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Levitation Control of IPM Type Rotating Motor

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Abstract: A new type of synchronous type bearingless motor is introduced. In previous work, PM type and induction type rotor has been used for bearingless motor. PM synchronous motor has a merit of independent control capability of rotation and levitation, but the levitation force is weak. Conversely the induction type motor produces a strong levitation force, but the efficiency is not good and the control of rotation and levitation would be coupled.

This paper introduces an internal permanent magnet (IPM) type bearingless motor which has the merits of strong levitation force and relatively easy control capability. The merits of the proposed IPM motor are confirmed experimentally.

1 Introduction

Active magnetic bearings have been used widely due to their noncontact supporting capability. For some applications, a rotating power motor should be installed between the radial magnetic bearings. A high-speed rotating motor usually produces an undesirable drag force which should be canceled by magnetic bearings. Hence, the size of magnetic bearings becomes relatively large thus slowing down the dynamic response. The structure of magnetic bearings is very similar to that of the AC motor and a combined control theory of rotation and levitation for the motor is highly desirable[1]. This allows one of the radial magnetic bearings to be eliminated through the use of a bearingless motor, which means that the design of the rotor is highly flexible.

A levitation control applicable to PM synchronous type and induction type rotating motors has been presented. The rotor of the permanent magnet motor is assumed to have sinusoidally distributed magnetic poles. The inner wall of the stator is also assumed to have a current sheet, which can produce an arbitrary current distribution. The same number of magnetic poles (pole number P) gives the rotating torque to the rotor, while the plus or minus two pole magnetic flux 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, the levitation force can be controlled in the radial coordinate [2]-[8]. In previous work, it was found that a PM synchronous motor has a merit of independent control capability of rotation and levitation, but the levitation force is weak. Conversely the induction type motor produces a strong levitation force, but the efficiency is not good. Moreover, the control for rotation and the x and y directional levitation would be coupled. Oshima, et. al.,[9] analyzed the thickness of the surface permanent magnet and found its optimum value. The solution is a relatively thin magnet having low strength.

An internal permanent magnet (IPM) type bearingless motor has been introduced which has the merits of strong levitation force and relatively easy control capability[10]. The rotor is made of laminated sheet inside which the thin permanent magnet is installed. A simple experimental apparatus is made to confirm the properties of the proposed motor. The levitation force of three types of rotors is measured and compared; surface permanent magnet (SPM), induction motor (IM) and internal permanent magnet (IPM) types. The squirrel-cage (induction) rotor produces the strongest levitation force. The IPM rotor produces a slightly smaller force, but this is much larger than the SPM force. The IPM rotor is expected giving strong levitation and rotation, but not tested in the previous work[10]. In this paper the levitated rotation of this IPM rotor is tested and reported. Only a 2-pole rotor can levitate and rotate in this case. The IPM rotor produces 20 times stronger torque than SPM and IM rotors.

2 Levitation Control for three types of rotors

A general solution for the levitation control applicable to three types of rotors; surface permanent magnet (SPM), induction motor (IM), internal permanent magnet (IPM) types are summarized and their properties are compared. These three types of rotors are shown in Fig. 1.

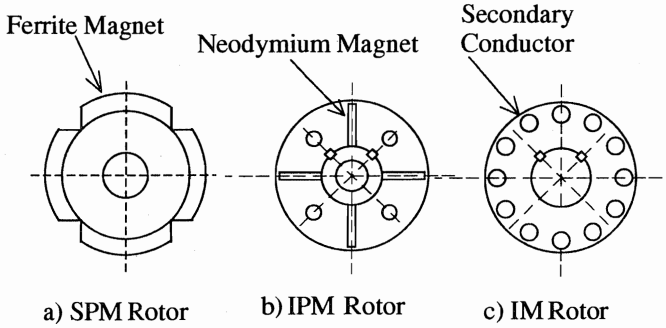

Fig. 1 : Three types of rotors

2.1 Surface Permanent Magnet Rotor

The standard PM motor has a relatively thick permanent magnet on the surface of rotor (SPM). Suppose that the rotor has M pole pairs (pole number $P = 2M$) produced by permanent magnet, the magnetic flux in the airgap is mainly determined by this permanent magnet. The stator is assumed to have a current sheet which produces an arbitrary distributed magnetic flux. The case for $M = 2$ ($P = 4$) is shown schematically in Fig. 2.

