HYBRID AMB TYPE SELFBEARING MOTOR

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ABSTRACT

A new type of selfbearing motor is introduced in this paper. It is intended for a rotor to have two functions of rotary motor and radial magnetic bearing. Previously developed selfbearing motor uses P$\pm$2 pole algorithm which has the demerits of complicated control and low maximum power. This paper introduces a hybrid active magnetic bearing (HB AMB) type selfbearing motor which uses DC magnetic flux to control radial forces and is similar to HB type active magnetic bearing. First, principle and theoretical background is introduced. Then the minimum pole number is theoretically derived which guarantees the control independency of rotation and levitation. Finally, the experimental setup is made to confirm the capability of the proposed motor. The results show high possibility of the proposed motor.

INTRODUCTION

Magnetic bearings have been used to support rotors without physical contact (Schweitzer et al., 1994; Dussaux, 1990). This requires a separate driving motor in addition to magnetic bearings, hence the rotor becomes long and is apt to produce bending vibration. Several types of selfbearing motor have been introduced which are a combination of a rotary motor and a magnetic bearing (Bichsel, 1992; Okada et al., 1992; Chiba et. al., 1991; Okada et. al., 1995; Okada et al., 1996; Oshima et al., 1994; Schob and Bichel, 1994). These motors can support the rotor without physical contact and give rotating torque to

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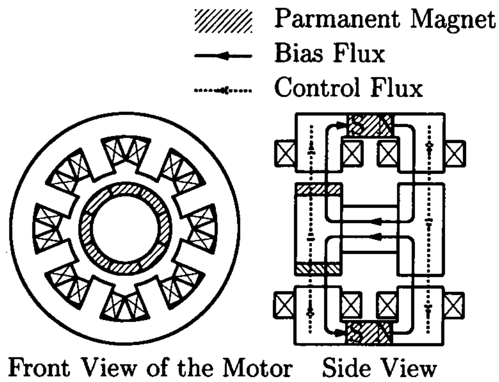

Figure 1: Schematic of Hybrid AMB Type Selfbearing Motor

the rotor. This replaces the contact components and leads to an overall reduction of size.

The previous motor uses two kinds of rotating magnetic flux: Rotational control is achieved with the same pole number P of the rotor, while the plus or minus two pole of the motoring one produces a pure drag force to the rotor. By controlling the magnitude and phase of this $P + 2$ or $P - 2$ pole current distribution relative to the motoring magnetic pole, levitation force can be controlled in the radial coordinate (Okada et. al., 1995; Okada et al., 1996). Hence the construction of the stator and the control method are complicated.

To overcome this difficulty, Toyoshima, et. al. have introduced a new type of selfbearing motor which uses DC flux to control radial force. They applied this idea to the homopolar motor (Toyashima et al., 1996). However, the minimum pole number of eight is relatively big which guarantees the control independency.

This paper introduces a simpler selfbearing motor which also uses DC flux to control radial force. This idea is applied to PM motor. First, the principle and theoretical background of this motor is introduced. Then the minumum pole number of six is derived which guarantees the control independency of rotation and levitation. Finally, a simple experiment is performed. The results are showing stable levitation of this type of motor.

HYBRID TYPE SELFBEARING MOTOR

The proposed motor is intended to have two functions of radial magnetic bearing and AC motor. Principle and theoretical background of DC biased HB AMB type selfbearing motor is introduced. Then the minimum pole number is derived.

Principle of HB type selfbearing motor

The schematic drawing of the proposed selfbearing motor is shown in Fig. 1. The side view indicates two components; The left side is the proposed motor, while the right side is the hybrid type magnetic bearing. Between them a permanent magnet (PM) is installed which gives the bias flux as shown by the solid line. The radial force is produced by the control flux which is shown by the dotted line. The figure indicates that the upper airgap flux is increased, while the lower airgap flux is decreased by the control flux. Hence the upward radial force is produced in both proposed motor and magnetic bearing.

