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Non-contact piezoelectric rotary motor modulated by giant electrorheological fluid

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ABSTRACT

A bidirectional non-contact rotary motor using a piezoelectric torsional vibrator and the giant electrorheological (GER) fluid is described in this paper. By applying the dynamic electric signal with a square waveform to the GER fluid, which is in phase with the vibration velocity of the torsional vibrator, bidirectional rotation at an excitation frequency of 118 Hz is achieved. This motor generates 1.04 mN m torque when the electric field strength of 2 kV/mm with 30% duty cycle is applied to the GER fluid, and the rotational speed of up to 7.14 rad/s is achieved if the electric field strength is increased to 2.5 kV/mm. Similarities and differences of the motor characteristics between this motor and the conventional standing wave ultrasonic motors are discussed. The motor performance is not ideal under high electric field strength, indicating that the response time of the GER fluid is dependent on the electric field strength.

1. Introduction

Non-contact ultrasonic motors, which are usually driven by radiation pressure or acoustic streaming, have been proposed as an alternative to the conventional contact-type ultrasonic motors [1–3]. Unlike the conventional ultrasonic motors, such kinds of motors do not suffer from the wear between the stator and rotor/slide due to their non-contact nature, which greatly prolongs the motor lifetime. However, non-contact ultrasonic motors are lacking in the most attractive feature of ultrasonic motors, i.e. high torque at low speed, and the output force of those motors is extremely low, which significantly limits their applications. To overcome this problem, electrorheological (ER) fluids, the rheological characteristics of which can be varied by applying electric field, are employed to non-contact piezoelectric motors. This idea is inspired from the desirable driving mechanism of contact-type ultrasonic motors, where the modulation of the positive and the negative friction forces should be efficient [4,5]. This type of non-contact piezoelectric motor was initially studied by Nakamura et al. [6], and the principle was verified. Meanwhile, another type of linear stepping piezoelectric motor using ER fluid was also developed [7,8]. However, previous studies have proven that the motor performance is highly dependent on the characteristics of the ER fluids, including the response time, yield stress, and viscosity at zero field. The microscopic motion opposite to the macroscopic motional direction was also observed in the existing motors [9], originating from the undesirable properties of the ER fluids. The recent breakthrough in ER fluids has been the discovery of giant electrorheological (GER) effect [10,11], which is different from the conventional dielectric ER fluids on the point that nano-sized molecular dipoles are utilized [12–15]. This effect provides the ER fluids with not only shorter response time (∼1 ms) but also much higher yield stress (>250 kPa), which exceeds the theoretical upper limit of the conventional dielectric ER fluids by one to two orders of magnitude, leading to the potential applications in non-contact piezoelectric motors.

In this paper, we report on a non-contact rotary motor actuated by a piezoelectric torsional vibrator the vibrational force of which is modulated by the GER fluid. After introducing the GER effect, the motor configuration and operating principle are described. The motor mechanical characteristics are measured and as high as 1.04 mN m torque is achieved at the rotational speed of up to 6.98 rad/s, showing significant improvement compared with the motor using the conventional dielectric ER fluid. The effect of the GER fluid under various duty cycles on torsional vibration velocity is clarified and the similarities and differences between this type of motor and standing wave ultrasonic motors are also discussed.

2. The GER effect

The discovery of the GER effect was motivated by the insufficient yield stress of traditional dielectric ER fluids, which largely

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limits their practical applications [13]. The GER effect is reported to be attributed to the saturation polarization of molecular dipoles, instead of the induced polarization mechanism in dielectric ER fluids [10,13,15]. This mechanism is achieved by dispersing barium titanyl oxalate ($BaTiO(C_2O_4)_2$) nanoparticles (~50 nm in diameter) with urea coating (2–5 nm in thickness) in silicone oil. The generated suspension exhibits strong ER behavior, resulting in a significantly improved yield stress of ER fluids [10,11,13]. In addition, the GER fluid also reveals several excellent features, including the low current density, the near-linear dependence of the yield stress on electric field strength, and the short response time (~1 ms), which cannot be observed in dielectric ER fluids.

