Fabrication of a micromotor driven by electromagnetic vibration

T. Honda[a)] and J. Yamasaki
Kyushu Institute of Technology, 1-1 Sensuichou, Tobata-ku, Kitakyushu 804, Japan

A new electromagnetic rotary mechanism utilizing a friction drive is proposed. An electromagnetic vibration excited on a permanent magnet is converted to a rotary movement through a frictional force. A trial motor, composed of a magnet rotor with inclined legs and an excitation coil, was fabricated and successfully operated. A no-load revolution speed up to 400 rpm and a reversible rotation were achieved. © *1998 American Institute of Physics.* [S0021-8979(98)49311-3]

I. INTRODUCTION

During the last decade there has been much work towards realizing micromotors for the microelectromechanical systems. Most of these efforts focused mainly on electrostatic side-drive micromotors and variable reluctance magnetic ones, which, however, face a serious problem. Their very high revolution speed over 10^4 rpm and poor torque are unacceptable for practical applications.

To solve this problem and realize the practical micromotor, two rotary mechanisms with large torque at a low revolution speed have so far been proposed. One is a wobble mechanism,[1,2] in which a cylinder rotor rolls inside a stator with either electrostatic or electromagnetic forces. The other is a friction drive mechanism, which converts a mechanical vibration to a rotary movement through a frictional force. Several kinds of ultrasonic micromotors based on a piezoelectric vibration have been proposed,[3,4] but only a few attempts have been made at the other friction drive motors.

In this study, we proposed a new magnetic micromotor utilizing the friction drive mechanism, which can convert the electromagnetic vibration to the rotary movement. In this article, the structure, principle, and no-load characteristics of the trial motor are described.

II. DEVICE STRUCTURE

Figure 1(a) shows a side view of a trial-fabricated friction drive motor. It consists of a cylinder rotor, 5 mm in diameter and 3 mm in height, and a small solenoid coil. The rotor is a NdFeB magnet, magnetized along the height direction, and has four elastic legs on the base. The legs, made of a polyethylene terephthalate (PET) film with a thickness of 0.1 mm, are inclined at a certain angle, θ, arranged equally round the perimeter of the rotor base, as shown in Fig. 1(b). The size of the legs is 1.5 mm long and 1.25 mm wide. In this study, we examined two different inclined angles: $\theta = 50°$ and 85°. The rotor is laid on a cover glass fixed on the end of the coil. In order to vibrate the rotor by using the attractive force, an ac current biased with a dc current is applied to the coil. The value of the dc current is the same as the amplitude of the ac current. Thus the rotor is magnetically fixed on the coil end without any external mechanical preload.

a)Electronic mail: honda@mag.ele.kyutech.ac.jp

III. OPERATION PRINCIPLE

Let the z axis be the vertical direction in Fig. 1. The vertical force, Fz, acting on the magnet with magnetization, Mz, and volume, V, is given by

$$Fz = Mz \cdot \int dHz/dz \cdot dV, \quad (1)$$

where Hz is the z component of the magnetic field produced by the solenoid coil. The attractive force by the sinusoidal current biased with the dc current can be represented by

$$Fz(t) = -F_0 z(1+\sin 2\pi f t)/2, \quad (2)$$

where $F_0 z$ is the maximum attractive force in the z direction and f is the excitation frequency. Since the legs act as elastic springs, the rotor vibrates downward and upward according to the attractive force. At the same time an angular movement occurs due to the frictional force of the tip of the legs.

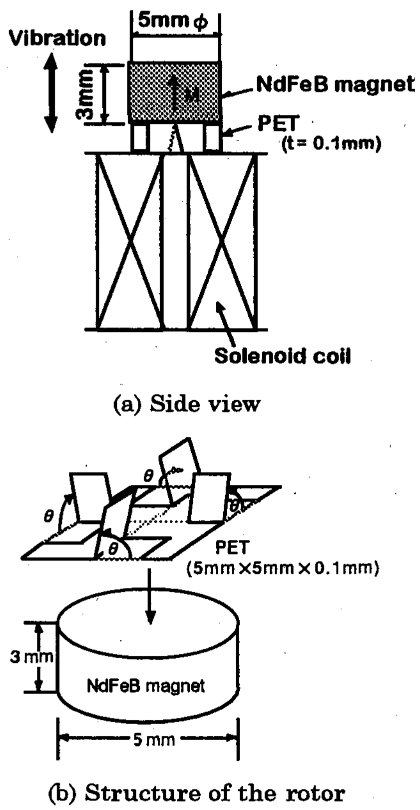

FIG. 1. Schematic view of the trial motor.

