MICRO PM MOTORS LEVITATED BY TWO TYPES OF ACTIVE MAGNETIC BEARINGS

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ABSTRACT

This paper describes magnetically levitated micro PM (permanent magnet) motors by two different types of active magnetic bearings (AMBs). The micro PM motors consist of a cylindrical rotor (2.0 ×10), a pair of electromagnets, a pair of photo diodes, and an analog PD controller. The motors are characterized by the small rotor levitated without mechanical contacts and one-axis controlled AMB with the analog PD controller. Horseshoe-shaped electromagnets and cylindrical ones are applied to the AMB. The rotor successfully rotates levitating in the center of the electromagnets. In this paper, dynamic characteristics of the two types of micro PM motors are discussed.

INTRODUCTION

Mechanical friction and pneumatic viscosity are very important factors for their easy and accurate motions in the field of micro-electro-mechanical system. In order to reduce mechanical friction, various kinds of actuators have been proposed. Among them, active magnetic bearing (AMB) is one of the most promising technique for its contact-free motion [1-3]. However, there are few reports quantitatively discussing AMBs due to difficulties in dealing with such small systems and in evaluating their dynamic motions. Moreover, papers quantitatively discussing AMBs with cylindrical rotors have rarely been reported. Thus, we have been studying AMBs with cylindrical rotors and successfully applied the AMBs to micro PM motors whose rotors have a permanent magnet (PM) and are driven by a pair of electromagnets [4].
In this paper, two different types of electromagnets are applied to the micro PM motors. The dynamics of the micro PM motors are discussed here. Furthermore, there is no report on quantitatively discussing micro PM motors with different types of AMBs.

SYSTEM & DESIGN

Figure 1 shows an illustration of the magnetically levitated micro PM motor. The motor consists of a millimeter-sized cylindrical rotor, a pair of electromagnets for rotor levitation, a pair of electromagnets for rotor driving, and a pair of photo diodes for position sensing. The rotor consists of a cylindrical iron bar (2.0 × 10) and a PM (3.0 × 2. 0), and it measures 139 mg in weight. The rotor is supported by AMB with two different types of electromagnets only in the axial direction. The rotor is so small that the rotor is passively stabilized in the radial direction. A pair of photo diodes are placed under the rotor to detect the rotor

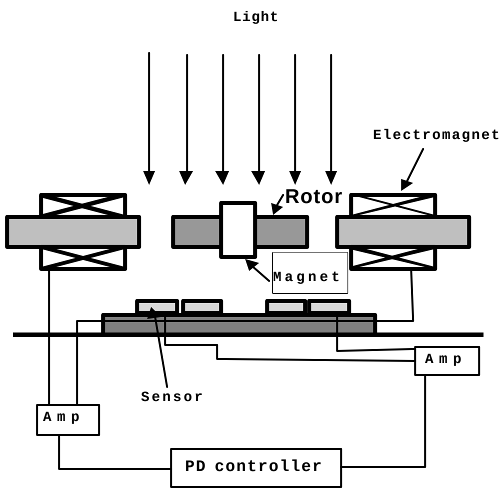


FIGURE 1: Illustration of the magnetically levitated micro PM motor.

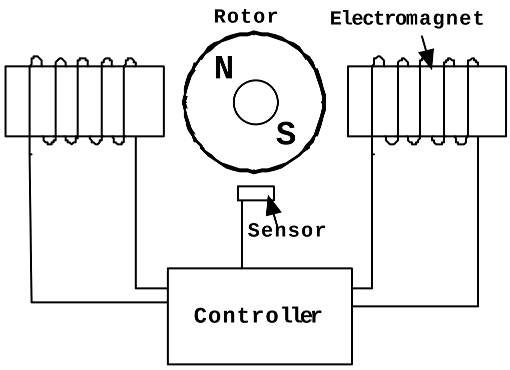


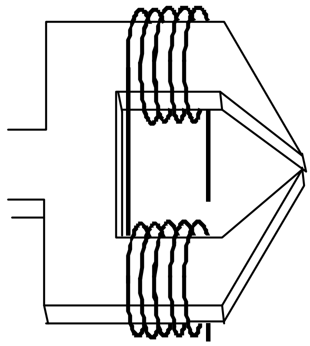
FIGURE 2: Driving mechanism for the magnetically levitated micro PM motor.

displacement. Collimated beam gives a rotor shadow on the photo diodes. Air gaps between the rotor and the electromagnets are 100 µm when the rotor is in the center of the electromagnets.

