ANALYSIS AND DESIGN OF A CONCENTRATED WOUND STATOR FOR SYNCHRONOUS-TYPE LEVITATED MOTOR

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ABSTRACT

A new method of levitation control of a synchronous-type motor has been introduced, that is, the radial position as well as the rotation of a PM rotor can be controlled. For analysis the rotor is assumed to have a sinusoidally distributed magnetic flux, while the stator is assumed to be a current sheet which can produce an arbitrarily current distribution. The levitation force can be produced by adding the plus minus two pole magnetic flux on the stator in addition to the usual motoring flux. This paper introduces the analysis of the least number of stator poles. The stator flux is assumed to be produced by the concentrated wound poles which produce the spatial higher harmonics. The rotor is assumed to have pure sinusoidal distributed flux which can be produced by permanent magnets. Increasing the pole number gives a better solution, but the motor becomes complicated and expensive. A practically recommended least pole number is introduced and tested experimentally.

INTRODUCTION

Magnetic bearings have been increasingly used because of their noncontact support capability[2]. For some applications, a power motor should be installed between the radial magnetic bearings. Such a high speed rotating motor may produce undesirable drag force which should be canceled by magnetic bearings. Hence, the size of magnetic bearing becomes relatively big which slows down dynamic response. The structure of magnetic bearing is very similar to that of the AC motor, hence a combined control theory of rotation and levitation for the motor is highly desirable. Then, one of the radial magnetic bearings can be removed by a levitated motor; this means that the design of the rotor will be highly flexible.

Reluctance type and induction type levitated motors have been introduced by A. Chiba, et. al. [3],[4]. PM type bearingless motor has also been reported by J. Bichsel [5]. But they proposed and tested the special solution of the radial position control of the rotating motor. From the analysis of the previous paper [1], $P\pm2$ pole stator can produce the levitation force to the P pole rotor. This theory is developed with the assumption that the rotor of the motor has sinusoidally distributed P magnetic poles along the axial surface produced by permanent magnets (PM). The inner wall of the stator is the current sheet, which can produce arbitrary current distribution along the axial coordinate. Usually the same number of poles (P poles) of the stator current distribution gives a rotating torque to the rotor: that is, the phase shift between the rotor magnetic poles and the stator current poles controls the rotating torque.

In addition to the standard P poles, we produce $P\pm2$ poles to the current sheet which produces a pure drag force to the rotor. By controlling the magnitude and phase of this $P\pm2$ pole current distribution relative to the rotor magnetic poles, the drag force can be controlled independently of the rotating torque.

If the magnetic flux density is a pure sinusoidal distribution, the levitation force can be controlled independently of the motor control. Practically this is not true, because the magnetic flux has spatial distortion. In this paper, the rotor is assumed to have a pure sinusoidal distributed magnetic flux, while the stator is assumed to include higher harmonics along the axial coordinate. By increasing the pole number, the levitation force can be controlled independent of the distortion. But the motor becomes complicated and expensive. The levitation force is calculated among the various pole numbers of ± 2 pole algorithm. Practically the best combination is that the motoring pole number is two and the levitation pole number is four. This pole number combination gives the best experimental results by using the concentrated stator.

LEVITATION CONTROL OF PM ROTOR

Suppose that the rotor has M pole pairs (pole number P $=2M$) produced by a permanent magnet(PM). The stator is assumed to have a current sheet which produces an arbitrary distributed magnetic flux. The proposed motor for the case M=2 (P=4) is shown schematically in FIGURE 1.

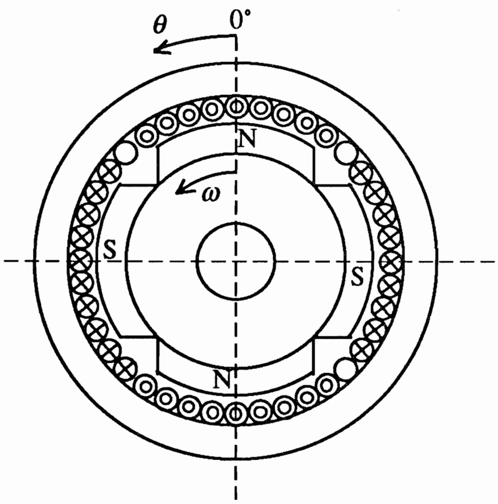

FIGURE 1: Scheme of 4 pole PM motor and the axial coodinate θ

Torque Control

The rotor is assumed to have the following flux density;

