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Can lubricant enhance the torque of ultrasonic motors? An experimental investigation

Wei Qiu,[a] Yosuke Mizuno, Marie Tabaru, and Kentaro Nakamura
Precision and Intelligence Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama 226-8503, Japan

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Lubrication has been proven to be an effective approach to drastically improve the efficiency of ultrasonic motors without losing the output torque. This phenomenon is attributed to the effective modulation of the friction force by lubricant, according to the theory described in the Stribeck curve. Previous findings even show a potential to increase the motor output torque with lubrication. Here, the torque enhancement of ultrasonic motors using lubricant is extensively studied in hybrid transducer-type ultrasonic motors (HTUSMs) with a size of 25 mm in diameter. The lubricated HTUSMs could withstand static preload as high as 267 N and maximum torque as large as 1.01 N m was obtained with lubrication, which were 3.5 times and 2.6 times higher than those in dry condition, respectively. This result clearly reveals that lubrication can enable ultrasonic motors to be operated under much higher static preload and hence significantly improve the motor output torque, instead of only reducing the friction force. © *2014 AIP Publishing LLC*.
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Ultrasonic motors are typically operated in dry condition and driven by the friction force between their stator and rotor/slider.[1–4] In the most cases, the friction force is modulated by the vibration in the preloading direction to produce high driving force in the positive half cycle of the vibration, while the friction force in the negative half cycle of the vibration should be suppressed. Ideally efficient modulation is, however, extremely difficult to obtain if the preload is high, because the vibration in the preloading direction is not sufficiently strong compared with the static preload.[5–7] Friction loss induced in the negative half cycle of the vibration and wear of the friction materials are inevitable, causing low efficiency and short life. This feature has been regarded as an inherent problem of ultrasonic motors, which cannot be fully overcome by the efforts from various aspects, including selection of appropriate friction materials,[8,9] optimization of the vibration systems,[10–12] or development of the drive/control techniques.[13–15] However, our previous study has shown that functional lubrication can largely reduce the friction loss and improve the motor efficiency.[16] Friction force can be modulated much more efficiently since the coefficient of friction can be dynamically varied by the characteristics of the lubricant, which is conceptually explained through the well-known Stribeck curve.[17] Somewhat surprisingly, the maximum torque of lubricated ultrasonic motors was not lower, but even slightly higher than that in dry condition. This phenomenon is significantly different from our original expectation that motors will lose some output force after being lubricated. Therefore, the potential to improve the torque of ultrasonic motors using lubricant needs to be further explored.

In this letter, we report on an experimental investigation of the torque enhancement in hybrid transducer-type ultrasonic motors (HTUSMs) using lubricant. After analyzing the factors that determine the motor output torque, the dependence of the maximum torque on static preload is examined. The maximum torque increases almost linearly with increasing preload and reaches 1.01 N m at the preload of 267 N after being lubricated, providing a marked contrast to the maximum torque of 0.39 N m at the preload of 76 N in dry condition. The no-load speed, the amplitude of torsional vibration velocity, and their ratio prove that high preload is desirable to the lubricated ultrasonic motors. The effect of longitudinal vibration on the maximum torque is also studied experimentally.

The stator of the HTUSM used in the experiment was 25 mm in diameter and composed of two 4-mm-thick torsional lead zirconate titanate (PZT) disks (polarized in circumferential direction) and six 1-mm-thick longitudinal PZT disks (polarized in thickness direction), as shown in Fig. 1(a). The rotor is pressed to the stator by a coil spring to apply the preload. Figure 1(b) illustrates the operating principle of the HTUSM, where a torsional vibrator generates the output force and a longitudinal vibrator controls the friction force. When the torsional vibrator moves rightward, the longitudinal vibrator extends to contact the rotor and the driving force is transmitted through the friction force between the rotor and the stator. The displacement of the longitudinal vibrator should reach its maximum to provide the highest stress when the torsional vibrator obtains its maximum velocity to the right, hence a 90° phase difference is required to drive this motor. In contrast, when the torsional vibrator moves leftward, the longitudinal vibrator shrinks to separate the rotor and the stator. Thus, the rotor can be rotated in one direction due to its inertia. However, this ideal operating principle can hardly be realized if high preload is applied to generate sufficient torque. The rotor and the stator cannot be detached in the negative cycle of the torsional vibration, which induces considerable friction loss and wear of the friction materials. This is the major reason for the low efficiency of ultrasonic motors, which has been extensively analyzed in Refs. 6, 7, and 16.