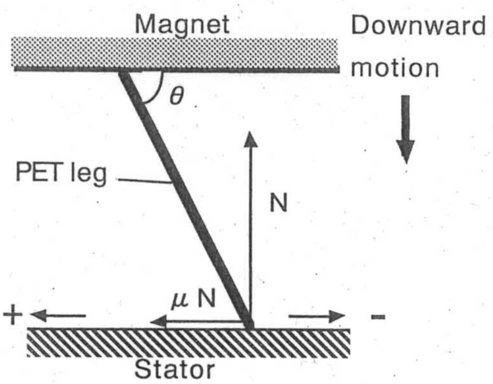

FIG. 2. Relation between the normal reaction and the frictional force.

Before turning to a closer consideration about the angular movement, we must describe the sliding condition of the leg during the downward motion. Figure 2 shows the relation between the normal reaction, N, and the frictional force, μN, at the tip of the leg when the rotor starts displacing downward. Here μ is the frictional coefficient. Taking account of the moment equilibrium about the hinge, the following relation is found:

$$\theta = \tan^{-1}(1/\mu). \qquad (3)$$

If $\theta \geqslant \tan^{-1}(1/\mu)$, the tip of the leg is self-locked and cannot slide during the downward motion. On the other hand, if $\theta < \tan^{-1}(1/\mu)$, the tip slides in the right-hand direction. In general, μ is 0.2–0.5 and, therefore, the angle that satisfies Eq. (3) may be 60°–80°. We will consider the predicted behavior of the rotor in the following two cases.

A. $\theta \geqslant \tan^{-1}(1/\mu)$

Figure 3 illustrates the predicted behavior for $\theta \geqslant \tan^{-1}(1/\mu)$. At a low frequency range, the rotor vibrates around the contact point without sliding and remains at the original position, as shown in Figs. 3(a) and 3(b). At higher frequencies, however, the tip slides in the left-hand direction during the upward motion because the increase in the z component of the acceleration of the vibration decreases the normal reaction and hence reduces the frictional force. If the z component of the acceleration is larger than that of the gravity, the tip may take off from the stator and touch down to the left side, as shown in Fig. 3(c). Thus, the rotor moves in the left-hand direction at higher frequencies.

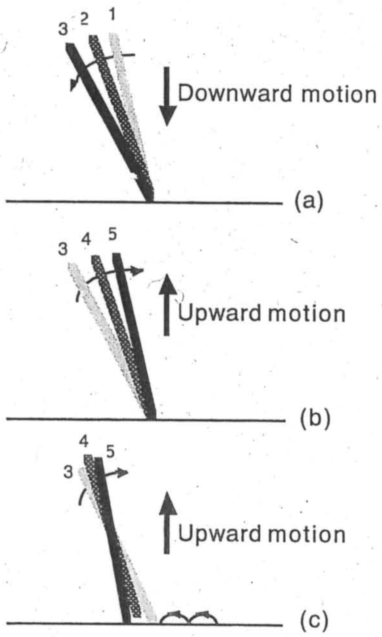

FIG. 3. Predicted behavior of the leg for $\theta \geqslant \tan^{-1}(1/\mu)$.

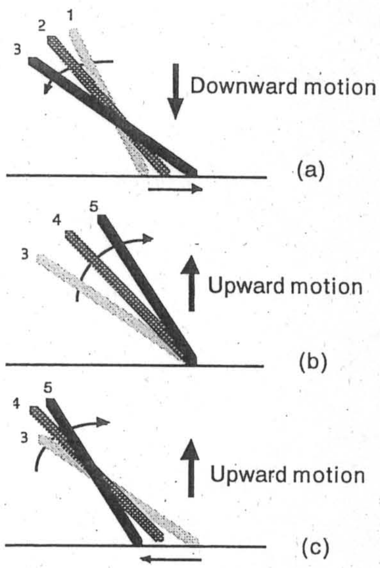

FIG. 4. Predicted behavior of the leg for $\theta < \tan^{-1}(1/\mu)$.

