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STATE OF ART OF SELFBEARING MOTOR

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Abstract

Magnetic bearings have been widely used to support rotors without any physical contact. This however, requires the control of five degrees-of-freedom and needs a separate driving motor. This paper introduces selfbearing motors which use the combination of a rotary motor and a magnetic bearing. These motors are suitable for use in high speed rotor or in special circumstances because they are small in size and can replace the contact components. The radial type one has the merit of being small in size and capable of controlling two degrees-of-freedom in x and y directions. The axial type motor controls only one degree-of-freedom in z direction. Theoretical background of the functions of the motor and magnetic bearing will also be introduced. New research works are reviewed and the application in rotary blood pump is discussed.

Introduction

Magnetic bearings have been used to support the rotating parts without physical contact [1, 2]. This requires a separate driving motor in addition to magnetic bearings which has a large control degree-of-freedom.

This paper introduces two types of selfbearing motors which are the combination of rotary motor and magnetic bearing [3]-[8]. These motors can support the rotor without physical contact and give rotating torque to the rotor and have high potential to be applied to the blood pumps. This replaces the contact components and leads to an overall reduction of size.

First, radial type motor is introduced. 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 [6, 7].

Next, axial type motor is introduced for its ability to control only one degree-of-freedom in z direction. The rotation is controlled by the phase of the magnetic flux between the rotor and the stator, while the levitation is controlled by changing the amplitude of this magnetic flux. This is theoretically simple and considerably easy to implement [8].

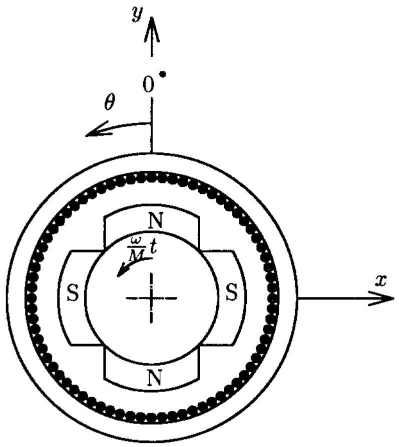


Figure 1: The schematic drawing illustrates the radial PM motor and coordinate system.

Two types of experiments are introduced. The experimental results show high potential of application. The application to rotary blood pump is discussed. Several new types of selfbearing motor are introduced and the merits of them are discussed.

Theoretical Background of Selfbearing Motor

Research of selfbearing motor has been started by three groupes almost the same time around 1990 [3], [4], [5]. This section introduces simplified theory of the selfbearing motor.

Radial Type Permanent Magnet Motor

Consider a rotor with M pole pair number (pole number $P = 2M$) produced by a permanent magnet. The stator is assumed to have a current sheet which produces an arbitrary distributed magnetic flux. The case of $M = 2$ ($P = 4$) is shown schematically in Fig. 1.

The rotor with M pole pair number is assumed

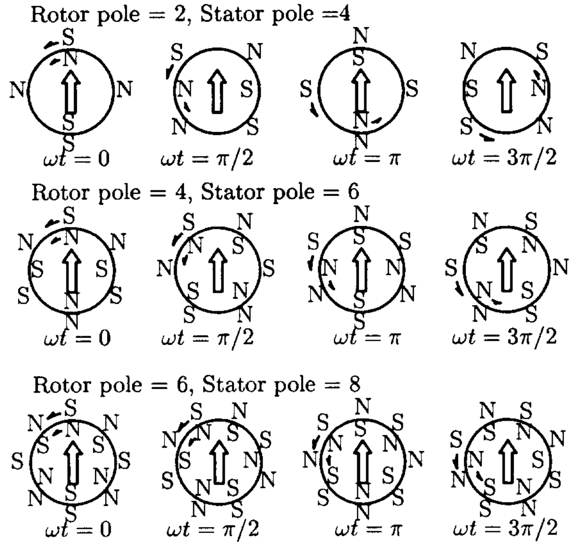


Figure 2: Levitation control of P+2-pole algorithm is shown.