The GER mechanism has been extensively discussed from both phenomenological [10] and microscopic explanations [14]. The former has proven that the surface saturation polarization in the contact zone of the neighboring particles directly contributes to the GER effect. Meanwhile, the latter has predicted that the formation of aligned (urea) molecular dipolar filaments induces the significant interaction between the two boundaries of the nanoscale confinement. In particular, the short-range (other than dipolar) interactions between the coating molecules and the core (barium titanyl oxalate) particle, and/or the oil, must be such that the molecular dipoles are unlocked from antiparallel pairings (which would imply insensitivity to the external field and hence a small dielectric response).

Under an applied electric field, induced polarization in the particles causes their aggregation into columns aligned along the field direction. These columns are responsible for the solid yield stress when the GER fluid is sheared perpendicular to the columns. Owing to the unideal thermodynamic nature of the urea-water solution, it is known that urea molecules tend to predominantly aggregate at the surface of hydrophilic solid particles, forming a (nonuniform) liquid-like coating. Formation of water filaments under constrained conditions may give rise to forces far stronger and longer in range than the van der Waals interaction, resulting in high yield stress. The finding of the GER effect has thus widened the potential applications in the mechanical devices, where the active control of force transmission is required.

3. Materials and methods

The key difficulty in designing a torsional vibrator for this motor is to lower the resonance frequency in order to compensate for the relatively long response time of the GER fluid compared with piezoelectric materials. The unique solution here is to press/stretch the two ends of an S-shaped spring with two multilayer PZT actuators driven by one signal, as shown in Fig. 1. The multilayer PZT actuators (NEC-Tokin Inc., Tokyo, Japan) with a dimension of 5 × 5 × 18 mm were bonded to the two ends of the spring with epoxy glue. The spring composed of phosphor bronze was embedded in a 6-mm-diameter shaft with an angle of 60°, which was connected with a 36-mm-diameter cylinder. The resonance frequency of the torsional vibrator is determined by the thickness of the spring, and a 0.5-mm-thick spring was employed in this experiment, resulting in a resonance frequency of the torsional vibrator at 118 Hz which is approximately 8 times longer than the response time of the GER fluid. The rotor with 42 mm diameter, acting like a reservoir of the GER fluid, was mounted on the base with a ball bearing, leaving a 0.4-mm gap from the bottom of the torsional vibrator. The weight ratio of the solid particles in the GER fluid used in this experiment was 44%, resulting in the viscosity of <100 Pa s without external electric field and 27.54 kPa s under 3 kV/mm electric field strength.