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

where B_R is the peak density of magnetic flux, ω is the rotating speed of the motor, θ is the angular coordinate and is assumed θ=0 at the center of N pole, as shown in FIGURE 1. The current sheet of the stator is assumed to have the following current distribution to produce the rotating torque

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

where I_M is the peak current, and ϕ is the phase difference. The motor is

a synchronous motor when $\phi \approx 90°$ or
a servomotor when $\phi = 0°$

Levitation control algorithm

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

$$B_f(\theta,t) = -B_F \cos(\omega t - N\theta) \quad (3)$$

where B_F is the peak value of the flux density. Then the magnetic flux distribution in the airgap is the summation of eqs. (1) and (3).

$$\begin{aligned} B &= B_r(\theta,t) - B_f(\theta,t) \\ &= B_R \cos(\omega t - M\theta) + B_F \cos(\omega t - N\theta) \end{aligned} \quad (4)$$

This flux produces the levitation force in the $\phi = 0$ direction

$$\begin{aligned} F = \frac{rL}{2\mu_0} \int_0^{2\pi} \{ & B_R \cos(\omega t - M\theta) \\ & + B_F \cos(\omega t - N\theta)\}^2 \cos\theta d\theta \end{aligned} \quad (5)$$

Equation (5) becomes a constant force

$$F = \frac{B_R B_F r L \pi}{2\mu_0} \quad (6)$$

when $M - N = \pm 1$. That is, pure levitation control can be obtained if

the stator pole number = the rotor pole number ± 2 (7)

These results are schematically summarized in FIGURE 2 (+2 pole) and in FIGURE 3 (-2 pole). This levitation control is independent of rotating control. The directional control in the radial surface is also realized by changing the phase angle of eq.(3). The detail of them is reported in the previous paper[1].

INFLUENCE OF THE DISTORTION OF FLUX DENSITY

In the previous analysis, the magnetic flux is assumed to have pure sinusoidal distribution. The resulting levita-

