SELF-SENSING OPERATIONS OF FREQUENCY-FEEDBACK MAGNETIC BEARINGS

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Abstract:—Two topics are treated in this paper for promoting industrial application of a self-sensing type of frequency-feedback magnetic bearing (FMB) which uses hysteresis amplifiers. First, a low-cost digital control system is developed in which the frequency of the switching signal of the amplifier is converted to a digital form by counting by a counter circuit. The converted signal is directly used for calculating control input for stabilization. Second, the incorporation of the observer-based self-sensing method to FMBs is discussed. It is shown that an observer estimating velocity and displacement can be constructed even in current-controlled magnetic bearing systems such as FMBs with hysteresis amplifiers. The estimated signals are used to improve the dynamic performance of a self-sensing type of FMB.

1 Introduction

The frequency feedback magnetic bearing (FMB) has a displacement sensor of frequency type and a frequency-feedback loop for stabilization [1, 2]. A self-sensing type of FMB can be realized by using a switching power amplifier whose switching times are controlled by a hysteresis comparator (hysteresis amplifier) [3]. In this system, the switching signal of the amplifier is modulated in frequency due to the position of the suspended object because the switching rate changes according to the load impedance that is a function of the gap between the electromagnet and the suspended object. Therefore, stable suspension can be achieved by using this signal in feedback control instead of a sensor of frequency type. The feasibility of the self-sensing FMB has been already shown experimentally [3].

For promoting the industrial application of FMBs, however, more reduction of cost and higher performance are required. This research develops a low-cost digital control system suitable to FMBs. In this system, the frequency of the switching signal is converted to a digital form by counting by a counter circuit so that analog-to-digital converters can be omitted.

Another topic treated here is the incorporation of the observer-based self-sensing method to FMBs for improving their dynamic performance. In this self-sensing method, an observer-based controller has been designed based upon the controllability and observability of *voltage-controlled* active magnetic bearings (AMBs) in which only the coil currents are sensed [4]. It has succeeded in suspending a high-speed rotating rotor with compensations for rotor unbalance [5]. This research presents a modification which makes the observer-based method applicable to current-controlled AMBs such as FMBs with hysteresis amplifiers.

2 Digital Control System for FMBs

2.1 System Configuration

Digital control is now often used in industrial active magnetic bearing (AMB) systems because of its advantage of flexibility over analog control. Analog-to-digital (AD) converter is a very critical component in most digital controllers because sensors of analog type are in the majority. When sensors of frequency type are used, however, AD converters can be omitted because frequency of a signal can be easily converted to digital form by counting by a counter circuit.

The basic configuration of a self-sensing FMB with the above-mentioned interface for digital control is shown in **Fig.1**. Each of the two opposite electromagnets is energized by a hysteresis amplifier whose switching frequency changes in proportional to the gap between the suspended object and the electromagnet. The switching signals are connected to a up/down counter which is interrupted by a measurement time T_m. The condition of the counter is inputted through a digital

