Improvement of Dynamic Response by Flux Feedback on Active Magnetic Bearings

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It is key point to get high value of dynamic stiffness which is more than 10^8N/m for adopting Active Magnetic Bearing to machining spindle. It requires high speed response to the control system. The frequency $\sqrt{stiffness/Mass}$ is a barometer as an upper limit of compensatory frequency against disturbance. The value should be more than 10kHz. But there are several problems on whole system, especially, on electro magnet and it's driver at such high frequency. The reason of slow response is due to eddy current in the magnet core. At high frequency, alternative component of coil current induces eddy current in the core, and then, flux response becomes slow and soft.

To avoid this problem, the selection of the core material is very important, though, almighty materials have never gotten in spite of great efforts.

Hence, the flux feedback is discussed in this paper. The flux feedback loop is attached between electro magnet driver and magnet air gap. The core is made of normal thin (0.35mm) Si-doped iron plate.

The response speed is higher than normal coil current feedback. There are data in two types of feedback. And the stability is discussed. Finally the compliance characteristic is shown adopted it on Active Magnetic Bearing.

Key Words : Flux Feedback, High Speed Response,
High Stiffness, Active Magnetic Bearing

1 Introduction

For adopting Active Magnetic Bearing (AMB) to machining spindle, the stiffness performance is one of the most important item. The static stiffness is already gotten enough value at low frequency, but dynamic stiffness can not be gotten yet in spite of many trying[1].

It is possible to separate the control system into two parts, one of them is a part of control signal compensator, and another is a subsystem of electro magnet and it's driver.

The subsystem of electro magnet and it's driver must play the role of force generator proportional to input signal. The subsystem must be evaluated by force response, not be done by coil current response. For this purpose, the flux density feedback may be useful. Because flux density has linear (or square) relationship with "force", and there is no time delay anymore between them.

Of course, the flux density feedback is popular idea. There are many letters already. The paper [2][3] discussed the constant force generation for handling maked up large iron plate. The letter [4][5] discussed the position or velocity observer by detecting flux density. But there are no discussion dealing with eddy current in the core. It is necessary to examine the response acceleration really by flux density feedback. The eddy current action is complicated by many parameters. It is worried that the eddy current action is taken into the feedback loop. But feedback depth can be taken widely according to the results of our examination.

The force response is measured on the electro magnet, which core is made of normal Si-doped iron plate and it's thickness is 0.35mm (Actually, the flux density response is measured in stead of force response). Then, the amplitude of the flux begins decreasing at 400Hz or higher. But, the amplitude of the coil current keeps almost of the input level. At high frequency, the difference between them becomes remarkable. It is considerable that eddy current in the core interferes the quick flux response.

Then, we tried to get high speed response about the same electro magnet. The two types of feedback are tried, one of them is conventional coil current feedback, and the other is flux density feedback. The sine response, Bode diagram and step response are measured. And the stability is discussed by Nyquist diagram. The flux density feedback shows good response than the other.

Finally, the flux density feedback is attached to Active Magnetic Bearing, and the compliance is measured. The stiffness can be increased stably. As a result, the stiffness became very strong compare to coil current feedback. Further more, the first bending mode at 2.5kHz is decreased and extinguished.

2 Electro Magnet

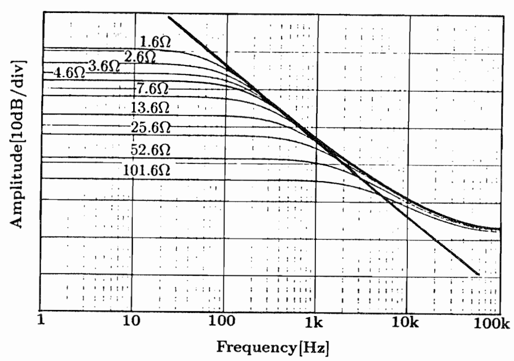

Fig.1 Transfer function to I_{coil} from V_{coil}

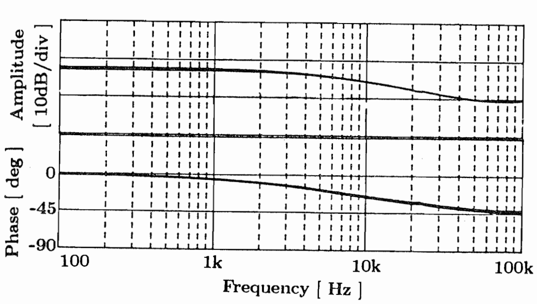

Fig.2 Transfer function to B from I_{coil}

Fig.1 is a transfer function (simply, trans.f as below) to the coil current I_{coil} from coil voltage V_{coil}, as a parameter of series resistance. The constant inductance is given within 1kHz. But at 1kHz or higher frequency, the slant becomes little, and it is near 0.5 by log-log scale. Fig.2 shows the trans.f to flux density "B" from coil current.

