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Unbalance Compensation for Lorentz-force-type Self-bearing Motor

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Abstract

A self-bearing motor is a combination of magnetic bearings and an electric motor, and many types of self-bearing motors have been proposed and developed. A Lorentz-force-type self-bearing motor consists of distributed windings as a stator, and permanent magnets as a rotor. This motor does not have a stator core and slots, then, the structure of the motor becomes simple, and it allows miniaturization and cost reduction. However, the manufacturing error of the distributed windings is not small, hence, the bearing force is affected by the rotating position of the rotor. This causes the rotor vibration, rotating losses, large stator current, and so on. To solve this problem, this paper introduces unbalance compensation for the position control of the rotor. The vibration synchronized with the rotation can be canceled by the integral feedback on the rotor coordinate system, and then, it is possible to reduce the vibration or motor current. The experimental results show that the unbalance compensation technique is effective for reducing motor currents.

Key words : Self-bearing motor, Bearingless motor, Unbalance compensation, Lorentz-force, Coreless motor, Slotless motor.

1. Introduction

A magnetic bearing supports a rotor without physical contact by using magnetic force of electromagnet or permanent magnet. A self-bearing motor is a combination of a magnetic bearing and an electric motor. In recent years, high durability and low noise characteristics are required for small size motors, and the magnetic bearings and self-bearing motors are paid attention to solve these problems.

Since a coreless and distributed winding stator is effective for miniaturizing the magnetic bearings or self-bearing motors, we have developed the small magnetic bearing and self-bearing motor which has similar structure to coreless motors, and have confirmed its non-contact levitation and rotation (Kato and Ueno, 2008, Ueno and Arakawa, 2011). However, the manufacturing error of the distributed windings is not small, hence, the bearing force is affected by the rotating position of the rotor. This causes the rotor vibration, rotating losses, large stator current, and so on. To solve this problem, this paper introduces unbalance compensation for the position control of the rotor. The vibration synchronized with the rotation can be canceled by the integral feedback on the rotor coordinate system, and then, it is possible to reduce the vibration or motor current. The experimental results show that the unbalance compensation technique is effective for reducing motor currents.

2. Lorentz-force-tyep Self-bearing Motor

The outline of the Lorentz-force-type self-bearing motor is shown in Fig. 1. The left is a whole structure, while the right is the structure of a winding. The rotor consists of a cylindrical permanent magnet and a back yoke, which is fixed to the permanent magnet to avoid the negative stiffness. Two windings are used for the stator to control four-degrees-of-freedom of the rotor position and generate a motor torque. The axial position is controlled by another axial magnetic bearing. The winding is a six-phase distributed winding without iron core, and it inserted to between the permanent magnet and the back yoke of the rotor. The right in Fig. 1 is a developed drawing of the stator winding. Wires were winded to have a hexagonal form, and then, it was formed cylindrically.

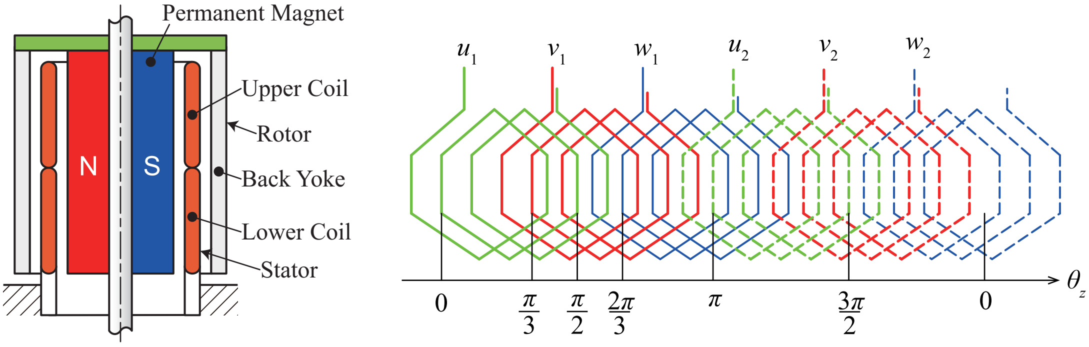

Fig. 1 Left: Structure of the self-bearing motor. The back yoke is fixed to the permanent magnet of the rotor to avoid unstable magnetic force. Right: Developed view of the stator windings. The interval between neighboring phases is 60 degrees. The nterval between plus-phase and minus-phase is 90 degrees.