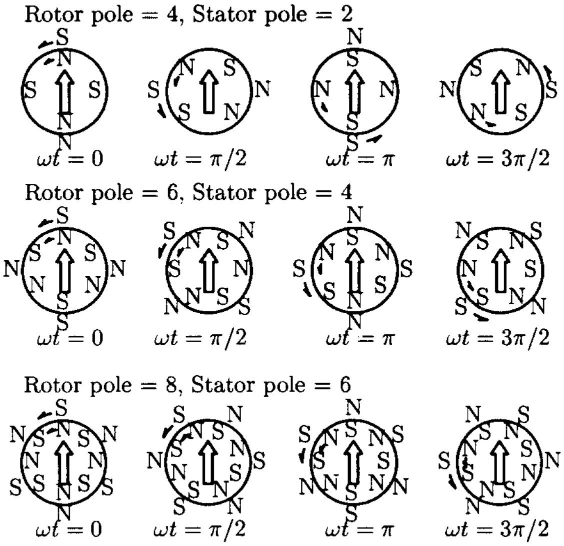


Figure 3: Levitation control of P−2-pole algorithm is shown.

to produce the following flux density;

$$B_r(\theta, t) = B_R \cos(\omega t - M\theta) \qquad (1)$$

where B_R is the peak density of magnetic flux, ω is frequency and θ is angular coordinate (assumed zero at the center of North pole).

The stator is assumed to have the following current distribution to produce the rotating torque

$$I_m(\theta, t) = -I_M \cos(\omega t - M\theta - \phi) \qquad (2)$$

where I_M is the peak current and ϕ is the phase difference. The rotating torque is controlled by changing the angle ϕ.

In addition to the torque control current of eqn. (2), a levitation control current is required. Let us consider the N pole pair current in the stator which gives the following magnetic flux,

$$B_f(\theta, t) = -B_{F1} \cos(\omega t - N\theta) - B_{F2} \sin(\omega t - N\theta) \qquad (3)$$

where B_{F1} and B_{F2} are the peak densities of two components of flux distribution. The total levitation force in $\theta = 0$ direction is calculated by the y component of attractive force

$$\begin{aligned} F_y &= \int_0^{2\pi} \int_0^L \frac{(B_r - B_f)^2}{2\mu_0} \Delta S \cos\theta \\ &= \frac{B_R B_{F1} r L}{4\mu_0} \int_0^{2\pi} \Big[\cos\Big\{(M - N - 1)\theta\Big\} \\ &\quad + \cos\Big\{(M - N + 1)\theta\Big\}\Big] d\theta \qquad (4) \end{aligned}$$

where L is the length of rotor, r is the radius of rotor and μ_0 is the permeability of free space.

Equation (4) becomes a constant force

$$F_y = \frac{\pi B_R r L}{2\mu_0} B_{F1} \qquad (5)$$

when $M - N = \pm 1$. This solution is schematically shown in Fig. 2 ($P + 2$ pole algorithm) and Fig. 3 ($P - 2$ pole algorithm).

The x-directional force is calculated by integrating the x component of the attractive force

$$F_x = \frac{\pi B_R r L}{2\mu_0} B_{F2} \qquad (6)$$

Hence, two dimensional radial position of rotor can be controlled by changing the magnitudes of B_{F1} and B_{F2}.

Summarizing the above theory, the rotation is controlled by the rotating magnetic flux which has the same pole number P of the rotor. While the levitation is controlled by the plus two or minus two ($P \pm 2$) pole flux in the stator [6, 7].

Induction Motor and the property compared with PM Type Motor

Similar levitation control algorithm is applicable to induction type motors [6]. The rotor is assumed to have a uniform magnetic property. In the rotor, current is induced from the stator current which influences the gap magnetic flux. This magnetic flux is assumed to have the same density form of the stator

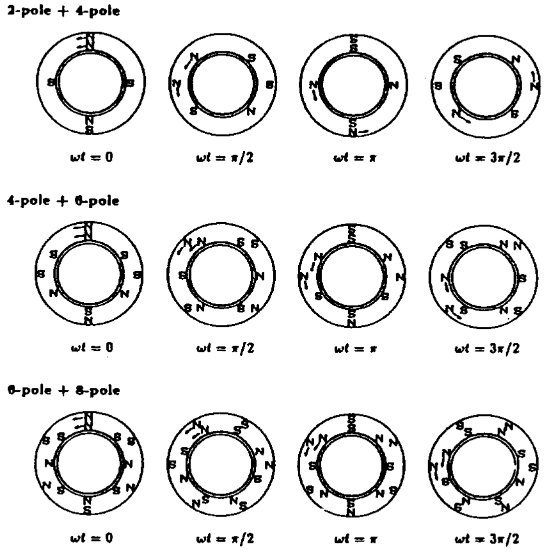


Figure 4: Levitation control of IM motor is shown.

flux. With this the levitation control of induction motor is derived. The solution is schematically shown in Fig. 4.