Fig.3 shows the core geometry of the electro magnet. The thickness is 0.35mm, material name is S-12 authorized by Japanese Industrial Standard (JIS). The pile upped width is 20mm. This is symmetry for 45 degree pitch, so the half is sketched in this fig. The rotor site is as same as stator site as thickness and material. The gap length x is 0.05mm, coil turn N is 56 through a flux loop. The inductance L is 0.005 Henry and wire resistance r_0 is 0.4 Ω.

According to the reference[6], the total impedance of the coil is displayed by parallel connection of sL and $k_e\sqrt{s}$, and the resistance is added serially. The term of sL generates the flux, otherwise, $k_e\sqrt{s}$ term is corresponding to eddy current.

$$I_{coil} = \frac{V_{coil}}{r_0 + \cfrac{1}{\cfrac{1}{sL} + \cfrac{1}{k_e\sqrt{s}}}} \tag{1}$$

$$B = \frac{\mu_0 N}{x} \times \frac{k_e\sqrt{s}}{sL + k_e\sqrt{s}} \times I_{coil} \tag{2}$$

μ_0 is permeability of the air. k_e becomes 1.253 by Fig.2. The $k_e\sqrt{s}$ term does not appear at low frequency, but it becomes remarkable over 1kHz.

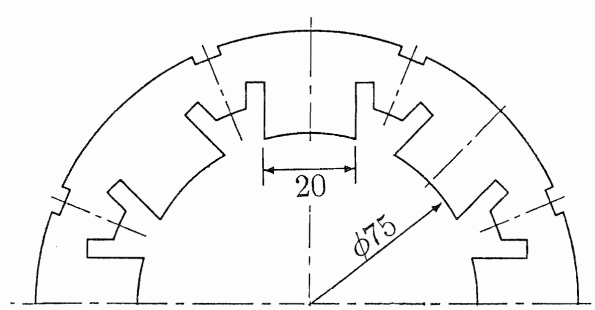

Fig.3 Core Size of Electro Magnet

3 Flux Density Feedback

Fig 4 shows the block diagram of flux density feedback to be examined. $G(s)$ is the trans.f of the Operational Amplifier (simply, Op Amp), $T_1(s)$ is a trans.f to the coil current from coil voltage, $T_2(s)$ is trans.f to the flux density from the coil current. Simply speaking, $T_1(s)$ is one pole low pass by L(inductance) and r_0(resistance) and $T_2(s)$ is constant, if eddy current in the core is negligible. Actually speaking, it is very complicated to display exact formula. K_i is a coefficient of coil current feedback. K_b is a coefficient of flux feedback, which is attached for examination circuit newly. There are tight relationship between the flux density and force as formula (3). Of course, the square characteristics is changed to linear relation by bias current as formula (4),(5),(6).

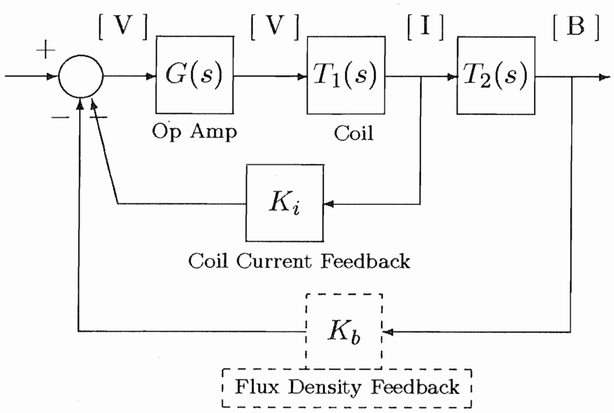

Fig.4 Block Diagram

$$F = \frac{1}{2\mu_0} B^2 S \tag{3}$$

S is a cross section of core (20 x 20mm^2). The coil voltage is sum of V_0 and $v_s(t)$. Then, coil current is sum of bias current "$I_0 = V_0/r_0$" and signal component "$i_s(t)$". Then formula (6) shows the linear relation between "F" and "i_s".