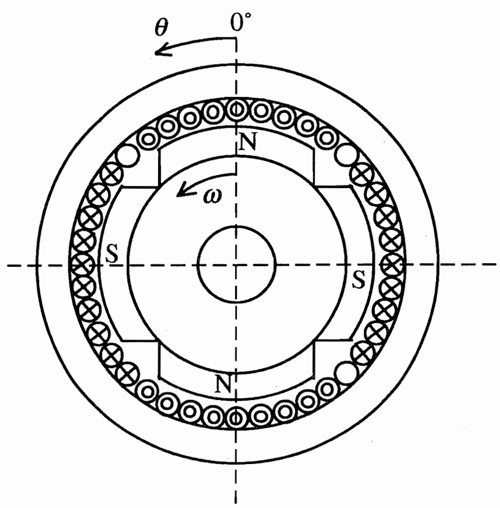

Fig. 2 : Scheme of 4 pole SPM motor and coodinate system

2.1.1 Torque Control

The rotor is assumed to have the following flux density;

$$B_r(\theta,t) = B_R \cos(\omega t - M\theta) \tag{1}$$

where

B_R = peak density of magnetic flux
ω = rotating speed of the motor
θ = angular coordinate

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

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

where

I_M = the peak current
ϕ = the phase difference.

The motor is

$$\begin{array}{ll} \text{a synchronous motor} & \text{when } \phi \approx 90^\circ \\ \text{a servomotor} & \text{when } \phi = 0^\circ \end{array} \tag{3}$$

2.1.2 Levitation control algorithm

In addition to the torque control current of eqn. (2), levitation control current is required. Let us consider that the pole pair number of the rotor and stator are M and N respectively. Then the stator has the flux distribution

$$B_f(\theta,t) = -B_{F1}\cos(\omega t - N\theta) - B_{F2}\sin(\omega t - N\theta) \tag{4}$$

where B_{F1} and B_{F2} are the peak densities of two components of flux distribution. This flux produces the attractive force in the θ-direction.

$$\Delta F(\theta) = \frac{B^2}{2\mu_0}\Delta S \tag{5}$$

By inserting $B = B_r - B_f$, the total levitation force in the $\theta = 0$ direction is given by

$$\begin{aligned} F_y &= \int_0^{2\pi}\int_0^L \Delta F(\theta)\cos\theta \\ &= \frac{B_R B_{F1} r L}{4\mu_0}\int_0^{2\pi}\Big[\cos\{(M-N-1)\theta\} \\ &\qquad + \cos\{(M-N+1)\theta\}\Big]d\theta \end{aligned} \tag{6}$$

where

L = length of rotor
r = radius of rotor
μ_0 = permeability of free space

Equation (6) becomes a constant force

$$F_y = \frac{\pi B_R r L}{2\mu_0} B_{F1} \tag{7}$$

when $M - N = \pm 1$. This solution is schematically shown in Fig. 3 (P+2 pole algorithm) and Fig. 4 (P-2 pole algorithm). The x-directional force is calculated by integrating the x component of eqn. (5):

$$F_x = \frac{\pi B_R r L}{2\mu_0} B_{F2} \tag{8}$$

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

The merit of this type of bearingless motor is that the torque control does not disturb the levitation control. Also, it has been proven that the levitation control does not disturb the torque control[6]-[8]. However, the thick surface magnet makes it difficult to produce the levitation flux which is given by eqn. (4).

2.2 Induction Motor

A similar levitation control algorithm is applicable to induction type motors. Secondly current is induced from the stator current which influences the airgap magnetic flux. This magnetic flux is assumed to have the same density form of the stator flux. With this the levitation control of an induction motor is derived.