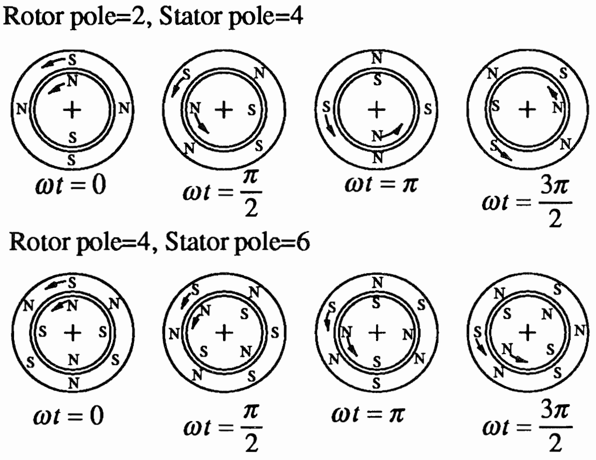

FIGURE 2: Levitation control of +2 pole algorithm

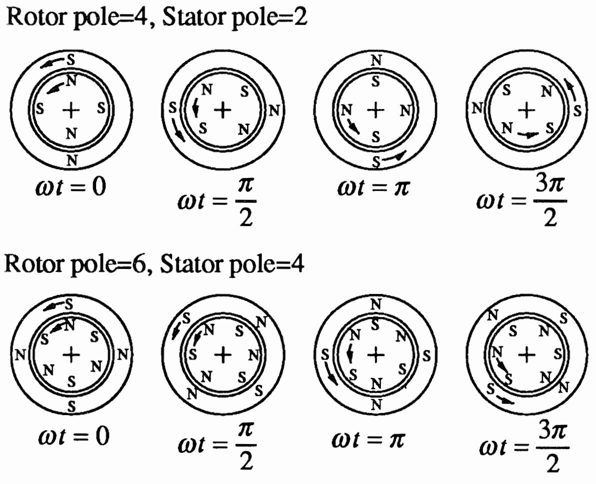

FIGURE 3: Levitation control of -2 pole algorithm

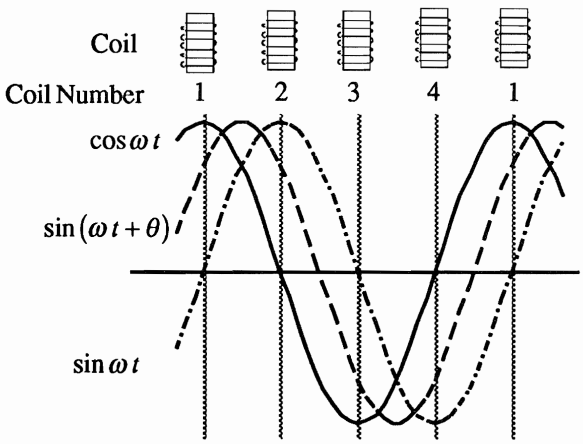

FIGURE 4: The rotating flux and the minimum pole number

tion force is constant and independent of the pole number. However, pure sinusoidal magnetic flux is very difficult to be reallized. Experimentally, there are some differences among the pole number combinations. In this section, the magnetic flux is assumed to have spatially higher harmonics and the levitation force is analyzed under this assumption.

Minimus Pole Number for Rotating Flux

The previous theory requires two rotating flux of pole number $2M$ and $2N$. Experimentally they are realized by a concentrated wound stator[1]. How many poles do we need to realize this? Shannon (or Nyquist) sampling theory says that the same sampling frequency can regenerate the original sine wave. But it causes the phase distortion. For a motoring control, twice pole number can produce the rotating flux without including the serious phase distortion. This corresponds to the sine and cosine decomposition of the rotating flux,

$$\cos(\omega t+\theta) = \cos\omega t\cos\theta - \sin\omega t\sin\theta \qquad (8)$$

This relation is schematically shown in FIGURE 4. Hence, twice of the pole number of the bigger number between $2M$ and $2N$ is requested for a concentrated wound stator for the levitation motor.

Fluctuation of the levitation force

Suppose that only the stator flux has spatial distortion.

$$B_f(\theta,t) = -B_F\cos(\omega t - N\theta) - B_H\cos H(\omega t - N\theta) \qquad (9)$$

Where B_H is the peak value of the higher harmonics and H is the multiplier order of the spatial frequency. Usually, B_H is smaller than B_F and H>=2. The total flux in the airgap is

$$\begin{aligned} B &= B_r(\theta,t) - B_f(\theta,t) \\ &= B_R\cos(\omega t - M\theta) + B_F\cos(\omega t - N\theta) \\ &\quad + B_H\cos H(\omega t - N\theta) \end{aligned} \qquad (10)$$

This gives the following levitation force in the θ=0 direction.

$$F = \frac{rL}{2\mu_0}\int_0^{2\pi}\{B_R\cos(\omega t - M\theta) + B_F\cos(\omega t - N\theta) + B_H\cos H(\omega t - N\theta)\}^2\cos\theta d\theta \qquad (11)$$

The integral of each squared term in eq.(14) vanishes, while the integrals of the remaining products give the following equations. The product of the first and second terms gives the constant levitation force

$$F_{1,2} = \frac{B_R B_H r L}{4\mu_0}\int_0^{2\pi}\left[\cos\{(M-N+1)\theta\}\right.$$
$$\left.+\cos\{(M-N-1)\theta\}\right]d\theta$$
$$= \frac{B_R B_F r L\pi}{2\mu_0} \text{ ,only when } N\text{-}M=\pm 1 \quad (12)$$

This is the same levitation force as the one given by eq. (6). The product of the second and third term may produce the following disturbing force

$$F_{2,3} = \frac{B_R B_H r L}{4\mu_0}\int_0^{2\pi}\left[\cos\{(H-1)\omega t - (N(H-1)-1)\theta\}\right]d\theta$$
$$= \frac{B_R B_F r L\pi}{2\mu_0}\cos\omega t \text{ ,only when } H=2, N=1, M=2 \quad (13)$$

The product of the first and third terms may also produce the disturbance

$$F_{1,3} = \frac{B_R B_H r L}{4\mu_0}\int_0^{2\pi}\left[\cos\{(H-1)\omega t - (M-HN+1)\theta\}\right.$$
$$\left.+\cos\{(H-1)\omega t + (M-HN-1)\theta\}\right]d\theta$$
$$= \frac{B_R B_F r L\pi}{2\mu_0}\cos\{(H-1)\omega t\}$$
$$\text{,only when } M\text{-}HN=\pm 1 \quad (14)$$

Notice that the disturbance of eq.(14) occurs only when N-HM=±1. But we also have the condition of eq.(12) which produces the constant levitation force: M-N=±1. These two conditions together imply that only the following two cases produce the disturbance given by eq. (14).

