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Design and performances of high torque ultrasonic motor for application of automobile

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Abstract We propose an ultrasonic motor of high torque with a new configuration for application in automobiles. The newly designed stator is a two sided vibrator consisting of a toothed metal disk with a piezoelectric ceramic ring bonded on both faces of the disk which generates a flexural traveling wave along the circumference of disk. In this configuration, the displacement on the surface of stator may not be confined. It also produces a large vibrating force and amplitude because the vibrator is sandwiched by two piezoelectric plates. It is possible to increase the torque by improving the vibration characteristics. We used the finite element method to compute the vibration mode of the motor of diameter 48 mm. A sixth mode was chosen as the operation mode with a resonance frequency of about 73 kHz. We fabricated a prototype according to this design and measured its performance. The performance measurement of the prototype motor showed that its stall torque was about 1.8 Nm and efficiency was 37% at 60% of the maximum torque. Compared to a conventional motor which employed a single sided piezoelectric vibrator of the same outer diameter, we obtained, with this prototype, a maximum torque of about twice as great. The motor may be useful to apply as an actuator in a mobile car.

Keywords Ultrasonic motor · Traveling–wave type motor · Two sided motor · High torque

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1 Introduction

Electromagnetic motors, such as permanent magnet motors, have been widely used as core parts of automobiles. These motors usually have high energy efficiency at low torque and a high speed range. So if these motors are set in automobiles, a gearbox is required to maintain a high torque at low speed. The gearbox makes it difficult to miniaturize mechanical equipments and to achieve high accuracy due to backlash.

As compared with an electromagnetic motor, the ultrasonic motor has some significant features. It has a suitable construction for direct-driving mechanism without gears and it can produce high torque at a low speed range despite of its relatively compact size. These features solve several problems and expand the range of practical applications.

The motor also has a number of advantages such as low profile, low power consumption, simple structure, high controllability (high resolution), and so on [1–3].

It would therefore appear that ultrasonic motors have the potential for use as actuators for functional automotive components. However, these applications are limited at

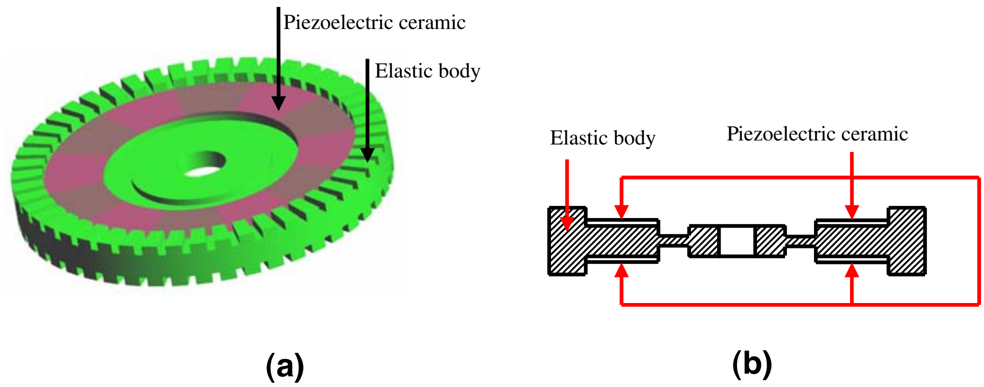

Fig. 1 The shape of a new type stator: (**a**) a full view, (**b**) the cross section

present because the currently available ultrasonic motors do not provide sufficiently high torque and power [4]. If ultrasonic motors can produce a higher torque, they would have wider applications.

For example, they may be used for window lifts, windshield wipers, or seat movers of a mobile car. Traveling wave type ultrasonic motors with high torque have been studied by many researchers.

As a result of notable research, 70～100 mm-diameter traveling wave type ultrasonic motors with stall torque of 2～4 Nm was developed [4–6]. However, despite enough torque, it is difficult to apply these motors as actuators in mobile cars because of their very big sizes.

To be used as parts of an automobile, it is not only important to obtain high torque but also to downsize structure. So, the motor is required to have an increasing torque density along with reduced size.

In principle, a stall torque of traveling wave type ultrasonic motor is proportional to the cube of the diameter. For that reason, motors are expected to produce higher torque are likely to become larger in size.

In order to solve this problem, we focused our research on reducing the mass and size of a motor while keeping up a certain level of torque. We designed and fabricated prototype motor for being appropriate parts automobiles. The maximum torque and diameter is 2 Nm and 48 mm, respectively.

