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Development and analysis of a longitudinal and torsional type ultrasonic motor with two stators

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Abstract

In this paper, a new longitudinal and torsional type ultrasonic motor with two stators is presented and investigated. Normally, such a motor consists of one rotor and one stator, and two types of transducers that are longitudinal PZT and torsional PZT are used to generate the desired elliptical locus on the stator surface. The operating frequency is at the resonance frequency of torsional transducer. In order to enhance the efficiency of the motor, however, the resonance frequencies of both transducers should be closed to each other. For the purpose of matching the resonance frequencies, a symmetrical structure is adopted in design of the motor. Furthermore, two rings are added to the stators in order to adjust the resonance frequencies of these two transducers. A finite element model is developed and ANSYS software is used to analyze the resonance frequencies of longitudinal vibration and torsional vibration as well as optimize the motor geometry. According to the FE results, an experimental prototype is fabricated and the experimental results agree well with the theoretical predictions.

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1. Introduction

Ultrasonic motors have excellent performance and many useful features such as high holding torque, high torque at low speed, quiet operation, simple structure, compactness in size and no electromagnetic interferences. It may be widely used as actuators for robots,

cameras, precise positioning devices, machines in space and medical treatment devices [1,2].

A longitudinal and torsional type ultrasonic motor uses longitudinal and torsional PZT transducers to generate the desired elliptical orbit of the stator surface. Compared to a traveling wave ultrasonic motor, this motor belongs to a standing wave motor and can produce larger output torque. Since Ueha [3] firstly proposed such motor in 1980s, more attentions have been attracted in this motor and various attempts to improving its performance have been reported in Refs. [4–11]. Generally, a longitudinal and torsional type ultrasonic motor operates at the resonance point of torsional vibration to achieve a long stroke in tangential direction and obtain a high efficiency. However, the normal force generated by longitudinal vibration is also important to enhance the output torque. It generates frictional force

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to drive the stator at the interface between rotor and stator. Normally, there are two ways to increase the normal force: one is to enlarge the contact area of rotor and stator; the other is to make the longitudinal and torsional transducer have an identical resonance frequency. Due to the different sound propagation speed of longitudinal and torsional vibrations within a motor, however, it is difficult to match the resonance frequency of longitudinal and torsional vibrations [12]. In order to improve such motor, several methods to matching the resonance frequencies of longitudinal and torsional vibrations have been proposed in Refs. [13–16].

In this paper, a new longitudinal and torsional type ultrasonic motor using one rotor and two stators is proposed and investigated. For the purpose of enlarging the contact area, the rotor is placed in the middle of the motor and is driven by two stators. A method, adding two rings to the outside circumference of two stators respectively, is proposed to adjust the resonance frequencies of longitudinal and torsional vibrations. A FE model of stator is developed to analyze the resonance frequencies of longitudinal vibration and torsional vibration as well as optimize the motor geometry. Finally, a prototype of the present motor is fabricated according to the FE results.

2. Working principle

The structure of present motor is shown in Fig. 1. The present motor consists of one rotor and two stators, in which the inverse piezoelectric effect is used to excite two orthogonal vibrations modes: one is longitudinal vibration excited by longitudinal transducer L-PZT and the other is torsional vibration excited by torsional transducer L-PZT. For the operation of the motor, the first mode of longitudinal vibration and the first mode of torsional vibration are used (see Fig. 1). When these two vibrations are excited, two stators extend and contract simultaneously. By pressing two stators against

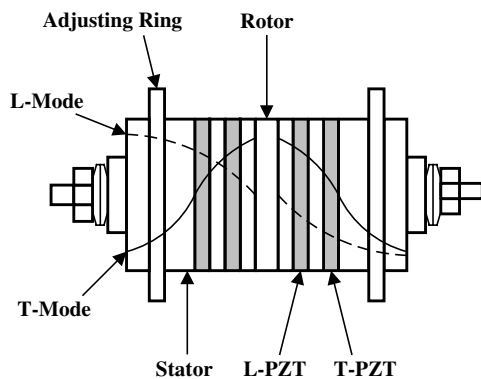


Fig. 1. Sketch of a longitudinal and torsional ultrasonic motor with two stators.

the rotor with a certain pre-load, friction forces between rotor and stator occur and lead to the rotor rotation. Obviously, the contact area between rotor and stator of the present motor is two times as large as the previous hybrid ultrasonic motor with one stator. Therefore, the present motor can produce much larger friction force on the contact areas. In addition, two adjusting rings are added to the outside circumference of two stators to support motor and to adjust the resonance frequencies of the vibrations excited in stator.

