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Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)
16-18 November, 2016

Torque improvement of polymer-based ultrasonic motor through optimal design of vibrator structure
ポリマー振動子を用いた超音波モータのトルクの向上の設計

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1. Introduction

Nowadays, rehabilitation robots and assist suits are attracting much attention of the countries facing the aging problems. A lightweight ultrasonic motor (USM) is suitable as the elbows or knees of these robots because it can reduce the weight of these robots. Our group has employed poly (phenylene sulfide) (PPS), a low-mechanical-loss polymer, to fabricate a ring-shaped vibrator, and formed a lightweight traveling-wave USM [1]. However, it yielded a torque of 0.7 mNm, and the application of this PPS-based USM was restricted. In this study, we improve the strcuture of the ring-shaped vibrator in order to increase the torque of the polymer-based USM.

2. Principle

In theory, if the preload applied to the rotor is sufficient, the maximum torque increases linearly with increasing voltage (**Fig. 1**), and the ratio of the maximum torque to the driving voltage is in proportion to the force factor [2]. Thus, under a certain voltage, it is feasible to obtain a higher torque by increasing the force factor, which is defined as the ratio of the output force to the applied voltage, or the ratio of the current to the vibration velocity. The force factor is generally determined by the piezoelectric parameters of the piezoelectric ceramic element and the vibrator structure.

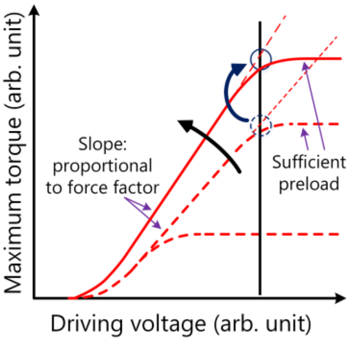

Fig. 1 Conceptual view of maximum torque versus driving voltage. Supposing that a sufficient preload is applied, the maximum torque increases with increasing force factor.

3. Model of USM

Though the torque of USM is generally determined by the outer diameter of the vibrator [2], other dimensions also affect the torque. In this study, we chose a 30-mm-diameter ring-shaped vibrator (**Fig. 2**), and considered several key dimensions: the thickness of the elastic plate and piezoelectric ceramic annular disk, t and p; the projection (teeth) height, h; and the slot width, w. For a bending vibrator with a certain diameter, t and p have significant influence on the force factor. As the first step of this study, we investigate how the force factor varies with the elastic-plate thickness, t, when the thickness of the piezoelectric ceramic annular disk, p, is fixed.

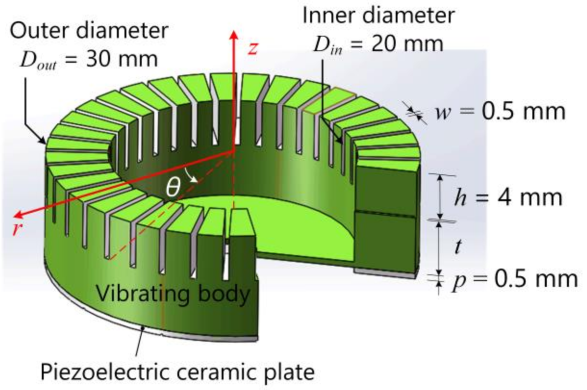

Fig. 2 Vibrator structure and key dimensions

4. Simulation

A simulation was performed to estimate how the force factor changed with the thickness of the elastic plate through the finite element analysis (FEA). The model is depicted in **Fig. 2**. The 0.5-mm-thick piezoelectric ceramic annular plate is evenly divided into 12 parts along the tangential direction (θ-axis). Thus, the 3rd bending mode is efficiently excited in this vibrator. The vibrating body is made of PPS, of which the elastic modulus, Poisson's ratio, and density are 3.45 GPa, 0.36, and 1.35×10^3 kg/m^3, respectively. The damping coefficient of this vibrator was set to 0.003 (Q_m = 150). In this model, the force factor is calculated as the ratio of the current flowing through the electrode of the piezoelectric ceramic plate to the

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maximum tangential vibration velocity in the θ-axis.

The simulation result is shown in **Fig. 3**. As the elastic-plate thickness varied from 1 to 10 mm, the force factor increased from 0.01 to 0.23 N/V.