$$I_{coil}(t) = I_0 + i_s(t) \tag{4}$$

$$B(s) = \frac{\mu_0 N}{x} I_0 + \frac{\mu_0 N}{x} \cdot \frac{1}{1 + \frac{L}{k_e}\sqrt{s}} i_s(s) \tag{5}$$

$$F(s) = \frac{1}{2} \cdot \frac{B_0^2 S}{\mu_0} + \frac{B_0^2 S}{\mu_0} \cdot \frac{1}{1 + \frac{L}{k_e}\sqrt{s}} \cdot \frac{i_s(s)}{I_0} \tag{6}$$

4 The Apparatus

Fig.5 shows the circuit to examine. R_C is a current detecting resistor, 0.2Ω. R_{in} is input resistor, 2kΩ. These are fixed. R_{ifb}, R_{bfb} are feedback resistor, 470Ω, 1.1kΩ respectively. The detecting coil is used for flux sensing. The induced voltage is lead to integrator, the output voltage is proportional to flux density "B". The R_{sat}, $3M\Omega$ is connected to avoid saturation.

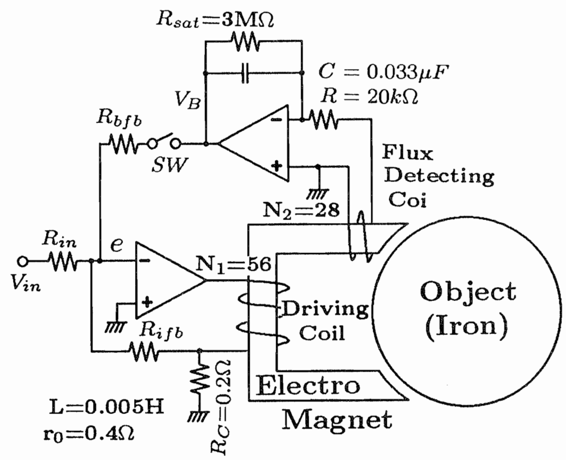

Fig.5 Circuit for Flux Density Feedback

Fig.5 is faithful for measurement concept, but conventionally, Fig.6 is more simple without flux detecting coil. It is assumed that sL or $k_e\sqrt{s} \gg r_0$. The key point is matching the cross frequencies "$1/CR_{sat}$ of the integrator" and "r_0/L of the coil". Be careful when the SW is turned off.

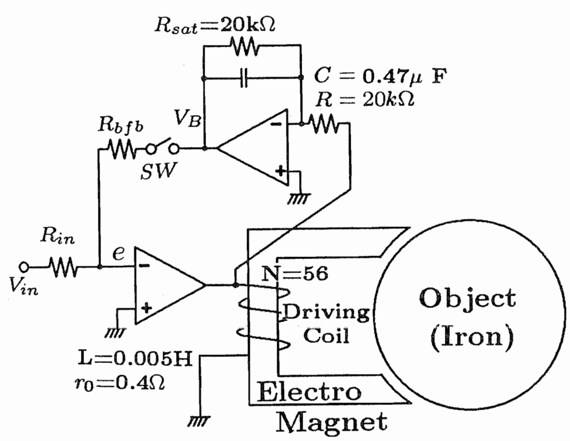

Fig.6 Circuit for Flux Density Feedback

5 Measurement

Fig.7 shows the sinusoidal response. In Fig.6, sine oscillator is connected to the input terminal, then the flux "B" is measured. The frequency is 2kHz,5kHz,10kHz respectively. The three kinds of the curve are plotted on the same figure so that the phase sift is shown clearly. The flux density feedback is better than the other.

