REALIZATION OF PHASE-LOCKED AND FREQUENCY-FEEDBACK MAGNETIC BEARINGS

Takeshi Mizuno
Saitama University, Urawa, Saitama, Japan.
Toshihiro Ishii
Zexel Corp., Higashi-Matsuyama, Saitama, Japan
Kenji Araki
Saitama University, Urawa, Saitama, Japan

ABSTRACT
Phase-locked and frequency-feedback loops are applied to stabilize an active magnetic bearing with displacement sensors of frequency type. In the phase locked loops, the control input is produced from the difference in phase between the reference and feedback signals. Since phase is the integration of frequency, integral feedback arises automatically. It leads to high-accuracy suspension. To speed up the process of phase-locking, a frequency-feedback loop is used in addition to the PLL loop. This loop can stabilize the system even without PLLs. Self-sensing suspension is realized with a switching power amplifier whose switching-time is controlled by a hysteresis comparator. Experiments demonstrate the feasibility of the phase-locked and frequency-feedback magnetic bearings of self-sensing type.

INTRODUCTION
The sensors for detecting the position of a suspended object (rotor) play an important role in active magnetic bearings (AMBs). Most of the AMBs use an analog type of sensor that converts changes in the gap between the rotor and the sensor pick-up into changes in the amplitude of an output signal. This type of sensor often uses amplitude modulation (**AM**) techniques.

Frequency modulation (**FM**) as well as AM are most commonly used in communications technology [1] and can be applied to sensor technology. A magnetic bearing with the frequency type of sensor can be stabilized by *directly* feeding back the frequency modulated signal. Phase-locked (**PLL**) and frequency-feedback loops are applied for this purpose in this paper. They are feedback systems in which the fed-back parameter is the angle or its derivative (frequency) of a signal [2]. For simplicity, such a magnetic bearing is called as **FMB** in contrast to conventional AMBs.

A conventional PLL contains three basic components: a phase detector (**PD**), a loop filter, and a voltage-controlled oscillator (**VCO**). In a FMB, the amplifier-rotor-sensor system works as a VCO because an input voltage to the power amplifier changes the position of the rotor through electromagnetic force, which in turns changes the output frequency of the sensor.

A frequency-feedback loop is often used to help the loop into locking. This can stabilize the suspension system even without a PLL.

On method of reducing the size and cost of AMBs is to use the coils of electromagnets as sensor and force coils [3-7]. This type of AMB is often called self-sensing or sensorless. A self-sensing type of FMB can be realized with hysteresis amplifiers. This is a switching power amplifier whose switching times are controlled by a current comparator with some hysteresis [4,8]. The switching rate varies with the load impedance, which means the rate depends on the rotor position.

Experiments are carried out with an apparatus in which a single-degree-of freedom of motion is controlled actively. They show the feasibility of the self-sensing FMB.

PHASE-LOCKED LOOPS FOR FMB
The basic model of a FMB in the one-sided case is shown in **Fig.1**. It consists of a rotor, an electro-magnet, an amplifier, a displacement sensor of frequency type, a reference oscillator, a phase detector and a loop filter. The equation of motion is given by

$$m\frac{d^2x}{dt^2} = F_e - F_s \tag{1}$$

where

F_e : electromagnetic force acting on the rotor
F_s : stationary force acting on the rotor
(A typical example is gravity force.)

The stationary value of F_e is set to balance F_s. Assuming that the force-displacement-current relation of the electromagnet is linear, (1) becomes

$$m\frac{d^2x}{dt^2}=K_s x+K_i i \tag{2}$$

where

K_s, K_i : coefficients of the electromagnet

The transfer function $G_p(s)$ is defined by

$$G_p(s)=\frac{x(s)}{i(s)}=\frac{b}{s^2-a} \tag{3}$$

where

$$a=\frac{K_s}{m},\quad b=\frac{K_i}{m}$$

Next, the components in the feedback loop are studied. The angular frequency ω of the sensor output is a function of the displacement of the rotor:

$$\omega=\omega(x) \tag{4}$$

It is assumed that $\omega(x)$ is linearized as

$$\begin{aligned}\omega(x)&=\omega_r+\Delta\omega(x)\\&=\omega_r+K_\omega x,\end{aligned} \tag{5}$$

