Development of a Magnetic Linear Motor Based on a Friction Drive

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Abstract— **A new type of magnetic linear actuator based on a friction drive is presented. It consists of a magnet mover with inclined legs and a solenoid coil wound around a pipe. An alternating magnetic field produced by the coil causes the magnet to vibrate angularly due to magnetic torque and then the vibration is converted to a linear movement through a friction between the legs and the stator wall. The prototype exhibited the maximum velocity of 33 cm/s and the maximum thrust of approximately 0.05 N around the mechanical resonant frequency.**

Index Terms—**Friction drive, linear motor, magnetic torque, vibration.**

I. Introduction

During the last decade a large number of studies have been made on micro-motors in sizes ranging from submilimeter to milimeter. In particular recent efforts focused mainly on the practical ones with large torque at a low speed. A wobble motor [1][2], in which a cylindrical rotor rolls inside a hollow cylindrical stator with either electrostatic or electromagnetic forces, is a typical example. Additionally, a friction drive is a promising mechanism as well. Several kinds of piezoelectric ultrasonic micro-motors have been proposed and their excellent performance such as large torque at a low speed and high response has been demonstrated [3][4].

In our previous work [5], we applied the friction-drive mechanism to an electromagnetic rotary micro-motor, in which an electromagnetic vibration was converted to a rotary movement through a friction. The successful operation of this motor indicated that the friction drive is useful for electromagnetic actuators as well. In this paper, we newly propose an electromagnetic 'linear' motor based on the friction drive. This paper describes its structure, actuation, and basic characteristics.

II. Device Structure

Fig. 1 shows a schematic view of the friction-drive linear motor. It has two segments: a magnet mover and a solenoid coil wound around a pipe. The mover is a cylindrical NdFeB magnet, attached to four inclined legs on both planes, as shown in Fig. 1(b). The magnet, magnetized along the height direction, has a diameter of 5 mm and a height of 3 mm. The legs, made of the polyethylene terephthalate (PET) film with a thickness of 0.1 mm, are inclined to 60 deg for front legs (i.e. an upper pair) and 30 deg for back ones (i.e. a lower pair). The mass of the mover is 0.45 g. The stator consists of a solenoid coil wound around a plastic pipe whose inner diameter is 7 mm and length is 100 mm. The mover is put into

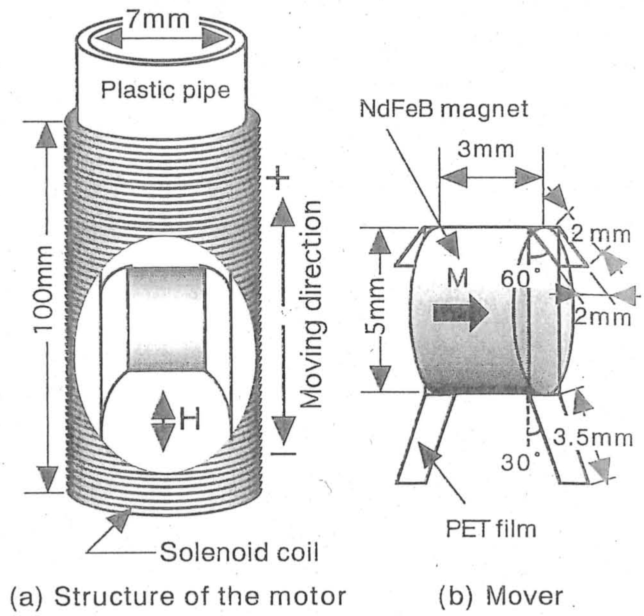

Fig. 1 Schematic view of the friction-drive linear motor.

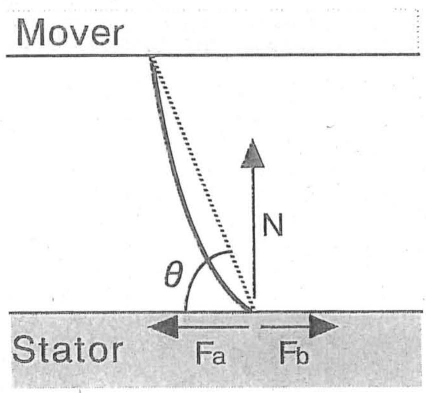

Fig. 2 Friction between an inclined leg and a stator wall.

the stator pipe and held by a friction between the legs and the inner wall. Here we define the positive direction as the upward direction. The holding forces of the mover are 0.1 N and 0.17 N in the positive and negative directions, respectively. If an alternating current is applied to the coil, an alternating magnetic field drives the mover in the axial direction of the stator.

III. Principle of Operation

First of all, a few remarks should be made concerning the basic concept of the friction. If one inclined elastic leg is pressed against the stator wall as shown in Fig. 2, the appar-

Manuscript received March 1, 1999.
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This research was supported in part by a grant from the Electro-Mechanic Technology Advancing Foundation.