1) The case of M=2, N=1 and H=3:

$$F_{1,3} = \frac{B_R B_H r L\pi}{2\mu_0}\cos 2\omega t \quad (15)$$

2) The case of M=3, N=2 and H=2:

$$F_{1,3} = \frac{B_R B_H r L\pi}{2\mu_0}\cos\omega t \quad (16)$$

Some remarks on the analytical results

In the previous analysis, the distortion is assumed to be only on the stator magnetic flux. If we exchange the pole pair numbers of M and N, the results are valid for the distortion of the rotor magnetic flux. If we include both the distortion of the rotor and the stator, we will have the added disturbance of the individual distortion plus the higher order small disturbance of the product term of each distortion. Hence we have the following remarks:

If the pole pair numbers are greater than 2, that is M, N >2 (the least cases are M=3, N=4 or M=4, N=3), then the levitation force is free from the flux distortion in both of the rotor and the stator. However, the motor becomes complicated and expensive. The pole number should be as small as possible. A comparison of the flux distortion of the rotor and stator shows that it is easier to reduce the rotor flux distortion. Then there is a recommended pole number combination. If we choose M=1 and N=2, the levitation force is free from the disturbance given by eq.(9). However PM rotor should have the pure sinusoidal magnetic flux.

EXPERIMENTAL RESULTS AND CONSIDERATIONS

To confirm the previous levitation control analysis, a simple experimental apparatus is constructed, as shown schematically in FIGURE 5. The stator has 12 concentrated winding poles diverted from the outer stator of the mega-torque motor (NSK-MRS6). Two rotors are used; one with 4 magnetic poles and another with 2 magnetic poles. One end of the rotor shaft is supported by a ball bearing and the other end is the levitated motor. The rotor has a diameter of 72 mm and the width of 25 mm. To reduce the distortion of the magnetic flux, a two-layered rubber magnet is used. The flux distributions are shown in FIGURE. 6 and 7. The dotted line is a pure sinusoidal curve while the solid line indicates the measured magnetic flux. The edge of the rubber magnet produces the peak flux, but flux density is not so distorted. The rotating torque is given by a synchronized motor control, while the levitation is produced using the previous algorithm. Two gap-sensors are installed near the rotor to produce the levitation control signal. The rotating angle is measured by an encoder and up/down counter. A Digital Signal Processor (TMS 320C30) is used to calculate the current in each one of 12 concentrated coils of the stator. The levitation control algorithm used is the classical PD controller