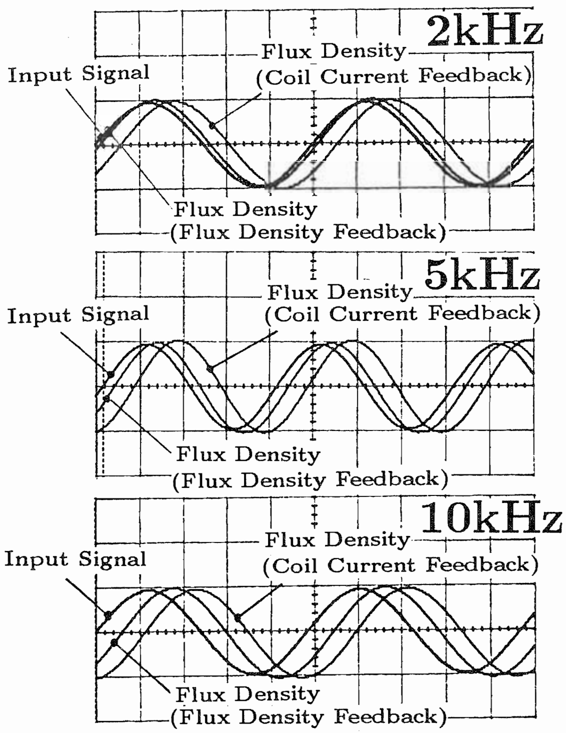

Fig.7 Sine Response of the Flux Density

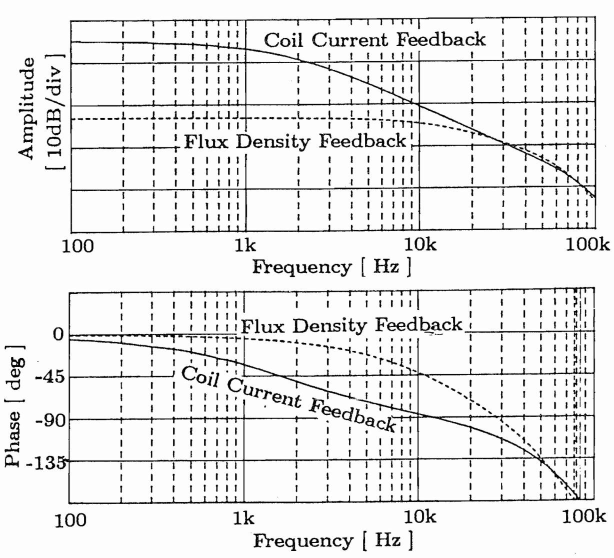

Fig.8 Bode Diagram of the Flux Density

Fig.8 shows the Bode diagram to flux density "V_B" from electro magnet driver input "V_{in}". (Fig.5 circuit is safe than fig.6.) The upper graph is the amplitude and lower is phase. The solid line is for coil current feedback only (sw is opened), the dashed line is for flux density feedback (sw is closed). The flux feedback is better about 10 times than coil current feedback.

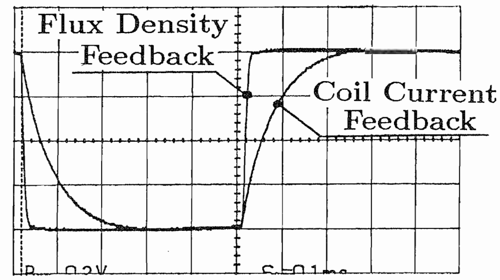

Fig.9 Step Response of Flux Density

Fig.9 shows the step response. The input signal is 1kHz square. The response of flux density feedback is high.

6 The Stability Discussion

It is necessary to get exact formula of trans.f to the flux from input. We should re-display the Fig.5 into new block diagram using circuit constants. It is assumed that the total input current is zero on Op amp, then the next formulae are concluded.

$$I_{coil}(s) = -T_1(s)G(s)e(s) \tag{7}$$

$$B(s) = T_2(s)I_{coil}(s) \tag{8}$$

$$\frac{V_{in} - e}{R_{in}} + \frac{I_{coil}R_C - e}{R_{ifb}} + \frac{V_B - e}{R_{bfb}} = 0 \tag{9}$$

V_B is output voltage of the integrator, and given as next.

$$V_B = K_b B = N_2 S/CR \cdot B \tag{10}$$

S is the cross section, and C, R, N_2 are listed in Fig.5. The coil direction must be connected for negative feedback.

