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5-Degree of freedom active position control of an axial self-bearing motor with six concentrated stator windings

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Abstract

In recent years, pumps of magnetic bearing type have been widely developed because that a magnetic bearing motor need not lubrication oil and has no friction loss. For downsizing and reducing cost of magnetic bearings, an axial self-bearing motor (ASBM) is developed in this paper. The ASBM is composed of two identical stators and on disk rotor which is sandwiched by the stators axially. Each stator has six concentrated winding coils which are driven by separate power amplifiers. Based on control principle of the developed ASBM, 5-degree of freedom (5-DOF) active position control system is designed to realize axial control, tilt control and radial control simultaneously. For generating rotation torque, open-loop torque control method and closed-loop torque control method are applied, respectively. After implementing the above mentioned control method, experimental results of rotation test are shown to verify the practicability of the developed ASBM and effectiveness of the designed control system.

Key words : Axial self-bearing motor, active magnetic bearing, axial position control, radial position control, tilt control, rotation speed control

1. Introduction

Recently, since a magnetic bearing motor has the advantages including no friction loss, no abrasion, and unnecessary lubrication oil, the pumps of magnetic bearing type have been widely used and developed (Ohmori, et al., 2001) (Ueyama, 2004) (Wakui and Sasaki, 2007) (Kitago, et al., 2011). However, to control the magnetic bearing motor needs multi-degree of freedom active control which leads the whole system to become large-sized and expensive. Considering the above problems, self-bearing motor has been expected to downsize and reduce cost of magnetic bearing.

There are two kinds of self-bearing motor: radial self-bearing motor (RSBM) and axial self-bearing motor (ASBM). For RSBM, two kinds of winding are needed to drive motor and control position. It leads the structure of stator of RSBM is complicated. For ASBM, only one kind of winding can realize torque generation and position control simultaneously by a single rotating magnetic flux (Ueno and Okada, 1999). So ASBM has much simpler structure than RSBM. In (Ueno and Honda, 2007), successful levitation of ASBM was confirmed. In order to solve problems of low stiffness for radial directions and the tilts around radial axis of ASBM, passive magnetic bearing was employed to enhance the stiffness in radial directions, and an active control method was used to control tilt angles (Sumino and Ueno, 2014). Moreover, a 5-degree of freedom (5-DOF) control method for a double self-bearing motor has been proposed (Osa, et al., 2014). In this study, 5-DOF active control of ASBM with six concentrated stator windings is proposed to obtain small and simple structure and control systems. Open-loop torque control method and closed-loop torque control method are applied to generate rotation torque for the ASBM. After implementing the designed control system, rotation test is done to verify the performance of the developed ASBM.

The rest of this paper is organized as follows. In Section 2, the structure of developed ASBM and control principle of ASBM are introduced. The 5-DOF active control system which is used to realize axial control, tilt control and radial control is described in Section 3. Including the 5-DOF active controllers, the designed open-loop torque control system and closed-loop torque control system for generating rotation torque are also shown. In Section 4, experimental results are shown to verify the practicability of the developed ASBM. Section 6 is the conclusion of this paper.