$$G(z) = K_P + \frac{K_D(z-1)}{T_D\left(z-e^{-\tau/T_D}\right)} \quad (17)$$

where K_P, K_D, T_D and τ are the proportional gain, deriva-

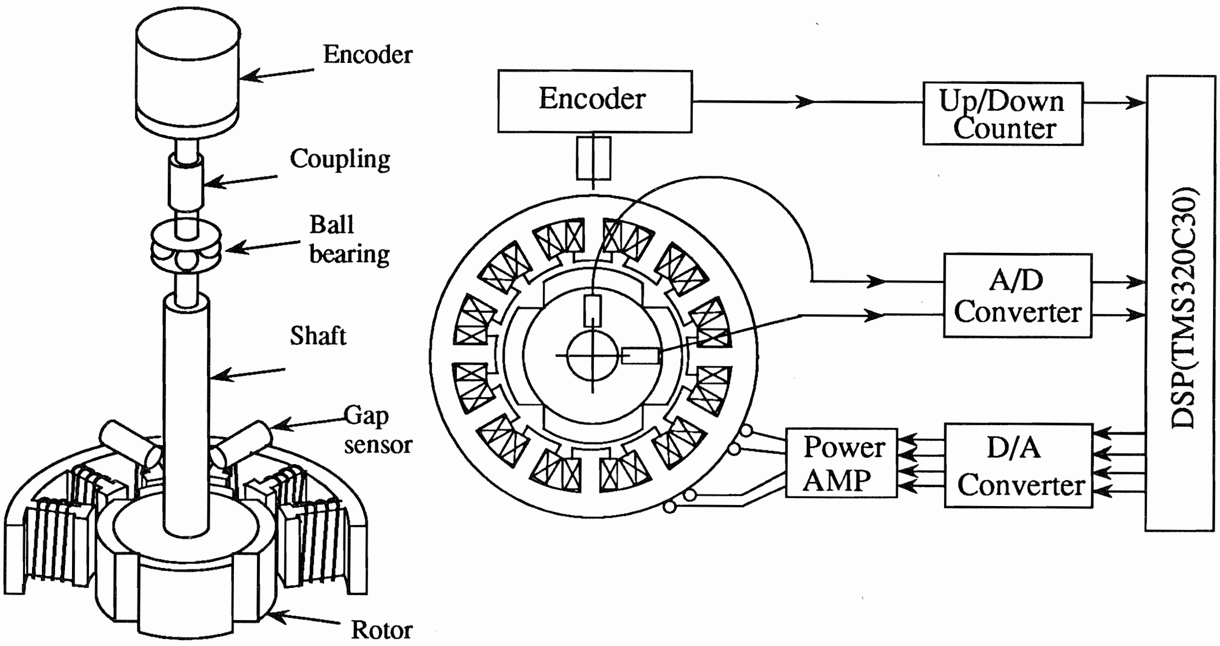

FIGURE 5: Scheme of experimental setup

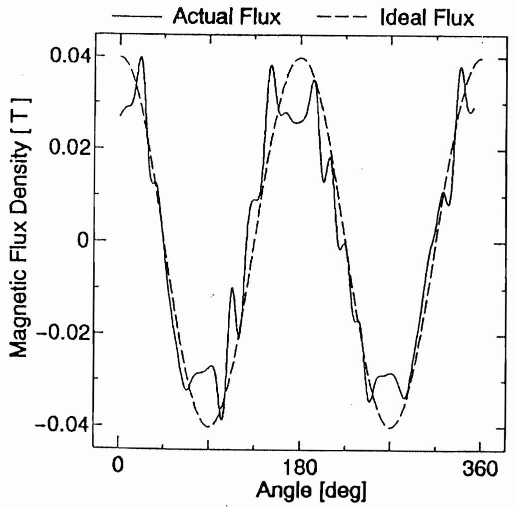

FIGURE 6: Distributed magnetic flux density of 4-pole rotor

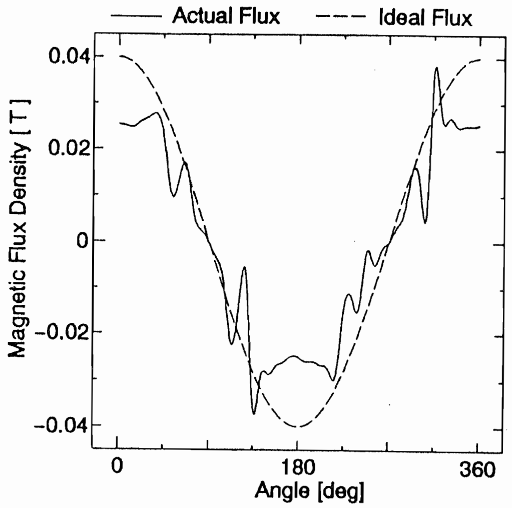

FIGURE 7: Distributed magnetic flux density of 2-pole rotor

tive gain, derivative time constant and the sampling interval (τ=0.3 ms) respectively.

TABLE 1: Experimental control patterns

Type	Rotation Control	Levitation Control
I	2-pole	4-pole
II	4-pole	6-pole
III	4-pole	2-pole

The experimental test patterns are shown in TABLE 1. The combined control of radial position and rotation is succeeded in all three cases. The levitated unbalance responses are shown in FIGURE 8, 9 and 10. These responses are obtained by increasing the motoring speed stepwise by 50 rpm and recording the vibration amplitude of fundamental frequency after the rotor reaches the steady-state speed of each 250 rpm increase.