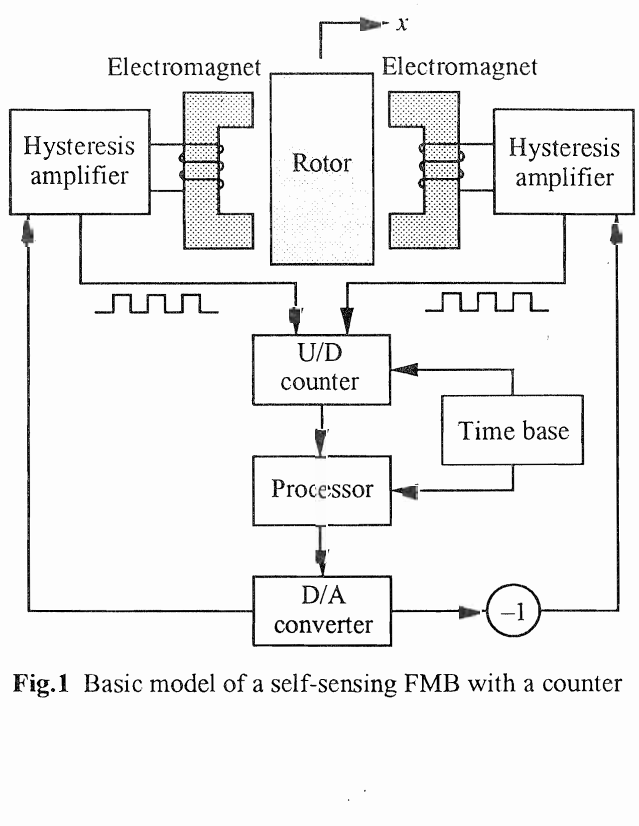

Fig.1 Basic model of a self-sensing FMB with a counter

interface to a signal processor before clearing the counter. In this processor, mathematical operations for calculating control input are performed. The signal is converted to analog with a digital-to-analog (DA) converter. The converted signal is connected to the hysteresis amplifiers directly or through an inverting amplifier.

One of the advantages of this system over the phase-locked FMB [2] is that it can adjust the suspension position easily.

2.2 Experimental System

The target controlled object is a single-degree-of-freedom model shown in **Fig.2**. It has an arm as a suspended object, and a pair of electromagnets. Each electromagnet has a solid core of ferrite. The nominal air gap is 0.4 mm.

The diagram of the hysteresis amplifier used in the experiment is shown in **Fig.3**. This is easier to manufacture and lower-cost than the amplifier used in the previous work [3]. The resistor R is selected so that the duty cycle becomes 0.5 when the value of the current setpoint equals the bias current (0.3 A).

A personal computer and a counter board are used as the up/down counter and signal processor in Fig.3. The measurement (sampling) time T_m is 2 msec. The frequency of the switching signal is multiplied by 96 with a frequency multiplier before it is connected to the counter board. This multiplication is necessary for achieving accurate position estimation during the measurement time because the range of the switching frequency is only 8-11 kHz (see **Fig.4**).