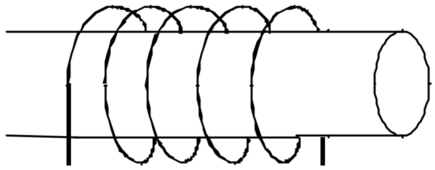
Figures 2 shows the driving mechanism for the magnetically levitated micro PM motor. The driving mechanism has the PM rotor, a pair of electromagnets on the same plane as the rotor, a controller (personal computer), and a Hall sensor attached just under the PM. The Hall sensor detects the rotation angle of the rotor. Driving current was given to the electromagnets according to control signals.

In this study, we used two different types of electromagnets as shown in Figure 3. One is horseshoe shaped electromagnet as shown in Figure 3(a), and the other is cylindrical electromagnet as shown in Figure 3(b). The dimensions of the horseshoe-shaped electromagnet for the length, width, and depth are 12.5 , 10 , and 1 , respectively. And the horseshoe-shaped electromagnet has two coils of 350 turns. The AMB with two horseshoe-shaped electromagnets has current stiffness of 0.047 N/A and position stiffness of 135 N/m. The cylindrical electromagnet has a core made of iron measuring f 1.2 ×20 . The cylindrical electromagnet has a coil of 500 turns. The AMB with two cylindrical electromagnets has current stiffness of 0.046 N/A and position stiffness of 145 N/m. These parameters for the AMB with horseshoe-shaped electromagnets are almost equal to those with cylindrical electromagnets.

In order to make the two AMBs conditions equal, the open loop transfer function of the system with horseshoe-shaped electromagnets is adjusted so as to be equal to the transfer function with cylindrical electromagnets. To investigate the two systems with different types of electromagnets, impulse responses of the rotors are measured. The impulses were applied to the rotor by using electrical impulses through the amplifier. The electrical impulses correspond to ≅ 13mN



(a) Horseshoe-shaped



Cylindrical

FIGURE 3: Two different types of electro-magnets showing (a) a horseshoe shaped electromagnet and (b) a cylindrical electromagnet

(≅ 0.3ms) for the rotor. Figures 6(a) and (b) show the impulse responses for the micro PM motors with horseshoe-shaped electromagnets and cylindrical electromagnets, respectively. In the figures, the displacement of 0 means the center position of the rotor. The rotor can go back to the center position within ≈ 1.0 ms in spite of the large displacement of ≈ 10 µm.

DYNAMIC CHARACTERISTICS

As a fundamental characteristic, rotation speeds for the two types of micro PM motors were investigated. In the experiment, the rotation angle was measured by using the Hall sensor. Figure 4(a) and (b) indicate the relationships between rotation speed and driving current for the micro PM motors with horseshoe-shaped electromagnets and cylindrical electromagnets, respectively. In the figures, dots and solid lines show experimental data and approximation functions, respectively. From Figure 4(a), it is found that the relationship is almost linear which is approximated by a linear function

$$\dot{f} = 35900\, i_d + 17500 \quad \text{[rpm]}, \qquad (1)$$

where $\dot{f}$ and i_d are rotation speed and driving current, respectively, and the coefficient of correlation is $r = 0.989$. The driving current is in the range smaller than ≈ 0.4 A. The range is small compared with normal-sized PM motors. The rotation speed higher than