By eliminating e and I_{coil}, the relation between V_{in} and B are displayed as next.

$$B(s) = -\frac{1}{\alpha} \cdot \frac{T_2 T_1 G}{1 + T_1 G \beta + T_2 T_1 G \gamma} \cdot V_{in}(s) \quad (11)$$

α、β、γ are constant, and are replaced next.

$$\alpha = 1 + \frac{R_{in}}{R_{ifb}} + \frac{R_{in}}{R_{bfb}} \quad (12)$$

$$\beta = \frac{1}{\alpha} \cdot \frac{R_{in}}{R_{ifb}} \cdot r_0 \quad (13)$$

$$\gamma = \frac{1}{\alpha} \cdot \frac{R_{in}}{R_{bfb}} \cdot K_b \quad (14)$$

These are displayed to the next block diagram.

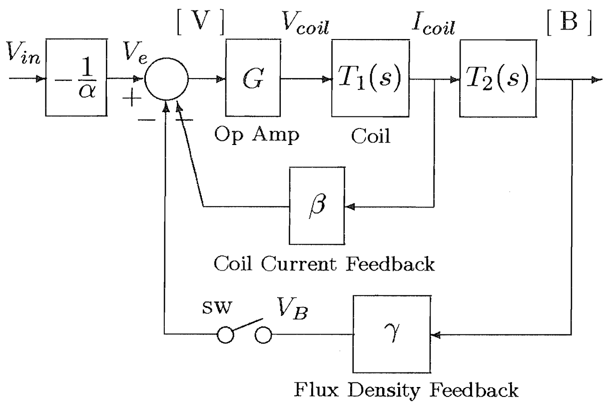

Fig.10 Block Diagram of Feedback

Now, the one loop trans.f to V_B from V_e is considered in the condition of opening γ loop (sw is opened). β loop is closed. The Bode diagram to V_B from V_{in} is shown in Fig.8. Then, the Nyquist diagram is gotten as Fig.11 from V_e to V_B. The system is stable by phase margin is 20 degrees, and gain margin is 3dB.

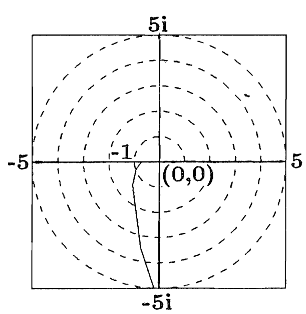

Fig.11 Nyquist Diagram (V_B/V_e)

The next step, we must decide the function $T_1(s), T_2(s)$. According to the formula (1),(2), we should consider the magnet coil into feedback loop. In the loop of β, $G\beta$ [Ω] is added at the denominator of formula (1).

$$T_1 T_2 = \frac{const}{sL + \frac{Lr_0}{k_e}\sqrt{s} + (r_0 + G(s)\beta)} \quad (15)$$

There is a 2nd order pole at 40kHz in Fig.8. The reason is the drive ability of power Op amp. This Op amp bandwidth is 4MHz (Gain 0dB point). $G\beta/r_0$ is 100 by β loop. So, the β loop decides the bandwidth within 40kHz, and the one loop trans.f of γ can be displayed as below.

$$GT_1T_2\gamma = T_1T_2 \times \frac{1}{s + 2\pi \cdot 40000} \times \gamma \quad (16)$$

As these result, to obtain stable condition, the necessity term is that one loop trans.f gain (V_e to V_B) must be less equal 1 at 40kHz, and the maximum γ is limited.

7 An Examination on AMB

The apparatus is shown in Fig.12. The rotational shaft is floated by compressed air [7]. The system is popular AMB. The shaft displacement is detected by position sensor. The signal is lead to PD (proportional and differential) circuit. It generates compensatory signal. The driver supplies coil current, and then feedback loop is constructed.

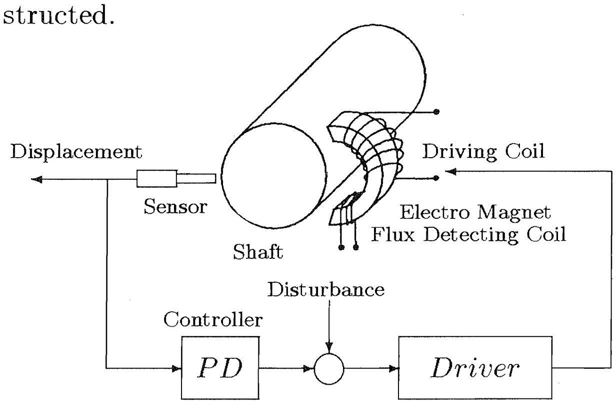

Fig.12 Block Diagram of Apparatus

The compliance to the shaft displacement from electric disturbance is measured. In Fig.13, the solid line is the compliance of the object. The dashed line is under the AMB operation as position feedback.