We selected a traveling wave type ultrasonic motor as base model. We designed a new type stator and carried out experiments on improving vibration characteristics of the motor in this study.

A typical traveling wave type ultrasonic motor consists of a stator and rotor. The stator includes a piezoelectric ceramic plate to excite flexural wave and teeth structure to enlarge the displacement due to vibration of piezoelectric ceramic plate. A piezoelectric ceramic plate is bonded to one side of the stator. An electrical input signal is applied on the piezoelectric ceramic plate, the flexural traveling wave is excited, and the movement of a point in the surface of the stator shows an elliptical trajectory. The rotor is contacted with another side of the stator, pressed against the stator with a normal force and rotated by a propulsive force due to the flexural wave of stator.

The tangential component of the displacement of the stator at the contact interface by the flexural wave is converted to frictional force between stator and rotor. As

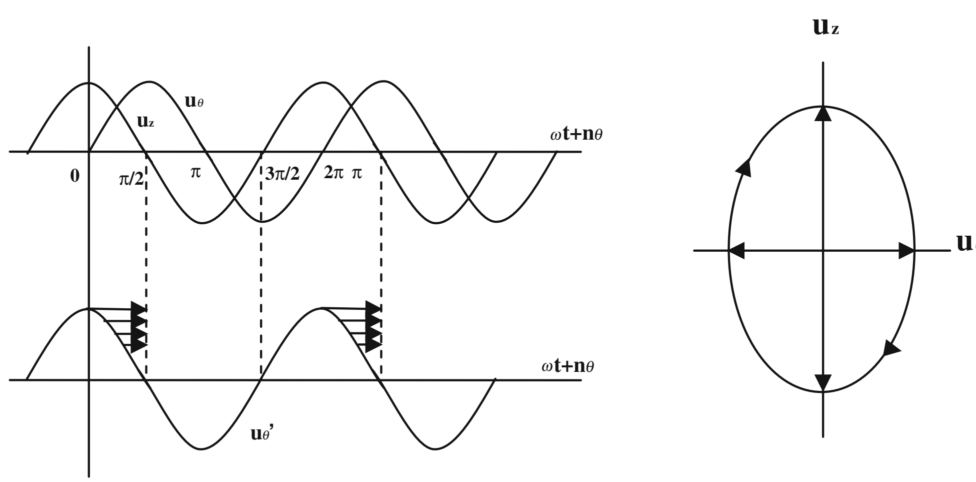

Fig. 2 Elliptical trace

Table 1 Piezoelectric and dielectric properties of the PZT–PMNS ceramic.

Characteristics		Units	Measured value
Electro-mechanical coupling factor, k_r		%	58
Mechanical quality factor, Q_m			1500
Piezoelectric constant	d_{33}	pC/N	340
	d_{31}	pC/N	−120
Frequency constant, N_p		Hz m	2100
Relative dielectric constant, $\varepsilon_{33}/\varepsilon_0$			1300

friction is enhanced, or tangential displacement of the stator is increased, or diameter of stator is increased, the torque of the motor may be increased. In this research, we tried to increase the displacement of the stator in order to improve the torque of the motor.

In this way, we designed this new motor for the actuator in mobile car.

Based on simulation results for the vibration of the motor, we made a prototype ultrasonic motor, measured its performance, and discussed the results.

2 The shape and principle of operation

Figure 1 shows the construction of the newly designed stator. The stator (vibrator) is made of a phosphor bronze plate with 48 teeth. We bonded two sheets of annular piezoelectric ceramic plates on the lower and the upper surface of a metal plate. The piezoelectric ceramic ring was divided into six positively and six negatively poled regions. These piezoelectric elements were arranged in such a way that their poling pattern deviated from each other by a quarter of a wavelength in order to generate a traveling wave along the circumference of the stator.

When a two phase voltage is applied to the upper and the lower piezoelectric ceramic plate respectively, a traveling wave is generated in the stator by superimposing two standing waves that are excited by the sinusoidal voltage of phase A and phase B with a phase difference of 90°.

In a conventional traveling wave ultrasonic motor, the radial position bonded piezoelectric plate in the stator is the same radius with the ones contacted in the rotor.

At this time, the displacement of particle of stator shows an elliptical trace. Figure 2 indicates this actual state.

