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Modeling and Performance Comparison of Ultrasonic Motors in Dry and Lubricated Contact

潤滑油の有無による超音波モータの性能比較

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1. Introduction

Ultrasonic motors (USMs) are typically operated in dry contact in order to keep sufficient torque, since they are generally driven by the friction force between rotor/slider and stator. However, this driving mechanism leads to the friction loss and the wear of the friction materials, which are the major reasons for the relatively low efficiency and short life of USMs.

Based on the mechanism of traction drive, the approach of employing lubricant to USMs had been proposed[1]. In this paper, we compared the mechanical characteristics of the hybrid transducer-type ultrasonic motor (HTUSM) in dry and lubricated contact conditions by both simulation and experiments, and verified the improvement of motor performance using lubricant.

2. Modeling

In order to numerically analyze the HTUSM characteristics in dry and lubricated contact conditions, an equivalent circuit model that simulates the torque transmission mechanism was employed as shown in **Fig. 1**. In dry contact, a Coulomb friction model was used, in which the torque τ is limited to the product of the coefficient of friction μ, the dynamic preload f_c, and the contact radius r. If lubricant is applied, the coefficient of friction varies according to the change of the relative velocity between the angular vibration velocity of the stator Ω_T and the rotor rotational speed Ω_R, and the dynamic preload f_c, as corresponds to the Stribeck curve without the consideration of the variation of lubricant viscosity, which is depicted in **Fig. 2**. The detailed explanation of this model was described in our previous paper[2].

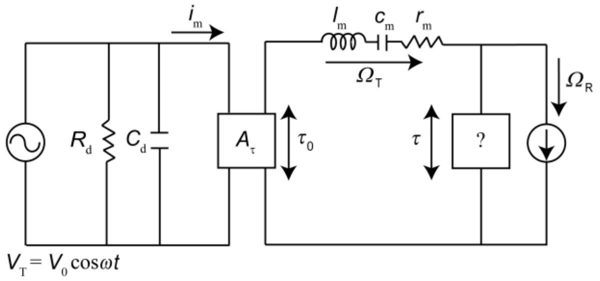

Fig. 1 Equivalent circuit of HTUSM for torque transmission mechanism.

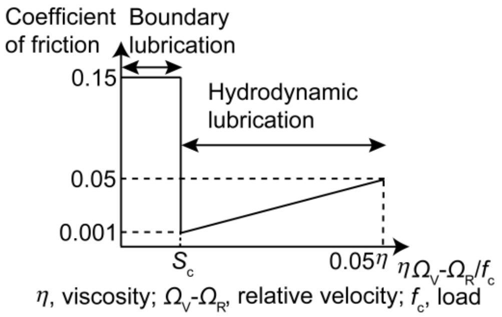

Fig. 2 Stribeck curve for calculation in lubricated contact.

Figs. 3(a) and **(b)** illustrate the effect of changing the applied voltage on the motor efficiency at various static preloads in dry and lubricated contacts. In this simulation, the amplitude of the longitudinal vibration was assumed to be constant while the static preload was changed. The efficiency was defined as the transduction efficiency of HTUSM, which was the ratio of the output power to the input power of the torsional vibrator. In dry contact, the optimal static preload for the motor efficiency clearly changed at different applied voltages to the torsional vibrator. Generally, better motor efficiency is obtained at lower static preloads if the applied voltage is low, while it shifts to higher static preloads if high voltage is applied. The highest value of the motor efficiency is achieved at low voltage, since the maximum efficiency is obtained under shorter contact duration[2]. When lubricant was applied, the trends of the motor efficiency at different applied voltages were similar to those in dry contact. However, the motor can be operated at extremely high static preloads, and the maximum efficiency at each applied voltage was higher than that without lubrication.

