Self-sensing Magnetic Bearing using the Principle of Differential Transfomer

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Abstract: A new method of self-sensing magnetic bearing is introduced. It is intended for push-pull type magnetic bearings to have both functions of forcing actuator and gap sensor. Each magnet has two coils; one is a bias coil which gives constant bias flux to the air gap. Another one is a control coil which increases one side of gap flux and degreases another side of gap flux. The magnetic force is linearized using this technique. The actuating coils are also used as a differential transformer type displacement sensor. The current of the bias coil is adjusted by changing the duty ratio of Pulse Width Modulated signal. The induced carrier frequency component in the control coil is detected and put into the demodulating circuit to get the rotor displacement. Two set of driving and demodulating circuits are made to detect the horizontal and vertical dispracements of the rotor. The position of the rotor is successfully controlled by the proposed method.

1 Introduction

Magnetic levitation has an advantage of non-contact supporting capability. The application is progressing to a various field such as a turbo molecular pump and spindle of machine tools.

Active magnetic bearings always require gap sensors and the number of which is the control degree of freedom. Cost and the complexity is a big problem. Moreover, there are several problems; the interaction between the sensor and the actuating magnet, a physical arrangement of sensor and actuator, and so on. If the electromagnetic actuator could be use as a sensor, the above problems can be solved. Several techniques have been proposed and reported: Vischer developed a self-sensing method based on an observer theory by measuring the electromagnetic coil current which is driven by voltage[1]. It depends on the negative stiffness of the electromagnet and the observability. Robustness is considered to be the biggest problem. Mizuno reported a frequency feedback type self-sensing method by using a hysteresis comparator[2]. The coil current which is driven by a chopper is directly connected to a hysteresis amplifire. It is considerd that the swiching frequency is restrected by the influence of noise. The authors proposed the pulse width modurated(PWM) type self-sensing method[3]. The electromagnetic coil is drivn by PWM signal. The coil current of the carrier component has a displacement information. Using a resonant curcuit and low pass filter, a gap displacement is estimated. However, the linear range of estimation is limited.

In this paper, a new type of self-sensing magnetic bearing is proposed by using a principle of differential transformer. This method can be applicable to a push-pull type electromagnet. Two kinds of coils are wound on a magnet, one is bias coil and another is control coil. Bias coil is connected in the same direction while the control coil is connected in the opposite direction. The actuating force is linearlized to the control current by using this method. Moreover the structure of the bias coil and the control coil is the same of the differential transformer. Therefore, the displacement of shaft can be estimated from the PWM carrier component of the control coil. The displacement output property estimated has a good linearity. An experiment using PID controller is performed and the stable revolution up to 12,000rpm is succeeded by proposed self-sensing technique.

2 Magnetic Bearing with Bias Coil and Linearization of Actuator Force

Schematic of the proposed magnetic bearing is shown in Figure 1. The left end is the magnetic bearing while the right end is supported by a ball bearing which is connected to a DC motor through coupling. The stator used is schematically shown in Figure 2.

Two kinds of coils are wound on each electromagnet; namely bias coil and control coil. The bias coil gives constant flax to the air gap while the control coil increases one side of gap flux and degreases another side of gap flux. One pair of magnets controls vertical (y direction) displacement while another pair of magnets controls horizontal (x direction) displacement.