The value of stiffness is calibrated from static stiffness measurement. The stiffness of the object is 10^7N/m at 100Hz. The conventional units 1kgf/μm is closely equal to 10^7N/m. On the dashed line, the value near 100Hz is calculated to 8×10^7N/m. But this system is not stable at this condition. The peek at 2.5kHz is increased high. To avoid this instability, the loop gain must be down. The unstable phenomenon disappears when the stiffness is less than 4×10^7N/m.

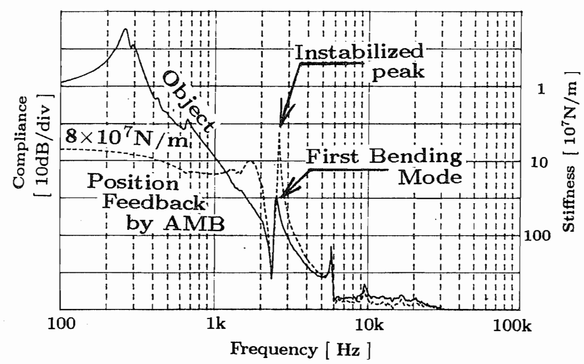

Fig.13 The Compliance of Apparatus (Coil Current Feedback)

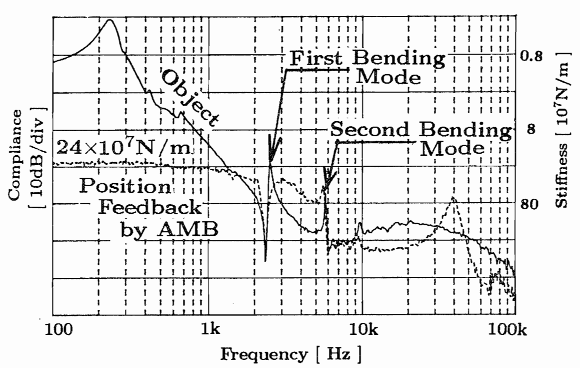

Fig.14 The Compliance of Apparatus (Flux Density Feedback)

Fig.14 shows the compliance in the case of examining flux feedback. The bending mode peak 2.5kHz is dumped and extinguished. This high viscosity allows the system very high stiffness. The value becomes 24×10^7N/m. This is very good performance compare to coil current feedback, up to 16dB. There is 2nd bending mode at 6kHz. The controllability is not so good between this two modes. The system may be under the "uncontrollable", because of magnet location.

8 Results

It is possible to get high speed response by flux density feedback on 0.35mm thin electro magnet core, which is made of Si-doped iron plate. The stability is discussed by Nyquist diagram. The maximum feedback gain is limited by Op amp band width.

Some problems are listed as below.

- The sensitivity to flux is decreased by flux density feedback. It is desired suitable gain partition in the whole system.
- It is worried that the core loss may be greater than coil current feedback, especially, at continuous high frequency operation.

References

[1]M.Brunet, B.Wagner "Analysis of the performance of an AMB spindlein creep feed grinding", Proc. of 4th Int. symp. on Mag. Bearings, ISBN 3 7281 21185, 519-524, (1994).

[2]T.Imazu, E.Masada, "The Numeric Analysis of non-contact Levitation and support for carrying of Iron plate". IEEJ Linear Drive Tech. Meeting report, LD-91-109(1991), 107p.

[3]T.Imazu, E.Masada, "Non-Contact Attractive Levitation for carrying of Iron plate and it's characteristics", IEEJ Linear drive technical meeting report, LD-92-93(1992), 55p.

[4]H.Kurita, "Displacement-sensorless Control Using Electromagnets", Proceedings of JSME Dynamics and Control, Vol. A(1992,7), 536p.

[5]H.Hashiya, Y.Okada, B.Nagai, "Sensorless Active Vibration Control", Tran.JSME Vol(C)58, No.554(1992-Oct).

[6]O.Miyashita, K.Ohniwa, T.Fujimaki, M.Morikawa, "Analysis of the Flux-Lag Effect in an Iron Core". J.M.Jpn19, 875-878(1995).

[7]S.Hara, "The Accuracy Improvement of Porous Air Bearing by Magnetic Compensation", The 5th Electromagnetics Symposium Proceedings, (1993,6), 305p.