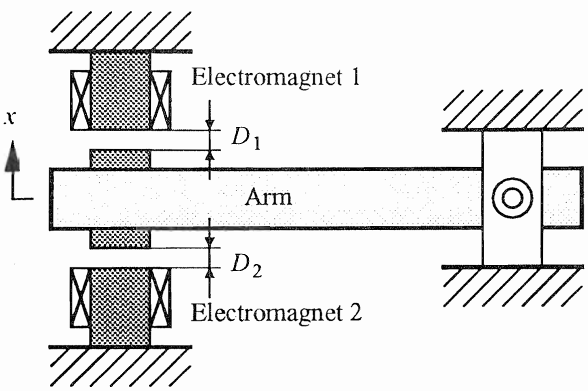

Fig.2 Experimental apparatus

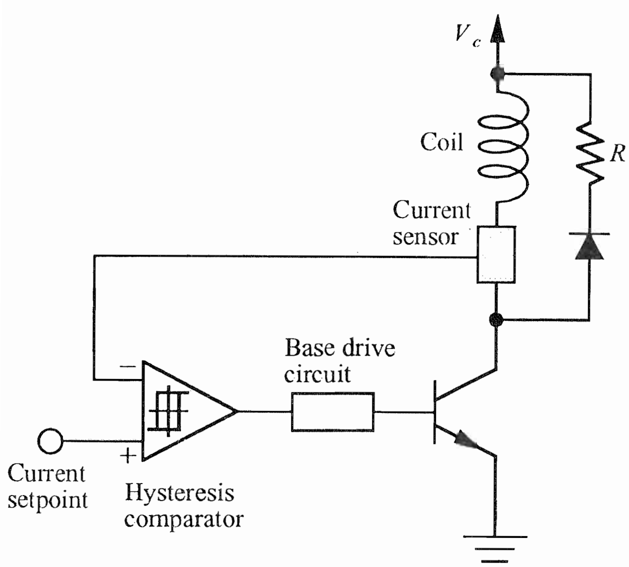

Fig.3 Hysteresis amplifier

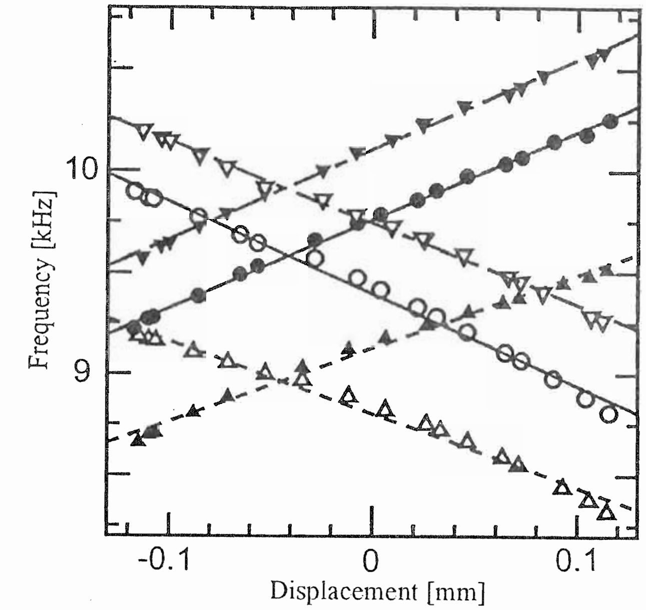

Fig. 4 Switching frequency of the hysteresis amplifiers.

V_c	30V	40V	50V
Electromagnet 1	▲	●	▼
Electromagnet 2	△	○	▽

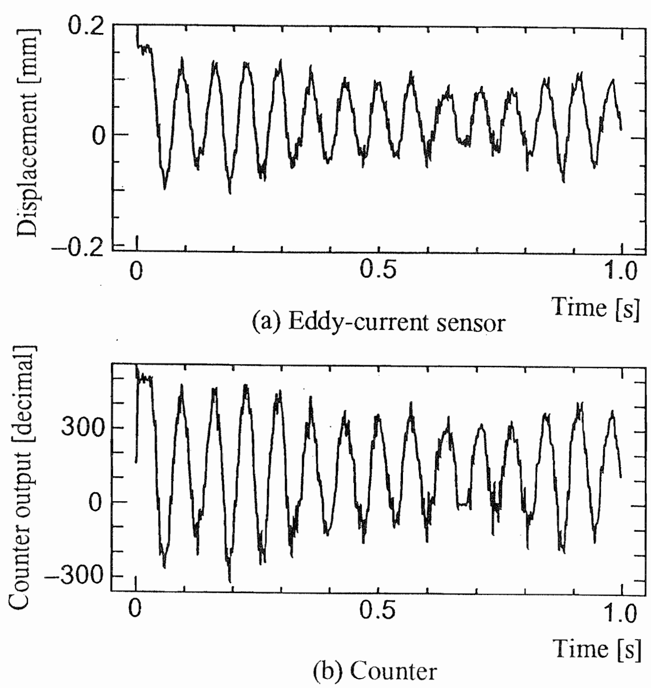

Fig. 5 Comparison between the outputs of the counter and the eddy-current sensor

An eddy-current displacement sensor is used for measuring and monitoring. This signal is also inputted to the computer through an AD board.

2.3 Experimental result

The switching frequency of the hysteresis amplifier at each position of the suspended object is shown in **Fig.4** where the air gap is nominal when the deviation of displacement is zero. The measurement results show the linear relationship between the frequency and the air gap between the electromagnet and the suspended object.

Figure 5 compares the digital output of the counter with the output of the displacement sensor when the suspension system is made oscillatory. This result shows that the counter output corresponds to the sensor signal very well both in phase and amplitude.

Figure 6 shows the response of the suspension system after start up when the counter output is fed back; the counter output is calibrated to agree with the output of the displacement sensor. The control algorithm is a digital PD control. This result demonstrates that accurate suspension can be realized with the proposed digital control system.