The stator currents are expressed as

$$i_{u1} = -i_x \cos(2\theta_0 - \psi) - i_y \sin(2\theta_0 - \psi) - i_m \cos(\theta_0 - \psi - \pi/4) \tag{1}$$

$$i_{v1} = -i_x \cos(2\theta_0 + 2\pi/3 - \psi) - i_y \sin(2\theta_0 + 2\pi/3 - \psi) + i_m \cos(\theta_0 + 4\pi/3 - \psi - \pi/4) \tag{2}$$

$$i_{w1} = -i_x \cos(2\theta_0 + 4\pi/3 - \psi) - i_y \sin(2\theta_0 + 4\pi/3 - \psi) - i_m \cos(\theta_0 + 2\pi/3 - \psi - \pi/4) \tag{3}$$

$$i_{u2} = -i_x \cos(2\theta_0 - \psi) - i_y \sin(2\theta_0 - \psi) + i_m \cos(\theta_0 - \psi - \pi/4) \tag{4}$$

$$i_{v2} = -i_x \cos(2\theta_0 + 2\pi/3 - \psi) - i_y \sin(2\theta_0 + 2\pi/3 - \psi) - i_m \cos(\theta_0 + 4\pi/3 - \psi - \pi/4) \tag{5}$$

$$i_{w2} = -i_x \cos(2\theta_0 + 4\pi/3 - \psi) - i_y \sin(2\theta_0 + 4\pi/3 - \psi) + i_m \cos(\theta_0 + 2\pi/3 - \psi - \pi/4) \tag{6}$$

where i_x and i_y are radial force control current, i_m is torque control current, ψ is a rotation angle, and θ_0 is winding position. Figure 2 shows the principle of generation of a force and torque. For simplicity, the figure illustrates the case in which the number of turns of the stator winding is one, and the back yoke is omitted. The Lorentz-force is generated as denoted by the green arrows, and then, the reaction force acts on the rotor. The radial forces and motor torque are proportional to i_x, i_y, and i_m, respectively.

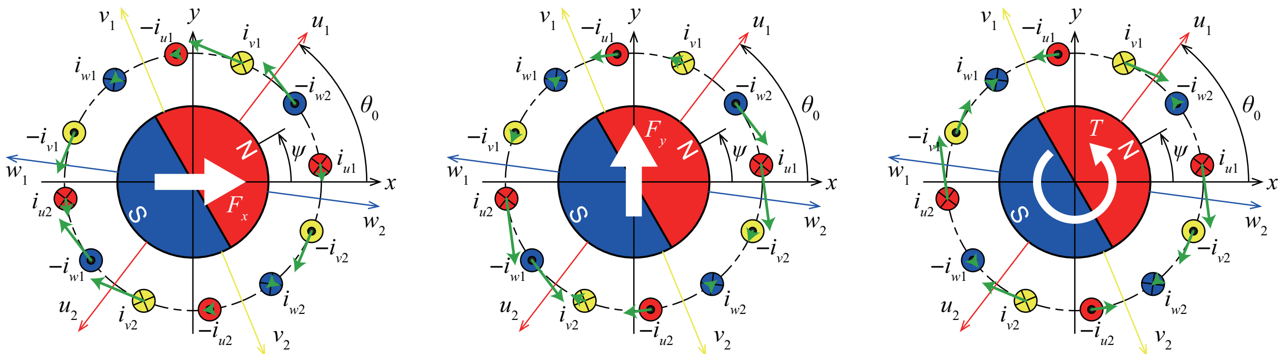

Fig. 2 Generation of radial forces and motor torque. The Lorentz-force at each wires is denoted by green arrows. Left: $i_y = i_m = 0$, Center: $i_x = i_m = 0$, Right: $i_x = i_y = 0$. The radial forces and the motor torque are proportional to each control currents.

3. Unbalance Compensation

When there is unbalance on the rotor, the rotor is excited by the periodic forces which frequency is the same as rotational speed. Therefore, large control currents are required to suppress the unbalance vibration. For some applications such as a rotary fan, the rotor position is not important, then it is possible to reduce the control current by closing the rotation center to the center of gravity. The controller which compensates the vibration caused by periodic disturbance forces has been proposed by Mizuno and Higuchi, 1986 and Habermann, et.al., 1978. The unbalance components can be obtained by using a synchronous signal with the rotor's angular position. The block diagram of the unbalance compensator is shown in Fig. 3. The control currents i_x and i_y are calculated by PD controllers, and transformed into the rotating coordinate system. The coordinate transfer matrix $\boldsymbol{T}$ is

$$\boldsymbol{T} = \begin{bmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{bmatrix} \tag{7}$$

By integrating the transformed signals, the same components as the unbalance forces can be obtained. Then, returning into x-y coordinate system and subtracting from the original currents, we can remove the unbalance components from the control currents.