2. Axial self-bearing motor

2.1. Structure of ASBM

The configuration of developed ASBM is shown in Fig. 1(a)). The motor is composed of two identical stators and one disk rotor which is sandwiched by the stators axially. Each stator has six concentrated winding coils which are driven by separate power amplifiers, and generates 2-pole and 4-pole rotating magnetic fluxes in the air gap. Two segment type permanent magnets are attached to each side of the rotor, and eighteen square type permanent magnets are set only on the underside of the rotor for measuring rotation angle. The axial position, radial position and tilt angle are measured by five eddy current sensors where three of them for axial displacement and two of them for radial displacement. The rotational angle is measured from the pulse wave generated by the Hall sensors. According to Fig. 1(a), the prototype of developed ASBM was set up as illustrated in Fig. 1(b). The stator with six concentrated windings is shown in Fig. 1(c). Figure 1(d) shows the underside of the rotor which has two segment type permanent magnets and eighteen square type permanent magnets. The signals from three eddy current sensors (OMRON, ZX-EDR5) mounted in axial direction were employed to calculate the axial displacement ($z_{average} = \frac{z_1+z_2+z_3}{3}$) and tilt angles of the rotor ($\theta_x = \tan^{-1}\frac{z_2-z_3}{l}, \theta_y = \tan^{-1}\frac{-2z_1+(z_2+z_3)}{\sqrt{3}l}$), where the sensor which was used to capture z_1 was mounted on x-axis and each distance between any two sensors is $l = 33$[mm]. The other two eddy current sensors mounted in x-axis direction and y-axis direction were used to measure the radial position. In order to detect rotational angle of the rotor, two hall sensors (AKM, HZ-312C) were applied.

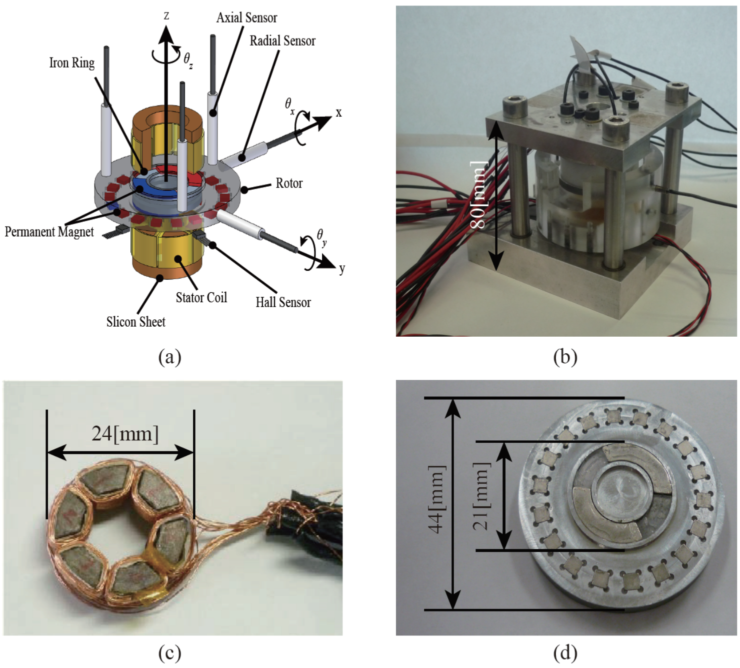

Fig. 1 Experimental device (ASBM). (a) 3D CAD sketch of the developed ASBM. (b) Photo of the developed ASBM. (c) Stator. (d) Rotor.

2.2. Control principle

According to the above ASBM, the axial force and rotating torque are controlled by varying the amplitude and phase of the 2-pole fluxes in the air gaps between stators and rotor, while the radial forces and tilt moments are controlled by 4-pole fluxes in the air gaps. In the following, each control principle will be introduced.

2.2.1. Principle of axial control Figure 2 shows the principle diagram of axial control, where the black arrows are magnetic fluxes, the green arrows are magnetic attractive forces, the yellow arrows are magnetic repulsive forces, and the pink arrows are direction of the forces acting on the rotor. As shown in Fig. 2, the attractive force occurs between the top stator and the rotor due to opposite magnetic poles, and the repulsive force occurs between the bottom stator and the rotor due to same magnetic poles. That is, the upward axial force acts on the rotor. The downward axial force can also be generated as long as the poles of both stators are exchanged simultaneously. In order to generate the above metioned magnetic fluxes, the axial control current fed to each coil is defined as

$$i_{zk} = \sqrt{\frac{2}{3}}\left[i_z \cos\left\{\phi + \frac{\pi}{3}(k-1)\right\}\right] \tag{1}$$

where ϕ is rotor angle, $k = 1 \sim 6$ is a coil number, and i_z is magnitude of axial control current.