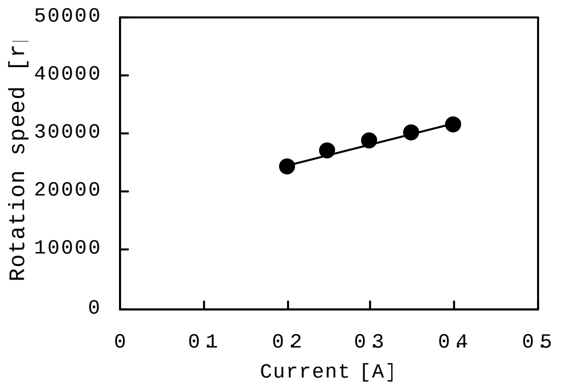
≈30000 rpm is very fast and marvelous. When the rotation speed increases up to higher speeds than ≈30000 rpm, the rotation gets unstable and the rotor comes off the fixed center position of the electromagnets. This is because the periodical electromagnetic driving force on the PM rotor leads to the unstable condition when the rotor spins. Anyhow, the rotation speeds higher than ≈30000 rpm with driving currents smaller than 0.4 A are remarkable. It is found that the micro PM motor with horseshoe-shaped electromagnets realizes the stable rotation and that the stiffness of the AMB is sufficiently large for the high speed rotation.

From Figure 4(b), the relationship is found to be almost linear. The driving current is in the range smaller than ≈0.004 A. The relationship is approximated by

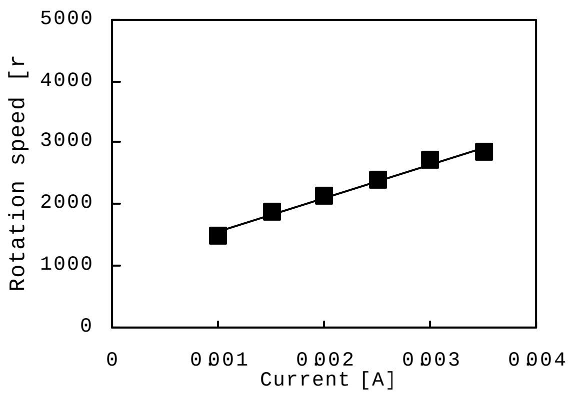
$$f = 548000\, i_d + 1020 \text{ [rpm]}, \qquad (2)$$

where the coefficient of correlation is $r = 0.994$. The coefficient of 548000 rpm/A in Eq. (2) is very large compared with 35900 rpm/A in Eq. (1). And, the range is very small compared with that of the motor with horseshoe-shaped electromagnets. These results show that the micro PM motor with cylindrical electromagnets is very sensitive compared with the motor with horseshoe-shaped electromagnets. This is because the friction of the levitated rotor of the micro PM motor with cylindrical electromagnets is extremely small. When the rotation speed increases up to higher speeds than ≈3000 rpm, the rotation becomes unstable and the rotor comes off the fixed center position. This is because the stiffness in the radial direction is not so large in comparison with the micro PM motor with horseshoe-shaped electromagnets.

In order to investigate the friction between the rotor and the electromagnets, natural rotation decays were investigated. At first, the rotors of the micro PM motors with horseshoe-shaped electromagnets and cylindrical electromagnets were forced to rotate up to speeds higher than ≈30000 rpm and ≈3000 rpm, respectively.

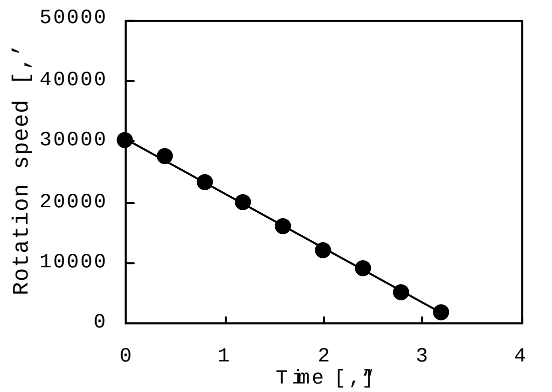


(a) Horseshoe-shaped

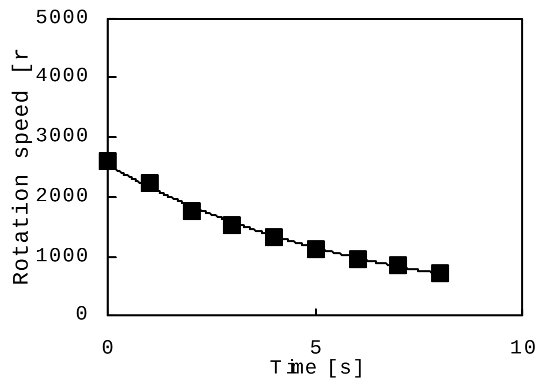


(b) Cylindrical

FIGURE 4: Relationships between rotation speed and driving current for the micro PM motors with (a) horseshoe-shaped electromagnets and (b) cylindrical electromagnets.