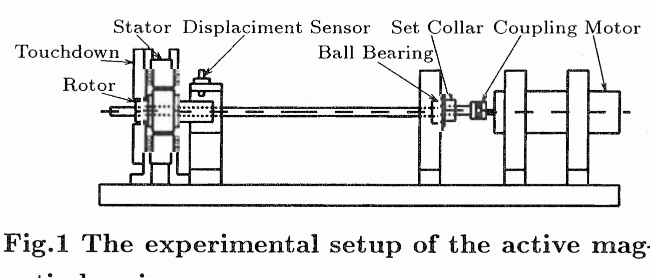


Fig.1 The experimental setup of the active magnetic bearings

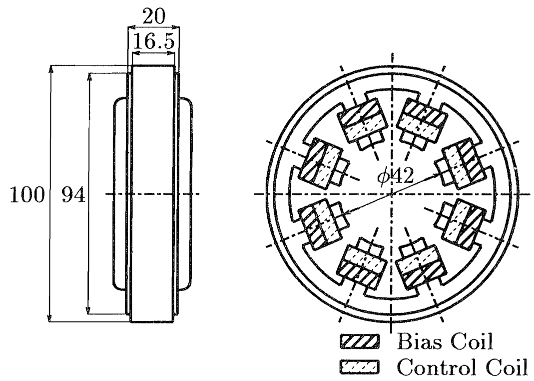


Fig.2 The stator of the active magnetic bearings

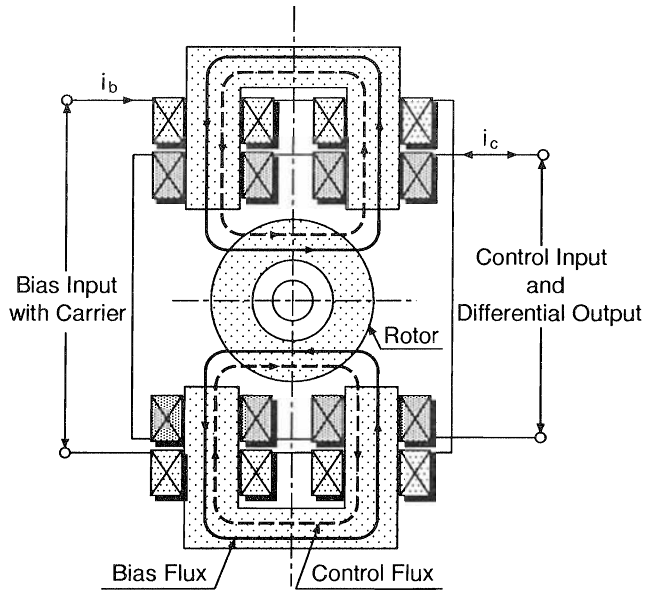


Fig.3 The connection and flux direction of the electromagnet

Figure 3 shows the connection of the coils and the direction of magnetic flux. The bias coils connect in the same direction and the control coils connect in the counter direction. The solid lines show the direction of the bias flux which is the same in upper and lower parts while the dashed lines are the control flux which is counter direction. This connection linearizes the actuating signal: Suppose the rotor is in a center, upper and lower magnetic flux densities B_1, B_2 are given by

$$\begin{aligned} B_1 &= B_b + B_c \\ B_2 &= B_b - B_c \end{aligned} \tag{1}$$

The symbols used are shown in Table 1 The sufixes 1 and 2 mean upper and lower magnets. Attractive force f of an electromagnet is given by

$$f = \frac{SB^2}{\mu_0} \tag{2}$$

Actuating force is the difference of the upper and lower

Table 1 The symbols

B_1, B_2	:	Flux density [T]
e_{dif}	:	Differential output voltage [V]
e_{x1}, e_{x2}	:	Induced voltage [V]
I_b, I_c	:	Bias and control current [A]
I_i	:	Current in coil i [A]
K_d	:	Derivative gain
K_p	:	Proportional gain
M_{ji}	:	Mutual inductance [H]
N, N_j	:	Number of coil turns
r	:	Resistance [Ω]
S	:	Cross-sectional area [m^2]
T_d	:	Derivative time constant [sec]
u	:	Demand signal
x, y	:	Displacement [m]
x_0, y_0	:	Average air gap [m]
μ_0	:	Permeability of free space [H/m]
τ	:	Sampling interval [sec]
ϕ_{ji}	:	Linkage flux [Wb]
ω_h, ω_v	:	PWM carrier frequency [Hz]

ones.

$$F = \frac{S}{\mu_0}({B_1}^2 - {B_2}^2) \tag{3}$$

Substitute equation (1) to equation (3), we have

$$F = 4\frac{S}{\mu_0}B_c B_b \tag{4}$$

Since bias magnetic flux density B_b is constant, equation (4) becomes

$$F = \alpha B_c \tag{5}$$

where

$$\alpha = \frac{4SB_b}{\mu_0} \tag{6}$$

Therefore the actuating force of the electromagnet is linearized to the control flux.