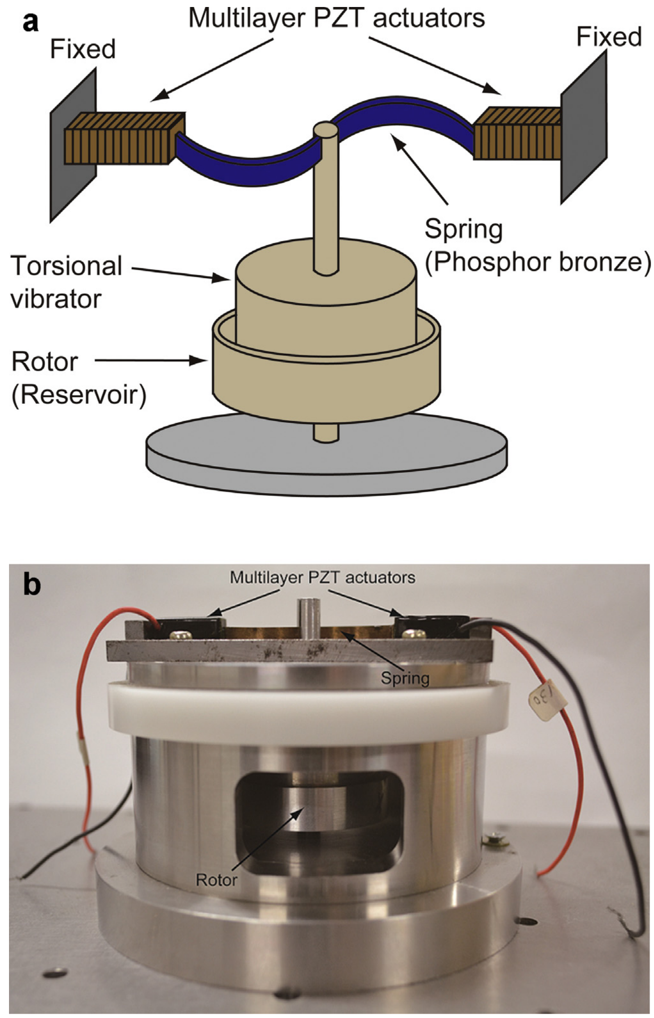

Fig. 1. (a) Configuration of the prototype piezoelectric motor using torsional vibrator and the GER fluid; (b) A completed prototype motor.

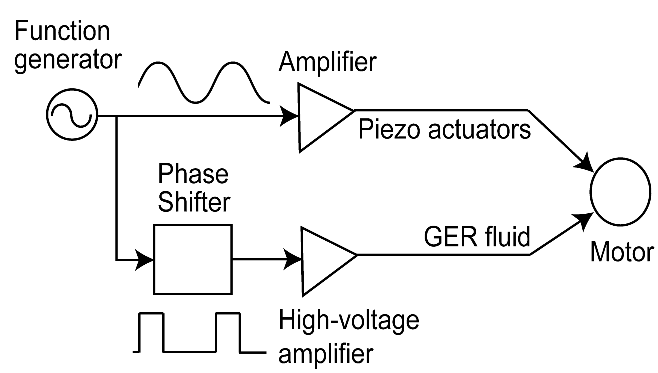

Fig. 2. Diagram of experimental setup.

4. Operating principle

The schematic diagram of the experimental setup is depicted in Fig. 2. A function generator with a phase shifter was employed to drive the proposed motor. The driving power to the GER fluid was amplified with a high-voltage power amplifier (Matsusada Precision Inc., Kusatsu, Japan). The square-wave electric pulses synchronized with the vibration velocity of the torsional vibrator were applied to the GER fluid to drive the motor. When the torsional vibration velocity was high, the external electric field was applied to

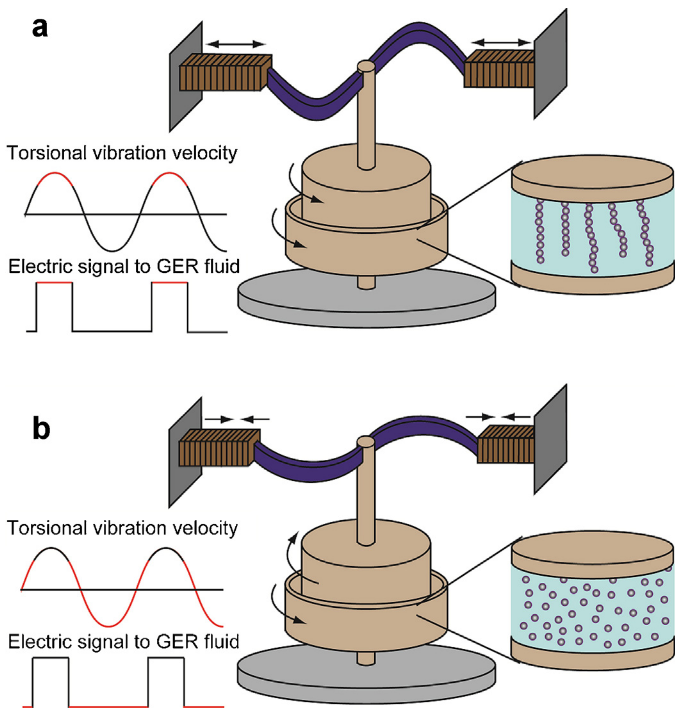

Fig. 3. (a) and (b) Illustration of the operating principle of the motor.

