# Development of a Millimeter-sized Active Magnetic Bearing System

**Mochimitsu Komori**

Kyushu Institute of Technology, Kawazu, Iizuka, Fukuoka, 820 JAPAN
tel:+81-948-29-7777; fax:+81-948-29-7777; e-mail:komori@mse.kyutech.ac.jp
University of Virginia, Thornton Hall, Charlotesville, VA, 22903 USA
tel: +1-804-982-2110;fax: +1-804-293-2761;e-mail:komori@romac1.mech.virginia.edu

**Takahiro Yamane**

Kyushu Institute of Technology, Kawazu, Iizuka, Fukuoka, 820 JAPAN
tel:+81-948-29-7777; fax:+81-948-29-7777; e-mail:yamane@komo1.kyutech.ac.jp

***Abstract:*** *In order to study contact-free levitation systems for micromachines, our group has developed a millimeter-sized active magnetic bearing (AMB) system. The system consists of a rotor (0.9mm $\phi$ ×6mm, 30 mg), a pair of electromagnets, a pair of photo sensors, and PID controller. Displacements of the rotor are detected by the photo sensors. The rotor and the electromagnets are so small that the rotor in the axial direction is passively stabilized. This paper describes open loop characteristics, closed loop characteristics, follow-up control characteristics to investigate the millimeter-sized AMB system. It is found that the millimeter-sized AMB system makes a very quick response, because of the small rotor mass of 30 mg. This characterizes the millimeter-sized AMB system.*

## 1 Introduction

Recently applying integrated circuit (IC) process techniques to micromachining are performed energetically by many researchers. Various kinds of micromachines fabricated by IC process techniques have been proposed [1]-[4] . According to these papers, mechanical friction and pneumatic viscosity in micromachines are very important factors for their easy motions. Because mechanical friction and pneumatic viscosity in micromachines are more dominant compared with normal-size machines for practical use. Almost all the micromachines reported in these papers have movers supported by some long beams for its contact-free levitation, or by some point-contacts for decreasing friction. Moreover, several kinds of contact-free micromachines with levitation mechanisms have been proposed [4]-[9]. These papers include both of AMB systems and passive magnetic bearing systems.

However, there have been few reports on micro AMB systems with contact-free rotors [7,8]. Moreover, no report on micro AMB system with a contact-free cylindrical rotor exists. If rotation mechanisms could be realized, various kinds of new micromachines and new millimeter-sized machines with rotational motion would be developed and it is possible that spectacular rotational speeds due to small rotor inertia would be achieved. Thus, contact-free rotational systems for micromachines are considered to be very promising.

Then, our group has developed a millimeter-sized AMB system with a cylindrical rotor able to rotate. Because our system has a very small rotor, static and dynamic characteristics different from normal-sized AMB systems are considered to exist. This paper discusses the rotor dynamics about the millimeter-sized cylindrical rotor such as open loop characteristics, closed loop characteristics, follow-up control, and impulse responses, which has not been reported elsewhere.

