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論文要約

Efficient Modulation of Friction in Ultrasonic Motors Using Functional Fluids

機能性流体を用いた超音波モータ における摩擦制御に関する研究

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This thesis describes the efficient modulation of friction in ultrasonic motors (USMs) using functional fluids, i.e. lubricants and giant electrorheological (GER) fluids. USMs have been extensively studied for three decades, due to their attractive features, such as high torque in low speed, simple structure, and precise positioning capability. However, since USMs are driven by the friction force between the rotor and the stator in most cases, they inherently possess the friction loss and the wear of contact materials, which cause their low efficiency and short life and limit their applications to some niche areas. Reducing the friction loss to enhance the efficiency and prolong motor life is, therefore, a significant issue for broadening the application areas of USMs.

To resolve these problems in conventional USMs, in this thesis, we propose to efficiently modulate the friction force in USMs using functional fluids, i.e. lubricants and GER fluids. The former can dynamically change the friction coefficient as it relates to fluid viscosity, sliding speed, and load, while the rheological characteristics of the latter can be varied by applying electric field.

First, the concept of friction modulation and the proposed lubrication mechanisms in USMs were introduced. We numerically analyzed the lubricating effect in hybrid transducer-type ultrasonic motors (HTUSMs) using an equivalent circuit. The dependence of the motor characteristics on the contact durations in dry and lubricated conditions was examined, and the reason of limited efficiency for HTUSMs in dry condition was clarified. The motor performance at various static preloads and applied voltages were also investigated, and the HTUSM characteristics, i.e. motor efficiency, no-load speed, and maximum torque, were shown to be more desirable at high static preloads in lubricated condition than in dry condition.

Then, the lubricating effect in standing-wave type USMs was experimentally investigated. The dependence of the motor characteristics on the contact pressure was in good agreement with the simulation results. With lubrication, the motor performance at low static preloads, including the motor efficiency, the no-load speed and the maximum torque, was lower than that without lubrication. However, it was drastically improved at high static preloads, which indicates that high pressure is required to keep sufficient friction force if lubricant is applied. The transduction efficiency of the motor was enhanced from 28% in dry condition to 68% in lubricated condition. We also examined the torque of USMs in lubricated condition, and significant improvement in motor output torque was observed. The maximum torque as high as 1.01 Nm was obtained in a 25-mm-diameter HTUSM, which was 2.6 times higher than that in dry condition. The torque enhancement was attributed to the fact that the motor with lubrication can withstand much higher static preload than that without lubrication. Both high efficiency and high torque were achieved under high static preloads, which solved the dilemma in dry condition. By employing a stroboscopic optical interferometry, the transient variation in lubricant film thickness was measured at an oscillating frequency >50 kHz. This is the first measurement of film thickness at such a high frequency. Current results provide preliminary information on the lubrication mechanisms in USMs, though direct connection with the results obtained in high-efficiency USMs is difficult due to different experimental conditions. This technique will be useful to measure the film thickness change in various mechanical systems.

This thesis further describes the tribological performance of engineering ceramics as friction materials in lubricated USMs. Mechanical fracture was found to be the main wear mechanisms of the tested ceramics in lubricated USMs. ZrO_2 showed the mildest wear of all the tested ceramics, indicating that the ceramics possessing high fracture toughness are desirable for lubricated USMs. In contrast, the hardness of ceramics plays a less important role than the fracture toughness, since SiC exhibited the most severe wear.

The lubricating effect in traveling wave ultrasonic motors was also experimentally studied. Unlike the situation in standing wave ultrasonic motors, lubricant significantly lowered the mechanical characteristics of motor, including motor efficiency, no-load speed, and maximum torque. This phenomenon was attributed to that the quality factor of the stator was largely reduced due to the presence of lubricant, resulting in high vibration loss and poor motor performance. A bending vibrator with higher vibration energy might be the solution for lubricated traveling-wave type USMs.

Last but not least, we also 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 USMs. Several similarities and differences between this motor and contact-type standing-wave type USMs were discussed, verifying the operating principle of this type of non-contact motor. The torque transmission mechanism of this motor was simulated by an equivalent circuit model. The simulation results had a good agreement with the experimental ones except the value of output torque. The discrepancy in torque might be attributed to the reduced contact area due to the centrifugal force and the slip between the GER fluid and the rotor surface. Simulated dependence of the rotational speed on the phase difference indicates that the actual response time of the GER fluid might be even smaller than 1 ms.