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ent frictions are represented by

$$Fa = \mu N / (1 - \mu \tan\theta) \quad (1)$$

$$Fb = \mu N / (1 + \mu \tan\theta). \quad (2)$$

Here Fa and Fb are the apparent frictions in the left and right directions respectively, N is the normal reaction, μ is the frictional coefficient, and θ is the equivalent contact angle. From the equations (1) and (2), it is found that Fa is always larger than Fb. In particular, if θ satisfies the following condition:

$$\theta \geqq \tan^{-1}(1/\mu), \quad (3)$$

Fa becomes infinity and thus the tip of the leg is self-locked in the right direction. In general, the angle that satisfies equation (3) is estimated to be more than 70 -80 deg.

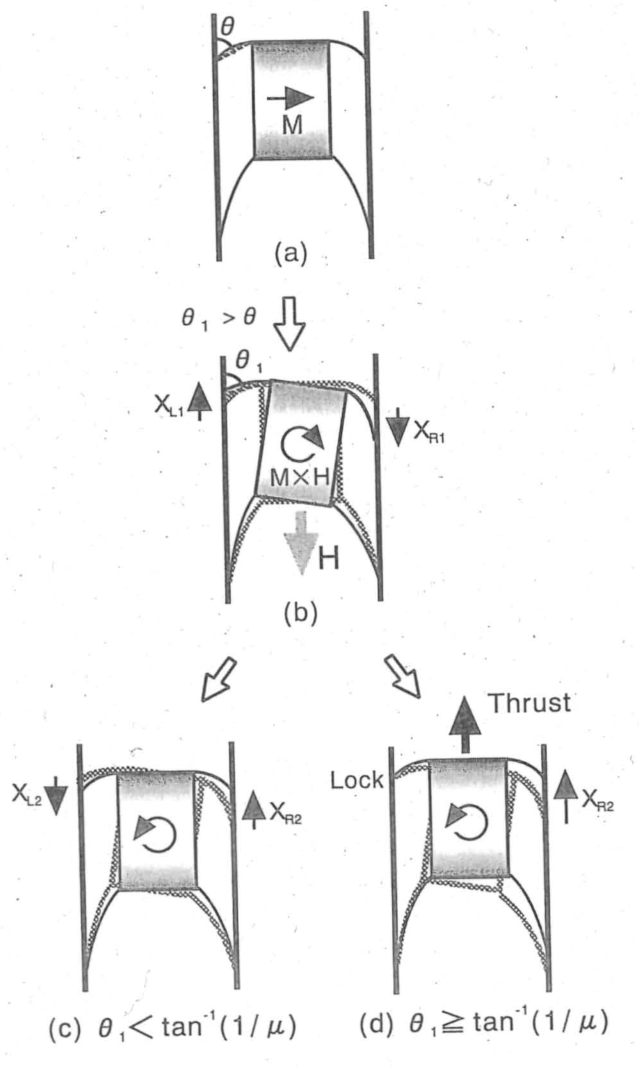

Fig. 3 Predicted actuation of the mover during a half cycle.

Fig. 3 shows the simple model of the predicted operation of the mover during the half cycle. In this model, two assumptions are made: first, the contribution of the back legs to the thrust is negligible compared with that of the front legs; second, the equivalent angle θ of the front legs doesn't satisfy the equation (3) in the initial shape shown in Fig. 3(a). Firstly the magnetic field is applied in the negative direction, as shown in Fig. 3(b). The mover rotates in the clockwise direction according to magnetic torque $\boldsymbol{T}$, which is given by

$$\boldsymbol{T} = \boldsymbol{M} \times \boldsymbol{H} \quad (4)$$

where $\boldsymbol{M}$ is the magnetic moment of the magnet and $\boldsymbol{H}$ is the applied magnetic field. Then the right front leg is pressed against the wall and slides in the negative direction, while the left front leg slides in the positive direction at the same time and the equivalent angle increases from θ to θ_1. Next the magnetic field decreases, causing the mover to rotate reversely due to the elastic forces of the legs. In this case, two operations are possible as shown in Figs. 3(c) and (d). If the amplitude of the vibration is small, each front leg slides backward its original position, as shown in Fig. 3(c). Since the sliding distance of the legs depends on many factors such as the contact conditions and the load, it is difficult to determine the moving direction in this actuation mode. On the other hand, if the amplitude of the vibration is large enough for θ_1 to satisfy the equation (3), the left front leg is self-locked and the thrust is produced in the positive direction. As a result, the mover moves in the positive direction.

IV. RESULTS AND DISCUSSION

Fig. 4 shows the experimental apparatus. The stator coil was kept in the vertical position. In order to measure the velocity, a ribbon with a scale, 0.12 g in weight, was attached to the bottom of the mover. In this experiment, the no-load velocity and the standstill thrust were measured.

