特 集 11
研 究 速 報

A Threaded Wobble Motor of Outer Rotor Type

アウターロータ型のねじ溝付きワブルモータ

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1. INTRODUCTION

This paper deals with the driving principle and the experimental demonstration of a micro motor which can convert rotation into linear motion and generate large displacement. The motor is a wobble type one; its rotor and stators have screw threads. When the rotor turns, it moves linearly in the axial direction like a screw. The range of linear motion is limited only by the length of the rotor. We have fabricated a threaded wobble motor by the electromagnetic actuation.

After the first success of electrostatic micro motors [1], [2], many motors with sizes ranging from 100 μm [3] to millimeters [4], [5] were reported. It is still unclear how to utilize the rotational motion in the micro scale except some applications where rotation itself is necessary such as driving micro disks and rotational gyros. Linear displacement is necessary in most applications. Linear actuators with elastic suspensions can easily fabricated by IC-compatible micromachining [6], however they have limited range of motion up to a few tens of microns. Our threaded wobble motor produces linear displacement out of rotational motion and is free from such limitation, although the fabrication depends on assembly at this moment.

We produced a threaded wobble motor of inner rotor type [10] and obtained a preferable characteristic. In this paper, a threaded wobble motor of outer rotor type are reported. We fabricated the motor of outer rotor type to achieve higher torque and to more easily transmit force to an external load. The shape of the outer rotor is a cylinder (the diameter: 14mm, the height: 20mm). The rotor rotates with wobbling by the attractive force to the inner stator pole. There are screw threads both inside of the outer rotor and outside of the inner stators. Thus, the outer rotor moves in the axial direction with wobbling rotation.

The advantages of this motor are the following;

・This wobble motor has the work range in a long distance without a particular equipment such as a link mechanism.

・This motor has mechanisms which enlarge the output force such as the wobbling mechanism (high torque at low rotational speeds) and the screw mechanism (rotary/linear conversion). The attractive magnetic force between the rotor and stators is utilized to realize the rolling motion of the rotor.

・Threads on the rotor mechanically support external load in the axial direction.

・Low friction is achieved by rolling contact between the rotor and stators.

This paper discusses the design, operating principle, the calculation of the torque, the magnetic flux distribution by FEM simulation and the driving characteristic.

2. MECHANISM

In this section, we show the actuation principle and the mechanism of a threaded wobble motor of outer rotor type. Figure 1 shows the actuation principle.

The actuation principle is the same as basic wobble motors [4], [5]. By sequentially energizing stator poles, the rotor is attracted to poles and wobbles around. The rotor rotates by 360 (R-r) /r degrees when the excitation travels around all the poles once; R is the inner diameter of the rotor cylinder and r is the outer diameter of the stator. The gap between the rotor and the stator is equal to R-r. We have slower speed and higher torque with the smaller value of R-r. The attractive force between the rotor and the stator is converted into rotational motion by the wobble mechanism and then the rotation is converted into linear displacement by threads.

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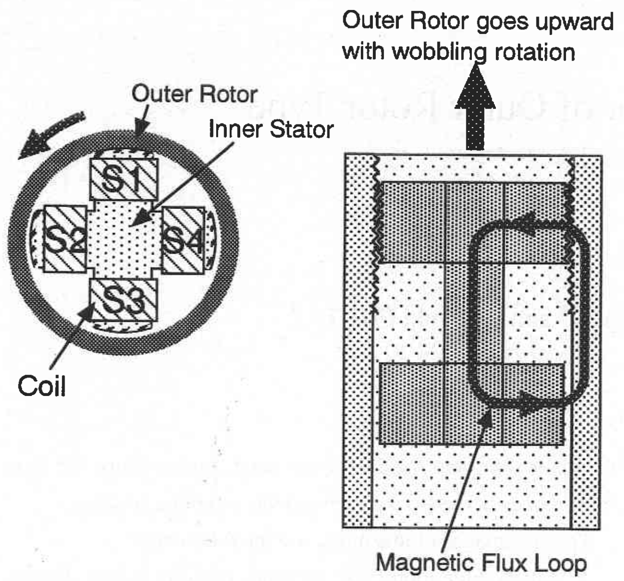

Figure 1 Actuation principle of a threaded wobble motor of outer rotor type

Therefore, when the rotor rotates by 360 degrees, it moves linearly by a screw pitch in the axial direction.

