Control of 6 Degrees of Freedom Salient Axial-Gap Self-Bearing Motor

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Abstract: This paper introduces the control of a 6 degree of freedom (DOF) axial-gap selfbearing motor (AGBM), in which a hybrid active magnetic bearing system is in charge of 4 DOFs for radial levitation in x and y directions, and a salient type permanent magnet AGBM takes charge of 2 DOFs for rotation and axial motion in z direction.
First, structure and working principle of the hybrid magnetic bearing and the AGBM are analyzed. The radial force equations of the hybrid magnetic bearing, and the electromagnetic torque equation as well as the axial force equation of the AGBM are then given. Finally,control structure is derived to confirm that the complete non-contact levitation can be realized by the simple construction and control system.
To demonstrate the proposed technique, a salient 2-pole AGBM has been constructed and tested. The experimental results confirm that the AGBM drive performs well when its rotor is completely levitated.

Keywords: Magnetic Bearing, Hybrid Magnetic Bearing, Combined-Bearing Motor, Self-Bearing Motor, Vector Control

Introduction

Magnetic bearing motors with non-contact rotor levitation have been designed to overcome the limitations of the conventional mechanical bearing motors. Magnetic bearing motors can work without lubrication and do not cause contamination; further, they can run at very high speeds. However, magnetic bearing motors are not widely used because of their high cost, complex control, and large size. To address these problems, axial-gap self-bearing motor (AGBM) is one of the most suitable choices.

The AGBM is an electrical combination of an axial magnetic bearing and an axial flux motor. In principle, the electromagnetic design of the AGBM is similar to the axial flux motor; however, the mechanical design, control system design, and assembly process are more complex. The AGBM can support both rotation and translation without any additional winding. Obviously, it is one of the simplest magnetic bearing motors since hardware components are reduced.

In our previous research, the modern control structure is applied for the salient PM AGBM [1]. The good dynamic results of the AGBM drive have been achieved. However the experiments just stay in control of 2-DOF AGBM, the radial magnetic bearings are replaced by two ball bearings.

In this paper, a complete rotor non-contact levitation is studied. A 6-DOF AGBM is constructed by using a hybrid magnetic bearing (HMB) to confirm that the complete noncontact levitation can be realized by the simple construction and control system. The HMB is similar to that used in [2], however in this paper the HMB utilizes only one PM placed in bottom to create the bias flux. The experimental results reveal that the performance of the

AGBM drive is significantly improved. The maximum speed that the AGBM can reach is nearly 11000rpm.