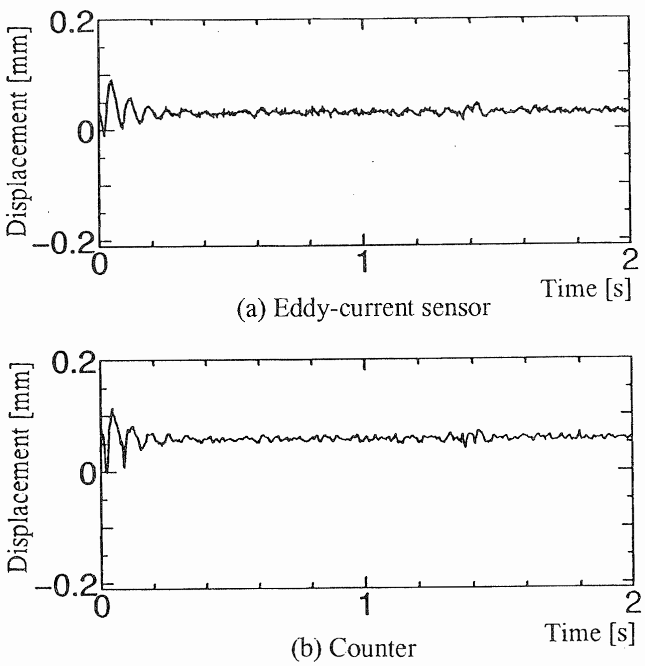

Fig.6 Motion of the suspended object after start-up when the counter output is fed back.

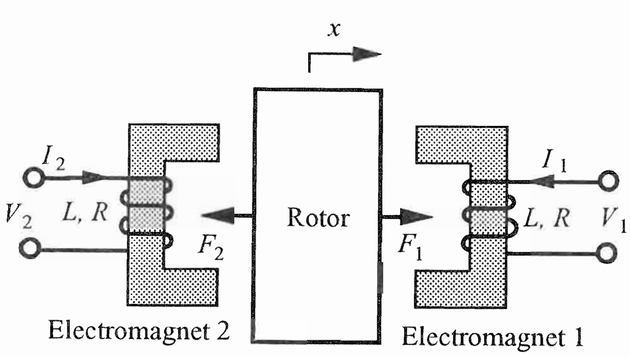

Fig.7 Basic model

3 Combination with the Observer-Based Self-Sensing Method

3.1 Background

Although the accuracy of suspension of the self-sensing FMBs is good both in the previous [3] and the above-mentioned works, considerable improvement in dynamic performance is necessary for industrial applications. In this section, we discuss on combining the method with another promising method of self-sensing suspension using an observer.

The observer-based self-sensing method has been targeted on *voltage-controlled* AMBs. The controller is designed based upon the controllability and observability of voltage-controlled AMBs in which only the coil currents are sensed [4]. It has succeeded in compensating the effects of rotor unbalance in addition to suspending a high-speed rotating rotor [5]. However, the effect of an unknown *static* disturbance on the displacement of the suspended object cannot be canceled [6]. To put it simply, the observer-based self-sensing AMBs lack an ability of accurate positioning but can achieve good dynamic performance. Therefore, this method complements the self-sensing method using hysteresis amplifiers in performance.

However, it does not seem that the observer-based controller is compatible with FMBs using hysteresis amplifiers because this amplifier is of current-output type. This research presents a modification which makes the observer-based method applicable to *current-controlled* AMBs such as FMBs using hysteresis amplifiers.

3.2 Observer-based Controller for Voltage-Controlled AMBs

An AMB with a pair of opposite electromagnets is considered (see **Fig.7**). When only the coil currents are sensed, The state-space equation of this system is given by [6]

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}v(t) \qquad (1)$$

$$y(t) = \boldsymbol{C}\boldsymbol{x}(t) \qquad (2)$$

where

$$\boldsymbol{x}(t) = \begin{bmatrix} x \\ \dot{x} \\ i \end{bmatrix}, \quad i(t) = i_1 - i_2, \quad v(t) = v_1 - v_2,$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 \\ a_{21} & 0 & a_{23} \\ 0 & -a_{32} & -a_{33} \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} 0 \\ 0 \\ b_0 \end{bmatrix}, \quad \boldsymbol{C} = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix},$$

$$a_{21} = \frac{2K_s}{m}, \quad a_{23} = \frac{K_i}{m}, \quad a_{32} = \frac{2K_b}{L}, \quad a_{33} = \frac{R}{L}, \quad b_0 = \frac{1}{L},$$

x: displacement of the suspended object,
i_k, v_k : control component of the coil current and voltage (k=1,2),
m: mass of the suspended object,
K_s, K_i : coefficients of the electromagnets,
K_b: back electromotive coefficient,
L, R: inductance and resistance of the coils.