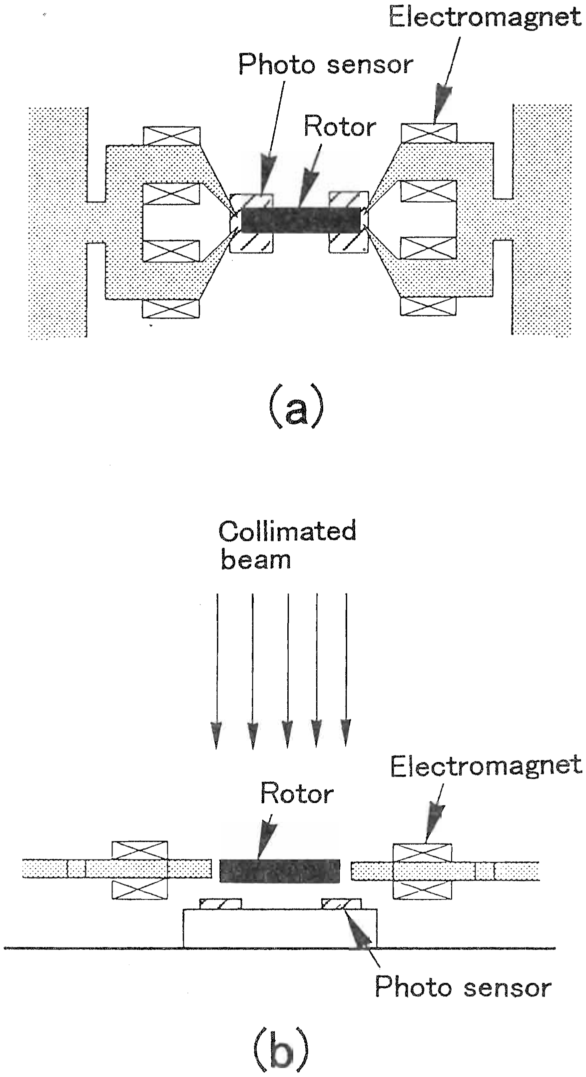


Fig.1. Illustration of (a) millimeter-sized ABM system and (b) electromagnet used in the system. The system consists of a rotor, a pair of horse-shoe shaped electromagnets, a pair of photo sensors, and PID controller.

## 2 System

### 2.1 Structure

Figure 1 shows the illustration of (a) the top view of the millimeter-sized AMB system and (b) the side view of the system. As shown in Fig.1, the system consists of a rotor, a pair of electromagnets, a pair of photo sensors, and PID controller. The rotor has a diameter of 0.9 mm, a length of 6.0 mm, and a weight of 30 mg. The system has two photo sensors, which can detect displacements of the small rotor in the axial direction by differential measurement principle. This measurement principle is robust against relative change of the sensor sensitivity. A collimated beam was used for the photo sensors detecting the rotor displacement. The sensor sensitivity for the displacement in the axial direction is 20 mV/μm. The electromagnets core are made of iron. The electromagnets have a horse-shoe shape with square of 8×8 mm$^2$, thickness of 1.0 mm, air gap of 0.38 mm, and two windings of 160 turns on each pole. The electromagnets are so small that the rotor in the radial direction is able to be passively stabilized. Therefore, the system needs only one controller in the axial direction. The gaps between the rotor and the electromagnets are 100μm when the rotor is in the center of the electromagnets.

For the controller, our group adopted analog PD controller. Because the analog circuits are considered to be easily assembled in the system. The system parameters of $k_a$, $k_i$, $k_m$, and $k_s$ are amplifier gain, current stiffness, position stiffness, and sensor gain, respectively. These parameters are previously given by some kinds of measurements. Tuning of the PID controller for the system was performed by using stability analysis for open loop system experimentally and theoretically. In this paper, dynamics of the rotor not in the radial direction but in the axial direction are discussed.

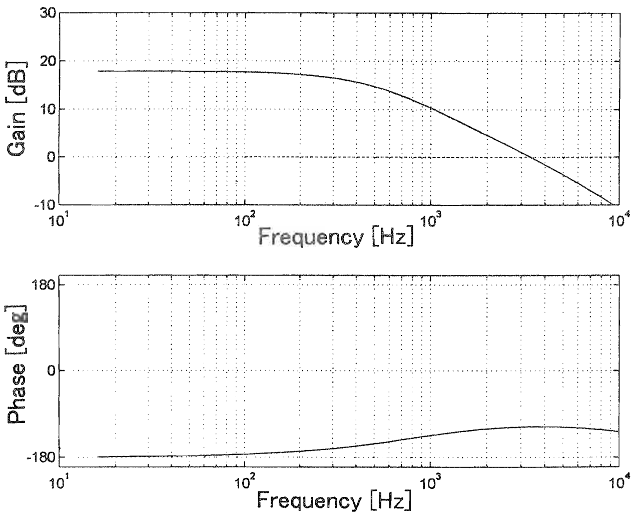


Fig.2. Theoretical open loop characteristics of the system. This shows that the system is stable.

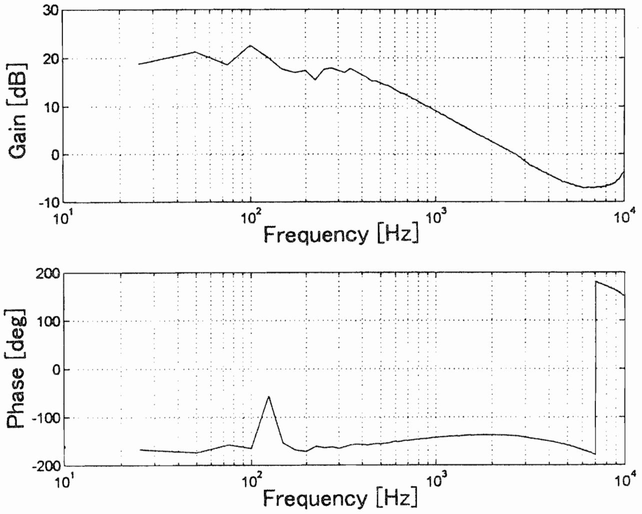


Fig.3. Experimental open loop characteristics of the system. This shows that the system is stable.