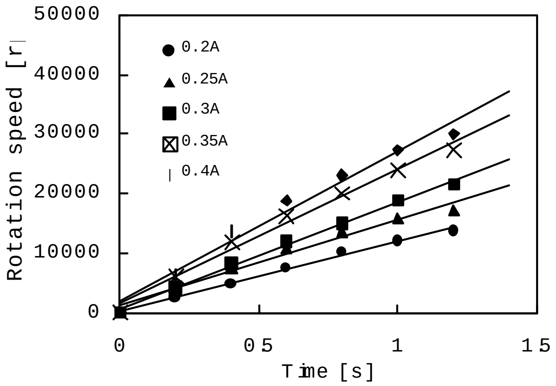


(a)Horseshoe-shaped

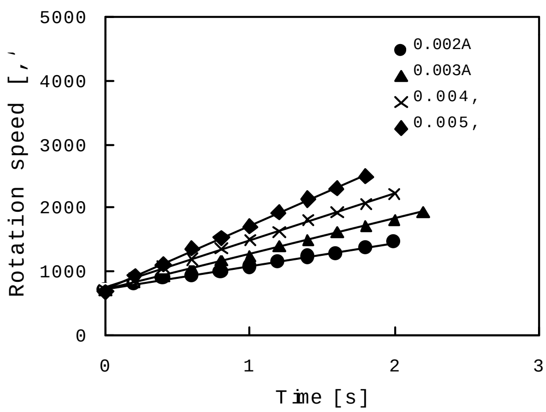


(b) Cylindrical

FIGURE 5: Relationships between rotation speed and time for the micro PM motors with (a) horseshoe-shaped electromagnets and (b) cylindrical electromagnets.



(a) Horseshoe-shaped



(b) Cylindrical

FIGURE 6: Relationships between rotation speed and time for the micro PM motors with (a) horseshoe-shaped electromagnets and (b) cylindrical electromagnets for various kinds of driving currents.

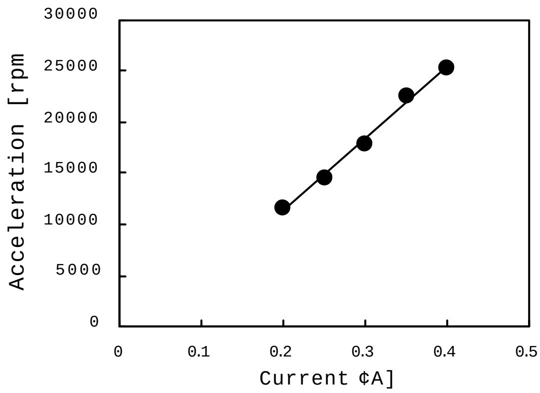
Just after that, the driving currents were stopped. Then, the natural rotation decays were measured. The results for the micro PM motors with horseshoe-shaped electromagnets and cylindrical electromagnets are shown in Figures 5(a) and (b), respectively. From Figure 5(a), it is found that the rotation speed decreases rapidly as the time increases. The decay curve is almost linear, whose approximation function is represented as

