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BRIEF NOTE

Traveling wave ultrasonic motor using polymer-based vibrator

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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.

Having the characteristics of low speed, high torque, and quick response, ultrasonic motors (USMs) have been applied to robots and optical instruments.[1–15] 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.[16–19] However, to the best of our knowledge, polymers have not been used as the elastomer in USMs because polymers usually have large attenuations for ultrasounds. 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,[20] 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 ether ketone) (PEEK), polyacetal (POM), PPS, aluminum, and stainless steel, whose structures are shown in Fig. 1(a).

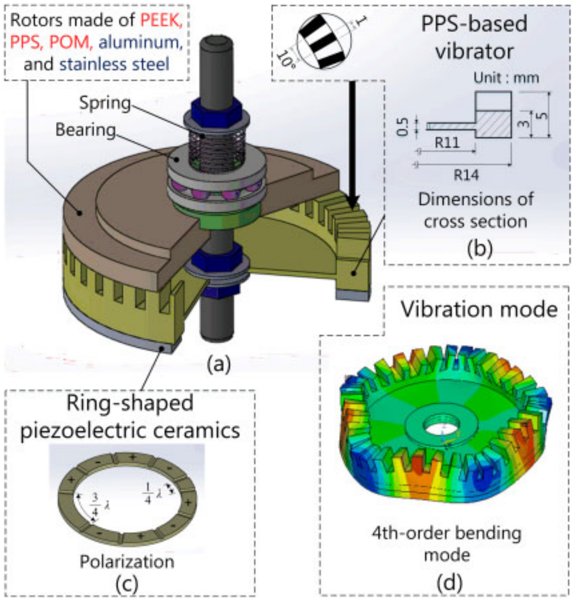

Fig. 1. (Color online) (a) Structure of the traveling wave rotary USM, (b) dimensions of the PPS-based ring-shaped vibrator with teeth, (c) polarization of the piezoelectric ceramic element, and (d) 4th-order bending mode of the vibrator.

Table I. Mechanical parameters of the tested PPS.

Density ($10^3\,kg/m^3$)	1.35
Elastic modulus (GPa)	3.45
Poisson's ratio	0.36

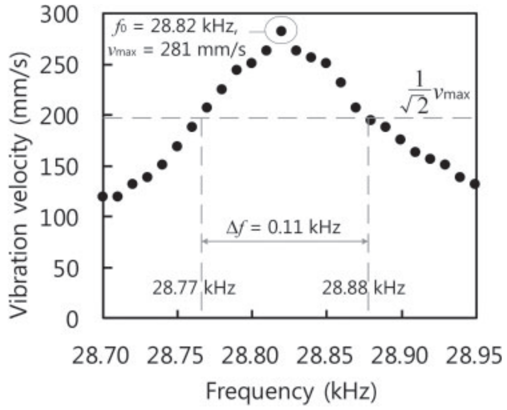

Fig. 2. Vibration velocity at one point at external edge of the vibrator as a function of driving frequency.

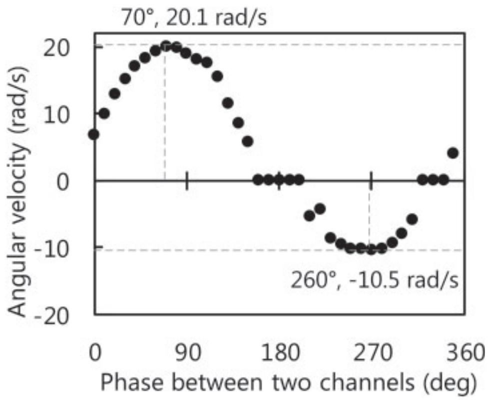

Fig. 3. Angular velocity as a function of phase difference between two channels of voltages.

