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A Rotary Motor Using Giant Electrorheological Fluid and Piezoelectric Torsional Vibrator
巨大電気粘性流体と圧電ねじり振動子を用いた非接触モータ

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1. Introduction

In the conventional friction-drive ultrasonic motors, wear and friction loss due to poor friction control with vibration limit their applications. To overcome the problem of friction control, new methods to transform the alternating force with vibration into one-directional traction force have been explored. Utilizing electrorheological (ER) effect, i.e. the rheological characteristics of the fluid can be varied by applying electric field, non-contact piezoelectric motors using ER fluids have been proposed[1, 2)]. However, previous studies have proven that the motor performance is highly dependent on the quality of ER fluids. With the recent breakthrough in ER fluids, i.e. the discovery of giant electrorheological (GER) effect[3)], much higher yield stress (>250 kPa) and shorter response time (approximately 1 ms) can be achieved, providing desirable characteristics for non-contact piezoelectric motors using ER effect.

2. Materials and Methods

The key difficulty in designing a torsional vibrator for this motor is lowering the resonance frequency in order to compensate the relatively low response time of GER fluid. The unique solution here is to press/stretch the two ends of an S-shape spring using two multilayer PZT actuators driven by one signal, as shown in **Fig. 1**. The multilayer PZT actuators (NEC-TOKIN Inc., Tokyo, Japan) had a dimension of 5×5×18 mm and bonded with the two ends of the spring by glue. The spring was made by phosphor bronze at a thickness of 0.5 mm and embedded in a 6-mm-diameter shaft with an angle of 60°. Being connected with a 36-mm-diameter cylinder, a resonance frequency of the torsional vibrator at 124 Hz was found, which is approximately 8 times longer than the response time of GER fluid. The rotor with 42 mm diameter, acting like a reservoir of GER fluid, was mounted on the base by a ball bearing, leaving a 0.4-mm gap with the bottom of the torsional vibrator. The GER fluid used in this experiment was composed of urea-coated barium titanyl-oxalate nanoparticles

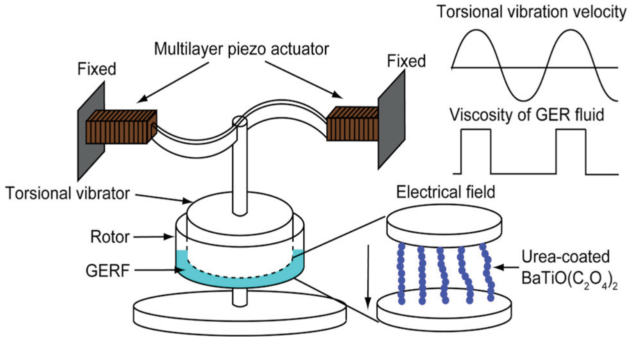

Fig. 1 Configuration of the prototype piezoelectric motor using torsional vibrator and GER fluid.

($BaTiO(C_2O_4)_2$) dispersed in silicone oil. The weight ratio between the solid and the liquid contents was 0.8:1, resulting in the viscosity of <100 Pa•s without external electric field and 27.54 kPa•s under 3 kV/mm electric field.

In order to drive this motor, the electric signal with a rectangular waveform, which is synchronized with the vibration velocity of the torsional vibrator, is applied to GER fluid. When the torsional vibration velocity is high, the external electric field is applied to GER fluid and hence the viscosity becomes high and large torque can be achieved. On the contrary, the electric field to GER fluid is switched off when the torsional vibration velocity is lower than or opposite to the rotational direction of the rotor, the negative torque can be small due to the low viscosity of GER fluid at zero field. As a result, the output torque in one vibration cycle, which is the sum of positive and negative torque, is always positive and motor can be rotated in one direction. If the phase difference between the applied electric field to GER fluid and torsional vibration velocity is shifted by 180°, the revolution direction can be reversed.

3. Experimental Results

In this experiment, the voltage applied to the multilayer PZT actuators was fixed at 80 $V_{p\text{-}p}$, while the electric field applied to GER fluid was at 2 kV/mm.