$$f = -8970\, t + 30400 \text{ [rpm]}, \quad (3)$$

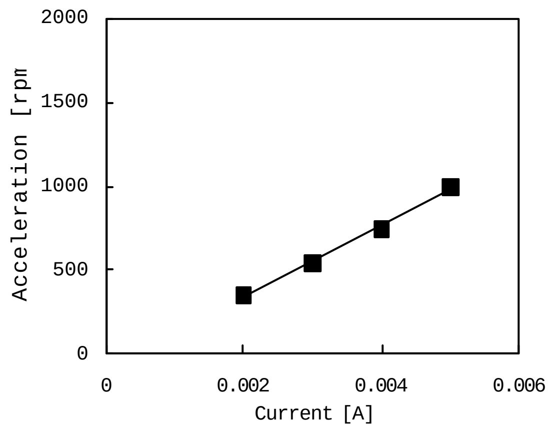
where t is time, and the coefficient of correlation is $r = 0.999$. The coefficient 8970 rpm/s in Eq. (3) is very large and shows a quick rotation decay. Eq. (3) indicates that the magnetic friction between the rotor and the electromagnets is dominant for the micro PM motor with horseshoe-shaped electromagnets [4]. On the other hand, the result for the micro PM motor with cylindrical rotor shows an exponential decay curve as shown in Figure 5(b). The decay curve is approximated by

$$f = 2530 \exp(-0.159\, t) \text{ [rpm]}, \quad (4)$$

where the coefficient of correlation is $r = 0.998$. This means that the rotation decay mainly depends on the air friction around the rotor instead of the magnetic friction. However, the decay shown in Eq. (4) is fast compared with normal-sized AMBs. This is because even the small air friction influences the rotation of the micro PM motor. Next, acceleration characteristics were studied for the micro PM motors with different electromagnets. The experimental setup was the same as that used in Figures 4 and 5. The relationships between rotation speed and time for the micro PM motors with horseshoe-shaped electromagnets and cylindrical electromagnets are shown in Figures 6(a) and (b), respectively. Various kinds of driving currents are also shown in the figures. From Figure 6(a), it is found the rotation speeds for various driving currents increase as the time increases



(a) Horseshoe-shaped



(b) Cylindrical

FIGURE 7: Relationships between acceleration and driving current for the micro PM motors with (a) horseshoe-shaped electromagnets and (b) cylindrical electromagnets.

and that the rotation speeds are proportional to the time. When the driving current is 0.4 A, the rotation speed rapidly increases up to ≈30000 rpm within ≈1.2 s. The time for increasing up to ≈30000 rpm is very short compared with normal-sized motors, because the rotor mass and the inertia are very small. From Figure 6(b), it is found the rotation speeds for the micro PM motor with cylindrical electromagnets are proportional to the time. The relationship in Figure 6(b) is almost the same as that with horseshoe-shaped electromagnets in Figure 6(a). However, the rotor speed range for the micro PM motor with cylindrical electromagnets in Figure 6(b) is 0.1 times as small as the range in Figure 6(a). From the result, it is found that for high speed rotations the micro PM motor with horseshoe-shaped electromagnets is better than that with cylindrical electromagnets.

We estimated the accelerations by calculating the gradients of the rotation speed characteristics shown in Figure 6. Thus, the driving current range is the same as the result in Figure 6. The relationships between acceleration and driving current for the micro PM motors with horseshoe-shaped electromagnets and cylindrical electromagnets are shown in Figures 7(a) and (b), respectively. The acceleration unit of rpm/s different from the standard unit of m/s^2 is used in the figures, because it is easy to understand the acceleration unit rpm/s by intuition. The accelerations in Figures 7(a) and (b) increase with increasing driving currents. The acceleration range for the micro PM motor with horseshoe-shaped electromagnets is very larger than that for the motor with cylindrical electromagnets. This means that the micro PM motor with horseshoe-shaped electromagnets accelerates within shorter time than the motor with cylindrical electromagnets.

Since the rotor of the micro PM motor is very small and levitates without mechanical contacts, it is difficult to measure the torques generated by the micro PM motor. Thus, we estimated the torques by using the accelerations shown in Figure 7. As a result, both torques for the two types of PM motors increase with increasing driving currents. The torque range for the motor with horseshoe-shaped electromagnets is very larger than that for the motor with cylindrical electromagnets.