3 Principle of Displacement Estimation

Figure 4 shows scheme of the displacement estimation circuit. Schematical operation of differential transformer is shown in Figure 5. The carrier component of the output coil is linear to the displacement x. When the bias coil is operated as a reference coil, the mutual inductance between the bias coil and control coil is equivalent to one of the differential transformer. Mutual inductance M_{ij} between a circuit i and j is defined as

$$M_{ji} = \frac{N_j \phi_{ji}}{I_i} \tag{7}$$

Then the induced voltage of circuit j from circuit i is given by

$$e_j = -M_{ji}\frac{dI_i}{dt} \tag{8}$$

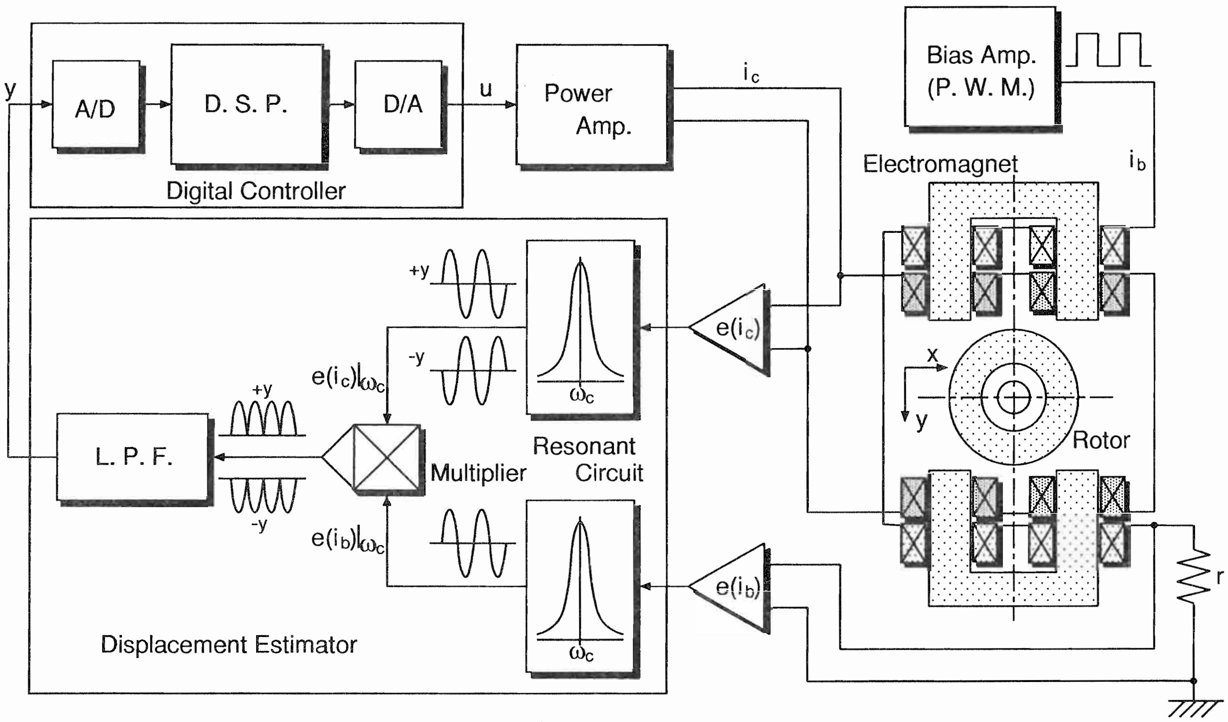


Fig.4 Schematic of electromagnet and estimation circuit

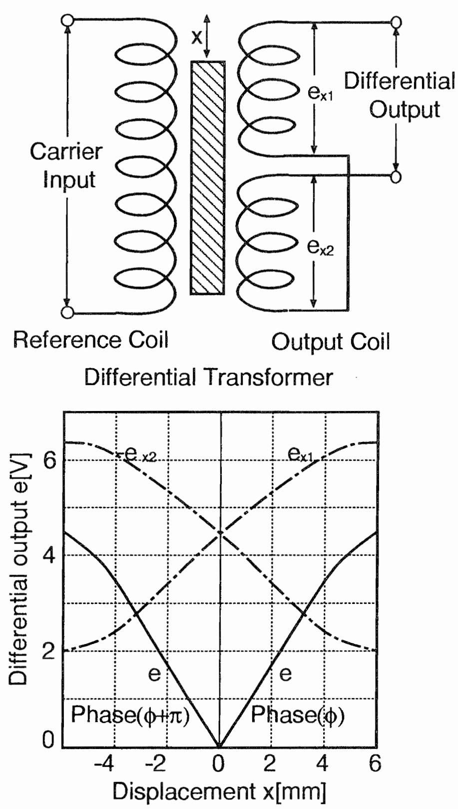


Fig.5 Differential transformer and the typical output property

Hence the upper side inductive voltage of the output coil is

$$e_{x1} = -M_{x1}\frac{dI_b}{dt} \tag{9}$$

Assuming that there is no leak flux, mutual inductance M_{x1} becomes