If components of elliptical motion put up u_z, u_θ, $u_\theta{}'$ individually, these have the following relationships:

$$u_z = (-u_0)\cos(\omega t + n\theta)$$

$$u_\theta = (z)\frac{n}{\gamma}(-u_0)\sin(\omega t + n\theta)$$

$$u_\theta{}' = \omega(z)\frac{n}{\gamma}(-u_0)\cos(\omega t + n\theta)$$

The frictional force F between stator and rotor is:

$$F = \mu n S_e u_z$$

The mechanical force P that affected to the rotor is:

$$P = \frac{1}{T}\int F u_\theta{}' dt = \frac{1}{T}\int \mu n S_e \frac{\omega(z)n}{\gamma}(-u_0)^2 \cos(\omega t + n\theta)dt$$

μ the coefficient of friction
n the number of contact points between stator and rotor
S_e the equivalent stiffness by variation of frictional material

From these equations, we take cognizance of the significance of the vibration amplitude and torque.

In the conventional type of stator, the radial position of piezoelectric plate and the teeth of stator are identical. Accordingly, the vibration of piezoelectric ceramic is re-

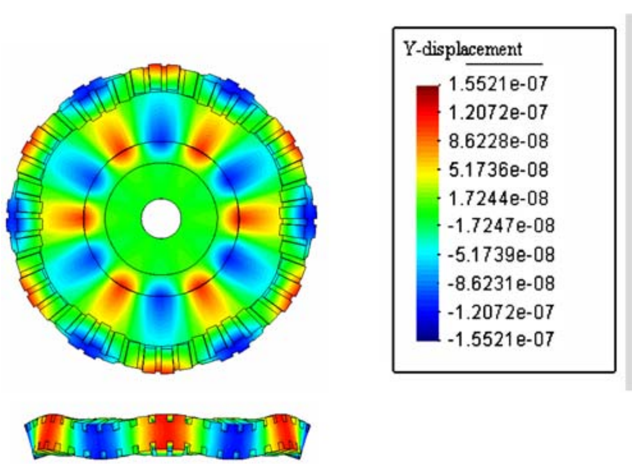

Fig. 3 The distribution of displacement in the stator

Fig. 4 The stator of the prototype motor

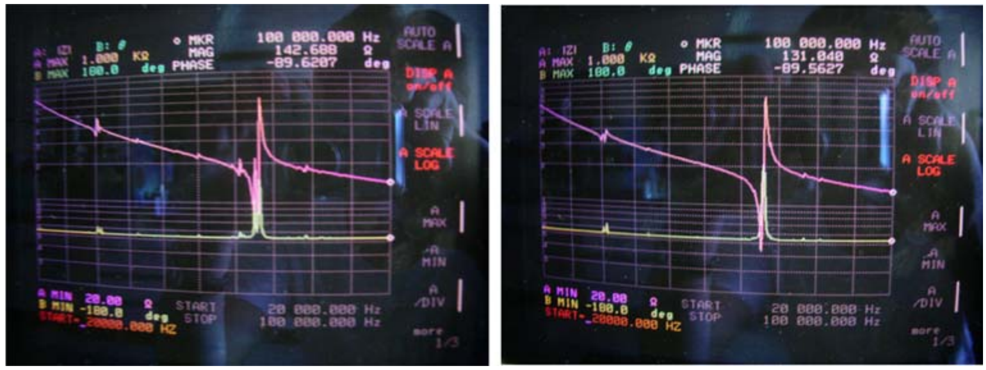

Fig. 5 The impedance characteristics of the stator (both sides)

stricted directly by the pressure of the rotor. The amplitude of wave which generated at piezoelectric plate and the displacement on the surface of stator are usually confined due to pressing of the rotor against the stator.

In the improved type of stator, the radial position of those two parts are different. The amplitude of wave which is generated at piezoelectric plate may not be confined. It also produces a large vibrating force and amplitude. Moreover, the vibrator is sandwiched by two piezoelectric plates. It is possible to increase the torque through improving the vibration characteristics. The two sided design of vibrator has already been suggested by a Massachusetts Institute Technology group for high torque ultrasonic motor [4]. They used the vibrator as rotor and used brushes for application of voltage to the vibrator.

3 Vibration analysis

We used a numerical simulation of the motor to verify and validate its design and we verified the operational principle through a modal and harmonic analysis. Finite element modeling package ATILA was employed in the simulations. The model consisted of an elastic metal disk and two piezoelectric rings.