[a]Author to whom correspondence should be addressed. Electronic mail: qiu@sonic.pi.titech.ac.jp

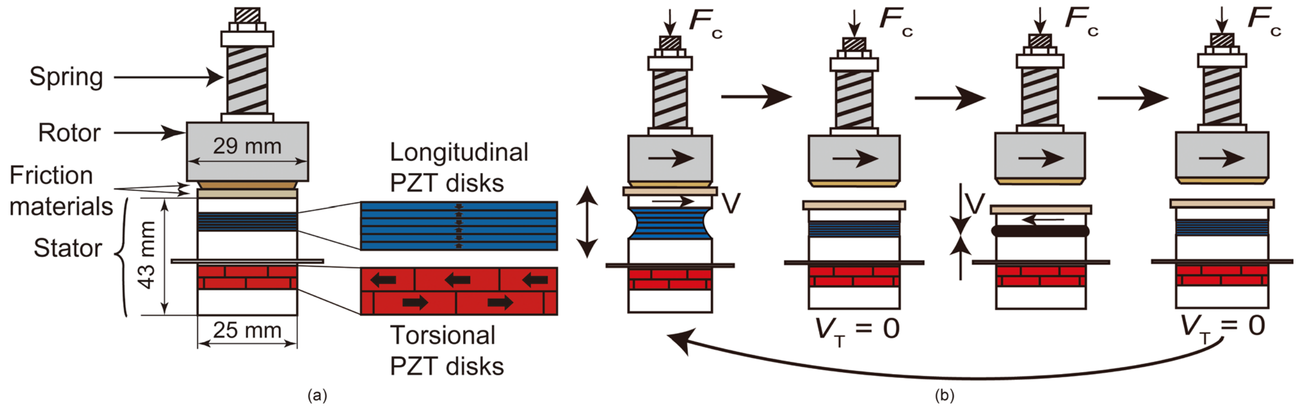

FIG. 1. (a) Dimension of the hybrid transducer-type ultrasonic motor used in this experiment. The polarization directions of torsional and longitudinal PZT disks are indicated by the arrows. (b) Operating principle of the hybrid transducer-type ultrasonic motor.

Functional lubrication is one of the promising candidates to solve the inherent problems in ultrasonic motors. To date, lubrication has not been used in commercial ultrasonic motors since the induced slip might lead to the significant loss of the output torque. However, considering that the preload and the slip between the two sliding surfaces are instantaneously changed during the motor operation, caused by the vibration in the preloading direction, different lubrication regimes can possibly be implemented in one vibrating cycle. According to the theory described in the Stribeck curve, the coefficient of friction becomes high at the instant of a small slip between the rotor/slider and the stator, or at a high preload, corresponding to the boundary lubrication regime, where large output force can be achieved; while it decreases for the period of a large slip or at a low preload, corresponding to the hydrodynamic lubrication regime, where the friction loss can be reduced. Based on this assumption, we applied lubricant to HTUSMs and the motor efficiency was drastically improved under the condition of high static preload.[16] Another interesting phenomenon after using lubricant is that the maximum torque was even slightly higher than that in dry condition. However, in our previous experiments, the applied voltage to the torsional vibrator was fixed and hence the friction force exceeded the torque generated by the torsional vibrator at high preload, which significantly limited the maximum output torque in lubricated condition.