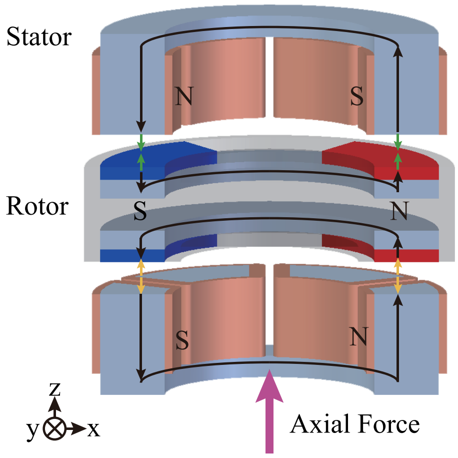

Fig. 2 Principle diagram of axial control

2.2.2. Principle of tilt control The principle diagram of tilt control is shown in Fig. 3. In the left figure of Fig. 3, when the top stator and the bottom stator produce the tilt torques around x-axis in the same direction, the radial forces produced by the stators cancel out. Therefore, only tilt torque around x-axis is generated. In a similar manner, tilt torque around y-axis can be also generated (see the right figure of Fig. 3). From aforementioned principle, the tilt control currents for tilt torques around x-axis and y-axis can be formulated respectively as

$$i_{txk} = \sqrt{\frac{2}{3}}\left[i_{tx} \sin\left\{\phi + \frac{2\pi}{3}(k-1)\right\}\right] \tag{2}$$

$$i_{tyk} = \sqrt{\frac{2}{3}}\left[i_{ty} \cos\left\{\phi + \frac{2\pi}{3}(k-1)\right\}\right] \tag{3}$$

where i_{tx} and i_{ty} are magnitudes of tilt control currents.

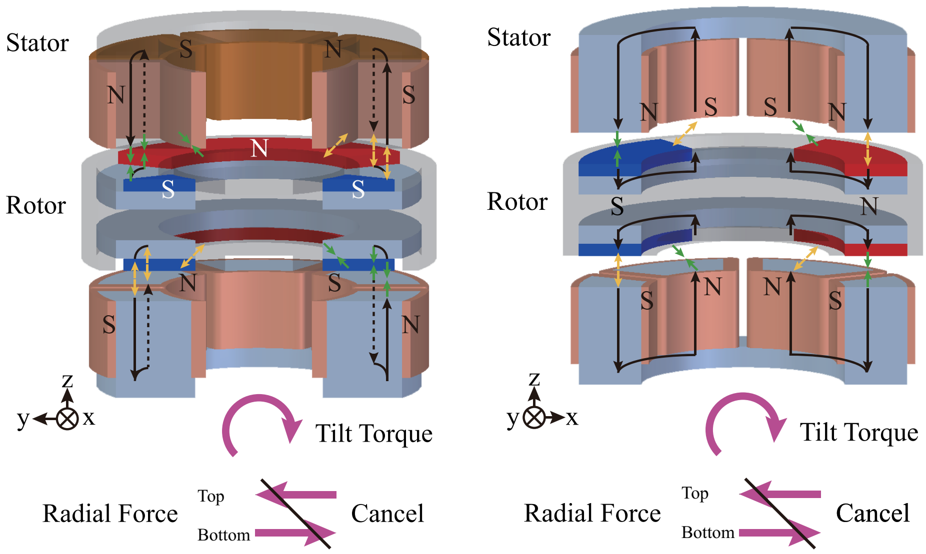

Fig. 3 Principle diagram of tilt control

2.2.3. Principle of radial control The principle diagram of radial control in x-axis and y-axis direction is shown in Fig. 4. As shown in the left figure of Fig. 4, tilt torques produced by the top stator and the bottom stator are regulated in opposite direction, radial force can be generated in x-axis direction. In a similar way, radial force in y-axis can also be generated as shown in the right figure of Fig. 4. The radial control currents in x-axis and y-axis direction are represented as

$$i_{rxk} = \sqrt{\frac{2}{3}}\left[i_{rx}\cos\left\{\phi + \frac{2\pi}{3}(k-1)\right\}\right] \tag{4}$$

$$i_{ryk} = \sqrt{\frac{2}{3}}\left[i_{ry}\sin\left\{\phi + \frac{2\pi}{3}(k-1)\right\}\right] \tag{5}$$

where i_{rx} and i_{ry} are magnitudes of radial control currents.