Properties of the materials used for the motor are listed in Table 1. Phosphor bronze was used for the elastic body. From modal analysis results, it is determined that flexural resonance mode was B16 and its operational frequency was 72.4 kHz.

Harmonic analysis was carried out to find out the distribution of the displacement. The results for the displacement distribution are shown in Fig. 3. In this figure, we can find the sixth vibration mode (B16) at the circumference of the stator. The displacement at the inner circumference is generated by excitation of the piezoelectric plate.

The displacement at the outer circle, which is in contact with rotor, shows same pattern with the inner ones. The difference of the spatial phase is 180° between the outer and inner patterns of displacement. We also found out that a traveling wave was induced at the stator.

In Fig. 3, the unit of Y-displacement value is [m].

4 Prototyping of the motor and its performance

According to the above analysis results, We succeeded in designing and fabricating a 48 mm diameter prototype motor. The piezoelectric ceramic was fabricated using a $0.9Pb(Zr_{0.51}Ti_{0.49})O_3{-}0.1Pb(Mn_{1/3}Nb_{1/3}Sb_{1/3})O_3+0.05Cr_2O_3$ composition[7] in order to make the ultrasonic motor used in this study. We used a conventional method for fabrication.

To increase the dielectric and piezoelectric property remarkably, the Lead zirconate titanate (PZT) and Lead-Manganate-Niobate-Antimonate (PMNS) were mixed. PbO,

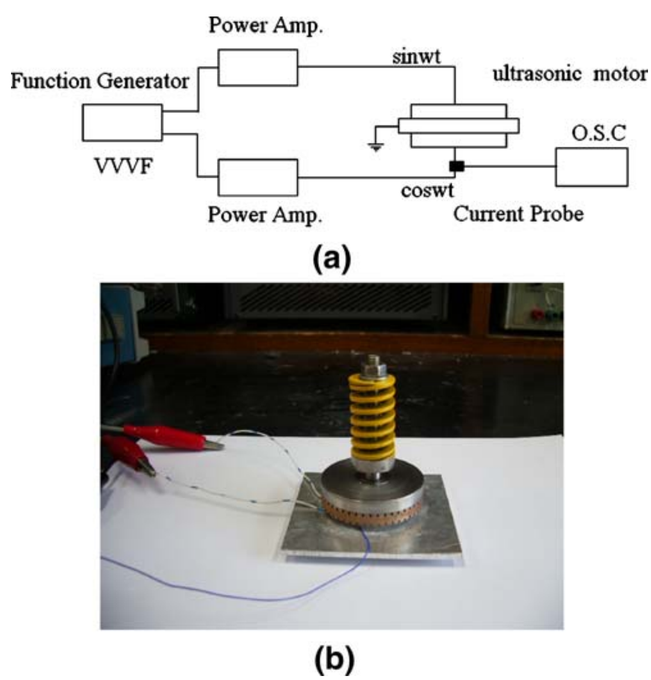

Fig. 6 The driving system of the ultrasonic motor: (**a**) driving system diagram, (**b**) pressurization form

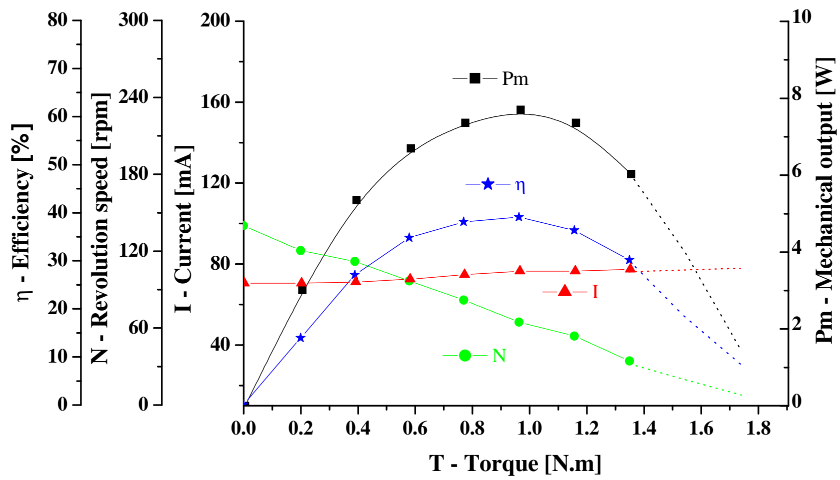

Fig. 7 The output characteristics of the prototype motor

ZrO_2, TiO_2, MnO_2, Nb_2O_5, Sb_2O_3, and Cr_2O_3 were synthesized by using the mixed method, and sintered at 1200 °C in air for 2 h. The mixing ratio was determined by considering morphotropic phase boundary. Cr_2O_3 was added to raise the mechanical quality factor (Q_m) and to drop the dielectric loss (tan δ).