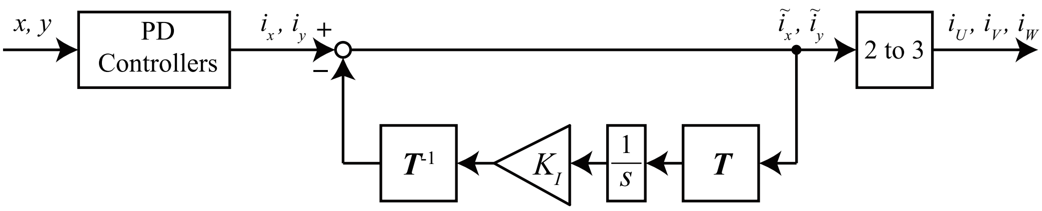

Fig. 3 Block diagram of radial position controller with unbalance compensation.

4. Experimental Results

4.1. Experimental dvice

The experimental device is shown in Fig. 4. The left picture is the entire device. The top of the device is the axial magnetic bearing which consists of an electromagnet and a button type permanent magnet attached to the rotor shaft. The radial and axial displacements of the rotor are measured by eddy current type displacement sensors. The center is the stator windings. The right picture shows arrangement of hall elements. The angular position is measured by two hall elements attached to the stator winding, and the rotational speed is calculated by the period of output of hall element.

The control system is shown in Fig. 5. A digital signal processor (DSP, dSPACE DS1104) was used for controlling the rotor's axial and radial position and rotation speed. The DSP receives signals from five displacement sensors and two Hall elements through A/D converters, and then, calculates the currents for each phases. However, the DSP cannot output all current command due to lack numbers of the D/A converter, it output only u- and v-phase to reduced the number of output signals. w-phase can be calculated from these phases, then, we obtain all phase signals by using analog operating circuit. Then, these current commands are fed to power amplifiers. Thirteen amplifiers; twelve for SBM and one for thrust AMB are used for supplying current to the motor. A PID controller and PI controller were used for the axial position and rotating speed control, respectively.

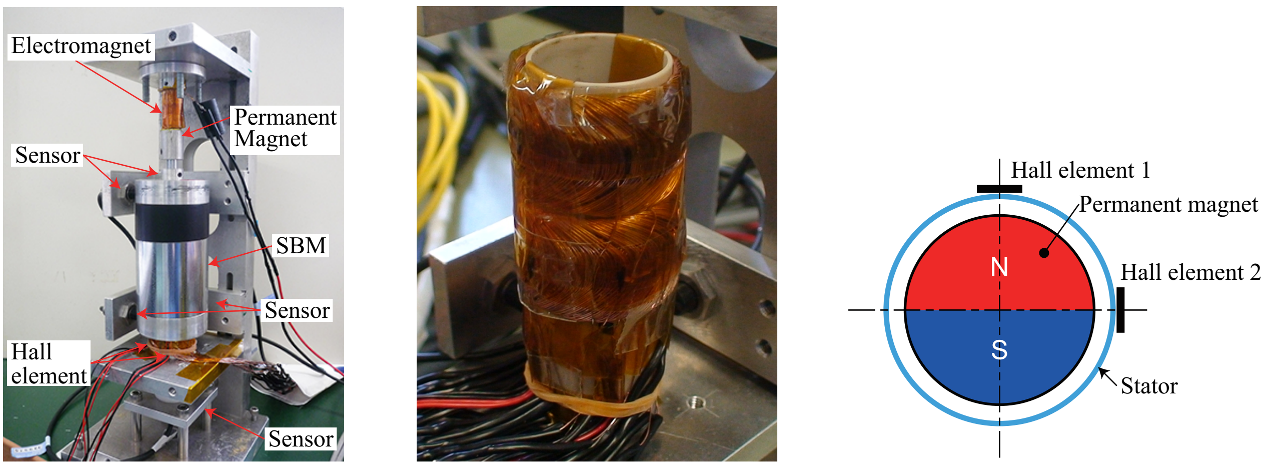

Fig. 4 Experimental setup. Left picture is appearance of the entire device; center is the stator winding; right is the position of Hall elements.