$$M_{x1} = \frac{NSB_{b1}}{I_b} \tag{10}$$

The magnetic flux density B_{b1} caused by the bias current is

$$B_{b1} = \frac{\mu_0 N I_b}{x_0 + x} \tag{11}$$

By substituting equation (11) to equation (10), we have

$$M_{x1} = \frac{\mu_0 N^2 S}{x_0 + x} \tag{12}$$

Therefore, by substituting equation (12) to equation (9), an upper side induced voltage is given by

$$e_{x1} = -\frac{\mu_0 N^2 S}{x_0 + x}\frac{dI_b}{dt} \tag{13}$$

Similarly, a lower side induced voltage is

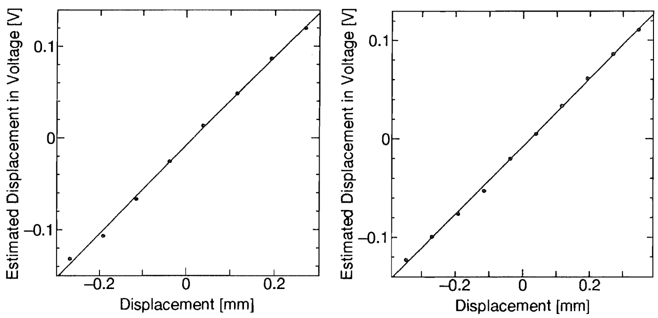
$$e_{x2} = M_{x2}\frac{dI_b}{dt} \tag{14}$$

The mutual inductance is given by

$$M_{x2} = \frac{\mu_0 N^2 S}{x_0 - x} \tag{15}$$

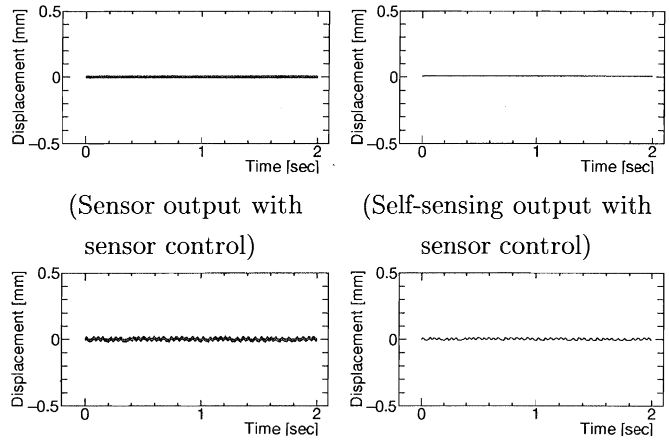
Substituting equation (15) to equation (14), we have

$$e_{x2} = \frac{\mu_0 N^2 S}{x_0 - x}\frac{dI_b}{dt} \tag{16}$$



(Vertical direction) (Horizontal direction)

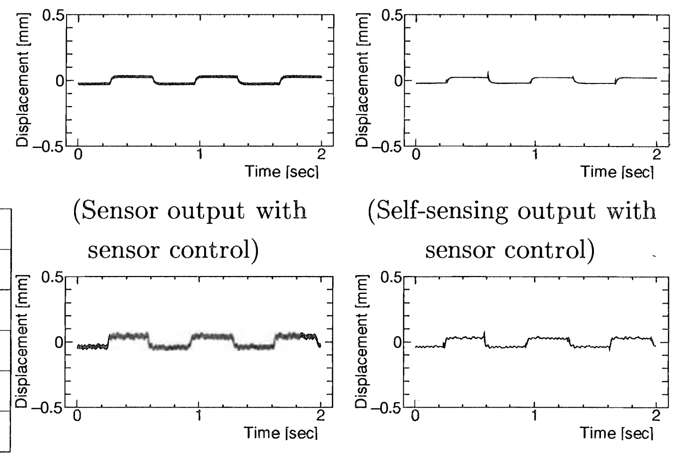
Fig.6 The displacement estimation property



(Sensor output with sensor control) (Self-sensing output with sensor control)