Controllers for the self-sensing AMBs are found in three steps [6]. First, assume that the state x is directly observed, and admit controls of the form:

$$v(t) = -Fx(t), \tag{3}$$

where

$$F = [p_d \;\; p_v \;\; p_i]$$

A matrix F is determined which stabilizes the closed-loop system:

$$\dot{x}(t) = (A - BF)x(t) \tag{4}$$

In the second step, an observer estimating $x(t)$ is constructed. When a full order observer is used, the equation of the observer is given by

$$\dot{\hat{x}}(t) = (A - EC)\hat{x}(t) + Bv(t) + Ei(t) \tag{5}$$

where

$$\hat{x} = \begin{bmatrix} \hat{x} \\ \hat{\dot{x}} \\ \hat{i} \end{bmatrix}, \quad E = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$$

Finally, the true state $x(t)$ is replaced by its estimate $\hat{x}(t)$ in the control law (3).

$$u(t) = -F\hat{x}(t) \tag{6}$$

The block diagram of the designed controller is shown in **Fig.8**. The input and output of this controller is the current and voltage, respectively.

3.3 Observer-based Controller for Current-Controlled AMBs

When current-output amplifiers are used for energizing the electromagnet, the dynamics of the current control loop in the amplifier can be neglected in designing controller. Thereby, the state-space equation of the system becomes

$$\dot{x}_c(t) = A_c x_c(t) + B_c i(t) \tag{7}$$

where

$$x_c(t) = \begin{bmatrix} x \\ \dot{x} \end{bmatrix}, \quad A_c = \begin{bmatrix} 0 & 1 \\ a_{21} & 0 \end{bmatrix}, \quad B_c = \begin{bmatrix} 0 \\ a_{23} \end{bmatrix}.$$

While an observer is designed based on the equation (7) in a conventional way, it cannot reconstruct the displacement and velocity of the suspended object from the coil current.

However, physical voltage-current relationships in current-controlled AMBs, are described by the same equations as in voltage controlled AMBs:

$$L\dot{i}_1 + Ri_1 + K_b\dot{x} = v_1 \tag{8}$$

$$L\dot{i}_2 + Ri_2 - K_b\dot{x} = v_2 \tag{9}$$

This means that the observer given by (5), which was designed based upon eq.(1), can reconstruct the displacement and velocity of the suspended object even in current-controlled AMBs; in this case, the voltage across the coil should be directly sensed instead of the coil current.

The block diagram of the modified controller is shown in **Fig.9**. In contrast with voltage-controller AMBs, the input and output of the controller is the voltage and current, respectively.

3.3 Experiment

The experimental system described in the section 2.2 is also used here. The voltage across the coil of magnet 2 is inputted to the computer through the AD board. The computer performs calculations necessary for estimation by an observer.

The estimated displacement and velocity are compared with the output of the displacement sensor and its derivative in **Fig.10** and **Fig.11**, respectively. These results show that the observer given by (5) can reconstruct the state vector even in current-controlled AMBs because the estimated signals agree well with the measured signals.

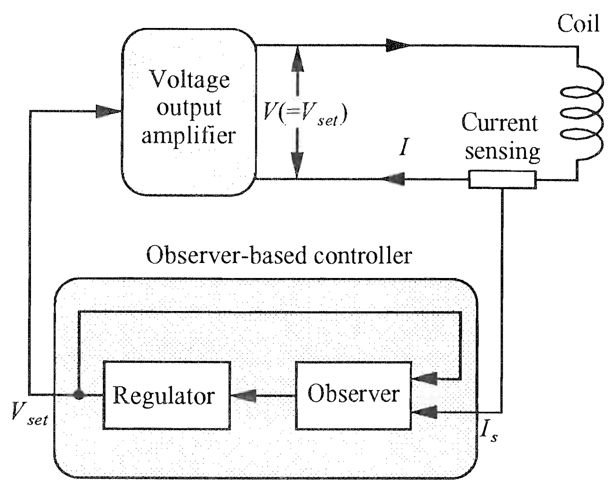

Fig.8 Schematic diagram of a self-sensing voltage-controlled magnetic bearing (V_{set}: voltage command, I_s: detected current)