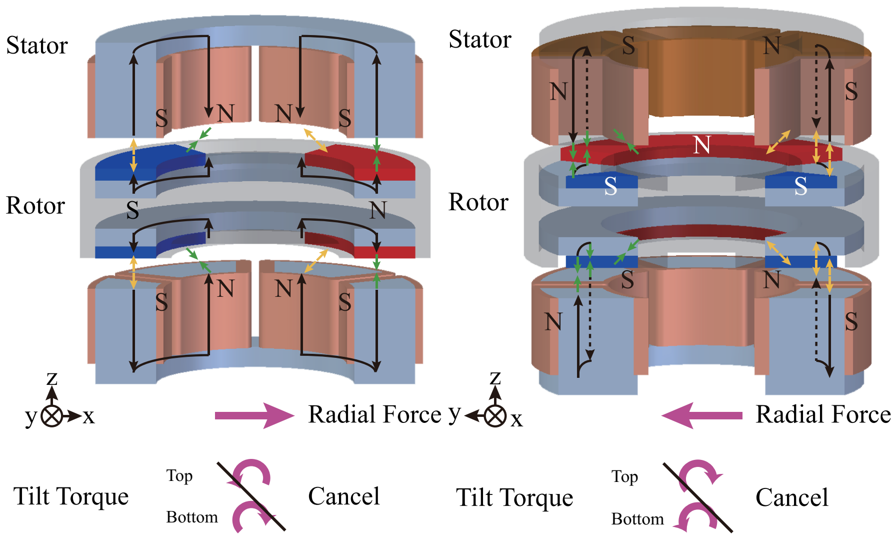

Fig. 4 Principle diagram of radial control

2.2.4. Principle of generation of rotation torque There are two kinds of method to generate rotation torque for ASBM: open-loop torque control method and closed-loop torque control method. According to different methods, the principles of generation of rotation torque are different. For open-loop torque control method, the magnitude and phase of currents fed to coils of top stator should be kept the same as the ones fed to coils of bottom stator for levitating the rotor. By regulating the phase of currents, rotating magnetic field is generated and used to provide rotation torque to make the rotor track the desired rotating speed of ASBM. The current is called **motor current** here, and its phase angle is the integral of angular velocity which is calculated from the desired rotating speed of ASBM. The principle diagram is shown as the left figure of Fig. 5. For generating the magnetic fluxes which are shown in the figure, the motor current is formulated as

$$i_{mk} = -\sqrt{\frac{2}{3}}\left[i_m\cos\left\{\phi + \frac{\pi}{3}(k-1)\right\}\right] \tag{6}$$

where i_m is magnitude of the motor current. Considering the axial control current, tilt control current and radial control current, the total currents fed to each coil of top stator and bottom stator are given in Eq. (7) respectively.

$$\begin{cases} i_{top} = (i_{mk} + i_{zk}) + (i_{txk} + i_{ryk}) + (i_{tyk} + i_{rxk}) \\ i_{bottom} = (i_{mk} - i_{zk}) + (-i_{txk} + i_{ryk}) + (-i_{tyk} + i_{rxk}) \end{cases} \tag{7}$$