The front view indicates the construction of the proposed motor. The stator has two kinds of winding; one is for levitation control and another is for rotation. There are two levitation coils for x and y directions, both of them are two pole windings. They produce the control flux as shown by the dotted line in the right figure and produce radial force.

Thin permanent magnets are attached on the surface of the rotor which gives polarity of M pole pair number to the rotor. Motoring coil is wound in the stator which has the same pole pair number as the rotor. The electric angle difference between the stator current and the rotor position controls the motoring torque.

Torque and levitation force

The motor coordinate system and flux distributions are shown in Fig. 2. The stator is assumed to have a current sheet which produces arbitrary distributed magnetic flux. The bias permanent magnet is assumed to produce a constant flux while the permanent magnets on the rotor produce stepwise flux. Then the total flux distribution produced by PMs is written by the following equation and is shown schematically in Fig. 2.

$$B_r = \begin{cases} B_0 + B_1 \\ \cdots \left(\omega t + \frac{2\pi(i-1)}{M} - \frac{\pi}{2M} \sim \omega t + \frac{2\pi(i-1)}{M} + \frac{\pi}{2M}\right) \\ B_0 - B_1 \\ \cdots \left(\omega t + \frac{2\pi(i-1)}{M} + \frac{\pi}{2M} \sim \omega t + \frac{2\pi(i-1)}{M} + \frac{3\pi}{2M}\right) \end{cases} \tag{1}$$

where

B_0 : gap flux density produced by bias permanent magnet
B_1 : peak flux value produced by rotor permanent magnet
θ : angular coordinate on the stator
ω : angular velocity of the rotor
t : time
M : pole pair number (=1, 2, 3, $\cdots$)
i : arbitrary integer number

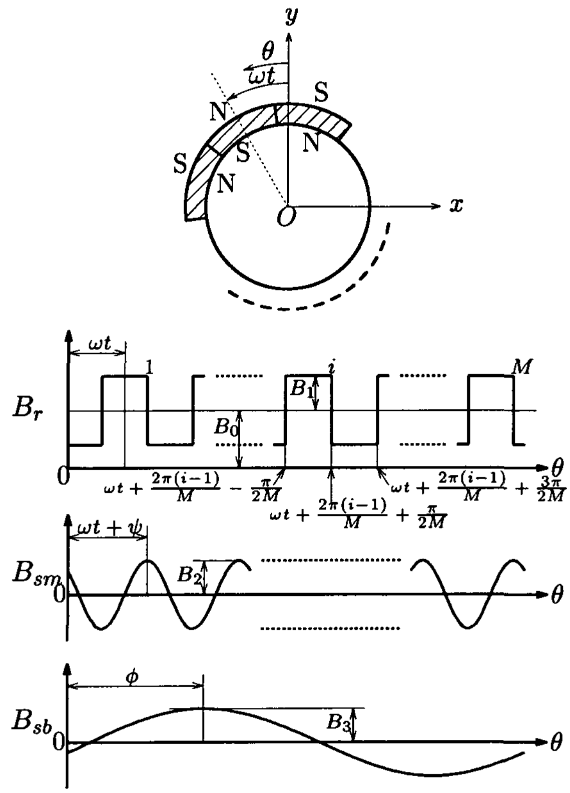

Figure 2: Coordinates and flux distributions

For simplicity, the flux distribution is assumed to be sinusoidal form.

$$B_r = B_0 + B_1 \cos M(\theta - \omega t) \tag{2}$$

The motoring coil produces the following flux distribution.

$$B_{sm} = B_2 \cos M(\theta - \omega t - \psi) \tag{3}$$

where B_2 is the peak flux value produced by the motoring current and ψ is the phase. The radial force control flux B_{sb} is produced by the levitation coil current as;

$$B_{sb} = B_3 \cos(\theta - \phi) \tag{4}$$

where B_3 is the peak flux value and ϕ is the phase. Then the total flux distribution B_g in the airgap is given by

$$B_g = B_r + B_{sm} + B_{sb} \tag{5}$$

Next magnetic energy is calculated. Let r be radius, g be air gap between the rotor and the stator, l be the length of rotor, $d\theta$ be an infinitesimal angle, then we have the following infinitesimal volume ΔV.