2.2.1 Torque and Levitation Control

Suppose that the motoring magnetic flux has M pole pair numbers and the levitation control flux has N pole pair numbers. Then the magnetic flux is produced as follows.

$$B_m(\theta,t) = B_M \cos(\omega t - M\theta) \tag{9}$$

$$B_f(\theta,t) = B_F \cos(\omega t - N\theta) \tag{10}$$

where B_M and B_F are the peak values of the motoring and

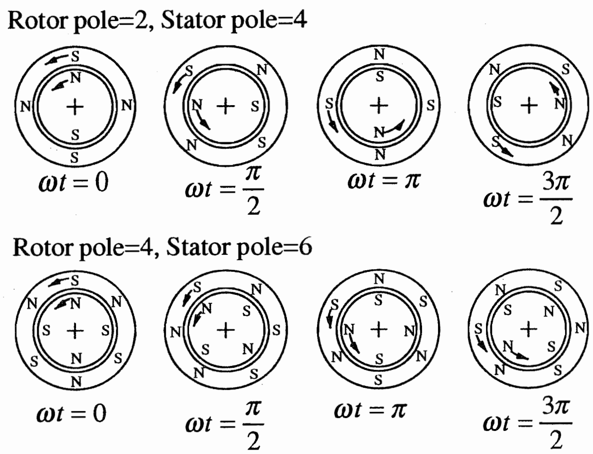

Fig. 3 : Levitation control of +2 pole algorithm

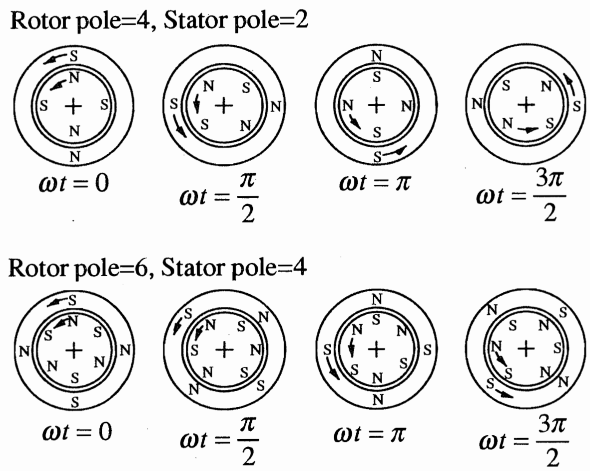

Fig. 4 : Levitation control of -2 pole algorithm

levitation flux respectively. The rotor current is induced and is assumed to produce the following magnetic flux.

$$B_r = -B_M \alpha_M \cos(\omega t - M\theta - \phi_M) - B_F \alpha_F \cos(\omega t - N\theta - \phi_F) \quad (11)$$

where α_M and α_F are the induced coefficients, and ϕ_M and ϕ_F are the phases. They will be determined by the structure of the motor and the slip rate. The strongest induction torque will occur when $\phi_M, \phi_F = 90^0$.

The magnetic flux in the airgap is the summation of eqns. (9), (10) and (11) and is given by

$$\begin{aligned} B(\theta,t) &= B_M \cos(\omega t - M\theta) + B_M \alpha_M \cos(\omega t - M\theta - \phi_M) \\ &\quad + B_F \cos(\omega t - N\theta) + B_F \alpha_F \cos(\omega t - N\theta - \phi_F) \\ &= B_M \beta_M \cos(\omega t - M\theta - \psi_M) \\ &\quad + B_F \beta_F \cos(\omega t - N\theta - \psi_F) \end{aligned} \quad (12)$$

where

$$\begin{aligned} \beta_M &= \sqrt{(1+\alpha_M \cos\phi_M)^2 + (\alpha_M \sin\phi_M)^2} \\ \beta_F &= \sqrt{(1+\alpha_F \cos\phi_F)^2 + (\alpha_F \sin\phi_F)^2} \\ \psi_M &= \tan^{-1}\{(\alpha_M \sin\phi_M)/(1+\alpha_M \cos\phi_M)\} \\ \psi_F &= \tan^{-1}\{(\alpha_F \sin\phi_F)/(1+\alpha_F \cos\phi_F)\} \end{aligned} \quad (13)$$

For simplicity, the magnetic coupling coefficients α_M and α_F are considered to be less than unity. Hence, the following assumption is made to simplify the levitation control..

$$\begin{aligned} \beta_M &\approx \beta_F \quad (=\beta) \\ \psi_M &\approx \psi_F \quad (=\psi) \end{aligned} \quad (14)$$