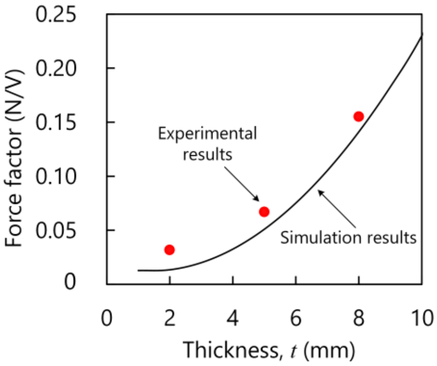

Fig. 3 Simulation results: force factor as a function of elastic-plate thickness.

5. Experimental results

We fabricated four USMs with the vibrators having the elastic-plate thickness of 2, 5, 8, and 10 mm (defined as t2, t5, t8, and t10 USMs). First, the force factors were measured and plotted in **Fig. 3**. As the thickness became higher, the force factor increased, which was in agreement with the simulation results. Then, the maximum torques of the t2, t5, and t8 USMs were measured. At the driving voltage of 250 V, the maximum torques of the t2, t5, and t8 USMs reached 0.9, 1.2, and 3.0 mNm, respectively (**Fig. 4**). As predicted, the maximum torque increased as the elastic-plate thickness became higher owing to the increasing force factor. However, the maximum torque of the t10 USM dropped to lower than 0.5 mNm. The low torque of t10 USM is thought to be attributed to the unwanted vibration in the radial direction (r-axis). **Figure 5** shows that the vibration-velocity ratio in the r-axis to that in the z-axis increased because of the increasing bending stiffness in the z-axis. The high slip between the vibrator and the rotor in the r-axis (**Fig. 6**) leads to the high friction loss, which resulted in the reduction in the USM torque [3].

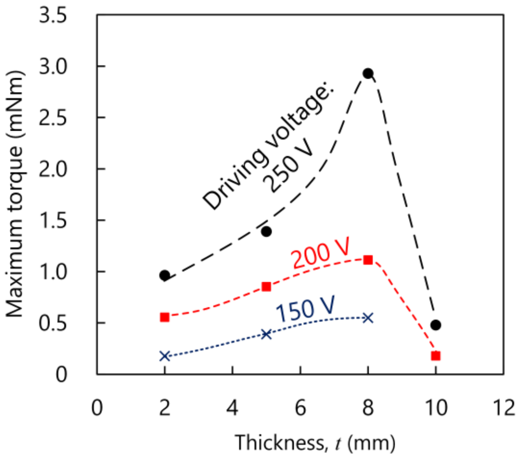

Fig. 4 Experimental results: maximum torque vs. driving voltage at different driving voltage.

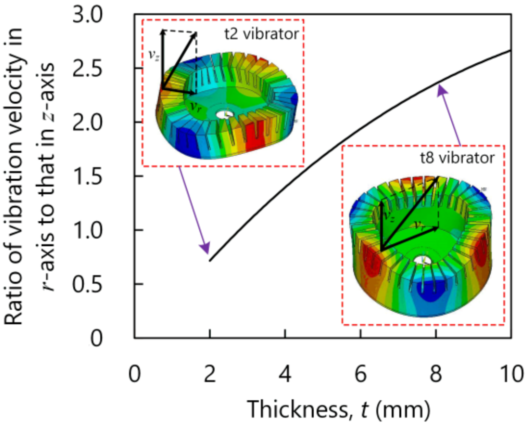

Fig. 5 Simulation results: ratio of vibration velocity in r-axis to that in z-axis.

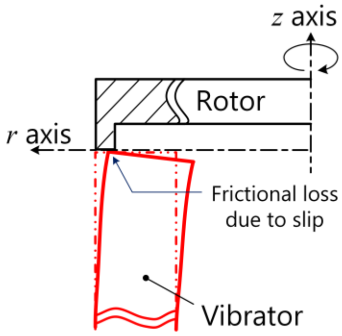

Fig. 6 Frictional loss caused by slip along r-axis.

6. Conclusion

In this study, we analyzed how the force factor and the USM torque varied with the elastic-plate thickness through simulation and experiments. At the driving voltage of 250 V, the maximum torque of the 30-mm-diameter PPS-based USM reached 3.0 mNm, which was the highest among the tested USMs with different elastic-plate thickness.

Acknowledgment

The authors are indebted to the Daicel Corporation for providing polymer samples in this study. This work was supported by the Adaptable and Seamless Technology Transfer Program, A-step, Grant Number AS2711904S, from the Japan Science and Technology Agency, JST.

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