In this experiment, sufficiently high voltage was applied to the torsional vibrator in order to ensure that the torque generated by the torsional vibrator was beyond the friction limit. The voltage to the torsional vibrator was increased until the maximum torque of the HTUSM stopped increasing under each preload.[5] In addition, the applied voltage to the longitudinal vibrator should be kept constant under different static preloads in order to avoid the effect of the longitudinal vibration on the maximum torque. An HTUSM with independently controllable torsional and longitudinal vibrations is therefore a desirable platform for this study. The resonance frequency of the longitudinal vibrator was adjusted to be close to that of the torsional vibrator by changing the length of the rotor. Since the resonance frequencies vary under different preloads, the rotors with different lengths were prepared. Alumina and silicon nitride were selected as the friction materials on the stator and the rotor sides, respectively. The contact shape on the rotor side followed the design in Ref. 16. The grease (Li-complex thickener) with a base oil viscosity grade of 460 and a worked penetration of 290 was selected as the lubricant. The driving signals for the HTUSM were provided by a function generator with a phase shifter. In order to drive the motor, power amplifiers and transformers were employed to obtain sufficient power. Different weights were applied for the torque measurements, and the maximum torque of the motor was calculated using the weight immediately after the motor stopped.

The dependence of the motor maximum torque on static preload in dry and lubricated conditions is shown in Fig. 2. The voltage applied to the longitudinal PZTs was fixed at 77 V_{rms}. The maximum torque increased with increasing preload until the motor stopped, irrespective of whether the lubricant was applied or not. Without lubrication, the maximum torque was much higher than that in lubricated condition when the preload was low, since a large slip occurred in the lubricated HTUSM due to the hydrodynamic lubrication. However, the motor perfectly stopped at 95 N in dry condition, providing a maximum torque of 0.39 N m. In contrast, the lubricated motor did not stop until the preload reached 286 N, and the maximum torque of 1.01 N m was obtained. This torque was 2.6 times higher than that in dry condition and is the recorded value among the HTUSMs with the same diameter. This fact that the maximum torque of the

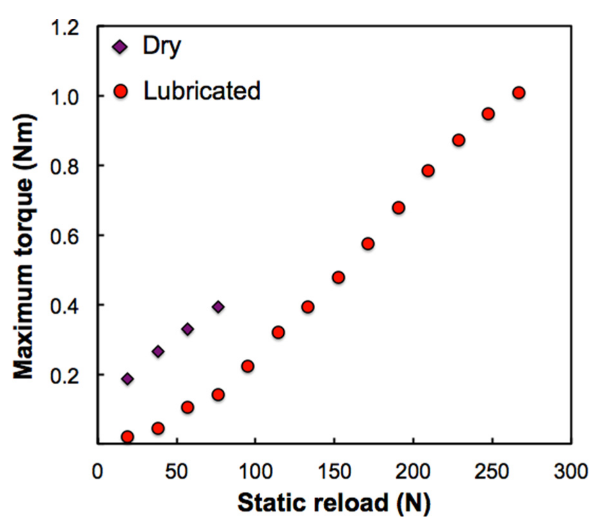

FIG. 2. Maximum torque as a function of static preload.

lubricated ultrasonic motor is significantly higher than that in dry condition has not been expected before. It can be explained that ultrasonic motors can withstand much higher static preload after being lubricated, increasing the friction limit which determines the output torque. At even higher static preload, the lubricated HTUSM did not completely stop and the rotation was still observed. However, the motor stopped automatically after several revolutions, which should be attributed to the extremely high preloading force. The generated friction force was so high that the desirable modulation by the longitudinal vibration was infeasible even with lubrication. Such high static preload should not be applied for lubricated ultrasonic motors for stable operation.