where the nominal frequency ω_r corresponds to the desired position x_r of the rotor. The reference oscillator produces a signal of the same frequency. Since frequency is the time derivative of phase, $\Delta\omega$ can be represented as

$$\Delta\omega=\frac{d\theta}{dt} \tag{6}$$

where

θ :the phase of the sensor signal

Although a phase detector usually has nonlinear characteristics, it can be accurately modeled as a linear device when the loop is in lock [1]. Then it is assumed that the phase detector output voltage is proportional to the difference in phase between its inputs; that is

$$v_d=K_d(\theta-\theta_r) \tag{7}$$

where

K_d : phase detector gain factor

θ_r : phase of reference signal ($\omega_r=\frac{d\theta_r}{dt}$)

The loop filter must be selected to stabilize the closed-loop system. When $F_1(s)$ is the transfer function of the loop filter, the voltage at the output of the filter can be described as

$$v_e(s)=F_1(s)v_d(s) \tag{8}$$

When the power amplifier is of current-controlled type, the amplifier changes the electromagnet current in proportion to its input; that is

$$i(t)=K_a v_d(t) \tag{9}$$

With these assumptions, the FMB in the one-side case can be represented by a linear model shown in **Fig.2**.

From (3), (5), and (9), the frequency deviating from the reference frequency is related to the filter output as

$$\Delta\omega(s)=K_\omega G_p(s)K_a v_e(s) \tag{10}$$

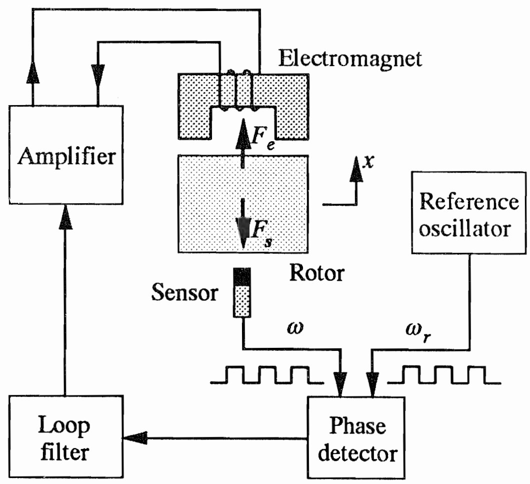


FIGURE 1: Schematic diagram of FMB in the one-sided operation

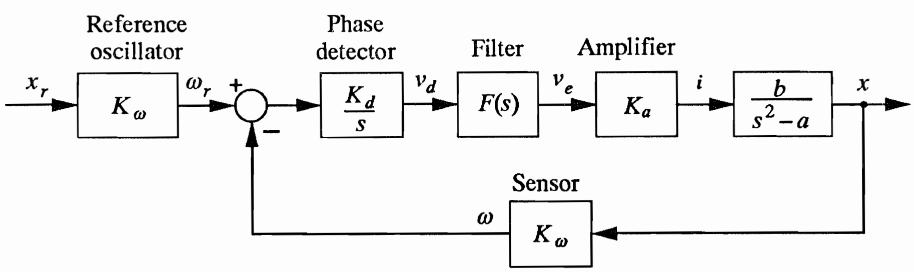


FIGURE 2: Block diagram of FMS using a linearized model in the one-side operation

From (6), (7), (8), and (10), the linear transfer function relating x_r and x is

$$T_1(s) = \frac{x(s)}{x_r(s)} = \frac{G_1(s)}{1+G_1(s)} \tag{11}$$

where

$$G_1(s) = \frac{K_1 G_p(s) F_1(s)}{s} \tag{12}$$
$$K_1 = K_a K_d K_\omega$$

Equation (12) shows that the open-loop transfer function of FMB has a pole at the origin. This leads to zero error in steady-state position for constant disturbances.

In AMBs with conventional position sensors, the so-called integral feedback is used for high accurate positioning. Most analog integrators, however, have some departures from ideal for the technical reason that commercially available op amps have DC error. Even with a digital controller, some error remains because of quantization with a *finite* number of word length. In contrast to these integrators, the integral operation performed by a PLL is ideal because it comes from the fact that frequency is the time derivative of phase (see (6)). It is thus expected that PLL's will accomplish extremely accurate positioning.