## 2.2 System design

The controller of the millimeter-sized AMB system was designed by using open loop characteristics of the system obtained theoretically and experimentally. In the simulations, the transfer function $G_1(s)$ of the open loop characteristics is

$$G_1(s)=\frac{0.648s+3536}{3.0\times10^{-10}s^3+3.0\times10^{-5}s^2-0.00456s-456}\,. \qquad (1)$$

Figure 2 shows the theoretical open loop characteristics of the system which are presented by Eq.(1). It is found that Fig. 2 shows that the millimeter-sized AMB system is stable according to the stability analysis for open loop system. The gain margin and the phase margin are 63.6 dB and 17.6 deg, respectively.

We experimented on the millimeter-sized AMB system to make sure whether the simulation results corresponded to the experimental results or not. In the experiments, Sinusoidal signal produced by FFT analyzer was applied to the amplifier. The experimental open loop characteristics of the system are shown in Fig. 3. It is found that the experimental open loop characteristics resemble the simulation results shown in Fig. 2. The actual gain margin and phase margin are 41.5 dB and 7.12 deg, respectively. The actual margins are a little smaller than the theoretical margins. In Fig. 3, there is no remarkable gain peak caused by rotor vibration modes. Because the rotor is considered to be rigid. Anyway, this shows that the block diagram used here is correctly modeled. The phase peak around 120 Hz is considered to be caused by the collimated beam excitation. Fortunately, this does not influence the stability of the system as shown in Fig. 3.

## 3 Rotor Dynamics

The closed loop characteristics on the millimeter-sized AMB system were investigated. The transfer function for the sensor output against the input to the amplifier is

$$G_2(s)=\frac{0.0026s+260}{3.0\times10^{-10}s^3+3.0\times10^{-5}s^2+0.6434s+3080}\,. \qquad (2)$$

Figure 4 shows the closed loop characteristics of the millimeter-sized AMB system, which are presented by Eq. (2). From this, it is found that the system has a constant gain and the constant phase in the frequency range less than 1.0 kHz. In other words, the system has a constant compliance over this range.

The experimental results of closed loop characteristics were obtained to make sure whether the previous simulation results correspond to the experimental results or not. In the experiments, sinusoidal signal produced by FFT analyzer as a disturbance for the rotor was applied to the amplifier. The experimental closed loop characteristics

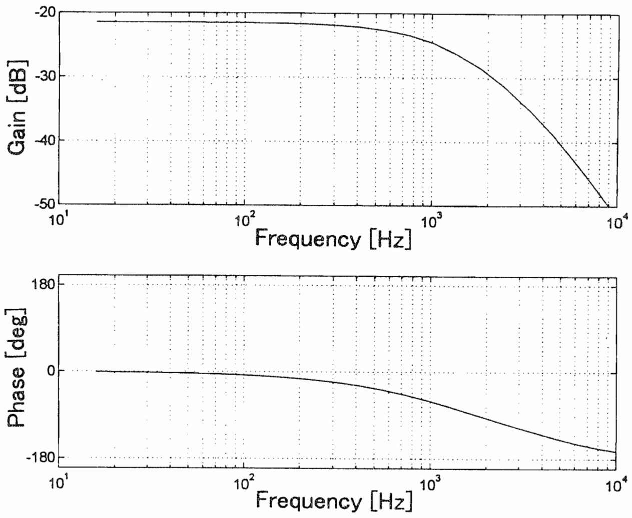


Fig.4. Theoretical closed loop characteristics of the system. The system has a constant compliance in the frequency range less than 1.0 kHz.

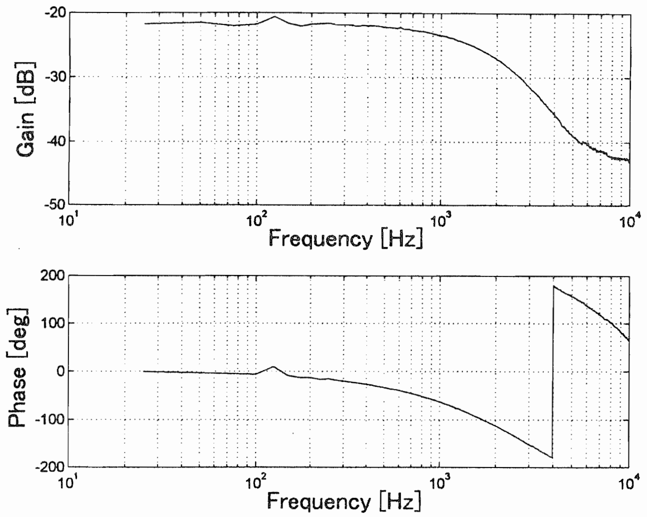


Fig.5. Experimental closed loop characteristics of the system. The experimental result resembles the theoretical result of close loop characteristics.