We have fabricated the wobble motor by the electromagnetic actuation. Figure 2 shows the external view and the size of the wobble motor.

There are a total of 8 poles and two stages of stators, where one stage is threaded and the other stage is not. Only half of the length of the outer rotor is threaded. This motor is made of iron. The 8 stator coils are wound in 30 turns each pole by the insulated copper wire (the diameter is 0.1 mm). The vertical two coils are connected in series. The screw pitch is 0.75 mm. This motor is fabricated with the ordinary mechanical machining and the wire electrodischarge machining.

The order of the poles excitation of a stator is the following steps (we use the notation of the stator shown in Figure 1). The excited poles of a stator shift clockwise such as (S1) → (S1 and S2) → (S2) → (S2 and S3) → (S3) →···. So when 8 steps proceed, the excited poles make one circle around the stator. It is also possible to energize poles of the stator counter-clockwise.Thus the outer rotor can go up and down in the axial direction. To realize this actuation, we have made a driving circuit shown in Figure 3.

This circuit consists of the shift register which has 8 binary values, 4 OR operational ICs and current amplifiers. The initial value of the shift register is shown in Figure 3. The binary value

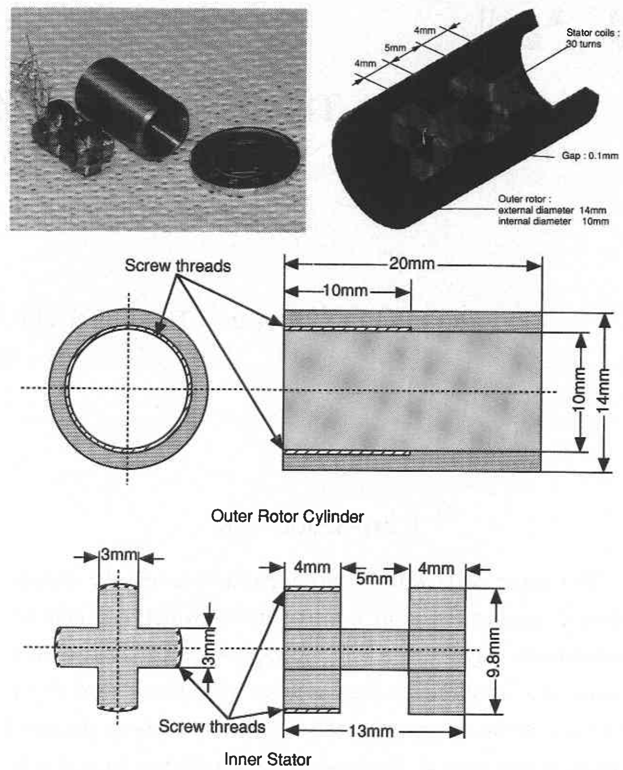

Figure 2 External view and the size of the wobble motor

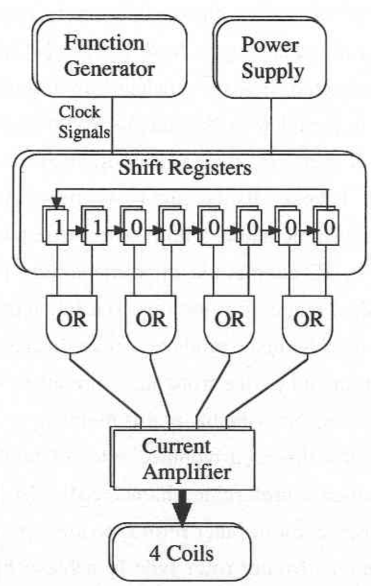

Figure 3 Driving circuit to energize coils of a stator

shifts to the right direction by the external clock signals and goes around. When 8 clock signals are applied to the shift register, the electrical excitation rotates once around the 4 poles of the stator.