$$\Delta V = rlgd\theta$$

The magnetic energy ΔW is calculated as,

$$\Delta W = \frac{1}{2\mu_0} B_g^2 \Delta V = \frac{1}{2\mu_0} B_g^2 rlgd\theta$$

The radial force dF is calculated as,

$$dF = \frac{1}{2\mu_0} B_g^2 rld\theta$$

Hence the x, y directional forces F_x, F_y are calculated by integrating the x and y components of dF over the entire gap of θ direction.

$$\begin{aligned}
F_x &= \int_0^{2\pi} \frac{1}{2\mu_0} B_g^2 rl \cos\theta d\theta \\
&= \frac{lr}{2\mu_0} \left[\frac{B_0 B_1}{2} \int_0^{2\pi} \cos\{(M-1)\theta - M\omega t\} d\theta \right. \\
&+ \frac{B_0 B_2}{2} \int_0^{2\pi} \cos\{(M-1)\theta - M(\omega t + \psi)\} d\theta \\
&+ 2B_0 B_3 \pi \cos\phi \\
&+ \frac{B_1 B_3}{2} \int_0^{2\pi} \cos\{(M-2)\theta - (M\omega t - \phi)\} d\theta \\
&\left. + \frac{B_2 B_3}{2} \int_0^{2\pi} \cos\{(M-2)\theta - M(\omega t + \psi) + \phi\} d\theta \right] \qquad (6) \\
F_y &= \int_0^{2\pi} \frac{1}{2\mu_0} B_g^2 rl \sin\theta d\theta \\
&= \frac{lr}{2\mu_0} \left[\frac{B_0 B_1}{2} \int_0^{2\pi} \sin\{(1-M)\theta + M\omega t\} d\theta \right. \\
&+ \frac{B_0 B_2}{2} \int_0^{2\pi} \sin\{(1-M)\theta + M(\omega t + \psi)\} d\theta \\
&+ 2B_0 B_3 \pi \sin\phi \\
&+ \frac{B_1 B_3}{2} \int_0^{2\pi} \sin\{(2-M)\theta + (M\omega t - \phi)\} d\theta \\
&\left. + \frac{B_2 B_3}{2} \int_0^{2\pi} \cos\{(2-M)\theta + M(\omega t + \psi) - \phi\} d\theta \right] \qquad (7)
\end{aligned}$$

The motoring torque T is calculated similarly,

$$\begin{aligned}
T &= \int_0^{2\pi} \frac{\partial \Delta W}{\partial \psi} \\
&= -\frac{rlgMB_1 B_2 \pi}{\mu_0} \sin M\psi \\
&+ \frac{rlgMB_2 B_3}{2\mu_0} \int_0^{2\pi} \sin\{(M-1)\theta - M(\omega t + \psi) + \phi\} d\theta \qquad (8)
\end{aligned}$$

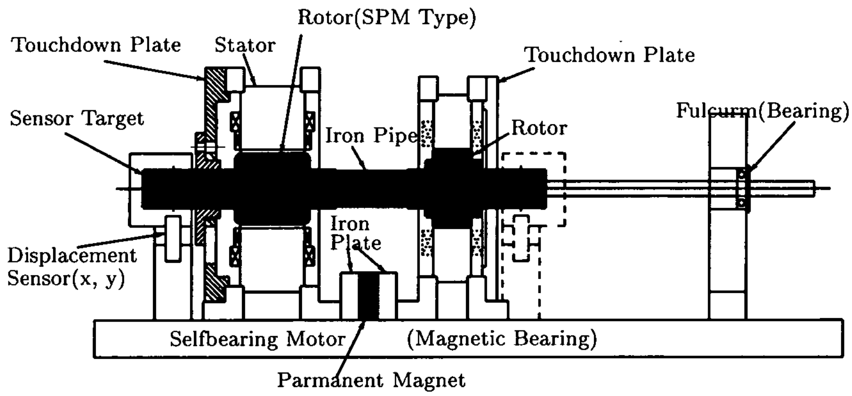

Figure 3: Schematic of experimental setup

Control independency

Finally, the minimum pole number which guarantees the control independent condition for rotation and radial force is developed.