For closed-loop torque control method, the principle diagram is shown in the right figure of Fig. 5. From the figure, we can see the magnetic attractive forces and magnetic repulsive forces in axial direction cancel each other, so only rotation torque is generated. The current which is used to generate rotation torque is called **torque current** here, and it is described as

$$i_{qk} = \sqrt{\frac{2}{3}}\left[i_q\sin\left\{\phi + \frac{\pi}{3}(k-1)\right\}\right] \tag{8}$$

where i_q is magnitude of the torque current. The total currents fed to each coil of top stator and bottom stator are given as

$$\begin{cases} i_{top} = (i_{qk} + i_{zk}) + (i_{txk} + i_{ryk}) + (i_{tyk} + i_{rxk}) \\ i_{bottom} = (i_{qk} - i_{zk}) + (-i_{txk} + i_{ryk}) + (-i_{tyk} + i_{rxk}) \end{cases} \quad (9)$$

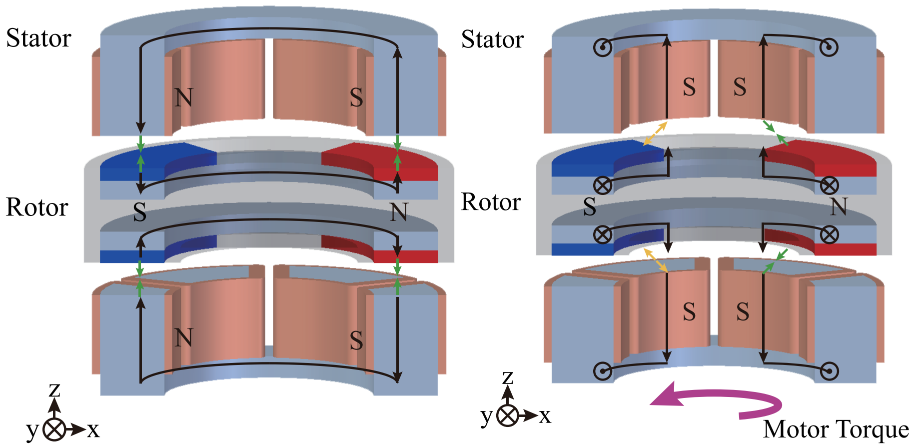

Fig. 5 Principle diagram of generation of rotation torque

3. Torque control system with 5-DOF active position control

The designed control system is shown in Fig. 6. Proportional-integral-derivative (PID) feedback controller whose transfer function is given as Eq. (10) was mounted into digital signal processor (DSP, dSPACE, DS1104). The signals from displacement sensors and hall sensors were captured through analog-digital (A/D) converters of DSP, and eight channels of control currents which were decided by the designed controller were outputed via digital-analog (D/A) converters of DSP. Since two kinds of methods to generate rotation torque for ASBM are considered in this research, block diagrams of these two torque control system are shown in Figs. 7 and 8, respectively. The representation of each control current is also given in the block diagrams.

$$G(z) = K_p + \frac{k_d(z-1)}{T_d\left(z - e^{\frac{-\tau}{T_d}}\right)} + \frac{K_i \tau z}{z-1} \quad (10)$$

According to Eqs. (7) and (9), all the control currents for coils of the top stator and the bottom stator are obtained by using the following equations, where $i_{\cdot t}$ and $i_{\cdot b}$ mean currents of the top stator and the bottom stator, respectively.

$$\begin{array}{lll} i_{1t} = i_{d1} + i_{f1} & i_{2t} = (i_{d1} + i_{d2}) + i_{f2} & i_{3t} = i_{d2} - (i_{f1} + i_{f2}) \\ i_{4t} = -i_{d1} + i_{f1} & i_{5t} = -(i_{d1} + i_{d2}) + i_{f2} & i_{6t} = -i_{d2} - (i_{f1} + i_{f2}) \\ i_{1b} = i_{d3} - i_{f3} & i_{2b} = (i_{d3} + i_{d4}) - i_{f4} & i_{3b} = i_{d4} + (i_{f3} + i_{f4}) \\ i_{4b} = -i_{d3} - i_{f3} & i_{5b} = -(i_{d3} + i_{d4}) - i_{f4} & i_{6b} = -i_{d4} + (i_{f3} + i_{f4}) \end{array}$$

4. Experimental results

As Section 2.2.4 introduced, there are two kinds of methods to generate rotation torque for ASBM: open-loop torque control method and closed-loop torque control method. In this section, we will show the results of rotation test by using each of them with 5-DOF active control respectively.