If the assumption of eqn. (14) is not true, the levitation control in the x and y directions causes a mutual interference. In such a case, decoupled levitation control should be developed. The attractive force is given by eqn. (5), hence the levitation force in the $\theta = 0$ direction is calculated as follows.

$$\begin{aligned} F_y &= \int_0^{2\pi}\int_0^L \Delta F(\theta)\cos\theta \\ &= \frac{B_M B_F r L(1+\beta^2+2\beta\cos\psi)}{4\mu_0} \\ &\quad \times \int_0^{2\pi}\left[\cos\{(M-N-1)\theta\} + \cos\{(M-N+1)\theta\}\right]d\theta \end{aligned} \quad (15)$$

Equation (15) is constant when $M - N = \pm 1$,

$$F_y = \frac{B_M B_F r L \pi}{2\mu_0}(1+\beta^2+2\beta\cos\psi) \quad (16)$$

For simplicity, the x directional radial force is not included in the previous analysis. However, eqn. (10) can be expanded to

$$B_f = B_{F1}\cos(\omega t - N\theta) + B_{F2}\sin(\omega t - N\theta) \quad (17)$$

where B_{F1} controls the y directional force and B_{F2} controls the x directional force.

The biggest problem for the induction type bearingless 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 speeds. The rotor is expected to rotate at the motoring synchronous speed. Then there is a big slip for the levitation synchronous speed; that is near $\omega / N - \omega / M$. This slip produces the internal current of the rotor causing the energy dissipation and the disturbing torque. Hence the efficiency is bad and the levitation control of the induction motor disturbs the rotating speed. Also, the assumption of eqn. (14) is not always true which causes the mutual interference between the x and y directional levitation control.

2.3 Internal Permanent Magnet Motor

The standard permanent magnet (SPM) type bearingless motor has the merit of independent control capabilities of rotation and levitation. But the thick surface permanent magnet makes it difficult to control the airgap flux along the radial coordinate according to the proposed $P \pm 2$ algorithm. Oshima, et. al., [9] analyzed the thickness of the surface permanent magnet and found its optimum value. However, thin surface magnet makes it weak and difficult for manufacturing.

The induction motor has the merit of a strong rotor which allows a high rotational speed. Also the airgap flux can be controlled easily. However, the efficiency is bad and decoupled control should be applied.

This paper introduces a new type of bearingless motor which uses an internal permanent magnet rotor. The rotor is made of laminated steel sheet inside which the thin permanent magnet is installed.

2.3.1 Torque and Levitation Control

The torque control can be carried out with the same method developed for the SPM which is shown by eqns. (1)-(3). However, the airgap flux is influenced by the rotating control current because of the use of the thin permanent magnet. Hence, the M-pole pair flux in the airgap is given by

$$B_m(\theta,\phi,t) = B_M \sin(\omega t - M\theta - \phi) \tag{18}$$

where B_M is determined by I_M and the magnetic resistance between the rotor and the stator. Hence, the levitation control should be developed by considering this effect. The motoring current is determined by the controller, hence the airgap flux is easily determined by measuring the angular displacement of the rotor. The total M-pole pair magnetic flux in the airgap is

$$\begin{aligned} B(\theta,\phi,t) &= B_R \cos(\omega t - M\theta) + B_M \sin(\omega t - M\theta - \phi) \\ &= B_G \cos(\omega t - M\theta + \varphi) \end{aligned} \tag{19}$$

where

$$\begin{aligned} B_G &= \sqrt{(B_R + B_M \cos\phi)^2 + (B_M \sin\phi)^2} \\ \varphi &= \tan^{-1}\{(B_M \sin\phi)/(B_R + B_M \cos\phi)\} \end{aligned} \tag{20}$$

The levitation control should be developed based on the flux distribution of eqn. (19) .

$$\begin{aligned} B_f(\theta,t) = &-B_{F1} \cos(\omega t - N\theta + \varphi) \\ &- B_{F2} \sin(\omega t - N\theta + \varphi) \end{aligned} \tag{21}$$

where B_{F1} and B_{F2} are the peak densities of two components of flux distribution. Hence, the forces in the x and y directions are given by

$$\begin{aligned} F_x &= \frac{\pi B_G r L}{2\mu_0} B_{F2} \\ F_y &= \frac{\pi B_G r L}{2\mu_0} B_{F1} \end{aligned} \tag{22}$$

As mentioned before, the peak flux B_G and the phase φ can be determined by the motoring control current and the measured rotor angle. Hence, the radial force of eqn. (22) is easily controlled by changing B_{F1} and B_{F2}.