The no-load speed and the amplitude of torsional vibration velocity with and without lubrication were also investigated, as shown in Figs. 3 and 4, in order to understand why lubricated ultrasonic motors can withstand much higher preload. The voltages applied to the torsional and longitudinal PZTs were fixed at 116 V_{rms} and 77 V_{rms}, respectively. The motor rotational speed was measured by a high-speed digital camera (Integrated Design Tools, Inc., Tallahassee, FL), and the torsional vibration velocity was measured by a 2D laser Doppler vibrometer (Polytec Gmbh, Waldbronn, Germany). The no-load speed in dry condition also showed clear superiority to that in lubricated condition, if low static preloads were applied. However, the no-load speed decreased linearly with increasing static preload, if the HTUSM was not lubricated. The dependence of the no-load speed on static preload with lubrication showed a different trend, where it increased first until 114 N was applied and then decreased. The no-load speed had some fluctuations in the high-preload region, which might be caused by the undesirable resonant condition. The no-load speed of the lubricated HTUSM still reached 13.89 rad/s at 267 N preload, which indicates that the motor operation with lubrication was quite stable even under high static preload. Unlike the maximum torque and no-load speed, the amplitude of torsional vibration velocity in dry condition was lower than that in lubricated condition even if the preload was low. It decreased in both conditions with increasing static preload, but the slope of the velocity decreasing with lubrication was much smaller than that without lubrication. With a certain input voltage to the torsional vibrator, the velocity amplitude can reach its maximum when the torsional vibrator vibrates freely (without any load). When a rotor is attached to the torsional vibrator with a certain load, it acts as a block to the torsional vibrator and the blocking force comes from the friction force between the rotor and the torsional vibrator. With higher static preload, the friction force is also increased, resulting in larger blocking force and the reduction in the torsional velocity amplitude. Under the same static preload, the friction force in lubricated condition is smaller than that without lubrication, because the average coefficient of friction in one vibration period with lubrication is lower than that in dry condition. Therefore, the blocking force to the torsional vibrator is also smaller, and the velocity amplitude with lubrication is always higher than that in dry condition.

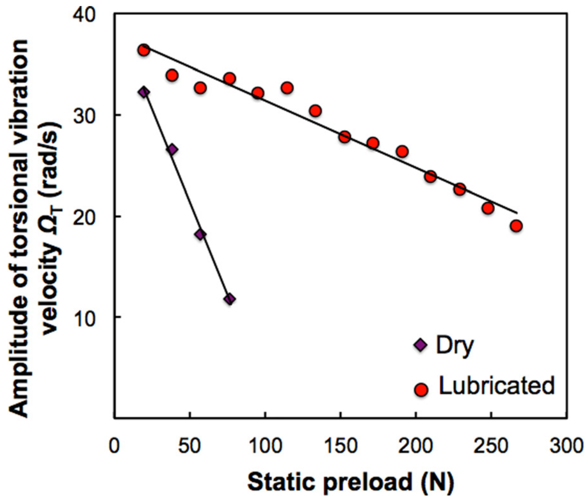

FIG. 4. Dependence of the amplitude of torsional vibration velocity on static preload.

Figure 5 illustrates the speed ratio of the HTUSM as a function of static preload. The speed ratio was defined as the ratio of the no-load speed to the amplitude of the torsional vibration velocity. This ratio describes the slip between the rotor and the stator in the driving period (the amplitude of torsional vibration velocity is higher than the rotational

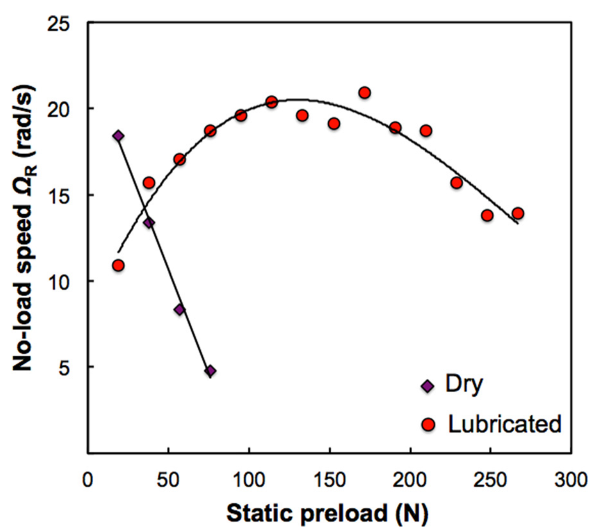

FIG. 3. No-load speed as a function of static preload.