The merit of PM motor is that the levitation control is independent of torque control. However, it has the defect that the surface magnet is easily separated for ultra-high speed.

On the contrary, IM motor is strong and has the capability of running ultra high speed. The biggest problem for the induction type motor is that the rotating speed is disturbed by the levitation control. The motoring synchronous speed is ω/M, while the synchronous speed of levitation control is ω/N. There are two different synchronous speed, hence the levitation control of induction motor disturbs the rotating speed [6].

Axial Type Selfbearing Motor

Radial type motor can control the x and y positions. But the control theory is complicated. A simpler selfbearing motor is introduced [8]. Schematic of axial type one is shown in Fig. 5. The rotating torque τ is controlled by the rotation of the stator magnetic field, while the z directional force is controlled by its magnitude. For simplicity, a 2 pole motor is presented.

The PM stator is assumed to produce the following magnetic flux density.

$$h_s(\theta,t) = H_s\cos(\omega t - \theta) \tag{7}$$

While the permanent magnet of the rotor is assumed to produce the following magnetic flux distribution.

$$h_r(\theta,t) = H_r\cos(\omega t - \theta - \psi) \tag{8}$$

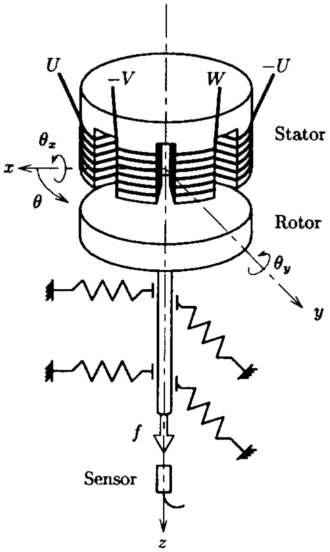


Figure 5: The schematic drawing illustrates the axial motor and coordinate system.

Where H_s, H_r are the peak values of the flux destribution, ω is frequency, t is time, θ is angle and ψ is the phase difference.

For simplicity, magnetic property inside the rotor and stator is assumed to be homogeneous and the reluctance is ignored when compared with the airgap one. Let z be the equivalent distance of airgap and the permanent magnet and the permeability has the same value of free space μ_0. Let r_1 and r_2 be the inner and outer radii of the rotor. Then the axial force f_z and the torque τ_z can be derived as follows [8].

$$f_z = -\frac{\mu_0(r_2^2 - r_1^2)\pi}{4z^2}[H_r^2 + 2H_rH_s\cos\psi + H_s^2] \tag{9}$$

$$\tau_z = -\frac{\mu_0(r_2^2 - r_1^2)\pi}{2z}H_rH_s\sin\psi \tag{10}$$

We can control the rotation by changing the angle ψ. Also the axial force can be controlled by changing the magnitude ΔH_s.

Experimental Results and Considerations

To confirm the capability of the proposed theory, two types of experimental results are presented.

Radial PM Motor

Schematic diagram of the experimental setup is shown in Fig 6. The current sheet stator is approximated by 8 concentrated wound pole stator, the current of which is controlled by the power amplifier (Apex

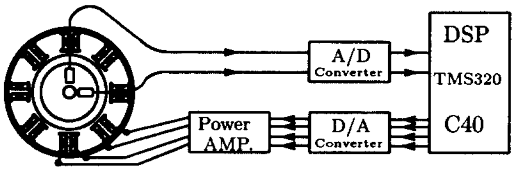


Figure 6: The schematic drawing illustrates the experimental setup and control system of the radial motor.

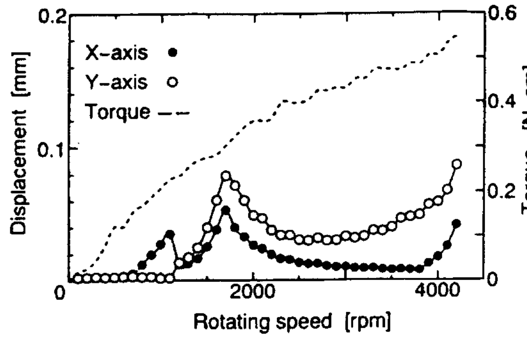


Figure 7: The plot shows the unbalance response and load torque of the PM 2 pole motor.

PA01) individually. The rotor of the motor has a diameter of 40.3 mm and a width of 35 mm. The average airgap is 0.8 mm. The torque produced is measured by using a noncontact load equipment.