the GER fluid and hence the viscosity became high and large torque was transmitted, as illustrated in Fig. 3(a). In contrast, the electric field applied to the GER fluid was switched off when the torsional vibration velocity was lower or opposite to the rotational velocity of the rotor, as shown in Fig. 3(b); the negative torque became small owing to the low viscosity of the GER fluid. As a result, the output torque in one vibration cycle, regarded as the summation of the positive and the negative torques, was always positive, and the motor was rotated in one direction. If the phase difference between the applied electric field to the GER fluid and the torsional vibration velocity was shifted by 180°, the rotational direction was reversed.

The operating principle of this motor is analogous to that of standing wave ultrasonic motors, in particular, hybrid transducer-type ultrasonic motors (HTUSMs), where a torsional vibrator is also utilized [16]. Their difference lies in that the traction force is actively modulated by the GER fluid in the non-contact piezoelectric motor developed in this paper, instead of the modulation of the dynamic preload by the longitudinal vibration in HTUSMs, where friction loss and wear often occurs owing to the friction-drive mechanism and the poor modulation of the friction force (note that strong longitudinal vibration can hardly be achieved if high static preload is applied to obtain sufficient torque) [5,17]. The active modulation of the traction force is ideal for piezoelectric motors since they convert the alternating vibration generated by the piezoelectric vibrator to one-direction movement. Such kind of force modulation in piezoelectric motors requires considerable difference between the positive and the negative forces as well as the fast response of a conversion material. The desirable characteristics of the GER fluid, i.e. the high viscosity (or yield stress) change ratio and short response time due to the GER effect, enable its potential utilization in non-contact piezoelectric motors.

5. Results and discussion

The dependence of the motor rotational speed on the phase difference between the applied electric field to the GER fluid and the torsional vibration velocity is shown in Fig. 4. The electric field

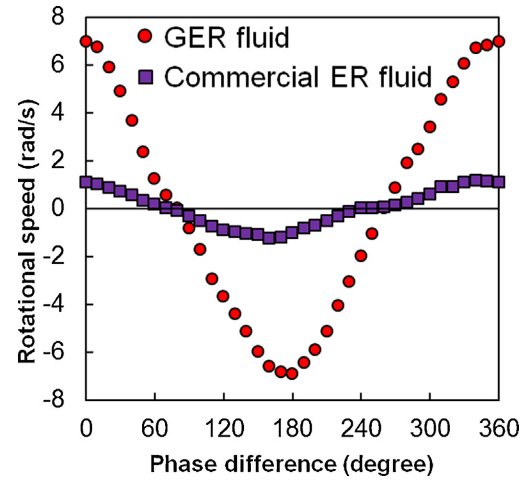

Fig. 4. Dependence of the rotational speed on the phase difference between the electric field applied to the GER fluid and the torsional vibration velocity.

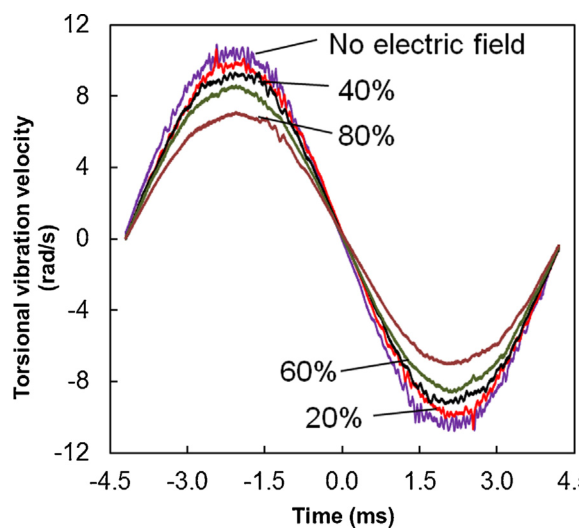

Fig. 5. Dependence of the torsional vibration velocity on duty cycle.