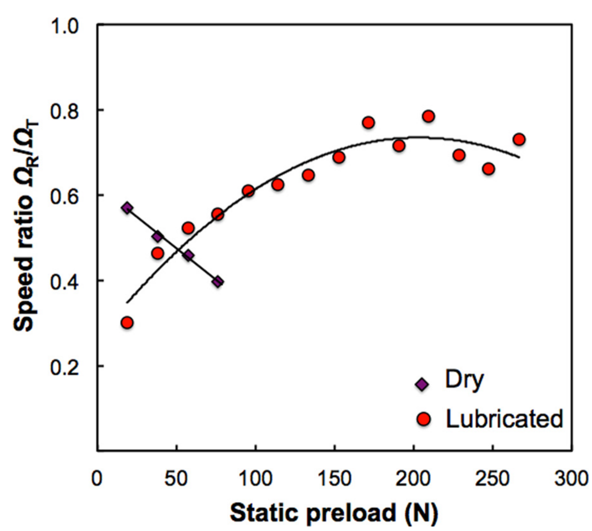

FIG. 5. Dependence of the speed ratio on static preload.

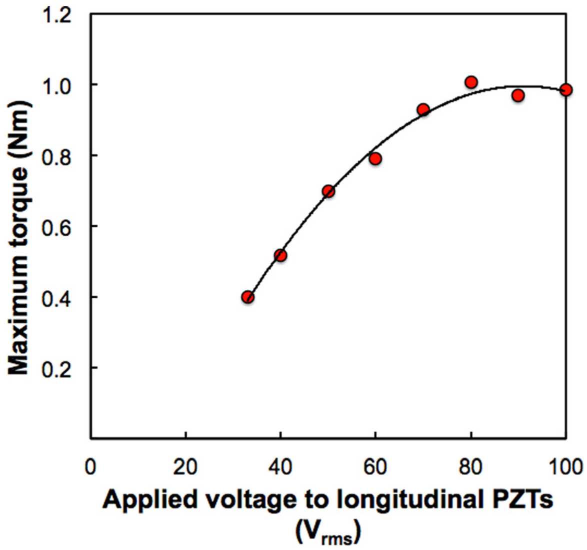

FIG. 6. Maximum torque as a function of the input voltage applied to the longitudinal vibrator at 267 N static preload.

speed of the motor). It is ideal that the speed ratio is high because a low speed ratio means that the slip between the rotor and the stator is large in the driving period. If the same velocity is obtained, i.e., the stick between the rotor and the stator, the friction loss and wear in the driving period can be suppressed.[13,14] In dry condition, the speed ratio was high at low static preloads, and in principle, the no-load speed should equal the amplitude of torsional vibration velocity if the rotor only contacts the stator when the torsional vibration velocity reaches its maximum. However, with increasing static preload, the speed ratio drastically dropped, indicating that a large slip occurred at high static preload and hence induced considerable friction loss and wear. In contrast, the lubricated HTUSM possessed a low speed ratio at low static preloads, since large slip occurred due to the presence of hydrodynamic lubrication, as we have analyzed before. With increasing static preload, boundary lubrication was achieved and the coefficient of friction became high in the driving period, resulting in the improvement of the speed ratio. Though the speed ratio also decreased if too high static preload was applied, it was still kept at ∼70% at high-preload region, which again indicates that the lubricated motor performed well at high preload.