In the case of +2 algorithm, rotation is relatively stable. The maximum rotating speed reaches to 8,850 rpm in

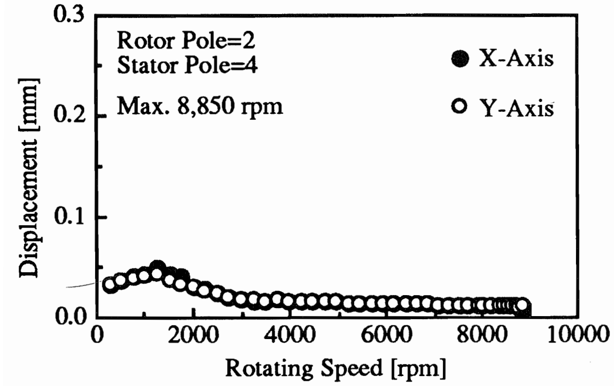

FIGURE 8: Unbalance responce (Type I)

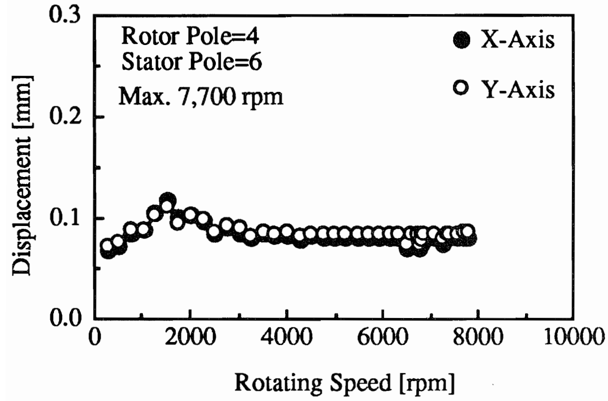

FIGURE 9: Unbalance responce (Type II)

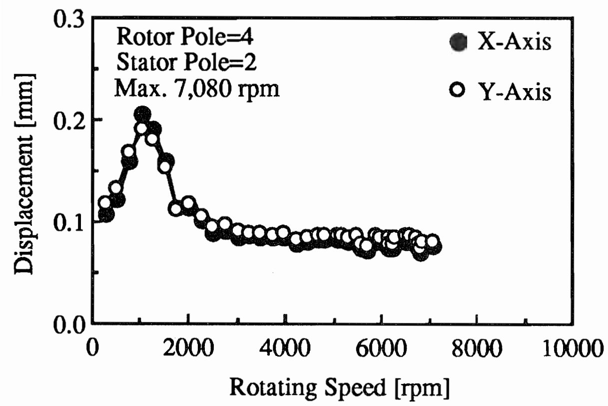

FIGURE 10: Unbalance responce (Type III)

Type I (FIGURE 8) and to 7,700 rpm in Type II (FIGURE 9). The result in FIGURE 6 shows very small vibration and smooth rotation.

Only one case of -2 algorithm is possible by using 4 pole rotor. The resulting unbalance response is shown in FIGURE 10 (Type III). The maximum speed of 7,080 rpm is lower than the previous cases of +2 algorithm. The vibration is also bigger than the previous ones.

CONCLUSIONS

The analysis of least pole number of synchronous-type levitated motor is introduced. Practically, it is impossible that magnetic flux density of the stator is a pure sinusoidal distribution, because of the stator slot winding. Then, the stator is assumed to include higher harmonics. Levitation force is calculated with this assumption.

As the result, some pole combination exists which causes interaction of levitation force. Hence, the least pole combination which does not cause disturbance for levitation is 2 pole rotor and 4 pole stator. Experimental result of this pole combination shows most stable levitated rotation.

Horizontal type experimental apparatus is designed and under construction. The apparatus has 8 concentrated wound stator, and produces high density magnetic field. 2 pole PM rotor which has sinusoidal flux distribution is prepared. Analytical and experimental torque load and radial force is planned.

REFERENCES

1. Y.Okada, T.Ohishi and K. Dejima, Levitation Control of Permanent Magnet (PM) Type Rotating Motor, Proc. of Magnetic Bearings, Magnetic Drives and Dry Gas Seals Conf. and Exhibition, July 29-31, 1992, Alexandria, VA, USA, p.157
2. M. Dussaux, The industrial applications of the active magnetic bearing technology, Proc. of the 2nd Int. Symp. on Magnetic Bearings, July 12-14, 1990, Tokyo, pp.33
3. A. Chiba, M. A. Rahman and T. Fukao, Radial Force in a Bearingless Reluctance Motor, IEEE Trans. on Magnetics, Vol. 27, No. 2, March 1991, pp.786-790
4. A. Chiba, T. Fukao and M. A. Rahman, Principles and No Load Characteristics of Induction Motor Type Bearingless Motor, Proc. of the IAS, IEE Japan, 1991, pp.324-329
5. J. Bichsel, The Bearingless Electrical Machine, Proc. of the International Symposium on Magnetic Suspension Technology '91, NASA Langley Research Center, p.561.