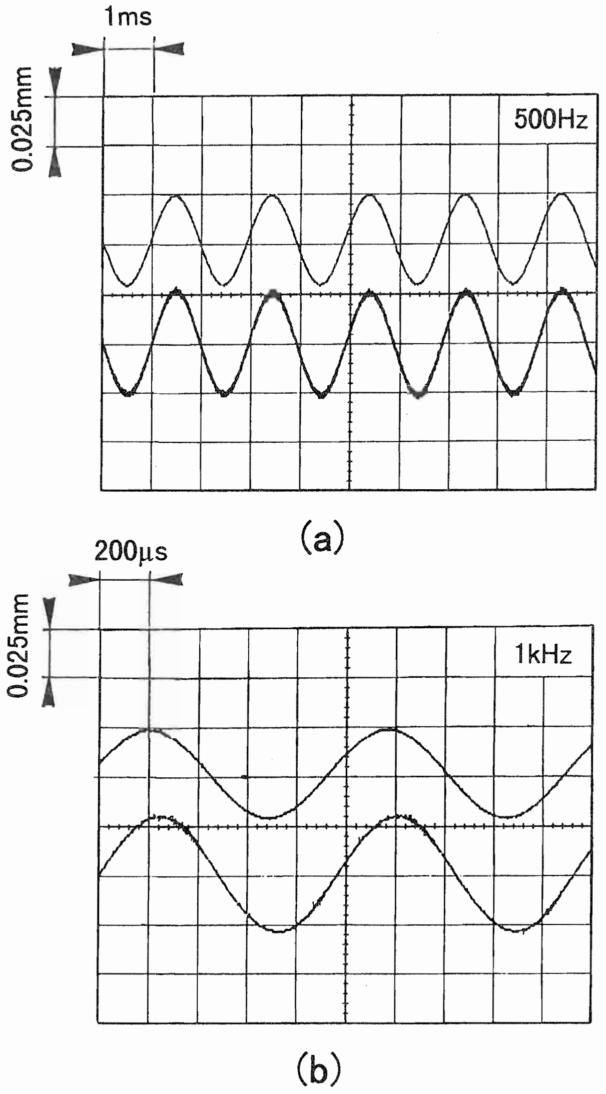


Fig.6. Follow-up control results of the millimeter-sized AMB system. The upper sinusoidal curve and the lower one in each figure show the desired displacement and the actual displacement of the rotor, respectively.

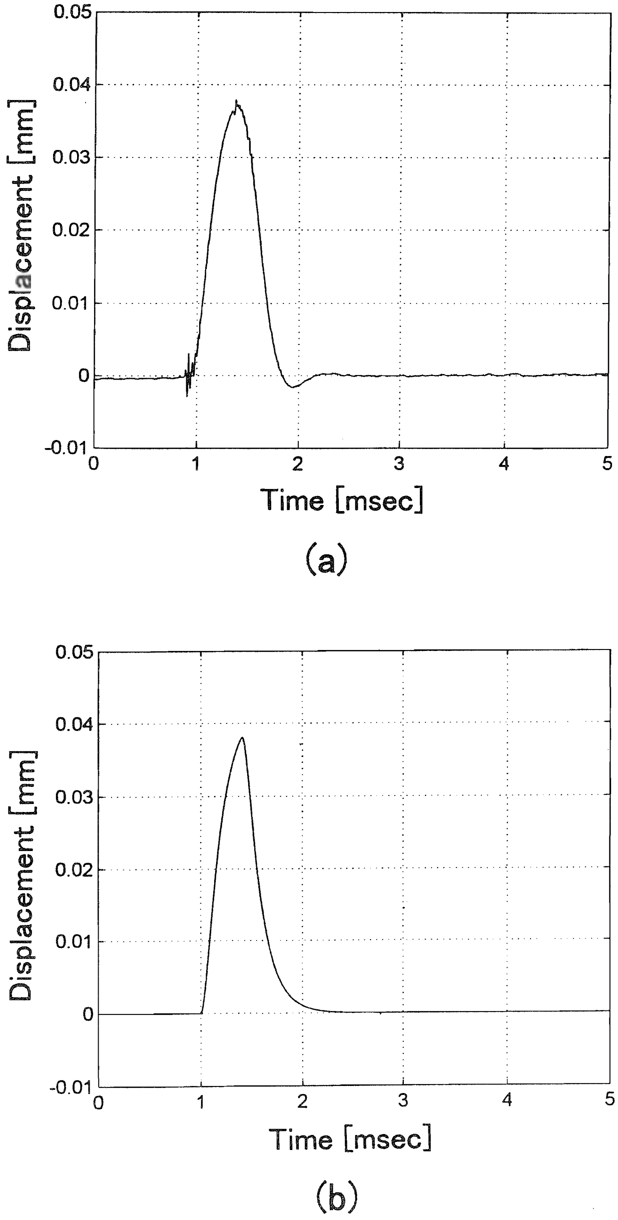
are shown in Fig. 5. The results resemble the theoretical close loop characteristics in Fig. 4. The experimental results also show that the compliance is almost constant over the frequency range less than 1.0 kHz. This is because the rotor mass is so small that the system can make a quick response in the axial direction like this. As shown in Fig. 5, the closed loop characteristics are not much influenced by the collimated beam around 120 Hz.