3 Experimental Results and Considerations

3.1 Radial Force Test

The radial force will change according to the type and construction of the rotor. To test the load capability of the previous three types of levitated motors, a simple experimental apparatus was constructed. Three types of rotors are made and tested; surface permanent magnet (SPM) type, internal permanent magnet (IPM) type and an induction type. Their cross sections are shown in Fig. 1. Two combinations of the motoring and levitation control algorithm are tested; one is 2-pole motoring and 4-pole levitation and the other is 4-pole motoring and 2-pole levitation.

3.1.1 Levitation Force Measurement

The levitation force is measured by inputting a stationary motoring and levitation current to the stator. The results are shown in Fig. 5. Figure 5 shows the results measured by inputting a 2-pole motoring and 4-pole levitation current. The squirrel-cage rotor produces the strongest levitation force. The IPM rotor produces a slightly smaller force, but this is still larger than the SPM force. This is due to the low magnetic resistance of the IPM rotor, giving strong levitation and rotation as expected.

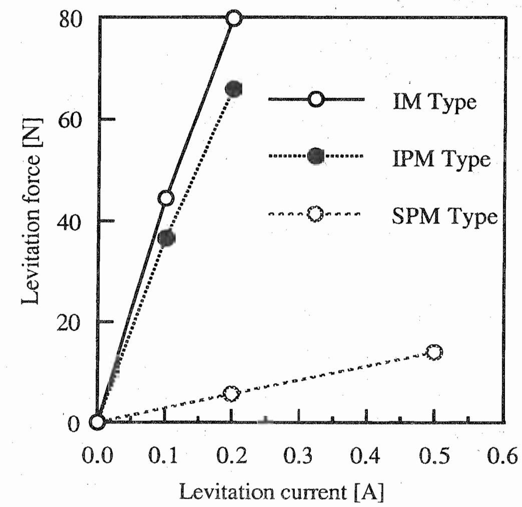

Fig. 5 Levitation force for three type of rotors

Next, the interaction between the torque and levitation control for IPM rotor is tested. The results are shown in Fig. 6. The rotor angle is assumed to be controlled as a synchronous motor. That is, the levitation force is controlled using eqn. (4) . If the rotor is subjected to a torque load, the rotor angle is not the same as the motoring electrical angle. Hence, the rotor angle is set at a 45 degree delay from the motoring current angle. The levitation force (y-direction) and side force (x-direction) are measured as shown in Fig. 6. If the airgap flux is only determined by the rotor angle, the side force should be zero. The results indicate that the side force could not be neglected and the levitation control should consider the influence of the stator current which is shown by eqn. (19).

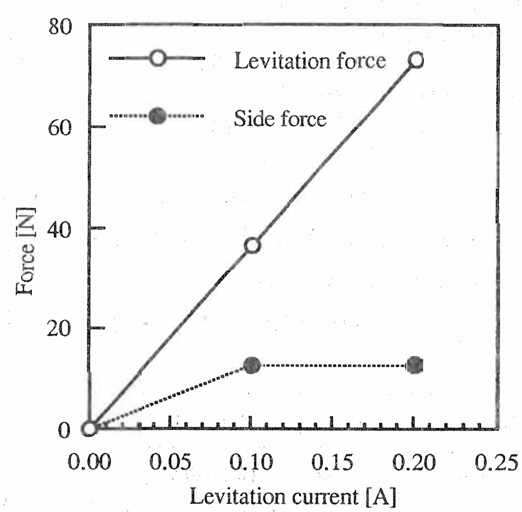

Fig. 6 Side force of IPM rotor

3.2 Rotation of IPM type Bearingless Motor

The surface magnet type and induction type bearingless motors have already been reported [6]-[8]. This paper introduces the results of motoring and levitation control using an IPM rotor.