A FMB with a pair of two opposite electromagnets is shown in **Fig.3**. In this configuration, the reference oscillator is omitted and the phase detector compares two sensor signals directly. The FMB in differential operation is described by nearly the same equations as that in one-sided operation [9]. However, it has several advantages in practical use. One of them is that reference oscillator is unnecessary. Another is avoidance of undesirable drift of the rotor due to some difference in frequency change with temperature between the reference oscillator and the sensor.

FREQUENCY-FEEDBACK LOOPS FOR FMB

To ensure the loop pulled in lock, frequency error is often fed back besides phase error. There are several methods of detecting frequency error. A simple way is to use frequency-to-voltage (F/V) converters. **Figure 4** shows a block diagram of a FMB with phase-locked and frequency-feedback loops in the one-sided operation. The F/V converted signal is given by

$$v_f = K_f K_\omega x \tag{13}$$

where

K_f : gain of the F/V converter

When $F_2(s)$ is the transfer function of a compensator in the frequency-feedback loop, the voltage at the output of the compensator is given by

$$v_c(s) = F_2(s)\, v_f(s) \tag{14}$$

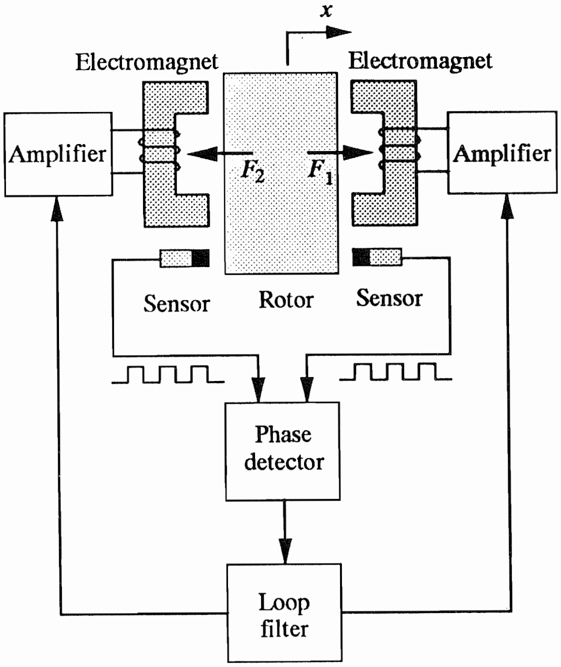


FIGURE 3 : Schematic diagram of FMB in the differential operation

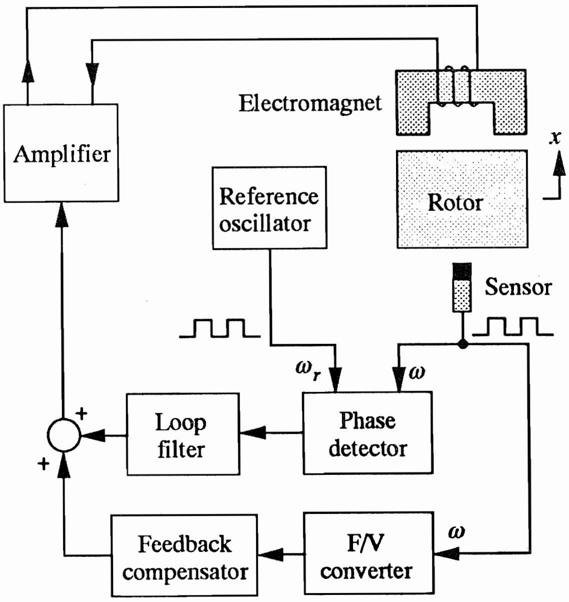


FIGURE 4 : Schematic diagram of FMB with phase-locked and frequency feedback loops in the one-sided operation

This input is added to the control input produced by the PLL loop. The transfer function is relating relating x_r and x is obtained as

$$x(s) = \frac{G_1(s)}{1+G_2(s)} x_r(s) \tag{15}$$

where

$$G_2(s) = G_1(s) + K_2\, G_p(s) F_2(s) \tag{16}$$
$$K_2 = K_a K_f K_\omega$$

CONTROL LAWS

There are three choices for stabilizing a FMB in the configuration shown in **Fig.4**. They are

(1)using only the frequency-feedback loop ($F_1(s) = 0$)
(2)using only the phase-locked loop ($F_2(s) = 0$)
(3)combining both