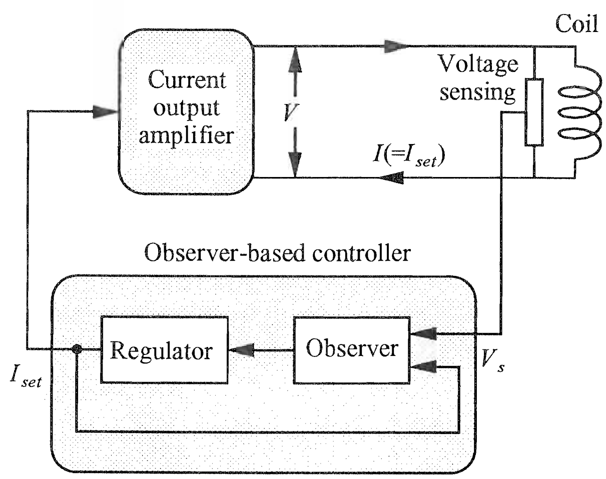

Fig.9 Schematic diagram of a self-sensing current-controlled magnetic bearing (V_s: detected voltage, I_{set}: current command)

One of the obstacles to improving the dynamic performance of FMBs is that the feedback gains had to be limited to low values because of a rather long measurement time and quantization error. When the estimated velocity signal is used instead of the digitally differentiated signal, the gains can be increased to higher values. As a result, the stiffness of the suspension system is made higher as shown in **Fig.12**.

Conclusions

A low-cost digital control system was proposed for a self-sensing type of FMB using hysteresis amplifiers. This system is characterized by a interface circuit with a counter. The developed controller succeeded in self-sensing suspension in a single-degree-of-freedom model.

The observer-based self-sensing method, which was originally targeted on voltage-controlled AMBs, was modified to be applicable to current-controlled AMBs. By this modification, this method became compatible with the self-sensing FMBs using hysteresis amplifiers. It is expected that high-performance self-sensing AMBs will be realized by combining both methods.

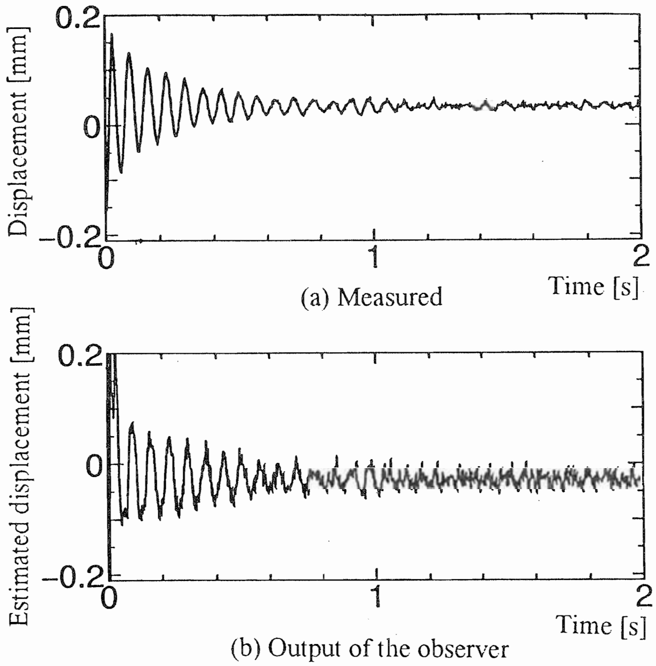

Fig.10 Comparison between the measured and estimated displacements.