3. Experiments

In this experiment, silicon nitride and alumina were chosen as the friction materials for the rotor and the stator, and high traction fluid (HTRF) with 100 cSt viscosity was selected as the

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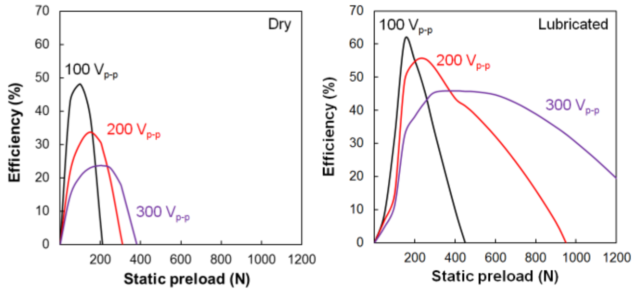


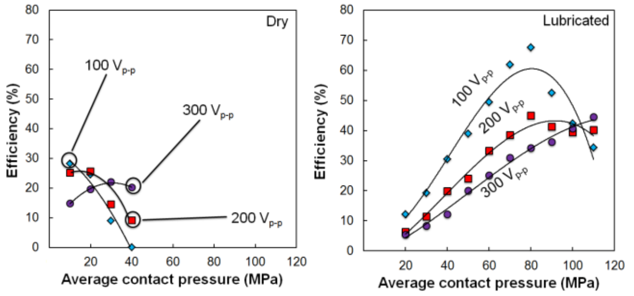
(a) (b)

Fig. 3 Calculated motor efficiency as a function of the static preload in (a) dry and (b) lubricated contact.

lubricant. The applied voltage to the longitudinal PZT disks was fixed at 450 V_{p-p} in order to avoid the effect of the longitudinal vibration on the transduction efficiency.

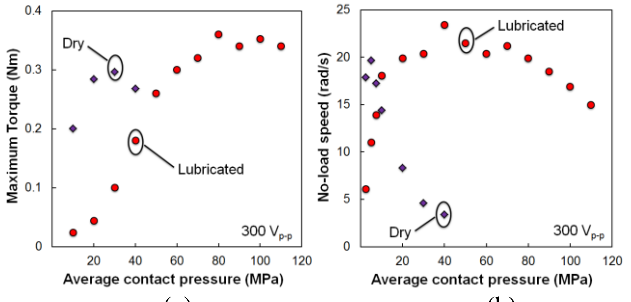
The effects of the average contact pressure on the motor efficiency at different applied voltages to the torsional PZT disks are shown in **Figs. 4(a)** and **(b)**. The experimental results were in good agreement with the simulation results that the maximum efficiency was achieved at low static preloads if low voltage was applied. In dry contact, the motor efficiency reached its maximum at low static preloads, where the efficiency was low with lubrication. However, without lubrication, the motor almost stopped at 40 MPa static preload even when high voltage was applied, so that the efficiency drastically decreased. In contrast, the motor efficiency was enhanced with increasing contact pressure after lubrication. The maximum efficiency was increased from 28% in dry contact to 68% in lubricated contact. In addition, the motor efficiency reached 44% at 300 V_{p-p} and 110 MPa contact pressure, which was the largest applicable pressure of the spring we used. Thus, the motor with lubrication operates well even under extremely high pressure, which shows that it can be utilized in the applications where high torque is required.

Figs. 5(a) and **(b)** depict the maximum torque and the no-load speed as functions of contact pressure, both at 300 V_{p-p}. When the contact pressure was low, the maximum torque in dry contact showed clear superiority to that in lubricated contact, and 0.3 Nm torque was obtained at 30 MPa contact pressure. In contrast, as the contact pressure increased, the maximum torque increased in lubricated contact until the maximum value of 0.36 Nm was achieved at 80 MPa contact pressure. When the contact pressure increased further, the maximum torque was still maintained at high values, corresponding to the high efficiency. Similar trend was found in no-load speed/contact pressure curve as well. As high as 14.95 rad/s no-load speed was achieved even at 110 MPa contact pressure, which is a distinctive difference between with and without lubrication.



(a) (b)

Fig. 4 Motor efficiency as a function of the contact pressure in (a) dry and (b) lubricated contact.



(a) (b)

Fig. 5 (a) Maximum torque and (b) no-load speed as functions of contact pressure.

4. Conclusions

We compared the characteristics of HTUSM numerically and experimentally in dry and lubricated contact conditions and examined the effect of improving the motor efficiency with lubrication at high static preloads. With lubrication, the motor performance, including the efficiency, the no-load speed and the maximum torque, was drastically improved at high static preloads, which indicates that high pressure is required to keep sufficient traction force if lubricant is applied. The transduction efficiency of the motor was enhanced from 28% in dry condition to 68% in lubricated condition. The results indicate that lubrication has the potential to enhance the motor performance in appropriate operating condition.

Acknowledgment

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