B. $\theta < \tan^{-1}(1/\mu)$

Figure 4 illustrates the predicted behavior for $\theta < \tan^{-1}(1/\mu)$. During the downward motion, the leg slides in the right-hand direction, as shown in Fig. 4(a). During the upward motion, on the other hand, two different behaviors are possible, depending on the frequency, as shown in Figs. 4(b) and 4(c). At a low frequency range, the tip is pushed against the stator and the rotor stands up around the tip without sliding. Thus the motor moves in the right-hand direction. At a high frequency range, the tip moves in the left-hand direction for the same reason as in Fig. 3(c). In this case, the rotational direction depends on the difference of the sliding distance between upward and downward motions.

IV. RESULTS AND DISCUSSION

In this study, we examined the no-load revolution speed when F_0z was approximately 120 mN. Figure 5 shows the revolution speed for $\theta = 50°$ and 85° as a function of the excitation frequency. The sign of the revolution speed means the rotational direction, in case of a plus sign, rotates in the left-hand direction in Fig. 2.

First, we focus on the result for $\theta = 85°$. The motor hardly rotated below 600 Hz though the slight rotation in the negative direction was observed around 200 Hz. The rotation in the positive direction suddenly occurred at 600 Hz and

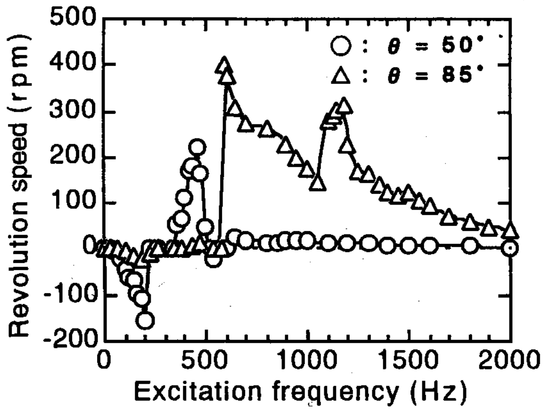

FIG. 5. Revolution speed as a function of the excitation frequency.

reached a peak of 400 rpm at the same time. This sudden rotation was caused by the mechanical resonance in the z direction. Afterwards the revolution speed decreased with increasing the frequency and then exhibited a second peak around 1.2 kHz, which may be due to the resonance in the angular direction.

On the other hand, the result for $\theta=50°$ showed a reversible rotation. At lower frequencies below 200 Hz, the motor rotated in the negative direction, as expected, and the revolution speed increased with increasing the frequency. The maximum revolution speed of 160 rpm was obtained at 200 Hz. But the rotation stopped at the range 200–300 Hz because the amplitude of the vibration in the z direction was too large to rotate stably. Afterwards, the rotational direction changed to the positive direction with the increasing the frequency and reached a peak of 230 rpm at 480 Hz. The rotation in the positive direction at higher frequencies suggests that the sliding distance is larger during the upward motion than during the downward motion.

Finally, we must remark on the torque of the motor. The torque measured was only the order of 10^{-5} Nm. Of course, the torque can be improved by increasing the electromagnetic attractive force. One promising method would be to insert the core into the driving coil. This point is currently under investigation.

V. CONCLUSIONS

We have proposed a new type of rotary micromechanism which can covert the electromagnetic vibration to the rotary movement through the frictional force of the inclined legs. The trial motor based on this mechanism successfully rotated and exhibited unique characteristics depending on the inclined angle of the legs. The unique characteristics obtained suggest that the mechanism is useful as a driving principle of a micromotor.

[1] S. C. Jacobsen, R. H. Price, J. E. Wood, T. H. Rytting, and M. Rafaelof, Sens. Actuators **20**, 1 (1989).
[2] W. Trimmer and R. Jebens, Sens. Actuators **20**, 17 (1989).
[3] K. R. Udayakumar, S. F. Bart, A. M. Flynn, J. Chen, L. S. Tavrow, L. E. Cross, R. A. Brooks, and D. J. Ehrlich, Proc. IEEE MEMS'91 Workshop, 109 (1991).
[4] T. Uchiki, T. Nakazawa, K. Nakamura, M. Kurosawa, and S. Ueha, Jpn. J. Appl. Phys. **30**, 2289 (1991).