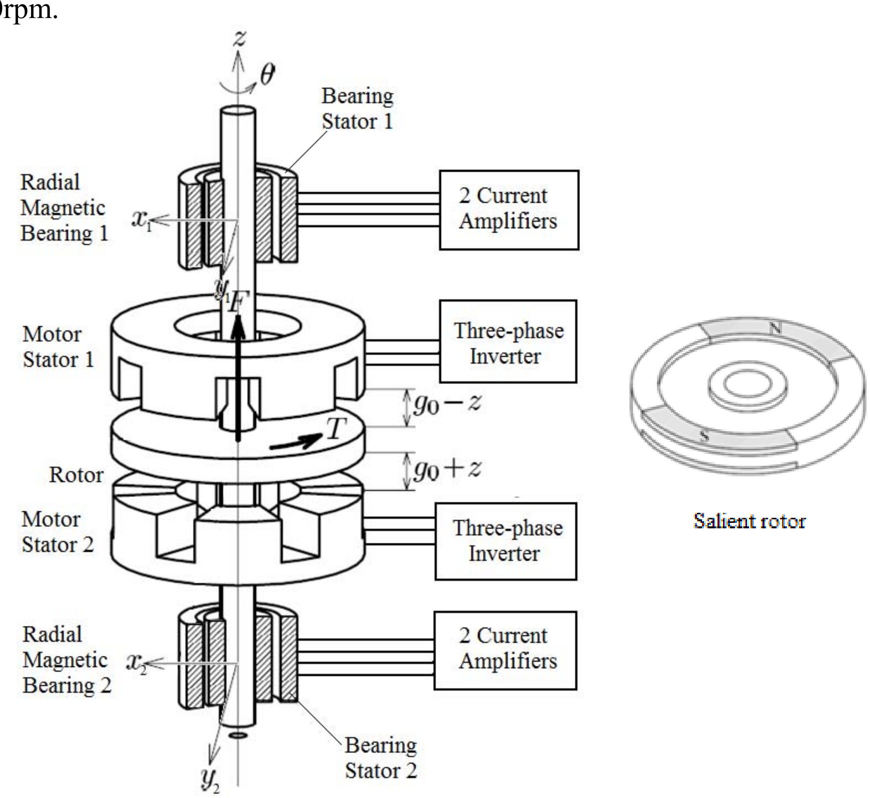

Fig. 1 Structure of a 6-DOF AGBM

Axial-Gap Self-Bearing Motor

The structure of an AGBM is illustrated in Fig. 1. The motor is placed between two radial magnetic bearings. The radial magnetic bearings generate radial forces in two perpendicular radial axes. The radial forces are controlled by closed-loop control system so that the rotor radial positions (x_1, y_1, x_2, y_2) are controlled to ensure that the rotor is kept at the centre of the stator bore. The axial position z and the rotational motion θ along z axis are controlled by controlling axial force and rotational torque of the motor. The axial force is controlled by closed-loop control system to ensure a similarly-desired air gap between the rotor and the stators. At the same time, the rotational torque is also regulated to meet a desired speed. As a consequence, the rotor of the AGBM has 6 DOFs, in which 4 DOFs (x_1, y_1, x_2, y_2) are controlled by the radial magnetic bearings, and 2 DOFs (z and θ) are controlled by the motor.

The rotor is a flat disc with PMs attached on both faces of the disc to create a salient pole. Two stators, one in each rotor side, have three-phase windings that generate rotating magnetic fluxes in the air gap. These produce motoring torques T_1 and T_2 on the rotor and generate attractive forces F_1 and F_2 between the rotor and the stators. The total motoring torque T is the sum of these torques, while the axial force F is the sum of the two attractive forces.

Similar to the conventional PM motor, the mathematical model of the AGBM is presented in a rotor-field-oriented reference frame using the so-called d, q coordinates, in which the stator current is decomposed into 2 components: one component is torque-producing current or i_q current, the other is force-producing current or i_d current (i_{q1}, i_{d1} in case of the stator 1 and i_{q2}, i_{d2} in case of the stator 2). The torque and force of the levitated motor can be calculated as follows: [1]

$$\begin{aligned} F = & K_{Fd}\left\{\left(i_{d2}+i_f\right)^2-\left(i_{d1}+i_f\right)^2\right\}+K_{Fq}\left(i_{q2}^2-i_{q1}^2\right)+2K_{Fd}\left\{\left(i_{d2}+i_f\right)^2+\left(i_{d1}+i_f\right)^2\right\}\frac{z}{g_0} \\ & +2K_{Fq}\left(i_{q2}^2+i_{q1}^2\right)\frac{z}{g_0} \end{aligned} \tag{1}$$

$$T = K_T\left(i_{q1}+i_{q2}\right)+K_T\left(i_{q2}-i_{q1}\right)\frac{z}{g_0}+K_R\left(i_{d1}i_{q1}+i_{d2}i_{q2}\right)+K_R\left(i_{d2}i_{q2}-i_{d1}i_{q1}\right)\frac{z}{g_0} \tag{2}$$

where $K_{Fd}=3L'_{sd0}/4g_0^2$ and $K_{Fq}=3L'_{sq0}/4g_0^2$ are the force factors, $K_T=-3PL'_{sd0}i_f/2g_0$ and $K_R=-3\left(L'_{sd0}-L'_{sq0}\right)/2g_0$ are the torque factors.

Assuming that the levitated motor is driven by a symmetric three-phase current

$$\begin{cases} i_{us}=\sqrt{2/3}I_s\cos(\omega t-\delta) \\ i_{vs}=\sqrt{2/3}I_s\cos(\omega t-\delta-2\pi/3) \\ i_{vs}=\sqrt{2/3}I_s\cos(\omega t-\delta+2\pi/3) \end{cases} \tag{3}$$

where $\sqrt{2/3}I_s$ is the current amplitude (s = 1 in case of the stator 1 and s = 2 in case of the stator 2), δ is phase angular between current and voltage. Hence, the d- and q-axis currents are calculated as:

$$\begin{cases} i_{ds}=I_s\cos\delta \\ i_{qs}=I_s\sin\delta \end{cases} \tag{4}$$