From eqns. (6) and (7) the radial force can be controlled independently when $M \geq 3$, then we have

$$F_x = \frac{B_0 B_3 l r \pi}{\mu_0} \sin(\phi) \tag{9}$$

$$F_y = \frac{B_0 B_3 l r \pi}{\mu_0} \cos(\phi) \tag{10}$$

That is F_x and F_y are controlled by B_3 and ϕ and is independent of the rotor angle θ and the motoring control.

Also the rotating torque T is independently controlled from the levitation control when $M \geq 2$.

$$T = -\frac{rlgMB_1B_2\pi}{\mu_0} \sin(M\psi) \tag{11}$$

That is, T is independently controlled by B_2 and ψ.

EXPERIMENTAL RESULTS AND CONSIDERATIONS

To confirm the capability of the proposed motor, a simple experiment is performed.

Experimental setup

Figure 3 shows the experimental setup. The left side is the proposed selfbearing motor, while the middle is the HB type magnetic bearing. For experimental simplicity, magnetic

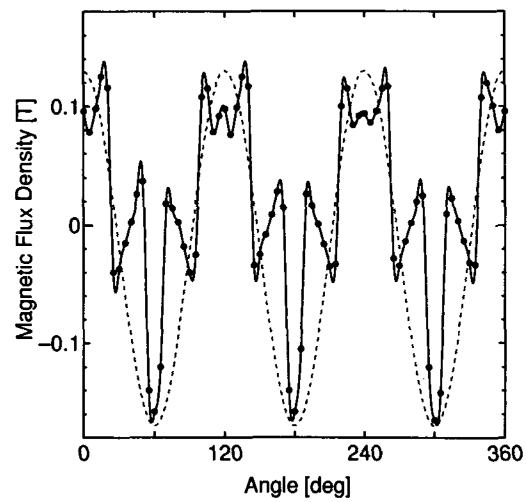

Figure 4: Flux distribution of the rotor

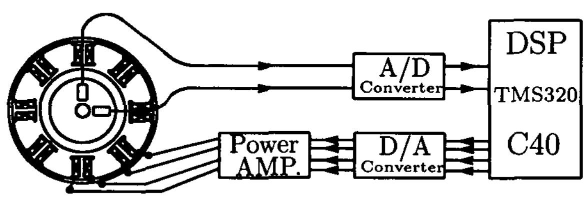

Figure 5: The schematic drawing illustrates the control system

bearing is not operated and is used as bias flux pass. The rotor is supported by a ball bearing at the right end. Hence the rotor has three degrees of control freedom; two in radial coordinate and one in rotation. All three degrees can be controlled by the proposed motor.

A ferrite permanent magnet is installed on the base plate to give the bias flux. On the surface of the rotor thin permanent magnets (Neodymium magnet, thickness 0.8mm) are glued to give the polarity to the rotor. In this paper six pole is selected. The flux distribution of the rotor in free space is shown in Fig. 4. The dotted line is the sinusoidal curve while the solid line is the measured flux distribution. The diameter of the rotor is 38 mm and the length is 35 mm.

Control system is shown in Fig. 5. The levitation control used is the standard digital PID controller.

$$G(z) = K_P + \frac{K_D(z-1)}{T_D\left(z - e^{-\tau/T_D}\right)} + \frac{K_I \tau z}{z-1} \tag{12}$$

where K_P, K_D, K_I and T_D are the proportional gain, derivative gain, integral gain and derivative time constant respectively. The values used were determined experimentally: $K_P = 25$ [A/mm], $K_D = 5$ [A sec/mm], $K_I = 0.2$ [A/sec mm] and $T_D = 30$ [ms]. The