By applying the AC voltages V_L and V_T , the first longitudinal mode and the first torsional mode can be excited in the stator, respectively. Considering that the excitation is harmonic in time, the displacement of a point on stator surface is given by

$$U_\theta(t) = A_1 \sin \omega t \quad (1)$$

$$U_Z(t) = A_2 \sin(\omega t - \phi_0) \quad (2)$$

in which $U_\theta(t)$ is the tangential displacement and $U_Z(t)$ is the longitudinal displacement on the stator surface. A_1 and A_2 represent the amplitudes of tangential and longitudinal displacements, respectively. ϕ_0 is the temporal phase shift between the tangential and longitudinal displacements and ω is the angular frequency.

Through Eqs. (1) and (2), the trajectory equation of a point on the stator surface reads

$$\frac{U_\theta^2(t)}{A_1^2 \sin^2 \phi_0} - \frac{2 \cos \phi_0}{A_1 A_2 \sin^2 \phi_0} \cdot U_\theta(t) \cdot U_Z(t) + \frac{U_Z^2(t)}{A_2^2 \sin^2 \phi_0} = 1 \quad (3)$$

Eq. (3) shows that the trajectory of a point on the stator surface depends on the temporal phase shift ϕ_0 , amplitudes A_1 and A_2 . If amplitude A_1 equals to A_2 , the trajectory will differ from the temporal phase shift ϕ_0 . In the case that ϕ_0 is $\pi/2$, the trajectory forms a circle. On the other hand, if the temporal phase shift ϕ_0 keeps the value $\pi/2$, the trajectory will depend on various ratios A_1/A_2 (see Fig. 2).

The working principle of the present motor can be illustrated by Fig. 3. The temporal phase shift ϕ_0 is as-

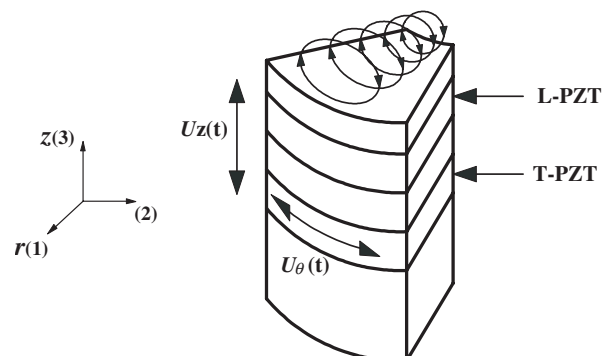


Fig. 2. Elliptical locus on the stator surface.

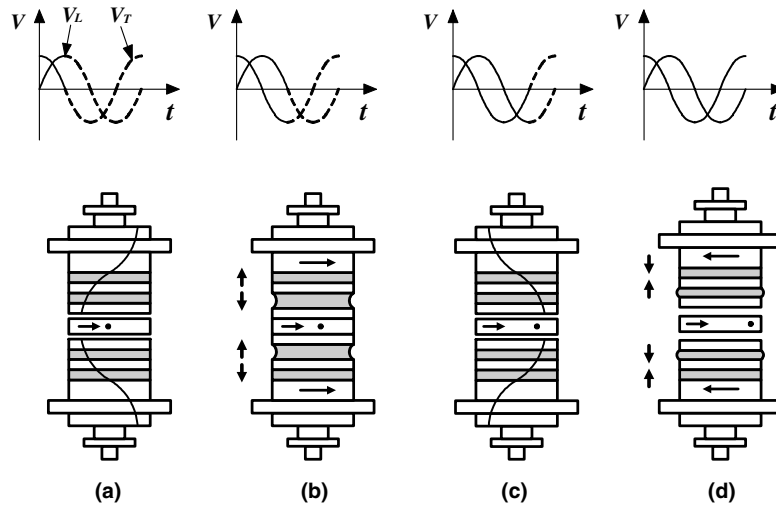


Fig. 3. Working principle of motor.