4.1. Rotation test with open-loop torque control

According to Fig. 7, we implemented the designed open-loop torque control system with 5-DOF active control and did rotation test. During this test, parameters of 5-DOF active control are given in Table 1, and motor current was set as $i_m = 0.9$[A]. The developed ASBM could be successfully levitated till 1800 rpm. At 1800 rpm, axial displacement of the rotor (z average), radial displacments and tilt angles of the rotor are shown in Figs. 9-11, respectively. Since tile angles

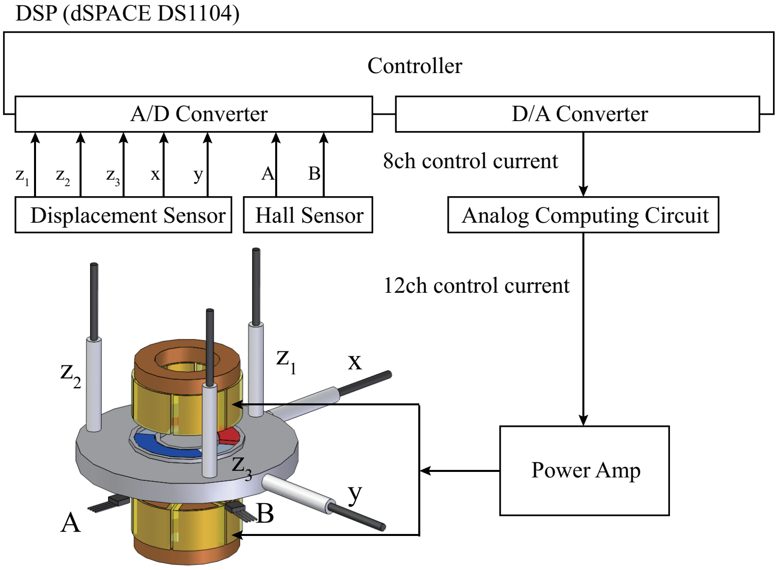

Fig. 6 Overview of the control system

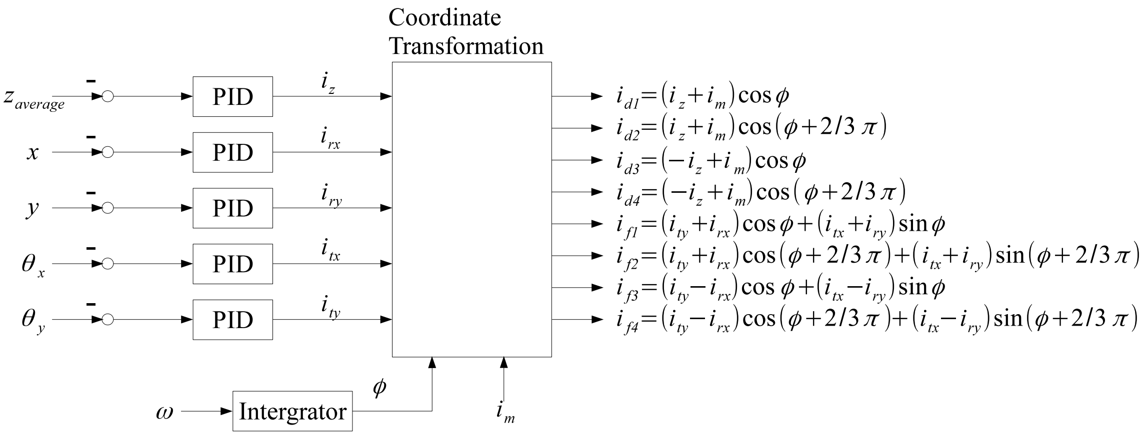