(Sensor output with self-sensing control) (Self-sensing output with self-sensing control)

Fig.7 Steady state response of the vertical direction of the rotor



(Sensor output with sensor control) (Self-sensing output with sensor control)

(Sensor output with self-sensing control) (Self-sensing output with self-sensing control)

Fig.8 Step response of the vertical direction of the rotor

Table 2 Characteristic values of the electromagnetic actuator

Number of coil turns (one coil)	:	50[Turn]
Diameter of the wire	:	0.5[mm]
Resistance (one coil)	:	0.3[Ω]
Cross-sectional area (single side)	:	0.16×10^{-3}[m^2]
Inductance (four coils)	:	1.937×10^{-3}[H]

Table 3 Control parameters of the PID controller

	Vertical	Horizontal
Proportional gain K_p[V/m]	2.2	2.5
Derivative gain K_d[Vsec/m]	0.0122	0.015
Integral gain K_i[V/sec]	0.2	0.2
Derivative time constant T_d[sec]	0.0005	0.0005
Sampling interval τ[msec]	0.1	0.1

The differential output voltage is the summation of each induced voltage and is given by

$$e_{dif} = e_{x1} + e_{x2} \simeq \frac{2\mu_0 N^2 S x}{{x_0}^2}\frac{dI_b}{dt} \tag{17}$$

Hence, the differential output signal is proportional to displacement x. Where, the assumptions ${x_0}^2 \gg x^2$ and ${x_0}^2 - x^2 \simeq {x_0}^2$ are made. From equation (17), mutual inductance M_x can be approximated by

$$M_x = -\frac{2\mu_0 N^2 S}{{x_0}^2}x \tag{18}$$

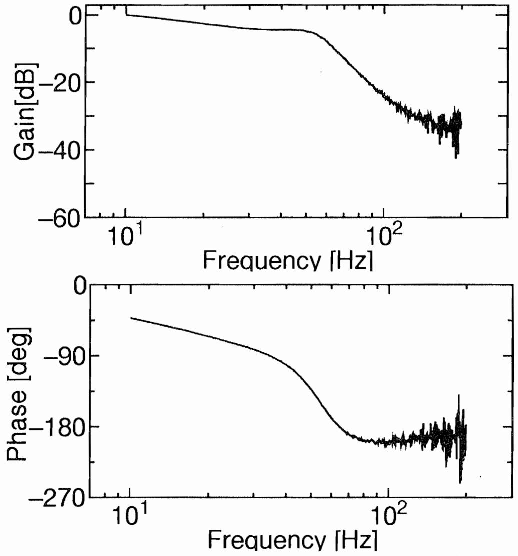
Therefore, by using pulse width modulated(PWM) signal to the bias coil and detecting the induced PWM component in the control coil of the actuator, the displacement of rotor gap can be estimated. The voltage of the carrier component is extracted by using a resonance circuit and the gap displacement of the rotor is estimated.
As shown in Figure 5, the output voltage indicates a V shaped absolute value of displacement. Since the phase characteristic has the sign information, the induced voltage and the carrier frequency component of the bias current is put into an analog multiplier. Then, the output is sent to a low pass filter to remove the carrier frequency. This demodulated signal is expected to be linear to the displacement of the rotor. The signal is taken into a DSP (Digital Signal Processor TI-TMS320C30) throuhgh A/D converter to calculate the actuating signal. Hence it is sent to a power amplifier through D/A converter.

4 Experimental Result and Consideration

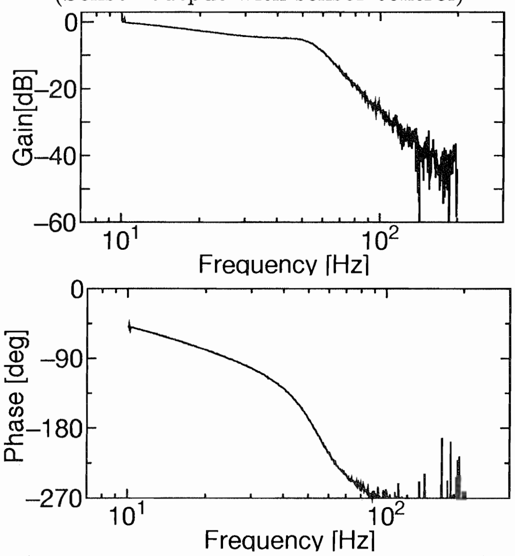
To confirm the proposed self-sensing technique, a simple experiment is performed using the canti-lever type magnetic bearing as shown in figure 1.

