Traveling wave ultrasonic motor using polymer-based vibrator

Jiang Wu, Yosuke Mizuno, Marie Tabaru, and Kentaro Nakamura

Precision and Intelligence Laboratory, Tokyo Institute of Technology, Yokohama 226-8503, Japan

*E-mail: wujiang@sonic.pi.titech.ac.jp

Received September 25, 2015; accepted October 19, 2015; published online November 25, 2015

With the characteristics of low density, low elastic modulus, and low mechanical loss, poly(phenylene sulfide) (PPS) is a promising material for fabricating lightweight ultrasonic motors (USMs). For the first time, we used PPS to fabricate an annular elastomer with teeth and glued a piece of piezoelectric-ceramic annular disk to the bottom of the elastomer to form a vibrator. To explore for a material suitable for the rotor surface coming in contact with the PPS-based vibrator, several disk-shaped rotors made of different materials were fabricated to form traveling wave USMs. The polymer-based USM rotates successfully as the conventional metal-based USMs. The experimental results show that the USM with the aluminum rotor has the largest torque, which indicates that aluminum is the most suitable for the rotor surface among the tested materials.

© 2016 The Japan Society of Applied Physics

Having the characteristics of low speed, high torque, and quick response, ultrasonic motors (USMs) have been applied to robots and optical instruments. A lightweight and powerful actuator is highly required to decrease the weight of the mechanical system and increase operability. Using polymers as the main body of USMs is a potentially feasible method to obtain a lightweight USM because some newly invented functional polymers have low densities and excellent workability. However, to the best of our knowledge, polymers have not been used as the elastomer in USMs because polymers usually have large attenuations for ultrasonic waves. In our recent report, through the mechanical-loss evaluation of some functional polymers, we concluded that the mechanical quality factor of poly(phenylene sulfide) (PPS) reaches 450, which indicates that PPS is potentially applicable to USMs. In this study, we used PPS as the elastomer to fabricate an annular vibrator and glued a piece of ring-shaped piezoelectric ceramic element to the bottom of the PPS-based elastomer to form a vibrator. When two voltage sources with a 90° phase difference are applied, a traveling wave is generated on the vibrator, and thus, the rotor pressed on the top of the vibrator is driven to rotate. Because the surface of the rotor coming in contact with the PPS-based vibrator also has influence on the motor performance, we tried using some typical metals and functional polymers for rotors and experimentally evaluated the mechanical characteristics of the USMs in order to find the material suitable for the rotor surface in contact to the PPS-based vibrator.

Figures 1(a) and 1(b) show the structure of the USM and the dimensions of the vibrator. The elastomer of the vibrator is made of PPS, whose mechanical parameters are listed in Table I. One piece of the ring-shaped piezoelectric ceramic element (Fuji Ceramics C213) with a thickness of 1 mm and a diameter of 28 mm, is glued to the bottom of the elastomer using epoxy. The outer diameter of the vibrator is 28 mm and the width of the contacting part is 3 mm. 36 teeth with 2 mm depth are formed for the contacting part. The method of exciting traveling waves and the working principle of the motion are the same as those of the conventional metal-based USM. As Fig. 1(c) shows, the electrodes are divided into ten parts along the circumference, which is as long as five wavelengths. The polarization directions alternate every half wavelength and two parts with 1/4 and 3/4 wavelengths are set without polarization. Being separated by the 1/4- and 3/4-wavelength slots, the electrodes are divided into two groups. With two channels of sinusoidal driving voltages applied to the two groups, two standing waves with a 90° phase difference in space are generated. Figure 1(d) shows the 4th-order bending mode, which is generated on the vibrator in the experiments stated later. When the phase difference between the voltages is set to 90°, traveling waves are generated. Thus, a rotor pressed on the top of the vibrator is driven to rotate by the traveling waves. To select the material suitable for the rotor is also an objective of this study. The disk-shaped rotors were fabricated using poly(ether ketone) (PEEK), polyacetal (POM), PPS, aluminum, and stainless steel, whose structures are shown in Fig. 1(a).
The vibration characteristics of the polymer-based vibrator were measured. Using a laser Doppler velocimeter (Polytec NLV1232), the vertical vibration velocities were measured at one point of the outer edge by sweeping the frequencies from 28.70 to 28.95 kHz. Figure 2 shows the dependence of vertical vibration velocity on driving frequency at a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.

Next, we placed a PPS-based rotor on the vibrator to determine whether a traveling wave is generated on the vibrator. When the phase between the two voltages was varied, the rotation velocity was measured using a high-speed camera (Integrated Designed Tools M5) at a driving frequency of 28.82 kHz and a zero-to-peak voltage of 180 V. The vibration velocity reaches its peak at a driving frequency of 28.82 kHz. The mechanical quality factor $Q$ of the vibrator is calculated to be 262 using

$$Q = \frac{f_0}{\Delta f},$$

where $f_0$ and $\Delta f$ represent the resonance frequency and bandwidth for $1/\sqrt{2}$ of the amplitude, respectively.
tested USMs, aluminum is considered to be the material suitable for forming the surface of a rotor coming in contact with the PPS-based vibrator among the tested materials. The maximum torque is determined by preload, friction coefficient, and arm length (the distance between the action point and the axis). As the arms are the same in length in all experiments and the preload is set to be approximately the same, the maximum torque should be mainly related to the effective friction coefficient on the contacting surface between the vibrator and the rotor. The effective friction coefficient between the PPS-based stator and the metal-based rotor is larger than that between the PPS-based stator and the polymer-based rotor.

In practice, to reduce the weight of the USM, polymers are suitable choices as the main body of the rotor because of their low densities. On the other hand, an aluminum annular thin sheet as the friction material should be attached to the bottom of the polymer-based rotor to increase the friction.

In this study, PPS is used as the elastomer in USM and the weight of the elastic body was largely reduced. However, the torque of the prototype USM is 0.05 times smaller than that of the commercial metal-based USMs with the same diameter. The vibration velocity of the polymer-based vibrator decreases sharply as the preload increases and only a small preload can be applied to this vibrator. This unique phenomenon for the polymer-based vibrator needs to be investigated in the future. Meanwhile, some low-density piezoelectric materials should be used to reduce the weight of USMs.

Acknowledgment The authors thank Daicel Corporation for providing some polymer samples tested in this study.