When the method (1) is adopted, the control design is almost same as in the conventional AMBs. A simple way is to use the PD control:

$$F_2(s) = -(p_d + p_v s) \tag{17}$$

The characteristic equation of the closed-loop system becomes

$$t_c(s) = s^2 + bK_2 p_v\, s + (bK_2 p_d - a) \tag{18}$$

When the method (2) is adopted, the closed-loop system can be stabilized with a second or higher order filter theoretically [9]. Although sophisticated filter design may modify the pull-in characteristics well, it is *technically* difficult to pull the loop in lock only with this loop because the open-loop system is unstable. Therefore, it is practical to combine both the loops to realize accurate suspension by a PLL. A simple combination is to use a loop filter of first order in the phase-locked loop and PD control in the frequency-feedback loop:

$$F_1(s) = \frac{d_0}{s + c_0} \tag{19}$$

$$F_2(s) = -(p_d + p_v s) \tag{20}$$

The characteristic equation is obtained as

$$t_c(s) = s^4 + (c_0 + bK_2 p_v)s^3 + \{bK_2(p_d + c_0) - a\}s^2 + c_0(bK_2 p_d - a)s + bK_1 d_0 \tag{21}$$

The poles of the closed-loop system can by assigned arbitrarily by choosing the coefficients of the filter and the feedback gains.

FMB OF SELF-SENSING TYPE

One of the main reasons why AMBs have been used only in special fields such as vacuum technology is the cost of the total system. Reduction of the cost, size and weight of AMBs is important to increase their industrial applications. An effective method for this purpose is the combined use of an electromagnet for force generator and position sensor.

In the pulse restrained magnetic suspension, the windings are used on a *time-sharing* basis to serve alternately as position sensor and force coils [3]. In the so-called *sensorless* or *self-sensing* magnetic bearing, an observer is used to reconstruct the displacement and velocity of the rotor from the coil current and voltage [4, 5, 6]. Another method of self-sensing is to make use of the PWM carrier frequency component [7]. In addition to the latter two methods, Vischer points out that the gap can be measured by demodulating the switching signal of a hysteresis amplifier [4].

The schematic diagram of a hysteresis amplifier is shown **Fig.5**. Since the switching rate depends on the load impedance [8], it changes with the gap between the rotor and the electromagnet. The switching signal is, therefore, modulated in frequency.

Figure 6 shows the *self-sensing* configuration of FMB in the differential operation. Switching signals from the hysteresis amplifiers are used instead of those produced by the frequency type of displacement sensors. These are directly inputted to the phase detector and the F/V converters.

EXPERIMENTS

Experiments are carried out with a single-degree-of-freedom model shown in **Fig.7**. It has an arm as a suspended object, and a pair of electromagnets. Each electromagnet has a solid core of ferrite. Two hysteresis amplifiers are used to excite the electromagnets. The

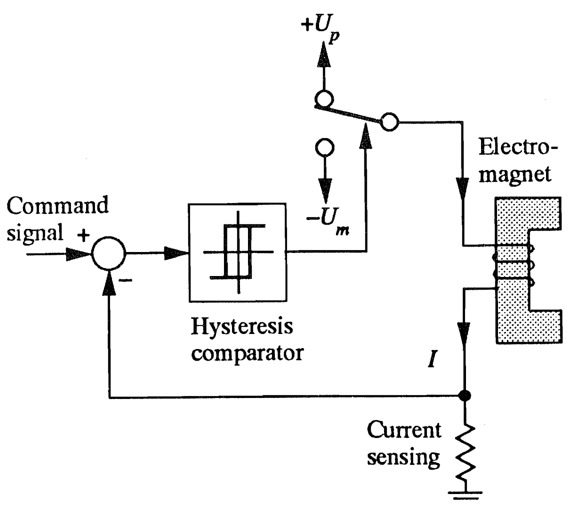


FIGURE 5 : Schematic diagram of a hysteresis amplifier

structure of the control system is almost same as shown in Fig.6.

The switching frequency of each of the hysteresis amplifiers is measured for the range of the gap from 0.25mm to 0.55mm (**Fig.8**). The measurement results show the linear relationship between frequency and gap.