4.1 Self-sensing Property

The stator of magnetic bearing is made using a laminated steel sheet. Both side of the pair magnets have bias and control coils as shown in Figure 3. Mass of the rotor is 0.39Kg. The average air gap is 0.7mm. The physical parameters are shown in Table 2.



(Sensor output with sensor control)



(Self-sensing output with sensor control)

Fig.9 Closed loop frequency response of the vertical direction of the rotor

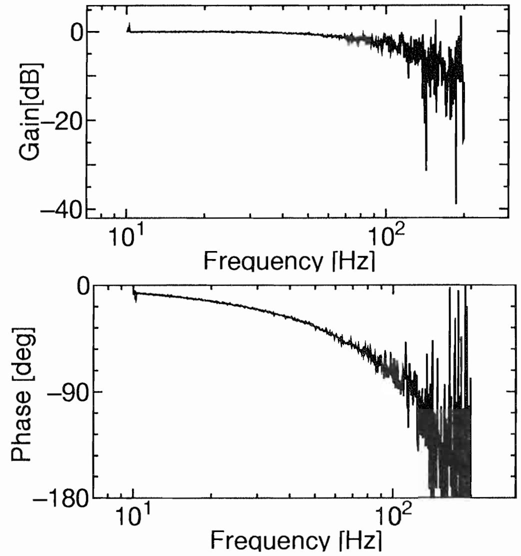
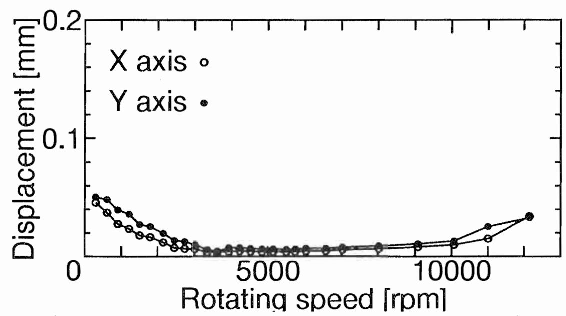
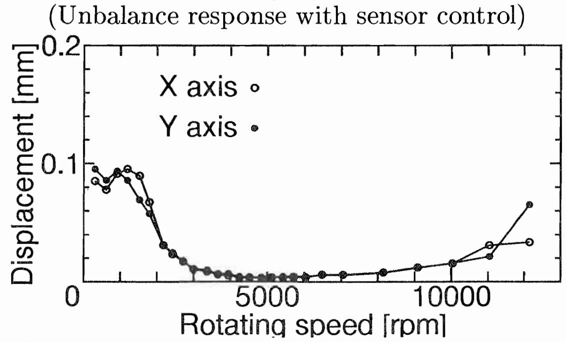


Fig.10 Dynamic property of the differential transformer type self-sensing



(Unbalance response with sensor control)



(Unbalance response with self-sensing control)

Fig.11 Unbalance response of the rotor

In order to check the sensing property of the electromagnetic actuator, non-magnetic gauge sheet is inserted between the rotor and stator and the output voltage is measured. The carrier frequencies used are ω_v =10.1 KHz for the virtical bias coil and ω_h =5.49 KHz for the horizontal bias coil. The current is adjusted about 0.9[A]. The output voltage versus displacement is shown in figure 6. The straight line is an ideal linear line. Though there is a little difference, the differential output of a control coil indicates a good displacement estimation.

4.2 Levitation and Rotation Test

Since the proposed electromagnetic actuator has a function of gap sensor, self-sensing levitation and rotation is tested. The controller used is a standard digital PID controller

$$G(z) = K_p + \frac{K_d(z-1)}{T_d(z - e^{-\tau/T_d}) - 1} + \frac{K_i \tau z}{z-1} \qquad (19)$$

Each direction for vertical and horizontal axies is controlled individually. The parameters of control system are shown in Table 3. The gains are slightly different between the virtical and horizontal directions, because the estimating circuits and the carrier frequencies are different causing sensitivity difference.