Fig. 7 Block diagram of open-loop torque control method

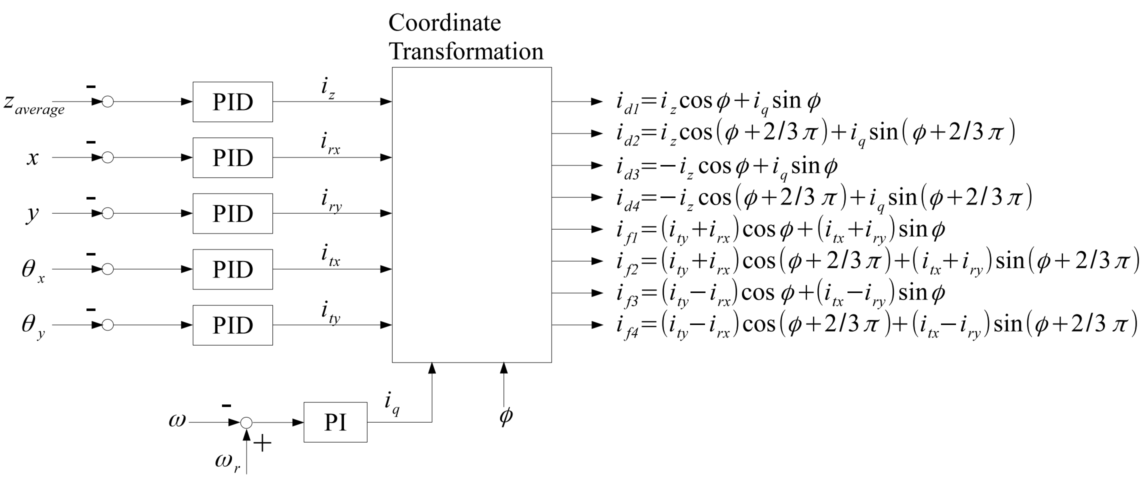

Fig. 8 Block diagram of closed-loop torque control method

veried during rotating, the displacement of each axial displacement sensor is also shown in Fig. 9 for checking whether the rotor was levitated or not. We can see that only one point of z_1 reached axial limit (±0.3[mm]). That is, 1800 rpm is the limit of rotation speed for open-loop torque control method.

Table 1 Parameters of 5-DOF active control

	Axial position control	Tilt control	Radial position control
k_p	26[A/mm]	250[A/mm]	0.5[A/mm]
k_d	0.028[A·s/mm]	0.5[A·s/mm]	0.01[A·s/mm]
k_i	10[A/(mm·s)]	20[A/(mm·s)]	0[A/(mm·s)]