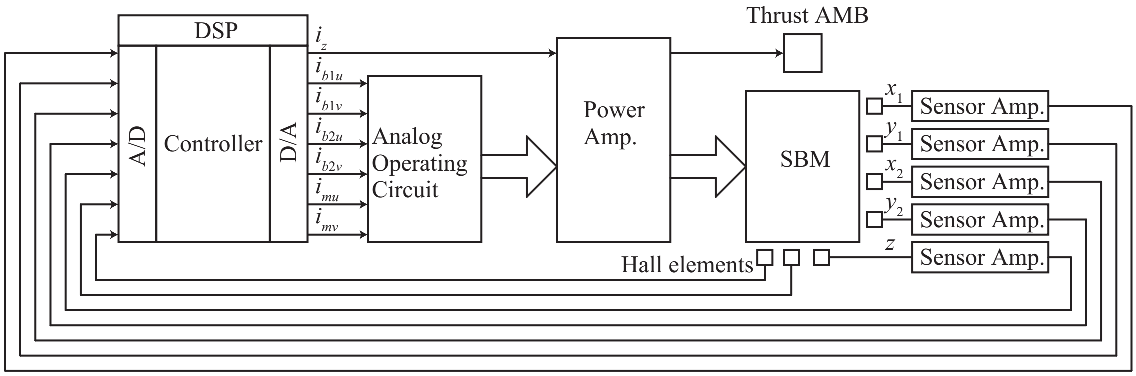

Fig. 5　Control System

4.2. Experimental Result

The experimental results without the unbalance compensation are shown in Fig. 6, while the results with the unbalance compensation are shown in Fig. 7. The left graphs show the displacement versus rotor's angular position, while the right graphs show the control current. The rotation speed was controlled at 6,000 rpm by vector control and PI controller. These graphs are plotted for 3 seconds at 1 ms intervals. The red and blue dots indicate x and y, respectively. The control current is significantly reduced by using the unbalance compensator. We confirmed that the unbalance compensation is effective to reduce the stator current of the self-bearing motor.

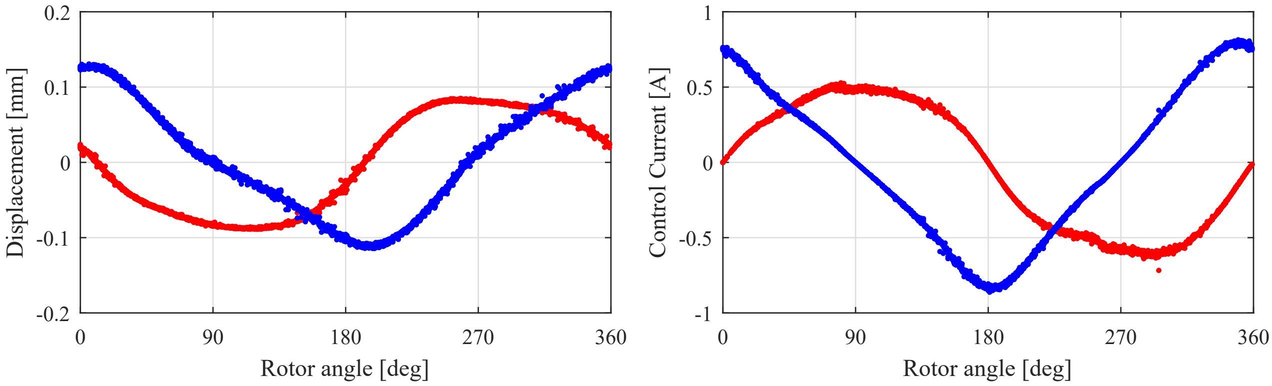

Fig. 6　Experimental results without unbalance compensator.

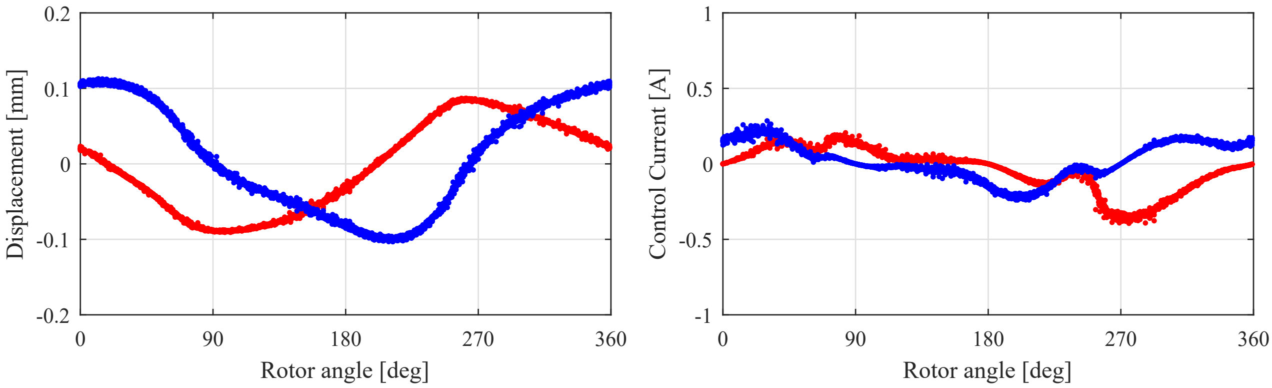

Fig. 7　Experimental results with unbalance compensator. The control current is significantly reduced.

5. Conclusions

This paper applied the unbalance compensation technique to the Lorentz-force-type self-bearing motor to reduce the stator current. The experimental results showed that the unbalance compensation technique was effective for reducing motor currents. In the future, the control system considered with radial force variation caused by misalignment of the stator winding will be developed.

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