We tried to control the rotation speed of the micro PM motor with horseshoe-shaped electromagnets by changing the driving current. First, the driving current of 0.4 A was applied to the micro PM motor so that the motor keeps a constant speed. Then, the driving current was reduced to 0.2 A. After this, the driving current was made to change alternatively like 0.4A→ 0.2A→ 0.4A. During these experimental processes, the rotation speed was measured. The result is shown in Figure 8. As shown in this figure, the rotation speed changes between ≈26,000 rpm and ≈15,000 rpm. Just after the

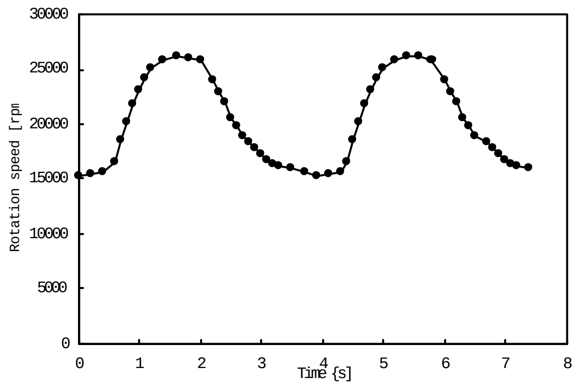


FIGURE 8: Acceleration and deceleration chracteristics of the rotor with the driving current applied to the PM motor:0.4A→0.2A→0.4A→0.2A

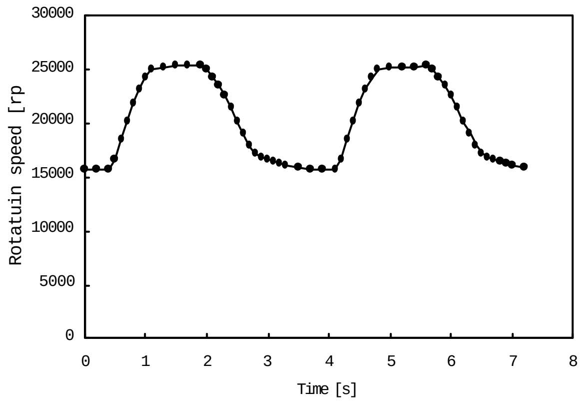


FIGURE 9: Acceleration and deceleration chracteristics of the rotor with the driving current applied to the PM motor : 0.4A→0A→0.4A→0A

driving current changes from 0.4 A to 0.2 A, the rotation speed decreases rapidly within ≈1.5 s.

Next, we tried to control the rotation speed of the micro PM motor with horseshoe-shaped electromagnets by using a different method from Figure 8. First, the driving current of 0.4 A was applied to the micro PM motor so that the motor keeps a constant speed. Then, the driving current was reduced to 0 A. After this, the driving current was made to change alternatively like 0.4A→ 0A→ 0.4A. Then, the rotation speed was measured. The result is shown in Figure 9. The rotation speed changes between ≈26,000 rpm and ≈150,000 rpm. The decreasing time from ≈26,000 rpm to ≈15,000 rpm is shorter than 1 s. This time is also shorter than the decreasing time in Figure 8. This is because the magnetic friction between the rotor and the electromagnets works effectively as the speed decreases. As a result, it is found that we can easily control the rotor speed of the micro PM motor with horseshoe-shaped electromagnets.

CONCLUSIONS

We have developed a magnetically levitated micro PM motor with a millimeter-sized cylindrical rotor. Two types of electromagnets are applied to the micro PM motors. And the dynamic characteristics of the micro PM motors were investigated. From the experimental results, it is found that the driving current ranges of these micro PM motors are small compared with other normal-sized PM motors. The micro PM motor with horseshoe-shaped electromagnets increases up to speeds higher than ≈30000 rpm, which is very fast and marvelous. The driving current range for the micro PM motor with cylindrical electromagnets is very small compared with that for the motor with horseshoe-shaped electromagnets. The magnetic friction for the micro PM motor with cylindrical electromagnets is very smaller than that for the motor with horseshoe-shaped electromagnets. From these results, it is found that for high speed rotations the micro PM motor with horseshoe-shaped electromagnets is better than that with cylindrical electromagnets. For quick responses, the micro PM motor with horseshoe-shaped electromagnets is better than that with cylindrical electromagnets.

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