strength applied to the GER fluid was 2 kV/mm with a duty cycle of 30% and the peak-to-peak voltage applied to the multilayer PZT actuators was fixed at 80 V. The motor rotational speed was measured by a high-speed digital camera (Integrated Design Tools Inc., Tallahassee, FL). The highest speeds in two rotational directions were obtained with 0° and 180° phase differences, which not only validates our original expectation but indicates that the response time of the GER fluid is sufficiently short at the frequency of 118 Hz. The motor performance using one kind of the conventional dielectric ER fluid (ER tec, Minoh, Japan) was also compared under the same electric field strength with a duty cycle of 10%. Without the GER effect, this conventional ER fluid possessed the response time of approximately 4 ms and the viscosity of 0.3 Pa s at zero field and 3.7 Pa s under 2 kV/mm electric field strength. The highest rotational speed was obtained with 20° phase difference and the motor was not drivable under the duty cycle of 30%, indicating that the response time of this type of ER fluid was too long at the frequency of 118 Hz. In addition, the rotational speed was much lower than that of the motor using the GER fluid, attributing to the much smaller change in viscosity and also the longer response time.

Fig. 5 illustrates the effect of the duty cycle on the torsional vibration velocity when the phase difference was 0°. Same electric field strength and driving voltage were applied to the GER fluid

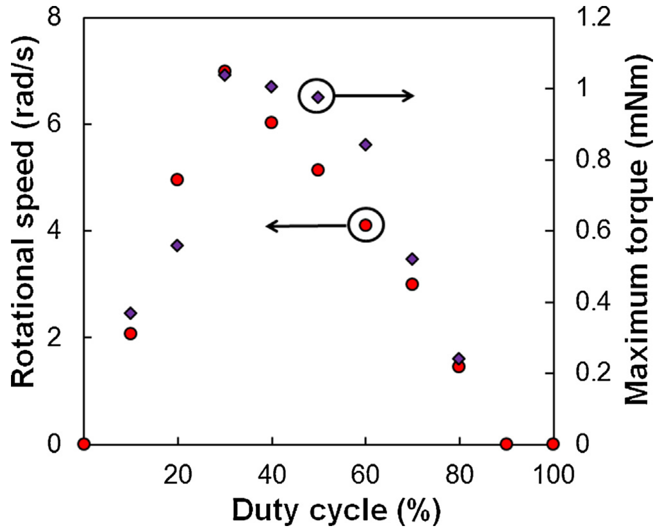

Fig. 6. Rotational speed and maximum torque as functions of duty cycle.

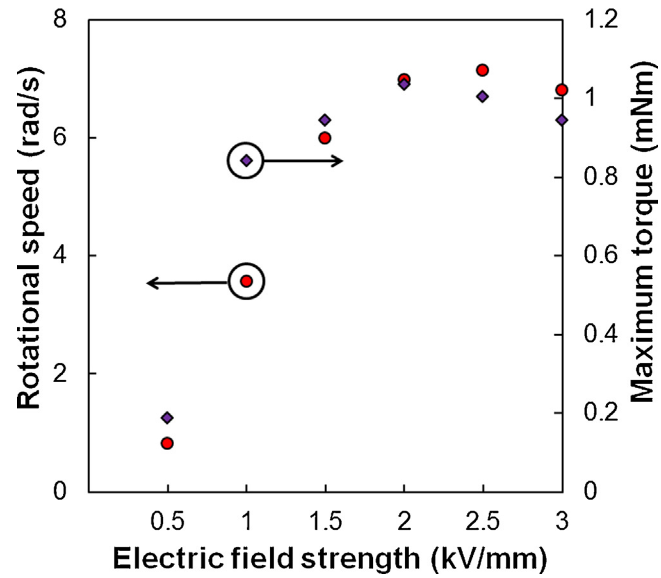

Fig. 7. Rotational speed and maximum torque as functions of electric field strength applied to the GER fluid.