sumed $\pi/2$. When the voltage V_T applied to T-PZT reaches its peak value, the torsional displacement obtains the maximum while the longitudinal transducer has no deformation. Two stators are in loose contact with the rotor (see Fig. 3a). As the voltage V_L applied to L-PZT increases and reaches the peak, the longitudinal transducer extends and two stators are in firm contact with the rotor (see Fig. 3b). At this moment, the tangential velocity of points at the interface between rotor and stator reaches the maximum, and the rotor will rotate undergoing the friction forces. In Fig. 3c, the torsional deformation of the stators will be along the same direction, but the longitudinal transducer will contract and its deformation decreases to zero. Two stators are in loose contact with the rotor again. Finally, the longitudinal transducer will continue to contact while the torsional transducer begins to deform in reverse direction, and the rotor will separate from two stators. Due to the inertia, the rotor will rotate in the same direction (see Fig. 3d). In such a cycle, the rotor has rotated by a small angle. With the high frequency AC voltages excitation, a continuous rotary motion occurs in this motor.

The present motor uses two stators and two adjusting rings to match the resonance frequencies of both transducers. To analyze properties of the motor and the functions of the rings, a FE model of stator is developed and a commercial software ANSYS is used. Because of the symmetrical structure, only one stator is used for FE modeling (see Figs. 4 and 5). The physical models of these two vibrations have the same geometry, but the

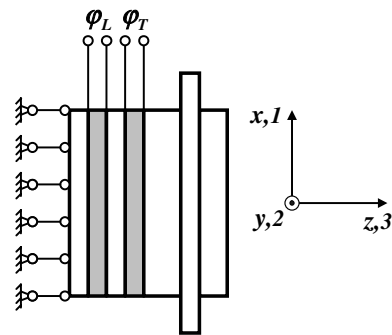


Fig. 4. Physical model for longitudinal vibration.

3. Resonant frequencies coincidence

The previous longitudinal and torsional ultrasonic motor usually works at the resonance frequency of the torsional vibration. In order to obtain a larger output torque and a higher efficiency, however, both the torsional transducer and the longitudinal transducer should be driven in resonance frequency. Theoretically, the eigenfrequency of longitudinal vibration is not equal to that of torsional vibration within a cylinder motor because of difference propagation speed of these two waves.

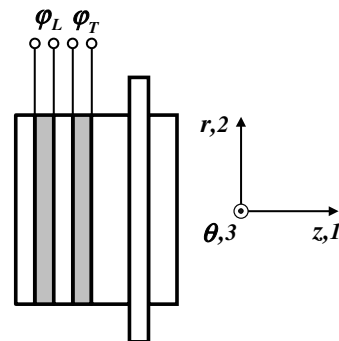


Fig. 5. Physical model for torsional vibration.

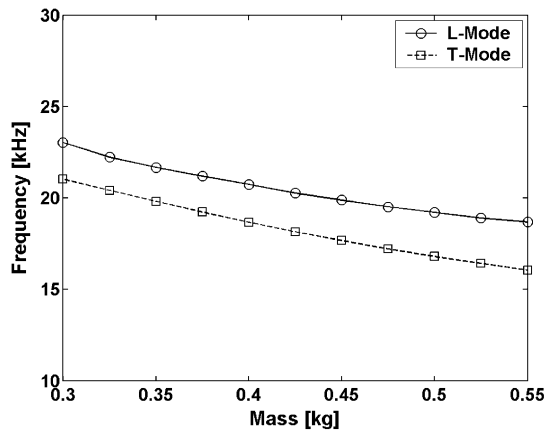


Fig. 6. Eigenfrequencies for changing mass of the ring using FE model.

coordinate systems and the boundary conditions are different. The direction of electric field for the longitudinal transducer is the same as that of the polarization, while the direction of electric field for the torsional transducer is orthogonal to that of the polarization.