Substituting (4) into (1) and (2) yields

$$\begin{aligned} F = & K_{Fd}\left\{\left(I_2^2-I_1^2\right)\cos^2\delta+2i_f\left(I_2-I_1\right)\cos\delta\right\}+K_{Fq}\left(I_2^2-I_1^2\right)\sin^2\delta \\ & +2K_{Fd}\left\{\left(I_2^2+I_1^2\right)\cos^2\delta+2i_f\left(I_2+I_1\right)\cos\delta+2i_f^2\right\}\frac{z}{g_0}+2K_{Fq}\left(I_2^2+I_1^2\right)\sin^2\delta\frac{z}{g_0} \end{aligned} \tag{5}$$

$$\begin{aligned} T = & K_T\left(I_2+I_1\right)\sin\delta+K_T\left(I_2-I_1\right)\sin\delta\frac{z}{g_0} \\ & +K_R\left(I_2^2+I_1^2\right)\sin\delta\cos\delta+K_R\left(I_2^2-I_1^2\right)\sin\delta\cos\delta\frac{z}{g_0} \end{aligned} \tag{6}$$

The amplitudes of the current I_1 and I_2 are changed when the levitated motor works. Let's assume that they can expressed as

$$\begin{cases} I_1=I_m-i_c \\ I_2=I_m+i_c \end{cases} \tag{7}$$

where I_m is the constant amplitude and i_c is controlled amplitude, equations (5) and (6) can be rewritten as follows

$$\begin{aligned} F = & 4\left\{K_{Fd}\left(I_m\cos^2\delta+i_f\cos\delta\right)+K_{Fq}I_m\sin^2\delta\right\}i_c \\ & +4\left\{K_{Fd}\left[\left(I_m^2+i_c^2\right)\cos^2\delta+2i_fI_m\cos\delta+i_f^2\right]+K_{Fq}\left(I_m^2+i_c^2\right)\sin^2\delta\right\}\frac{z}{g_0} \end{aligned} \tag{8}$$

$$T = 2K_T I_m \sin\delta + 2K_T i_c \sin\delta \frac{z}{g_0} + K_R\left(I_m^2 + i_c^2\right)\sin 2\delta + 2K_R I_m i_c \sin 2\delta \frac{z}{g_0} \tag{9}$$

From equation (8), it can be seen that the axial force depends on the phase angular δ and the controlled current i_c. However, in steady state, the phase angular becomes constant, the axial force can be independently controlled by current i_c.

The axial motion equation of the levitated rotor can be illustrated as

$$\begin{aligned} F = m\ddot{z} &= 4\left\{K_{Fd}\left(I_m \cos^2\delta + i_f\cos\delta\right) + K_{Fq} I_m \sin^2\delta\right\} i_c \\ &+ 4\left\{K_{Fd}\left[\left(I_m^2 + i_c^2\right)\cos^2\delta + 2 i_f I_m \cos\delta + i_f^2\right] + K_{Fq}\left(I_m^2 + i_c^2\right)\sin^2\delta\right\}\frac{z}{g_0} \end{aligned} \tag{10}$$

Obviously, this system is unstable. To stabilize the system, a controller with the derivative component must be used.

When the axial displacement is well controlled, it becomes much smaller than the equilibrium air gap g_0 hence equation (9) can be rewritten as

$$T = 2K_T I_m \sin\delta + K_R\left(I_m^2 + i_c^2\right)\sin 2\delta \tag{11}$$

The total torque consists of two components. The first component is caused by the current I_m, and the second component is caused by the difference between d- and q-axis inductance. Although the total torque still depends on the controlled current i_c, its main component is proportional to the current I_m, so this current can be utilized to regulate the rotating torque.

The control structure for the levitated motor is illustrated in Fig. 2.