In order to study the rotor responses, the rotor motions in the frequency range less than 1.0 kHz were observed by using memory oscilloscope. Fig. 6 shows the follow-up control results of the rotor in the axial direction at frequencies of (a) 500 Hz and (b) 1.0 kHz. In each figure, the upper sinusoidal curve and the lower one show the desired displacement and the actual displacement of the rotor, respectively. In both cases of 500 Hz and 1.0 kHz, the rotor follows up the desired displacement well as shown in Fig. 6. From these results, it is found that the rotor can move very quickly in the axial direction. However, there is a little delay between the desired displacement and the actual displacement in the case of 1.0 kHz as shown in Fig. 6 (b). This result corresponds to the error between the constant compliance over the lower frequency range less than 500 Hz and that at the frequency of 1.0 kHz as shown in Figs. 4 and 5.

The impulse responses were investigated on the millimeter-sized AMB system. Impulse (10 volt×3 ms) was applied to the amplifier instead of to the rotor. The impulse could be observed by using the memory oscilloscope. Fig. 7 shows the impulse responses obtained (a) experimentally and (b) theoretically. From the response in Fig. 7 (a), it is found that the rotor is centered within a very short time less than 1.0 ms in spite of the large displacement amplitude of 38 μm. The simulation result for the impulse response is shown in Fig. 7 (b). The impulse applied to the amplifier in the simulation was the same as that in the experiment. The impulse response in the simulation resembles the experimental result as shown in Fig. 7. The quick responses shown here are considered to be related to the constant compliance within the frequency range less than 1.0 kHz shown in Figs. 4

and 6.

We tried to rotate the contact-free small rotor of the millimeter-sized AMB system. Six turbine blades (L3.0 × W0.5 × H0.8mm) for air turbine were attached to the rotor. Then, compressed air through a small nozzle with inner diameter of 0.5 mm was applied to the rotor blades to spin it. Right after the compressed air is applied to the rotor, the rotor begins spinning very quickly. Also, right after the compressed air stops, the rotor stops spinning very quickly. Because the rotation energy of the spinning rotor can be reduced to zero very quickly by the electromagnetic friction between the rotor and the electromagnets. This shows that it is found that the electromagnetic friction due to magnetic field is effective upon the rotor spin. From this, it is regarded that it is necessary that the millimeter-sized AMB system needs a uniform magnetic field for the purpose of frictionless rotation. In the experiments, the rotational speed and the magnetic friction could not be measured, because we do not have any techniques to do so. The details about these will be discussed elsewhere.



(a)

(b)

Fig.7. Impulse responses of the rotor which are obtained (a) experimentally and (b) theoretically. Impulse was applied to the rotor through the electronic circuits.

## 4 Summary

Our group has developed a millimeter-sized AMB system. The system consists of a rotor (0.9mm $\phi$ × 6mm, 30mg), a pair of horse-shoe shaped electromagnets, a pair of photo sensors, and analog PID controller. It is found that the stable millimeter-sized AMB system with one axis control can be designed using the stability analysis for open loop system. In the experiments, the rotor of the system makes a quick response for the follow-up control in the frequency range less than 1.0 kHz, because the rotor mass (30 mg) is very smaller than other normal-sized AMB systems. The compliance of the system is almost constant in the frequency range less than 1.0 kHz. In the rotation tests, the rotor makes a quick increase of rotation and a quick decrease of rotation according to the air forces. This shows that it is found that the rotor rotation depends greatly on the magnetic friction between the rotor and the electromagnets.

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