The dependence of the motor rotational speed on the phase difference is shown in **Fig. 2**. The duty cycle of the electric signal to GER fluid was kept as 30%. The motor rotational speed was measured by a high-speed digital camera (M3, Integrated Design

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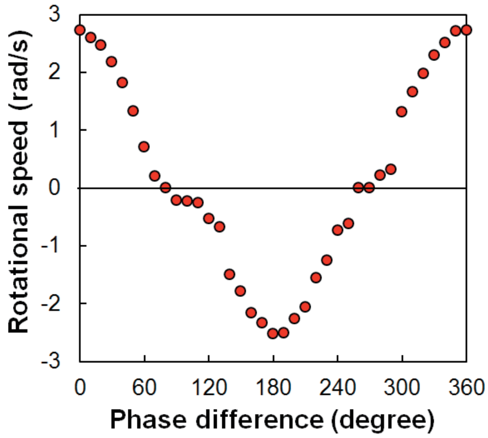

Fig. 2 Dependence of the rotational speed on the phase difference between the electric field applied to GER fluid and the torsional vibration velocity.

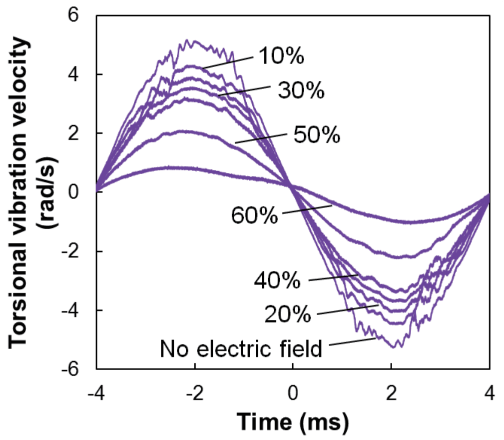

Fig. 3 Dependence of the torsional vibration velocity on duty cycle.

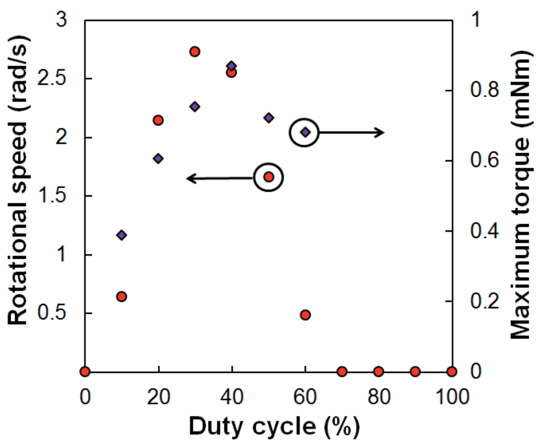

Fig. 4 Rotational speed and maximum torque as functions of duty cycle.

Tools Inc., Tallahassee, FL). The highest speeds in two rotational directions were obtained at 0° and 180° phase differences. The results validate our original expectation, which indicates that the response time of GER fluid is short enough at the frequency of 124 Hz.

Fig. 3 illustrates the effect of the duty cycle on torsional vibration velocity when the phase difference was 0°. The torsional vibration velocity was measured by a 2D laser Doppler vibrometer (Polytec Gmbh, Waldbronn, Germany). It is found that the torsional vibration velocity decreased with the increasing duty cycle. This phenomenon is analogical to the effect of contact duration on vibration velocity in driving direction in standing wave ultrasonic motors, where the vibration velocity decreases with the contact duration increasing. High duty cycle increased the average viscosity of GER fluid in one vibration cycle, and hence increased the load to the torsional vibrator, resulting in the reduction of the torsional vibration velocity.

Then, the dependence of motor rotational speed and the maximum torque on duty cycle was investigated, as shown in **Fig. 4**. Desirable motor performance was obtained at around 30-40% duty cycle, and the rotational speed as high as 2.73 rad/s and the maximum torque as large as 0.87 mNm were achieved at 30% and 40% duty cycle, respectively. The motor mechanical performance became poor irrespective of too low or too high duty cycle, and the motor could not be driven when the duty cycle was higher than 70%. When the duty cycle was too low, though the torsional vibration velocity was high, the driving force was largely reduced and the reserve torque induced by the fluid drag at zero field became dominating, as well as the power loss in the ball bearing. On the other hand, if too high duty cycle was applied, the reverse torque was increased because GER fluid was active in most period of one vibration cycle, causing the stop of motor. Similar mechanism was found in lubricated ultrasonic motors as well.

4. Conclusions

The characteristics of a non-contact rotary motor actuated by a piezoelectric torsional vibrator, of which the vibrational force is modulated by ER fluid, have been largely improved by GER fluid. The motor generated 0.87 mNm torque at the rotational speed of up to 2.73 rad/s. The similarities between this type motor and standing wave ultrasonic motors were also discussed.

Acknowledgment

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