The effect of longitudinal vibration on the motor maximum torque in lubricated condition was also examined, as shown in Fig. 6. The static preload was kept at 267 N, where the highest maximum torque was obtained. The motor did not rotate when the applied voltage to the longitudinal PZTs was lower than 33 V_{rms}. With increasing static preload, the maximum torque increased until reaching its maximum when 80 V_{rms} was applied to the longitudinal vibrator. The saturation of the maximum torque is due to the limit of the friction force. The output torque of ultrasonic motors is the integral of the instantaneous torque, which is calculated as the production of the coefficient of friction, the dynamic preload, and the contact radius. The time-averaged dynamic preload should equal the static preload, and hence the limit of the output torque is equal to or less than (depends on the contact duration) the production of the coefficient of friction, the static preload, and the contact radius. The output torque does not increase with increasing the input power to the longitudinal vibrator, if it has already reached its limit. The maximum torque slightly decreased when the input voltage to the longitudinal vibrator was higher than 80 V_{rms}. It might be caused by the undesirable coupling system to the rotor, which induced some irregularities in longitudinal vibration when too high power was applied. This operating condition should be avoided because it may destroy the PZTs and significantly increase the power consumption for longitudinal vibration as well as the wear of the friction materials.

In conclusion, we investigated the torque of ultrasonic motors in lubricated condition, and significant improvement in motor output torque was observed. The maximum torque as high as 1.01 N m 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. The results of the no-load speed, the amplitude of torsional vibration velocity, and the speed ratio illustrate that high static preload is desirable for lubricated ultrasonic motors. The finding in this work will explore the high-torque applications of ultrasonic motors to a great extent.

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[1]S. Ueha and Y. Tomikawa, *Ultrasonic Motors—Theory and Applications* (Clarendon Press, Oxford, 1993).
[2]K. Uchino, *Piezoelectric Actuators and Ultrasonic Motors* (Kluwer Academic, New York, 1992).
[3]J. Wallaschek, Smart Mater. Struct. **7**, 369 (1998).
[4]B. Watson, J. Friend, and L. Yeo, Sens. Actuators, A **152**, 219 (2009).
[5]K. Nakamura, M. Kurosawa, and S. Ueha, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **38**, 188 (1991).
[6]K. Nakamura, M. Kurosawa, and S. Ueha, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **40**, 395 (1993).
[7]K. Nakamura and S. Ueha, Electron. Commun. Jpn. Part 2 **81**, 57 (1998).
[8]K. Nakamura, M. Kurosawa, H. Kurebayashi, and S. Ueha, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **38**, 481 (1991).
[9]K. Uchino, Smart Mater. Struct. **7**, 273 (1998).
[10]T. Morita, M. Kurosawa, and T. Higuchi, Jpn. J. Appl. Phys., Part 1 **35**, 3251 (1996).
[11]M. Aoyagi and Y. Tomikawa, Jpn. J. Appl. Phys., Part 1 **38**, 3342 (1999).
[12]J. Satonobu, D. Lee, K. Nakamura, and S. Ueha, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **47**, 216 (2000).
[13]T. Ishii, T. Shinkoda, S. Ueha, K. Nakamura, and M. Kurosawa, Jpn. J. Appl. Phys., Part 1 **35**, 3281 (1996).
[14]T. Ishii, H. Takahashi, K. Nakamura, and S. Ueha, Jpn. J. Appl. Phys., Part 1 **38**, 3338 (1999).
[15]A. E. Glazounov, S. Wang, Q. M. Zhang, and C. Kim, Appl. Phys. Lett. **75**, 862 (1999).
[16]W. Qiu, Y. Mizuno, D. Koyama, and K. Nakamura, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **60**, 786 (2013).
[17]H. Czichos, *Tribology—A System Approach to the Science and Technology of Friction, Lubrication and Wear* (Elsevier Scientific Publishing Company, New York, 1978).