enough, and the PWM functionality of a microcontroller, which is usually capable of a small number of channels, may be usable. Otherwise additional electronics has to be used for PWM signal generation.

With the technique of displacement sensing using switching drive, simple sensor electronics can be designed, and performances comparable to those achieved by other techniques can be obtained. Besides, sensor electronics designed for eddy-current or inductive probes can support either types of probes (not a mix of the two types). For different types of probes only parameter values of a few passive components (resistors and capacitors) are different.

With simplified power and sensor electronics, an MBC can be designed to be as compact as a single printed circuit board of 100 cm^2, and still have all the necessary functionalities for a five-axis magnetic bearing that uses five pairs of dc-biased electromagnets and five channels of displacement sensing. Then, with carefully designed control algorithms and firmware, such an MBC can be used for a turbomolecular pump to achieve up to standard performances.

References

Buhler P., Magnetic bearing device with simplified wiring, United States Patent, US8018106B2, 2005.

Li L., Linearizing magnetic bearing actuators by constant current sum, constant voltage sum, and constant flux sum, IEEE Trans. Magnetics, Vol. 35, No. 1, pp. 528-535, 1999.

Li L., Eddy-current displacement sensing using switching drive where baseband sensor output is readily available, IEEE Trans. Instrumentation and Measurement, Vol. 57, No. 11, pp. 2548-2553, 2008.

Zhong J. and Li L., Comparative study of autobalancing in active magnetic bearings under different control, Proc. 4th China Symp. Magnetic Bearings, pp. 315-318, Shanghai, China, 2011, (in Chinese).

Zhou L. and Li L., Comparative study of impact resistance in active magnetic bearings under current drive and voltage drive, Proc. 5th China Symp. Magnetic Bearings, pp. 158-162, Changsha, China, 2013, (in Chinese).

Zhou L. and Li L., Modeling of a solid-core active magnetic bearing including eddy currents, Proc. 6th China Symp. Magnetic Bearings, pp. 185-190, Xi'an, China, 2015, (in Chinese).