Steady state response is shown in figure 7. Upper two responses are the sensor and self-sensing outputs with sensor control and lower ones are the sensor and self-sensing outputs with self-sensing control. The reason why the sensor output line is thick is that two eddy current sensors for monitoring the x and y displacements are the same carrier frequency. Which causes mutual interference between them. Self-sensing control could solve such a interference problem. Though the self-sensig responses are vibrating slightly, stable levitation property

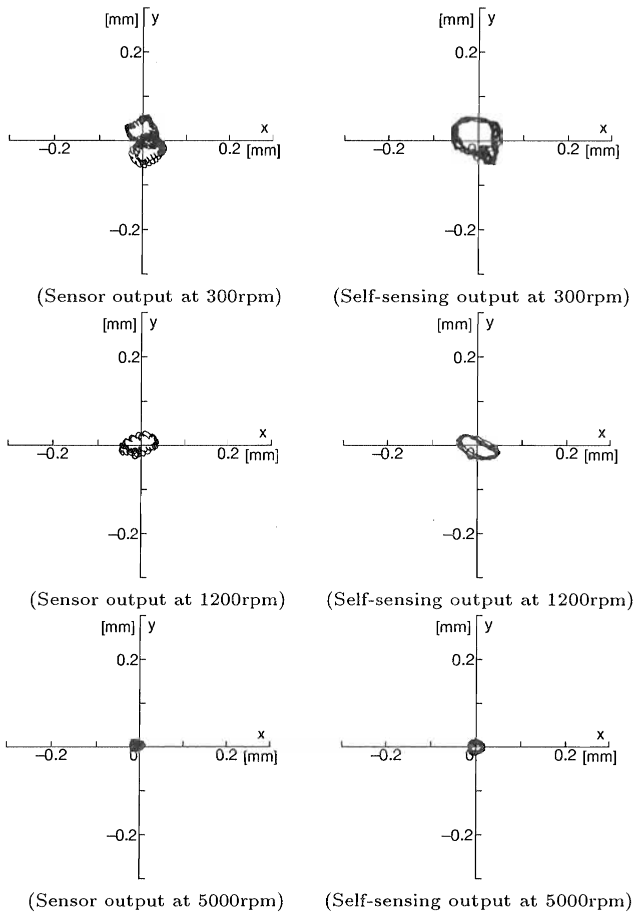


Fig.12 The orbital trajectory of the unbalance response with self-sensing control

is obtaind as shown in Figure 7.

Figure 8 shows the step response with about 0.05mm amplitude. The upper two responses are the sensor and self-sensing outputs with sensor control and the lower ones are the sensor and self-sensing outputs with self-sensing control. They also show stable levitation.

Frequency response is tested by adding the sinusoidal signal to the powor amplifier and recording the response. Figure 9 shows the frequency response of the virtical direction of the rotor. The upper curve is the sensor output with sensor control while the lower is self-sensing output with sensor control. Taking the difference of these two responses, the frequency response characteristics of the proposed self-sensing is measured as shown in Figure 10. The gain is constant until about 100[Hz], but the gain is decreased above that frequency. The sensor noise also becomes big.

In order to reduce the influence of high frequency noise, a low pass filter is installed to cut off frequency above 100[Hz]. By influence of this low pass filter, phase lags gradually from 10[Hz] and the lag becomes 90° near 100[Hz]. For this reason, the effect of derivative control is not enough and the small oscillation is left.

The unbalance response is shown in figure 11. The left respone is the unbalance response with sensor control while the right one is with self-sensing control. The rotor can run up to 12,000[rpm] which is the limited speed of the motor used. In the case of self-sensing control, a peak of 1,200[rpm] is recognized which is considered as a resonant frequency. However the rotation is stable.

The orbital trajectory of rotation with self-sensing control is shown in Figure 12. The vibration properties of x and y directions are similar and stable. However the rotation over 10,000rpm is influenced by the vibration of the ball bearing which supports the motor side of the rotor. The self-sensing magnetic bearing dos not indicate any problem for high speed rotaton.

5 Conclution

In order to reduce the sensor cost and the system size, a new type of self-sensing technique has been developed. The electromagnet has two kinds of coils; bias and control coils. When a bias coil is driven by PWM signal, induced voltage of control coil has a good information of rotor displacement. The band width of the self-sensing sensor is about 100Hz. The levitation and rotation using PID controller is performed and succeed in stable. The rotor runs up to 12,000rpm with self-sensing control.

From the results, the self-sensing magnetic bearing of differential transformer type has a high possibility for practical use.

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