and the multilayer PZT actuators. The torsional vibration velocity was measured by a 2D laser Doppler vibrometer (Polytec Gmbh, Waldbronn, Germany). The torsional vibration velocity decreased with the increasing duty cycle, which is analogical to the effect of the contact duration on the vibration velocity in driving direction in standing wave ultrasonic motors, where the vibration velocity decreases with the contact duration increasing. This is because that long contact duration increases the load to the vibrator and hence the vibration velocity is lowered. For the non-contact motor described here, high duty cycle increased the average viscosity of the GER fluid in one vibration cycle, and hence increased the resistance to the torsional vibrator when the torsional vibration velocity was lower or opposite to the rotational velocity of the rotor, resulting in the reduction of the torsional vibration velocity.

Then, the dependences of the motor rotational speed and the maximum torque on duty cycle were investigated with the same driving conditions mentioned above, as shown in Fig. 6. Different weights were pulled to measure the torque, and the maximum torque was calculated from the weight that just stopped the motor. Desirable motor performance was obtained at 30% duty cycle, where the rotational speed of as high as 6.98 rad/s and the maximum torque of as large as 1.04 mN m were achieved. The motor mechanical performance became poor as the duty cycle was too low or too high, and the motor was not driven if the duty cycle was higher than 80%. When the duty cycle was too low, though the torsional vibration velocity was high, the driving force was drastically reduced and the reserve torque induced by the fluid drag at zero field as well as the power loss in the ball bearing became dominant. On the other hand, if too high duty cycle was employed, the reverse torque was increased due to the long active time of the GER fluid in one vibration cycle, stopping the motor.

The relationship between the motor characteristics and the electric field strength applied to the GER fluid was also investigated at the duty cycle of 30%, as shown in Fig. 7. Low rotational speed and small maximum torque were obtained when the electric field strength was low, due to the small change in the viscosity of the GER fluid. With the increase of the electric field strength, the rotational speed became closer to the torsional vibration velocity owing to the increase of the viscosity change ratio, which was described in Ref. [6]. However, the maximum torque and the rotational speed slightly decreased when the electric field strength was higher than 2 kV/mm and 2.5 kV/mm, respectively, which was different from our expectation. Under higher electric field strength, the change in the viscosity of the GER fluid with and without electric field is more considerable if the response time keeps the same, which should be desirable for this type of motor. Nevertheless, it was found that the highest rotational speeds under 2.5 kV/mm and 3 kV/mm electric field strength were obtained with 10° and 20° phase difference, respectively. This phenomenon indicates that the response time of the GER fluid is prolonged after applying higher electric field strength. Therefore, the reverse torque was increased due to the longer response time of the GER fluid, resulting in the decrease of the maximum torque and the rotational speed, though same duty cycle was applied.

6. Conclusions

In conclusion, we developed a non-contact rotary motor using a piezoelectric torsional vibrator and the GER fluid. By comparing with the motor using the conventional dielectric ER fluid, drastic improvement in the motor characteristics was observed because of the short response time and high yield stress of the GER fluid. Ideal motor performance was obtained under 2 kV/mm electric field strength with 30% duty cycle, and 1.04 mN m torque at the rotational speed of up to 6.98 rad/s was achieved, offering force at least two orders of magnitude larger than that of conventional non-contact ultrasonic motors. Several similarities and differences between this motor and contact-type standing wave ultrasonic motors were discussed, verifying the operating principle of this type of non-contact motor. The response time of the GER fluid was affected by the applied electric field, which limited the motor performance under high electric field strength.

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