The levitation and rotation is controlled by a digital signal processor (DSP; TMS320C40). Two gap sensors are installed 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. The levitation control algorithm used for the selfbearing motor and for the magnetic bearing is based on the classical PD controller, with $K_P = 2.0$, $K_D = 0.007$, $T_D = 0.1$ [ms] and the sampling interval $\tau = 0.1$ [ms].

Two PM rotors are made and tested; 2-pole and 4-pole ones. Two types of experiments can be performed using these two disks with the proposed $P \pm 2$ algorithm. The combined control of levitation and rotation shows promising results. The levitated unbalance responses and the load torque are shown in Figs. 7 and 8. The responses of P+2 algorithm are shown in Fig. 7 ($M = 1$, $N = 2$), while the responses of P−2 algorithm are shown in Fig. 8 ($M = 2$, $N = 1$).

In the case of P+2 algorithm, the rotation is relatively stable. The maximum rotating speed reaches 4,200 rpm. (Fig. 7).

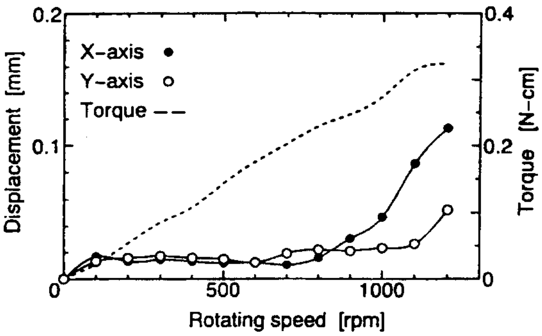


Figure 8: The plot shows the unbalance response and load torque of the PM 4 pole motor.

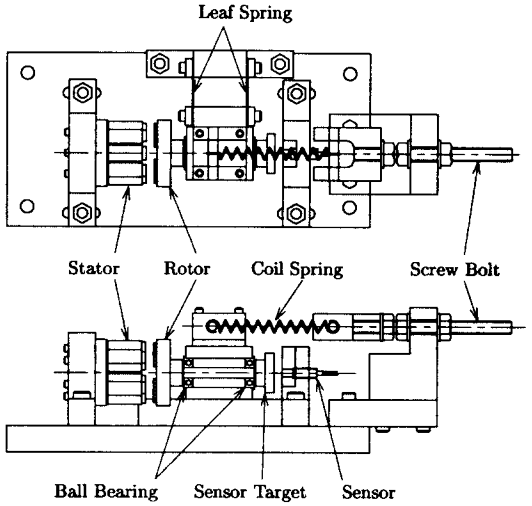


Figure 9: The schema shows the experimental setup of the axial motor.

In the case of P−2 algorithm, the rotation is weaker. The resulting unbalance response is shown in Fig. 8, which indicates a relatively low maximum speed of 1,200 rpm. This is mainly due to the flux distortion of the stator which in turn influences the results.

Axial PM Motor

Schematic diagram of the experimental setup is shown in Fig. 9. For experimental convenience, the rotor is supported by two radial ball bearings and two thin plate springs in order to restrict the radial motion. The rotor has only two degree of z and θ_z directions. The rotor surface produces an attractive force. To balance the static attractive force, a coil spring is installed and the spring force is adjusted by a screw as shown in Fig. 9. An eddy-current type displacement sensor is installed on the opposite side of the stator.

The rotation and levitation is controlled by a DSP. The DSP reads the displacement signal from the sen-

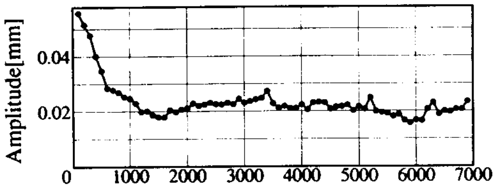


Figure 10: The graph shows the vibration amplitude versus the rotating speed.

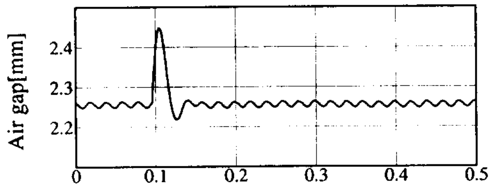


Figure 11: The impulse response was recorded at 3,000 rpm.

sor through an A/D converter, and then calculates each coil current from the summation of rotation and levitation control algorithm. The levitation control algorithm used is a standard digital PD controller. As mentioned before, the levitation force is controlled by the magnitude of magnetomotive force of the stator. Hence the combined control of rotation and levitation is

$$\begin{aligned} i_U &= A\sin(\omega t) \\ i_V &= A\sin(\omega t + 2/3\pi) \\ i_W &= A\sin(\omega t + 4/3\pi) \end{aligned} \tag{11}$$

where i is current in each coil, A is the magnitude which is also the demand signal for levitation. The DSP outputs i_U, i_V and i_W to the power amplifiers through D/A converters.