Figure 9 shows a step response of the suspension system stabilized by the frequency-feedback loop. An eddy-current displacement sensor is only used for measuring and monitoring, and not for control. This result shows that the F/V converted switching signal coincides well with the sensor signal.

Figure 10 compares floating accuracy of a conventional AMB and a *self-sensing* FMB with a PLL; the former feeds back a sensor signal of analog type. This result demonstrates that PLL can improve static accuracy of floating.

CONCLUSIONS

Phase-locked and frequency-feedback magnetic bearings (FMBs), which were characterized by the frequency type of displacement sensor, were studied both theoretically and experimentally. The self-sensing type of FMB was realized with hysteresis amplifiers. The linear relationship between the switching frequencies and the position of the rotor were certified experimentally. Stable suspension was obtained by feeding back the F/V-converted switching signals. When the phase-locked loop was activated in addition to the frequency-feedback loop, the suspension system was pulled in lock. It improved accuracy of positioning.

Further experimental study is needed to apply FMBs to industrial instruments.

ACKNOWLEDGMENT

Mizuno would like to express his thanks to Prof. H. Bleuler, Dr. D. Vischer and Mr. C. Gähler for valuable discussions on FMB during his stay at ETH.

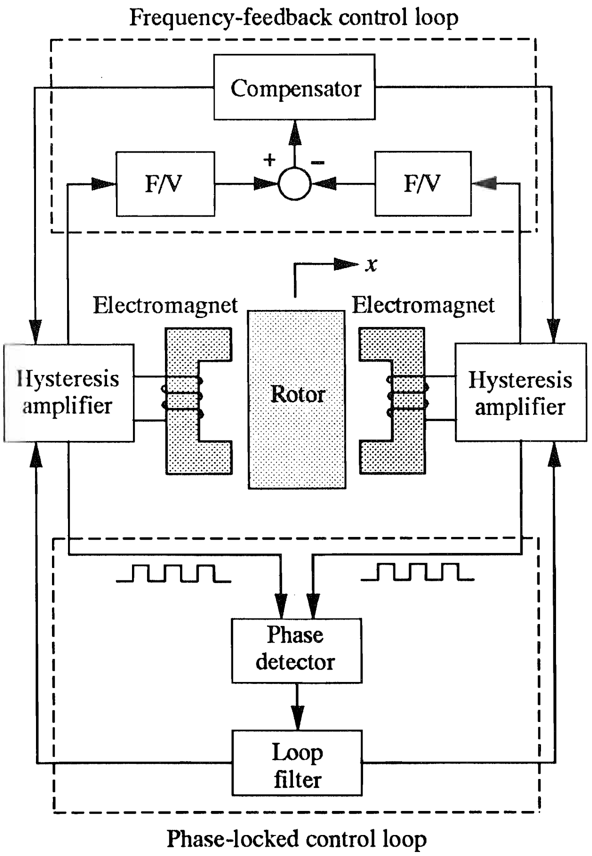


FIGURE 6 : Schematic diagram of a self-sensing FMB

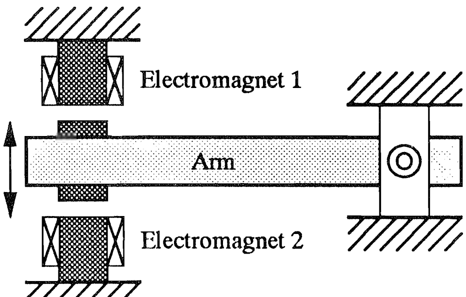


FIGURE 7: Experimental apparatus

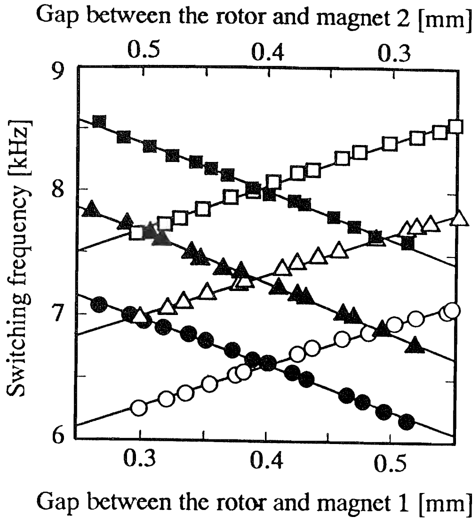
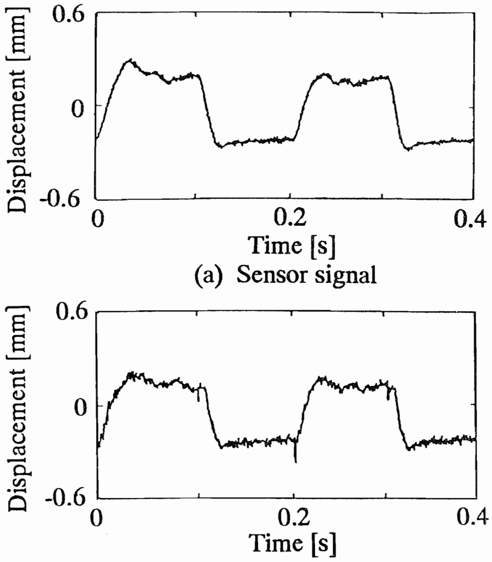