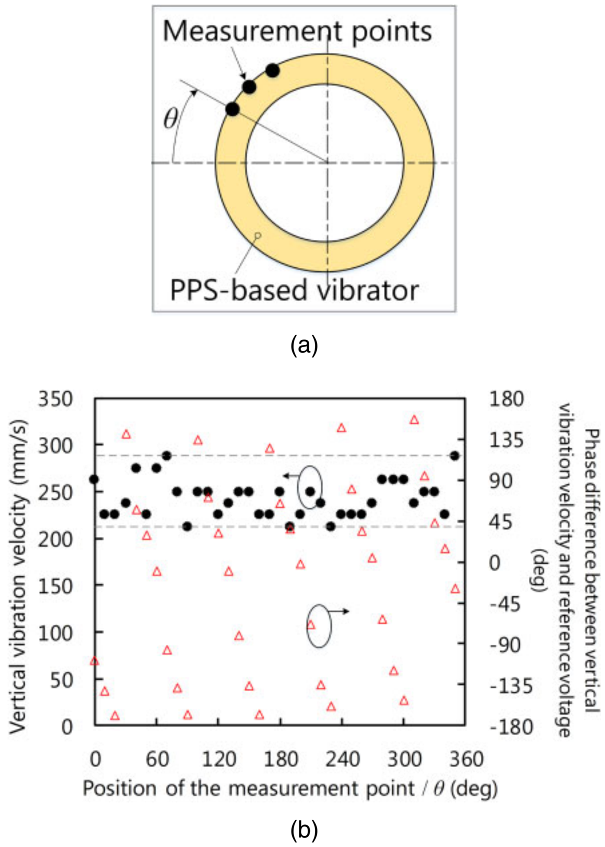

Fig. 4. (Color online) (a) Position of vertical-vibration-velocity measurement and (b) vibration velocity distribution on external circumference.

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

$$Q = \frac{f_0}{\Delta f}, \quad (1)$$

where f_0 and Δf 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. Similarly to the conventional USM with the metal-based vibrator, the prototype USM rotated clockwise and counterclockwise as the phase difference changes. Figure 3 shows that the angular velocity reaches maximum in clockwise and counterclockwise directions at the phases of 70 and 260°, respectively. The maximum speed in the counterclockwise direction is approximately half of that in the clockwise direction because of some irregularities in assembly. At the driving frequency of 28.82 kHz and the phase of 70°, the vibration velocity distribution on the circumference of the vibrator was measured. The amplitude and phase were measured using the laser Dropper velocimeter and a lock-in voltmeter (NF Electronic Instruments 5560), respectively. The driving voltage for one channel was used as a reference signal to the lock-in voltmeter. Figure 4 shows that the phase varies from −180 to 180° almost linearly five times, which indicates that a traveling wave of five wavelengths is generated on the vibrator. On the other hand, the maximum and minimum velocities (v_{max} and v_{min}) are 287 and 212 mm/s, respectively. Thus, the standing wave ratio is 1.35, which indicates that the existence of a standing wave is satisfactorily small.

To discuss the motor performance, we summarized the mechanical characteristics for the USMs with the rotors made of different materials under approximately the same preloads. The driving frequency, zero-to-peak voltage, and phase difference were set to be 28.82 kHz, 180 V, and 70°, respectively. Figure 5 shows the mechanical characteristics of the tested USMs. The no-load angular velocity of the USM with the PPS-based rotor reaches 18 rad/s, which is higher than those of the other USMs. The angular velocities of the USMs with the PPS-, POM-, and PEEK-based rotors decrease sharply as the preload increases and fell to zero when the torque reaches approximately 200 μNm. The maximum torques of the USMs with the aluminum- and stainless-steel-based rotor are 670 and 500 μNm, which are larger than those of the USMs with polymer-based rotors. As the USM with aluminum-based rotor has a larger torque than the other

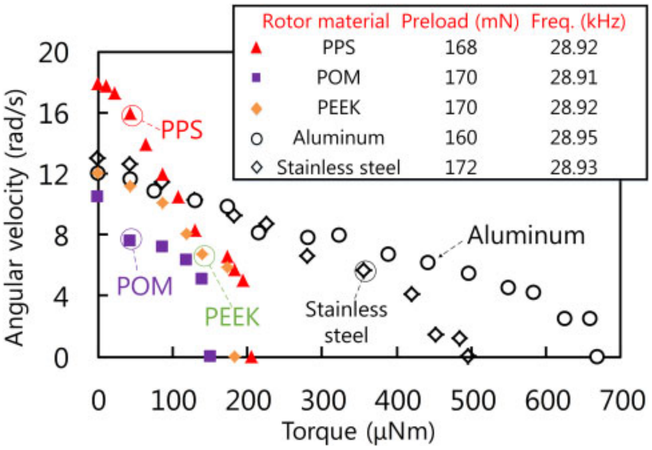

Fig. 5. (Color online) Mechanical characteristics of USMs with the PPS-, POM-, PEEK-, aluminum-, and stainless-steel-based rotors.

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).[1] 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.

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