3.2.1 Experimental Setup

A diagram of the experimental setup is shown in Fig. 7. One side of the rotor shaft is supported by a standard magnetic bearing while the other end is the proposed motor. The rotor of the motor has a diameter of 40.3 mm and a width of 35 mm, while the magnetic bearing differs only in the width, it being 25 mm. The average airgap is 0.8 mm. In the middle of rotor, a non-contact load system is installed to test the produced torque.

The levitation and rotation is controlled by a digital signal processor (DSP; TMS320C40). The control system is shown in Fig. 8. Four gap sensors are installed to measure the x and y displacements of the rotor. One pair is used to control the magnetic bearing, while the other is used to control the bearingless motor. 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 is based on the synchronous motor; that is the rotor angle is assumed equal to the stator demand angle. The radial position control for the bearingless motor and for the magnetic bearing is the classical PD controller

$$G(z) = K_P + \frac{K_D(z-1)}{T_D\left(z - e^{-\tau/T_D}\right)} \tag{23}$$

where K_P, K_D and T_D are the proportional gain, derivative gain and derivative time constant respectively. They are determined experimentally as $K_P = 0.93$, $K_D = 0.001$ and $T_D = 0.1$ [ms]. The sampling interval τ used is 0.1 [ms].

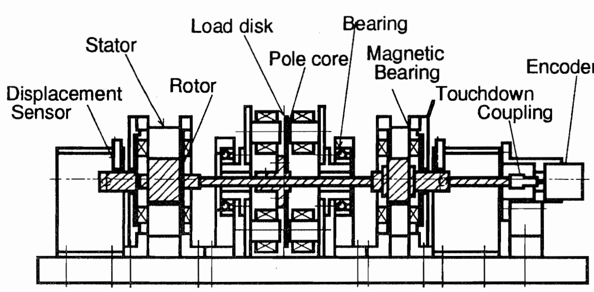

Fig. 7 Diagram of experimental setup

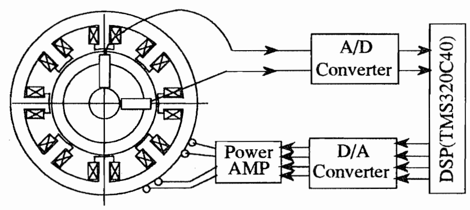

Fig. 8 Schematic of control system

3.2.2 Experimental Results

Only a 2-pole rotor can levitate and rotate in this case. The unbalanced response with no-load is shown in Fig. 9. The maximum speed is limited to 2,200 rpm. The reason for the slow top speed is due to the flux distortion. The IPM rotor has a distorted flux distribution which causes adverse rotational effects. The non-contact load system is made for measuring the torque. The system is constructed using aluminum disc and DC electric magnets. Load torque is generated by eddy current induced in the disc under rotating condition. The results of the load tests are shown in Figs. 10, 11 and 12. Fig 10 indicates displacement of rotor under the torque load which is generated by 1.0A magnetizing current. Fig. 11 shows the result of 1.5A load condition, and Fig 12 shows the result of 2.0A load condition. In three cases, maximum load torque produced reaches to about 10 N-cm at the top speed. These maximum torques are about 20 times stronger than the other cases in the previous work [8]. The IPM rotor is considered to have strong possibilities as a high performance bearingless motor.

4 Conclusions

A general solution of levitation control applicable to PM synchronous type and induction type motors is proposed. The traditional PM (SPM) motor has a merit of individual control capable of rotation and levitation, but the levitation force is weak. The induction motor can produce a strong levitation force, but it has the defects of bad efficiency and interaction between the rotation and levitation. The internal permanent magnet motor is introduced which has the merits of strong levitation force and easy control capability. A zero load test is carried out to reach the top speed of 2,200 rpm. In the load test, IPM rotor can be levitated with the 10 N-cm load torque. Further work is continuing to improve the experimental setup so as to achieve both higher rotating speeds and torques.