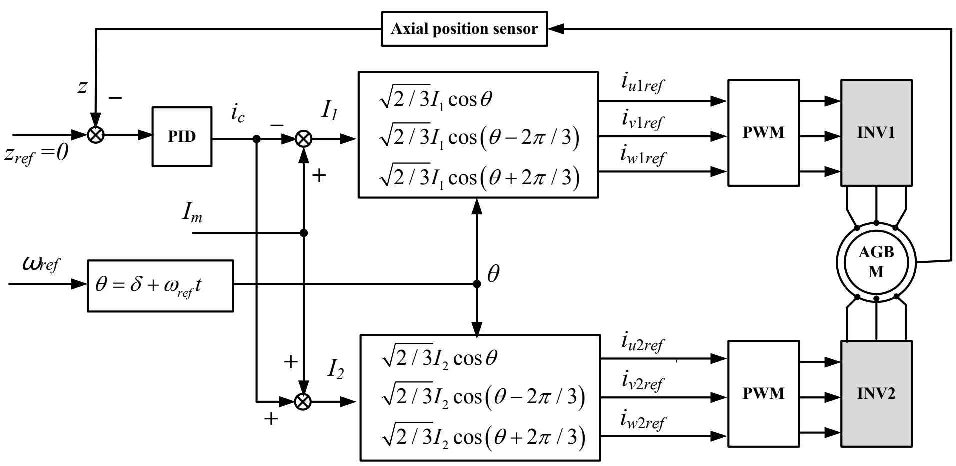

Fig. 2 Control structure for the AGBM

Hybrid Magnetic Bearing

The hybrid magnetic bearing (HMB) is a combination of permanent magnet (PM) and the active radial magnetic bearings which is utilized to levitate the rotor in radial direction. Using the HMB can enhance the stability and stiffness of non-contact rotor levitation because it is possible to decide the dynamic characteristics of the HMB through closed-loop control. As the result, the AGBM drive can reach full speed with good dynamic.

Fig. 3 shows structure and principle of the HMB. The PM is placed between two RMBs to create a bias flux as shown by the solid arrow line. The front view indicates the construction of the RMB. The rotor has cylindrical shape with a centre shaft surrounded by the ferromagnetic steel. The stator surrounds the rotor. It consists of a stator yoke and 4 poles. The stator yoke has duty to conduct and to close the magnetic paths of the 4 stator poles and the bias flux. The dimension of the stator yoke is designed to be large enough to avoid magnetic saturation, and to have high mechanical stiffness to avoid vibration caused by radial magnetic forces.

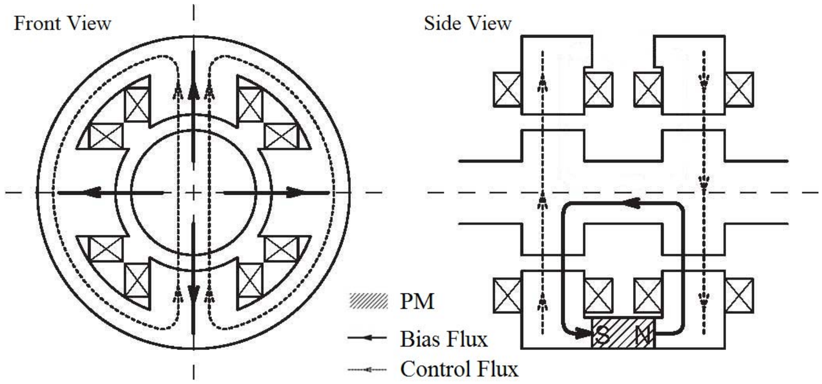

Fig. 3 Structure of the HMB

The areas between the stator poles are the slots which contain the windings. One stator has 4 concentrated coils. Two up and down coils are connected in series to control the radial levitation in y direction, while two left and right coils are connected in series to control the radial levitation in x direction. By this way only 4 current amplifiers are utilized for the HMB drive, the system loss can be reduced. By inserting the DC controlled currents ($i_{x1}, i_{x2}, i_{y1}, i_{y2}$) from linear current amplifiers, these coils produce DC magnetic fluxes in the air gap, as shown in dotted line, these fluxes then generate correspondingly the radial forces ($F_{x1}, F_{x2}, F_{y1}, F_{y2}$) to levitate the rotor.

These radial forces can be calculated as follows: [2],[4]

$$\begin{cases} F_{x1} = K_a i_{x1} + K_n x_1 \\ F_{y1} = K_a i_{y1} + K_n y_1 \\ F_{x2} = K_a i_{x2} + K_n x_2 \\ F_{y2} = K_a i_{y2} + K_n y_2 \end{cases} \tag{12}$$

where K_a is the bearing gain factor, and K_n is the bearing stiffness.

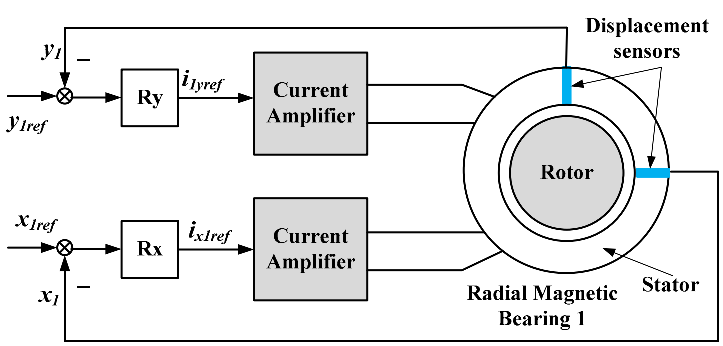

Fig. 4 Decentralized control structure for the RMB

The decentralized control structure for one RMB is shown in Fig. 4. It consists of two independent control loops, one is for controlling levitation force in x direction, and the other is for controlling levitation force in y direction. For the closed-loop control, two gap sensors are utilized to measure the displacements in x and y directions.