In this experiments, no load rotation is tested. The rotor has a stable rotation while the z-direction levitation is controlled. The maximum rotating speed reaches 6,900 rpm. The magnitude of vibration in axial direction versus rotating speed is shown in Fig. 10. The vibration is large at low rotating speed, and settles about 0.02mm when rotating speed is over 1,000rpm. The z-direction impulse response at 3,000 rpm is shown in Fig. 11. These responses indicate that the proposed motor has the functions of an axial bearing as well as a rotary motor.

Application and New Approaches

The experimental results confirmed that the proposed motors have both functions of a rotary motor and magnetic bearing. Application has started to the special fields such as to the rotary blood pump.

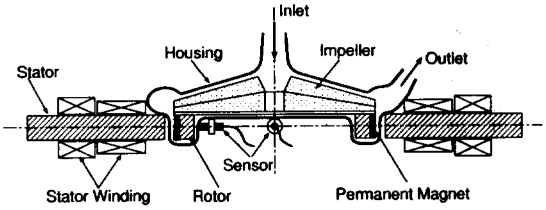


Figure 12: The schema shows the application of the radial slice motor to the inplantable blood pump.

Application to the rotary blood pump

The radial slice motor produces a rotating torque to the rotor and simultaneously controls the radial x and y positions. The movement of the other directions are passively stable. The design configuration also allows a centrifugal pump to be attached next to the slice motor. The schematic layout of the inplantable blood pump is illustrated in Fig. 12 which is now under development.

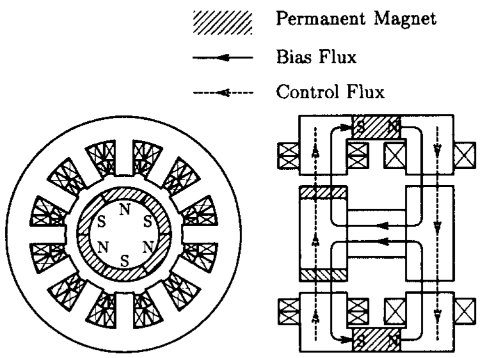
Recent approaches of selfbearing motor

Since the developed selfbearing motor does not have enough power, several new techniques have been tried: Ohshima et al. [9] analyzed the thickness of the surface permanent for a PM motor and found that the optimum solution is relatively thin. Okada et al. [7] proposed the internal permanent magnet motor which has the merits of strong PM rotor.

Induction motor is miracle in the sense that the rotor is strong and adequate for high speed rotation. However the rotation is affected by the levitation control. A new rotor design is introduced which has the specific magnetic polarity [10], [11]. Then the rotation is not disturbed by the levitation control and the efficiency is improved. Also the vector control is introduced to get the stable levitation. But the construction of the rotor and the control scheme are complicated.

As introduced in this paper, axial type selfbearing motor is simple. Furuichi et al. [12] also tried this idea, but they involved the P+2 or P=2 theory to control the inclination θ_x and θ_y of the disc. Then the control strategy becomes complicated.

A new idea of radial type selfbearing motor is introduced by Toyoshima et al. [13]. The levitation of this motor is controlled by a DC magnetic flux which is superior to the traditional selfbering motor. The original idea is applied to a special homopolar motor [13]. The similar idea is introduced to the standard DC motor by Ueno et al. [14]. The fundamental



Front View of the Motor

Side View

Figure 13: The schema shows the hybrid type selfbearing motor.

operation is shown in Fig. 13. All the motor pole is biased by a DC magnetic flux by a permanet magnet. The levitation is controlled by a DC electromagnet the construction and control of which are the completely same as the standard hibrid type (HB) magnetic bearings. The motor surface has 6 poles with permanet magnets. The rotation is controlled by this 6 pole current. Independent control capability for rotation and levitation is theoretically confirmed [14], but not tested yet.

Conclusions

Theoretial backgroud and experimental results of selfbearing motors are reported. They have the capability to levitate and rotate the rotor without any physical contact. However, the selfbering motor has some drawbacks at low rotating power when compared with the traditional motors. The problems are still under investigation. The proposed selfbearing motor has shown to be the best energy source to the rotary blood pump. Recent new research work is introduced to improve the control scheme and produced power and its size. First application to inplantable rotary pump is also introduced.

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