The prototype was successfully operated and the mover smoothly moved in the travel range of 100 mm. Fig. 5 shows a no-load velocity as a function of the excitation frequency when the alternating magnetic field of 4.8 kA/m was applied. The sign of the velocity means the moving direction indicated

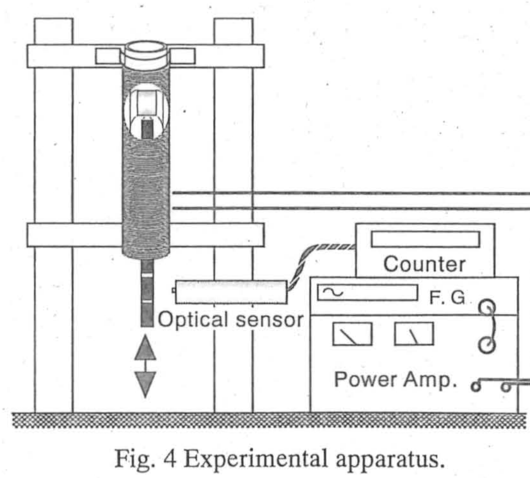

Fig. 4 Experimental apparatus.

in Fig. 1(a). At low frequencies below 340 Hz, the mover moved in the negative direction and the negative velocity gradually increased with the frequency. It is highly probable that the mover was in the actuation mode as shown in Fig. 3 (c). Then the moving direction was suddenly reversed at 350 Hz and the velocity reached a peak of 33 cm/s at the same time. Afterwards further increase in the frequency caused the velocity to decrease rapidly. The drastic change around 350 Hz can be explained as due to the mechanical resonance, which was observed at the frequencies between 350-400 Hz. The resonance increased the amplitude of the vibration, causing the equivalent angle θ_1 to satisfy the equation (3). As a result, the actuation was switched to the self-locking mode as shown in Fig. 3(d).

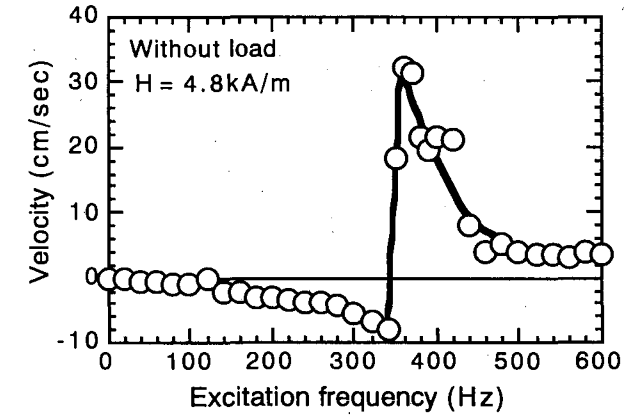

Fig. 5 Moving velocity as a function of the frequency.

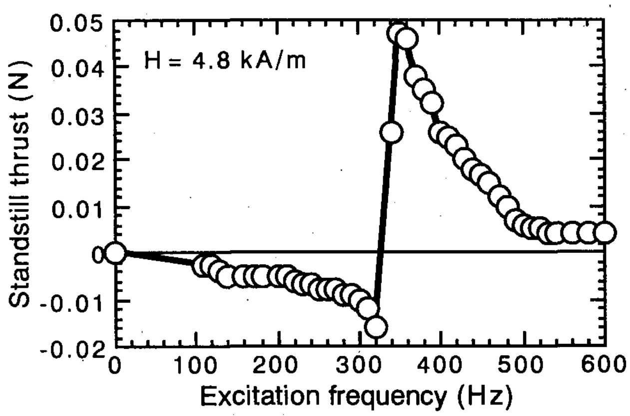

Fig. 6 Standstill thrust as a function of the frequency.

Fig. 6 shows the standstill thrust as a function of the frequency when the alternating magnetic field of 4.8 kA/m was applied. The frequency dependence of the thrust corresponded with that of the velocity. The direction of the thrust was converted from negative to positive around 340 Hz. The standstill thrust was so small as to be less than 0.01 N at frequencies below 300 Hz and above 480 Hz. However, the standstill thrust increased largely between 340-400 Hz and exhibited the maximum value of 0.048 N. This result suggests that the self-locking mode is effective to increase the thrust as well as the velocity.

V. Conclusions

We have proposed a new friction-drive micro-mechanism for a moving-magnet-type linear motor. A trial linear motor based on this mechanism showed a high-speed motion over 30 cm/s with a long stroke. This successful operation indicates that the mechanism proposed here would be applicable to industrial and medical microrobots, where. high-performance microactuators with a long-stroke and a high response are required. Forthcoming efforts will focus on the optimum design to increase the thrust and to miniaturize the size.

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