Due to the symmetrical characteristic of the RMB, the design of the decentralized control system will be made in x_1 direction. The others are derived in the same way.

The radial motion equation of the levitated rotor can be illustrated as

$$F = m\ddot{x}_1 = K_a i_{x1} + K_n x_1 \qquad (13)$$

Obviously, this system is unstable. To stabilize the system, a controller with the derivative component must be used.

The controller parameters in other directions are received in the same way

$$\begin{cases} K_{px2} = K_{py2} = K_{py1} = K_{px1} \\ K_{dx2} = K_{dy2} = K_{dy1} = K_{dx1} \end{cases} \qquad (14)$$

Actually, steady-state error occurs when only the PD controller is used, and to remove this, a PID controller should be utilized.

Implementation and Results

To demonstrate the capability of complete non-contact levitation with simple control and structure, an experimental setup has been constructed and tested. It is shown in Fig. 5.

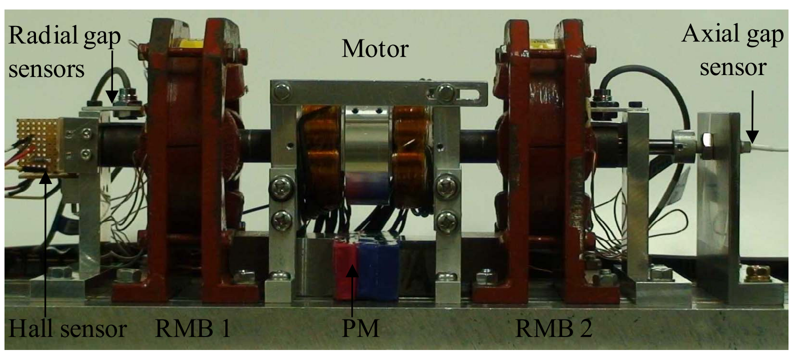

Fig. 5 Picture of the experimental setup

The disc rotor of the motor has a diameter of 50 mm. Two neodymium iron magnets with a thickness of 0.8mm for each side are inserted into the disc's surfaces to create one pole pair. Each stator of the motor has a core diameter 50 mm and six concentrated windings, each with 200 turns.

The PM with the dimension of 40x25x10mm (width, height, and thickness) is placed in the bottom of the AGBM to create the bias flux. To conduct the bias flux from the PM to the RMBs, the iron bars are used to fill up in the space between them.

Two RMBs are arranged in both sides of the AGBM to levitate the rotor in radial direction. The bearing rotor is made of laminated silicon steel to reduce the eddy current loss. Its outer diameter is 40mm, and its length is 20mm. Similar to the bearing rotor, the bearing stator core is made of laminated silicon steel sheet. Inside diameter of the stator core is 42mm, therefore the air gap between the rotor and the stator is 1mm. The stator has 4 windings, each has 200 turns.

In addition, 4 eddy-current-type gap sensors (Sentec-LS500) are installed to measure the radial displacements (x_1, y_1, x_2, y_2). To measure the axial displacement (z), the other eddy-current-type gap sensor (Shinkawa-VC-202N) is used.

The control system is based on the dSpace DS1104 which is dedicated to the control of electrical drives. In this experiment, two DS1104 cards are utilized: one is for control of the motor and the other is for the HBM.

The results show that the highest speed of the motor is approximately 11000rpm when the complete non-contact levitation of the rotor is realized. The main reason of limitation in the highest rpm is because the supplied DC voltage of the inverter has been saturated. The other may come from the iron loss and winding copper loss, these losses will increase very fast at high speed. Moreover, the vibration of motor structure also contributes to the reduction of the highest speed.