3. RESULTS

In this section, we show the results of the torque calculation and the magnetic flux distribution by FEM simulation and the driving characteristics of a threaded wobble motor of outer rotor type.

The ratio between the rotation of the electrical excitation and the outer rotor, so called the reduction gear ratio of a wobble motor is 6.25: 1. This means that when the electrical excitation makes 6.25 circles, the rotor rotates once mechanically. Moreover, the rotor goes up by the pitch of the threads (0.75mm) in the axial direction, when the rotor rotates once.

Figure 4 shows the parameter for the calculation of the torque [11]. The amount of attractive force generated by two stators acting on the rotor is approximated by the following equations :

$$F = \frac{B^2 S}{2\mu_0} = \frac{S}{2\mu_0}\left(\frac{NI}{\frac{2\delta}{\mu_0}+\frac{d}{\mu_{iron}}}\right)^2$$

$N : Number\ of\ turns\ for\ two\ coilss\ 60turns$

$I : Current\ passing\ through\ coil\ 1A$

$S : Cross-sectional\ area\ of\ stator\ 1.2\times10^{-5}m^2$

$d : Length\ of\ magnetic\ flux\ loop\ 3\times10^{-2}m$

$\delta : gap\ between\ stator\ and\ rotor\ 1.0\times10^{-4}m$

$\mu_0 : 4\pi\times10^{-7}$

$\mu_{iron} : 250$

$l : length\ of\ lever\ arm\ 7\times10^{-3}m$

$$T = F_l\times l = \frac{1}{\sqrt{2}}F\times l$$

$Thus\ we\ obtain\ the\ torque\ of\ 3.37mN\cdot m$

In order to improve the design, FEM simulation to determine the flux density distribution was performed using Ansys software. Figure 5 shows the magnetic flux distribution by FEM simulation.We can observe the flux leak to the other poles is less than 1 percent of the flux density of the actuated pole.

Figure 6 shows the relation between the rotary speed of the excitation in 4 poles and the mechanical rotary speed of the outer rotor. The rotary speed increases linearly with the electromagnetic rotary speed theoretically. We observed a sliding of the outer rotor. So experimental measurement is smaller than the theoretical one. The maximum rotary speed is 3rps at the current of 1A in the coils. The maximum speed in the axial direction is 2.25 mm/s.

We experimentally measured the maximum torque which the outer rotor can lift up at several currents. We obtained the torque to pull up the weight by a string, and to use the spring (a spring constant k = 0.6 gf/mm) and a scale. We measured the relation between the maximum torque and the current in the coils, shown in Figure 7.