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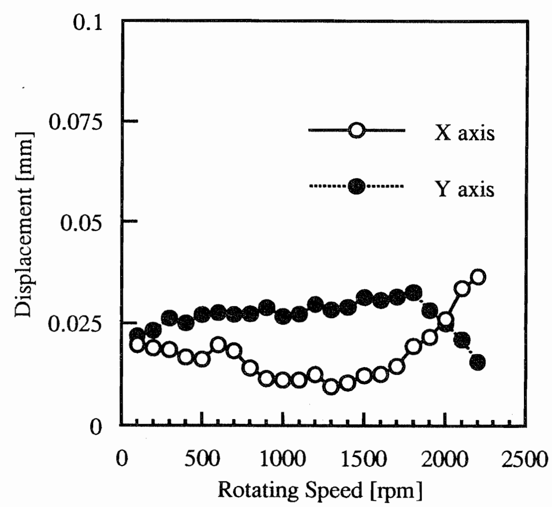

Fig. 9 Unbalanced response for zero-load condition

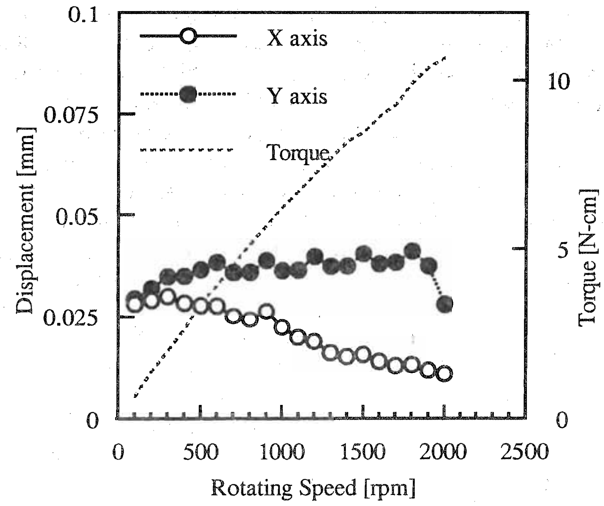

Fig. 10 Unbalanced response for 1.0A load condition

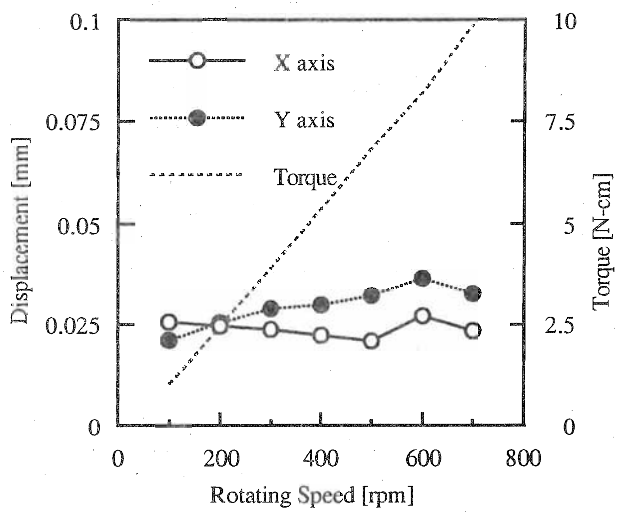

Fig. 11 Unbalanced response for 1.5A load condition

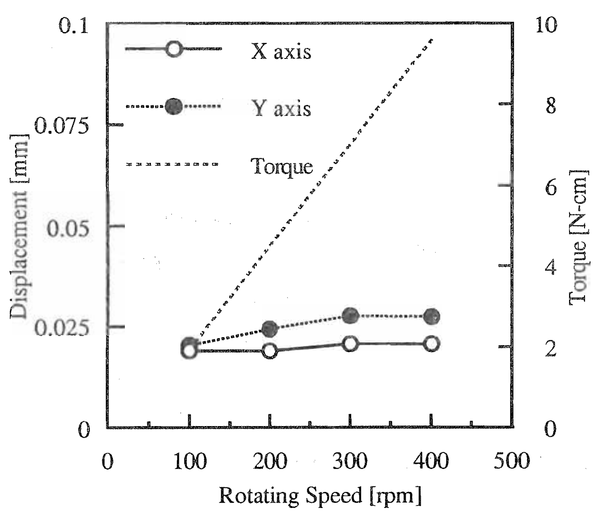

Fig. 12 Unbalanced response for 2.0A load condition

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