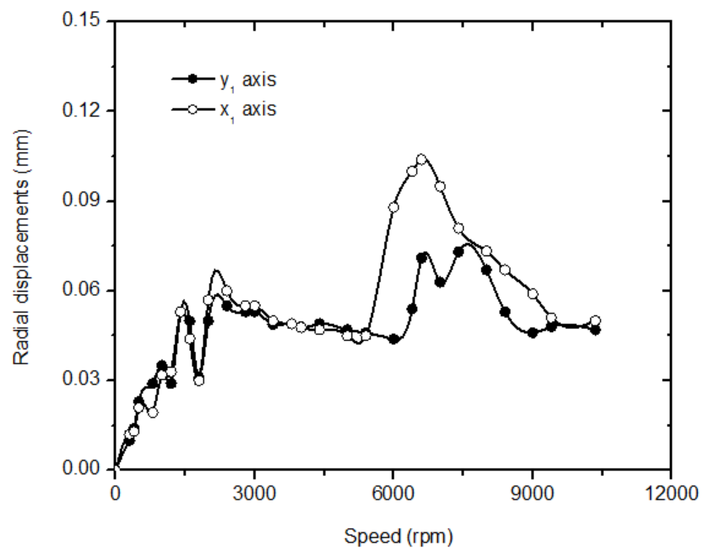

Fig. 6 Relation between radial displacement and speed in bearing 1

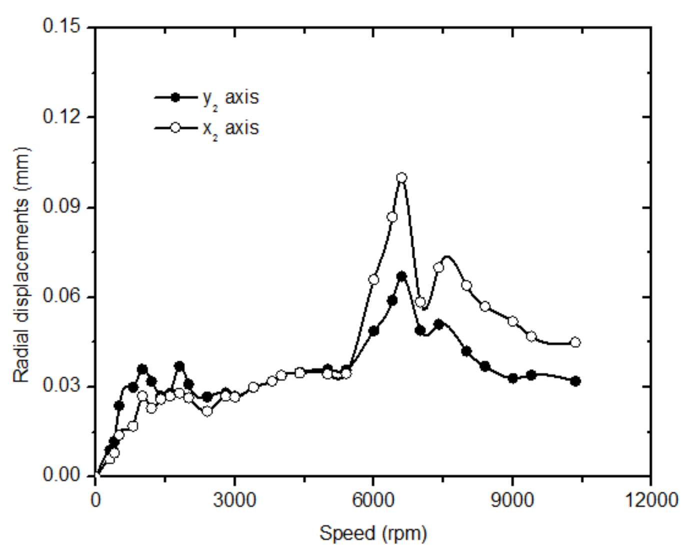

Fig. 7 Relation between radial displacement and speed in bearing 2

To find out the relation between the radial and axial displacements with the rotational speed, the motor is setup at different speeds, the radial and axial gaps are measured. The displacements are then calculated and analyzed to take the amplitude of the vibration. The results are shown in Figs. 6, 7, and 8.

The maximum of displacement error for all bearings appears at the speed of about 6500rpm. The maximum error in the HMB is about 0.1mm that is much smaller than the equilibrium air gap of the bearing (1mm), and the maximum error in axial displacement is about 0.03mm that is also far smaller than the air gap of the motor (2mm). The resonance of the system is the main reason to cause this vibration.

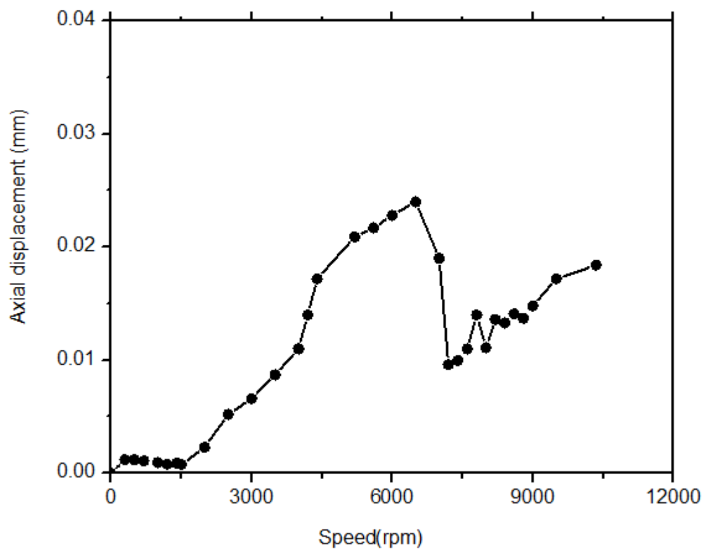

Fig. 8 Relation between axial displacement and speed

Conclusion

This paper introduces a simple structure and control system for a 6-DOF salient type PM AGBM, in which a hybrid magnetic bearing system is utilized for rotor levitation in radial direction. The results confirm that non-contact levitation of the rotor is successfully achieved in all speed ranges. The AGBM can provide both rotation and levitation in axial direction. The highest speed that the AGBM can reach now is about 11000rpm.

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