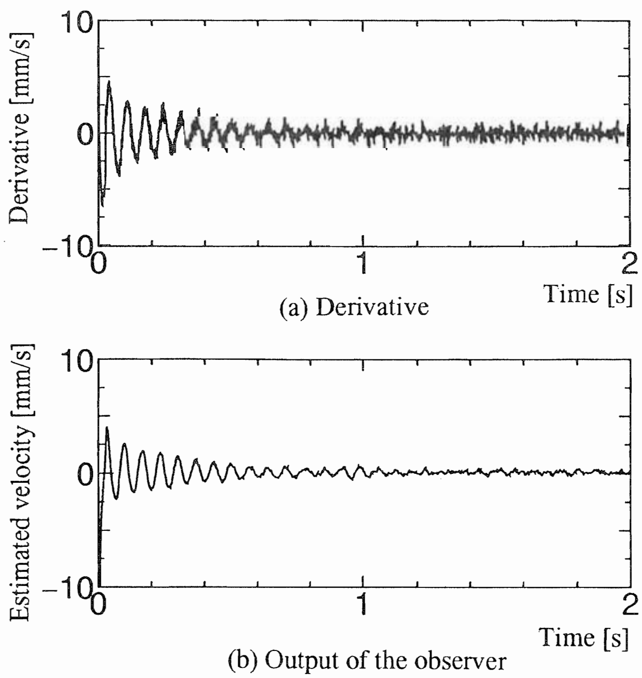

Fig.11 Comparison between the derivative of measured dispalcement and the estimated velocity.

References

[1]Mizuno, T., *Frequency Feedback Magnetic Bearings*, Proc. 1st Int. Conf. on Motion and Vibration Control, Vol.2, pp.639-644 (1992).

[2]Mizuno, T., *Phase-Locked Loops for the Stabilization of Active Magnetic Suspensions*, JSME International Journal, Series C, Vol.37, No.3, pp.499-503(1994).

[3]Mizuno, T., Ishii, T. and Araki, K., Realization of Phase Locked and Frequency Feedback Magnetic Bearings, Proc. 4th International Symposium on Magnetic Bearings, pp.311-316(1994).

[4]Vischer, D., *Sensorlose und spnnungsgesteuerte Magnetlager*, doctor thesis Nr.8665, ETH Zürich, (1988).

[5]Mizuno, T., Bleuler, H., Tanaka, H., Hashimoto, H., Harashima, F. and Ueymama, H., *An Industrial Application of Position Sensorless Active Magnetic Bearings* (in Japanese), Trans. IEE of Japan, Vol.116-D, No.1, pp.35-41 (1996).

[6]Mizuno, T. and Bleuler, H., *Self-Sensing Magnetic Bearing Control System Design Using the Geometric Approach*, Control Engineering Practice, Vol.3, No.7, pp.925-932 (1995).

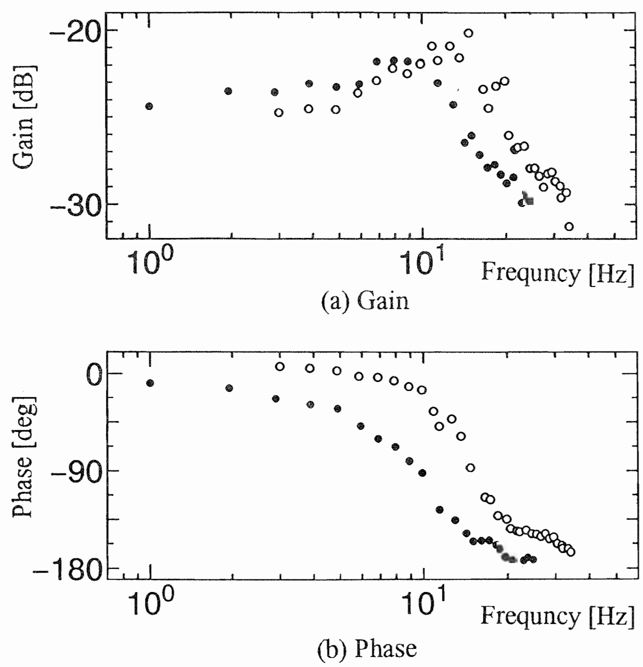

Fig.12 Frequency responses of the displacement of the suspended object to disturbance which is generated by the electromagnets; velocity feedback is implemented using the digitally differentiated signal (●) or the estimated velocity (○) in the FMB with hysteresis amplifiers.