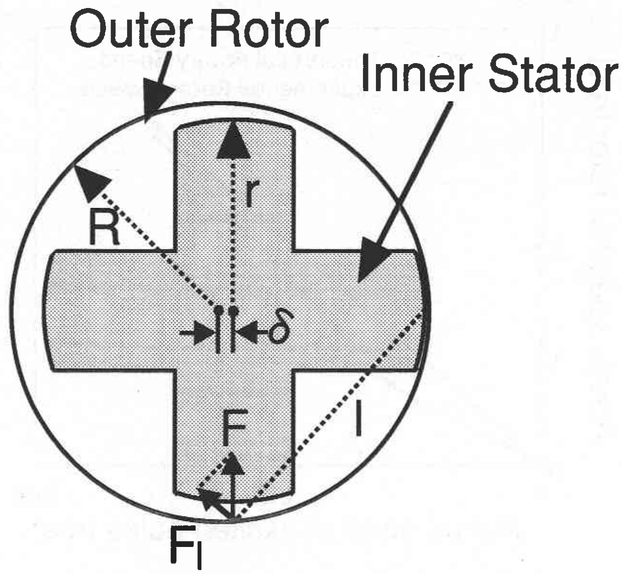

Figure 4　Parameter for the calculation of the torque

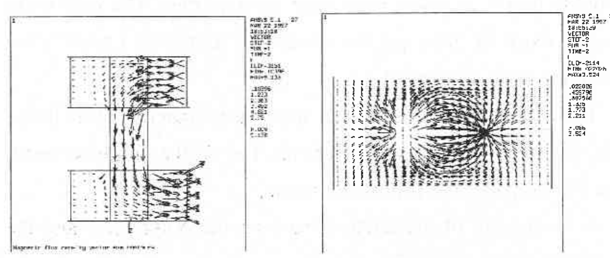

Figure 5　Magnetic flux distribution by FEM simulation

We observed whether the motor could lift the weight or not, and determined the maximum load capacity. Theoretically, the maximum torque is proportional to the square of the current, however the loss of the friction, the Joule effect, the flux leak and the hysteresis effect influence to the experimental measurement. We have obtained the maximum Torque of 1.6mNm at 1A.

At low currents below 600mA, the rotor is unable to overcome the frictional forces and does not rotate smoothly.

4. CONCLUSION

The driving principle and the characteristics of a threaded

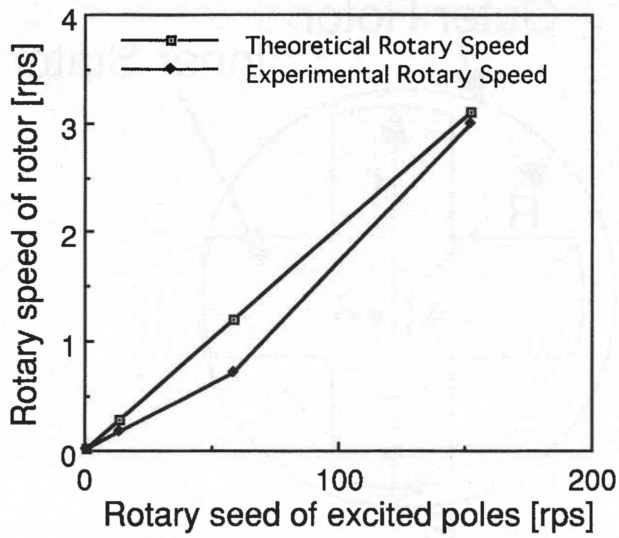

Figure 6　Relation between the rotary speed of the excitation in 4 poles and the mechanical rotary speed of the outer rotor

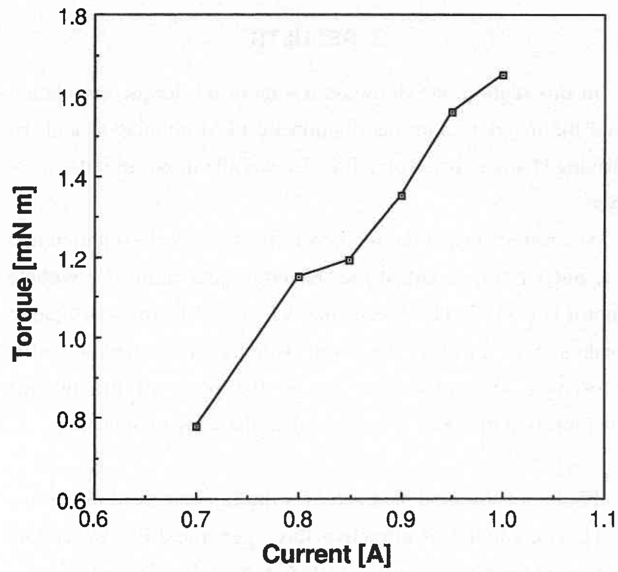

Figure 7　Relation between the maximum torque and the current in the coils

wobble motor of outer rotor type are reported. The maximum rotary speed of 3rps and the maximum torque of 1.6mNm are obtained at the current of 1A.

The advantage of this wobble motor is to generate large linear displacement in the axial direction. For further improvement, we will consider the following points;

・Reduction of the friction between the outer rotor and the external object.

・Heat radiation of the coils.

・Optimal design as the magnetic circuit (This depends on the parameters the turn number of the coil, the maximum current, the length of the magnetic flux loop and the yoke shape for the closed flux loop).

・Reduction of the whole size by the compact stator.

ACKNOWLEDGEMENT

The authors wish to thank Workshop members in our institute on the fabrication.

(Manuscript received, October 2, 1997)

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