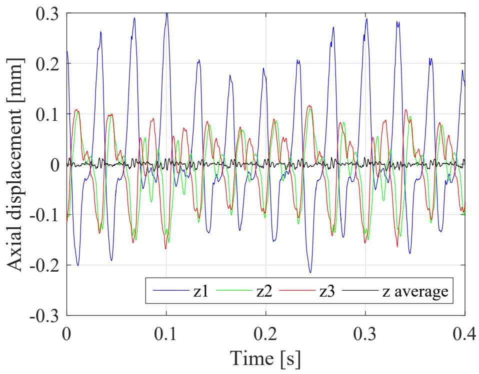

Fig. 9 Axial displacement

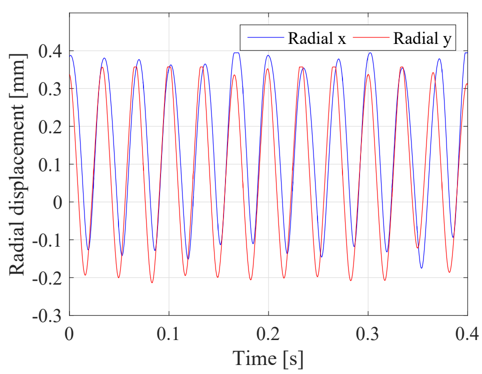

Fig. 10 Radial displacement

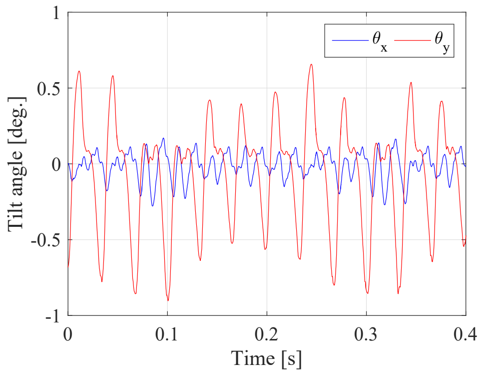

Fig. 11 Tilt angle

4.2. Rotation test with closed-loop torque control

In this section, we showed rotation test by using closed-loop torque control system. During this test, we applied 5-DOF active control for levitation and continued to using the same parameters. The developed ASBM could be successfully levitated till 3000 rpm. At 3000 rpm, axial displacement of the rotor (z average), radial displacments and tilt angles of the rotor are shown in Figs. 12-14, respectively. Since tile angles veried during rotating, the displacement of each axial displacement sensor is also shown in Fig. 12 for checking whether the rotor was levitated or not. Compared with Fig. 9, we can see each value of axial displacement sensors is much smaller. That means closed-loop torque control method could improve the performance of rotation of the developed ASBM. Since there are only eighteen square type permanent magnets on the rotor for measuring rotation speed, it is difficult to measure rotation speed over 3300 rpm by using 1[kHz] sampling frequency. That is the reason why the ASBM can not pass much higher rotation speed in this test.

5. Conclusion

In this paper, the structure and control principle of the developed ASBM were introduced. Based on the control principle, 5-DOF active position control system was designed for the ASBM. Open-loop torque control method and closed-loop torque control method were applied to generate rotation torque for the ASBM. By using the designed control

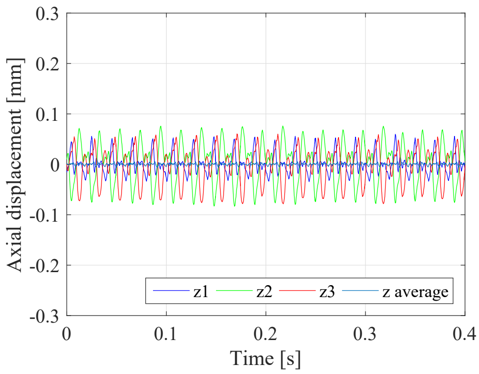

Fig. 12 Axial displacement

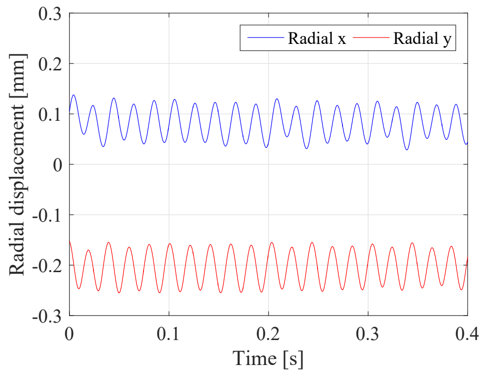

Fig. 13 Radial displacement

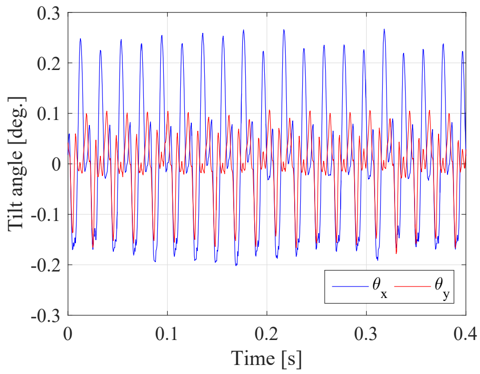

Fig. 14 Tilt angle

system, rotation test was done. The experimental results showed the performance of the developed ASBM and verified its practicability.

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