This material can be used in other piezoelectric device because of high mechanical quality factor, high electromechanical coupling factor (k_r), and low dielectric loss.

Its piezoelectric and dielectric properties are listed in Table 1. The piezoelectric ceramic was fabricated to an annular type plate 25 mm in inner diameter, 40 mm in its outer diameter and 0.3 mm in thickness. The thickness of phosphor bronze elastic body was 2.4 mm, the outer diameter was 48 mm and teeth height was 1.3 mm both sides. Teeth structure was fabricated through the processing of metal by using wire cutting method.

The piezoelectric ceramic plate was bonded on the upper and the lower surfaces of the elastic disk for the stator. A quick glue was used in bonding process (Loctite 648). Two piezoelectric ceramic plates were adhered to elastic body at a normal temperature for 3 h. The stator of the prototype motor assembled at the base is shown in Fig. 4.

The resonant frequency of the stator was measured by an impedance analyzer (HP 4194A Impedance/Gain-Phase Analyzer). Its value was about 73 kHz. This result is shown in Fig. 5. The performance of the motor was measured by means of simulation and measurement were very close.

The performance of the motor was measured by the driving system shown in Fig. 6(a). The driving system was composed of Function Generator (HP 3245A, Universal Source), Power Amplifier (NF 4015, High Speed Power Amplifier), Oscilloscope (Tektronix TDS 3032B) and so on. Figure 6(b) shows pressurization form. The pre-load was calculated by using the modulus of elasticity and contraction length of spring. The value was 300N. The voltage applied on the piezoelectric plate was 120 V_{rms}.

In Fig. 6(a), the meaning of 'VVVF' is 'variable voltage and variable frequency', 'O.S.C' is 'oscilloscope'.

The measurement result shows that its stall torque is about 1.8 Nm and the maximum rotation speed without load is about 140 rpm as shown in Fig. 7. The high efficiency shows 37% at about 60% of stall torque and maximum output power of about 7.7 W.

The prototype motor was compared with a one-sided traveling wave type motor, USR60. This one-sided motor is already available commercially from Shinsei, Japan. Its elastic body is made of phosphor bronze, its diameter is 60 mm, and it has 72 teeth. One piezoelectric ceramic plate is bonded to the lower surface of its stator. It produces a traveling wave with nine-wavelength.

The maximum torque is 1 Nm, the no-load speed is 150 rpm in voltage condition of 130 V_{rms} and 40 kHz. The efficiency is about 35%. These characteristics are shown in Table 2.

Table 2 The motor performance of this study's motor and a commercial product (operating manual, http://www.shinsei-motor.com).

Characteristics	Units	This work	USR60
Diameter(motor size)	Mm	48	60
Operational voltage	V_{rms}	120	130
Operational frequency	kHz	72.3	40
Rotational speed(no load)	Rev/min	140	150
Maximum torque	Nm	1.8	1
Output power	W	7.7	5.0
Efficiency	%	37	35
Remarks		Two sided stator	Shinsei Co., one sided stator

The maximum torque of prototype motor is about twice as high compared to conventional type motor with the similar diameter. But the rotational speed of prototype motor is slightly less than the conventional ones.

5 Conclusion

In this paper, we proposed a new configuration of traveling wave type ultrasonic motor for high torque. To improve the interaction between the stator and the rotor, a new configuration of a two sided vibrator was used as the stator. The displacement of the surface of the stator may not be confined in this configuration. It also produces a large vibrating force and amplitude because the vibrator is sandwiched by two piezoelectric plates. It is possible to increase torque with improving the vibration characteristics without increasing the size of the motor. A 48 mm diameter prototype traveling wave type ultrasonic motor was designed by FEM simulation and fabricated.

The performance measurement on the prototype motor shows that its stall torque was about 1.8 Nm and the efficiency is 37% at 60% of the maximum torque. The motor may be useful to apply as an actuator in a mobile car.

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