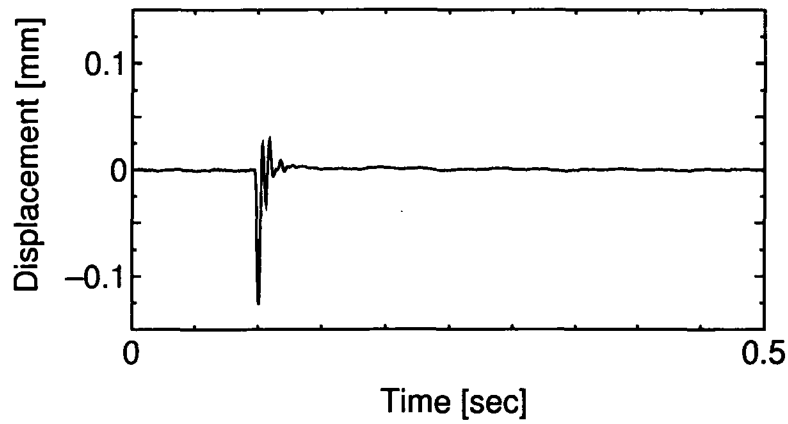

Figure 6: Y directional impulse response when the motoring current is 0.5[A]

sampling interval τ used is 0.1 [ms].

The stator has 12 concentrated windings, each of them are controlled individually by a digital signal processor (DSP; $TMS320C40$). Two gap sensors were used to measure the x and y displacements of the rotor. According to the measured gap displacement, the DSP calculates each coil current from the summation of the motoring current and the levitation control current. Then they are fed to each power amplifier through D/A converter.

Results

The rotor can levitate and rotate. The levitation is very stable which indicates the superiority of the proposed motor. The levitation force is recorded up to 20 [N] using a steelyard. The impulse response in y-direction is indicated in Fig. 6. Transient vibration is quickly decayed. The motoring current in this case is 0.5 [A] for 150 turns ciol. The levitation is stable and the levitation force is relatively strong.

Next the unbalance response is tested as shown in Fig. 7. The rotor can run up to 4,400 [rpm]. By grasping the shaft, strong rotating torque was felt. However, the top speed is limited due to the higher harmonics of the flux distribution produced by the surface permanent magnets which is shown in Fig. 4. The arrangement of rotor SPM is now modifying to get the smooth flux distribution and high rotating speed.

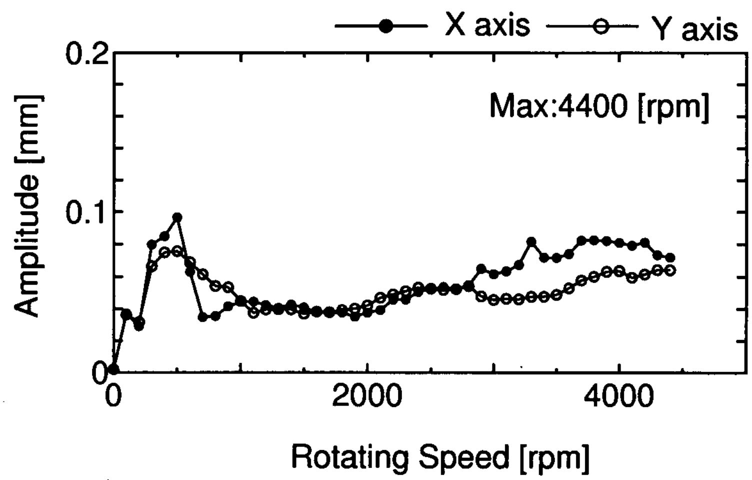

Figure 7: Unbalance response when the motoring current is 0.5[A]

CONCLUSIONS

New type of selfbearing motor is introduced. The levitation is controlled by DC flux, while the rotation is controlled as a traditional PM type motor. The minimum pole number of six is theoretically derived which guarantees the control independency of rotation and levitation. Simple experiments are performed to confirm the proposed technique. The results are showing stable levitation and strong rotating torque. Further work is continuing to get high speed rotation and applying this motor to rotary blood pump.

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