FIGURE 8 : Switching frequency of the amplifiers
○, ●: U_p, U_m = 40V
△, ▲: U_p, U_m = 50V
□, ■: U_p, U_m = 60V

REFERENCES

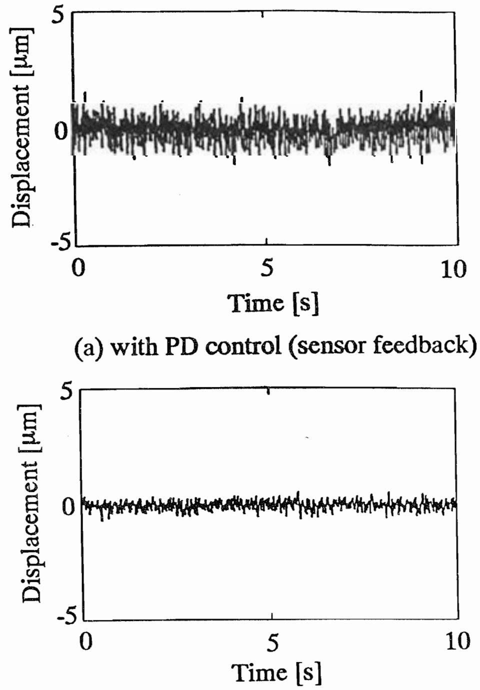
1. Bohde, U.L., *Digital PLL Frequency Synthesizers --- Theory and Design ---*, Prentice-Hall, Inc.(1983), pp.1-67.
2. Klapper, J. and Frankle, J. T., *Phase-Locked and Frequency-Feedback Systems*, Academic Press, pp.2-11(1972).
3. Frazier, R. H., Gilinson, Jr., P. J., Oberbeck, G. A., *Magnetic and Electric Suspensions,* The MIT Press, pp.265-284 (1974).
4. Vischer, D., *Sensorlose und spnnungsgesteuerte Magnetlager*, doctor thesis Nr.8665, ETH Zürich, (1988).
5. Vischer, D. and Bleuler, H., *Self-Sensing Active Magnetic Levitation*, IEEE Trans. on Magnetics Vol.29, No.2, pp.1276-1281 (1993).
6. Mizuno, T. and Bleuler, H., *A Geometric Approach to Self-Sensing Magnetic Bearings*, Preprints of Papers, 12th World Congress IFAC, Vol.4, pp.517-522 (1993).
7. Okada, Y. Matsuda, K. and Nagai, B., *Sensorless Magnetic Levitation Control by Measuring PWM Carrier Frequency Component*, Proc. 3rd Int. Symp. on Magnetic Bearings, pp.176-183 (1992).
8. Keith, F. J., Maslen, E. H., Humphris, R. R., and Williams, R. D., *Switching Amplifier Design for Magnetic Bearings*, Proc. 2nd Int. Symp. on Magnetic Bearings, pp.211-218 (1990).
9. Mizuno, T., *Frequency Feedback Magnetic Bearings*, Proc. 1st Int. Conf. on Motion and Vibration Control, Vol.2, pp.639-644 (1992).



(a) Sensor signal

(b) F/V converted switching signal

FIGURE 9 : Comparison between the sensor output and the F/V converted switching signal



(a) with PD control (sensor feedback)

(b) with a PLL (self-sensing)

FIGURE 10 : Accuracy of floating