It is assumed that two electrodes of the PZT are connected (short-circuited). For the physical model of longitudinal vibration, it is considered that one end of stator is fixed and the other is free. For the physical model of torsional vibration, both ends of the stator are free. To match the eigenfrequencies of both vibrations, two cases are considered: one is to change the mass of the ring and the other is to change the position of the ring.

Fig. 6 shows that the first-order eigenfrequency of longitudinal vibration decreases slightly with an increase of the mass of the ring. This is due to the well-known fact that the eigenfrequency is in counter proportion with the mass. The eigenfrequency of longitudinal and the eigenfrequency of torsional vibration have the same tendency when the mass of the ring is changed. There-

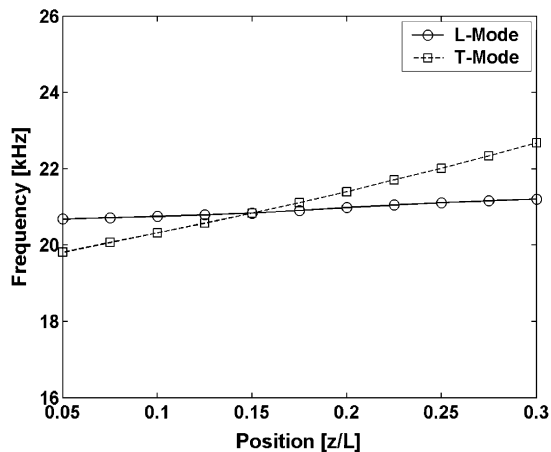


Fig. 7. Eigenfrequencies for changing position of the ring using FE model.

fore, it is impossible to obtain better effect of matching the two eigenfrequencies only via changing the mass of the ring.

Fig. 7 shows that the first-order eigenfrequency of the longitudinal vibration is almost independent of the position of the ring while the first-order eigenfrequency of the torsional vibration is much affected by this factor. When the rings are moved to a certain position, the eigenfrequency of longitudinal vibration has the same value as that of torsional vibration and the resonance frequency of both vibrations is 20.75 KHz. Obviously, this property can be used to match the eigenfrequencies of longitudinal and torsional vibrations.

4. Experimental investigations

The geometries of the present motor are optimized based on the FE analytical results and a prototype of this motor is fabricated (see Fig. 8). The length of the motor is 120 mm, the outside diameter of the stator is 40 mm and the outside diameter of the adjusting ring is 60 mm. Two ring-shaped piezoelectric ceramics with an inside diameter of 25 mm, an outside diameter of 40 mm and a thickness of 4 mm are used as the longitudinal transducers in two stators for generating the longitudinal vibration. Two layers of rectangle-shaped shear PZT in a stator are bonded with an epoxy adhesive forming a ring shape and generating the torsional vibration. A ring-shaped ceramic with the same size as L-PZT is used as an isolator, which is placed between two transducers.

Fig. 9 shows the scheme of experimental setup. A signal generator is connected via a phase-shifter to two amplifiers for excitation of longitudinal vibration and torsional vibration. The phase-shifter allows phase shift between 0 and π . The amplitudes of two exciting voltages and the phase shift between them can be adjusted separately to control the rotary speed and the direction

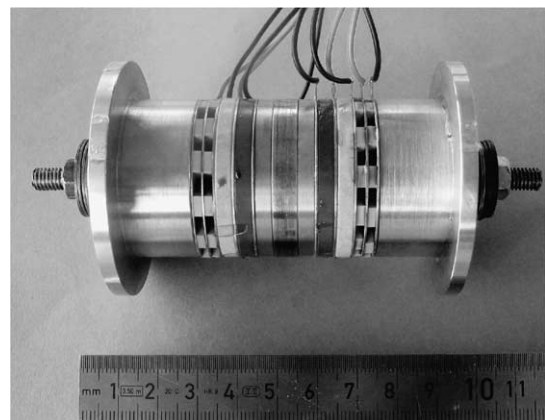


Fig. 8. The prototype of present motor.

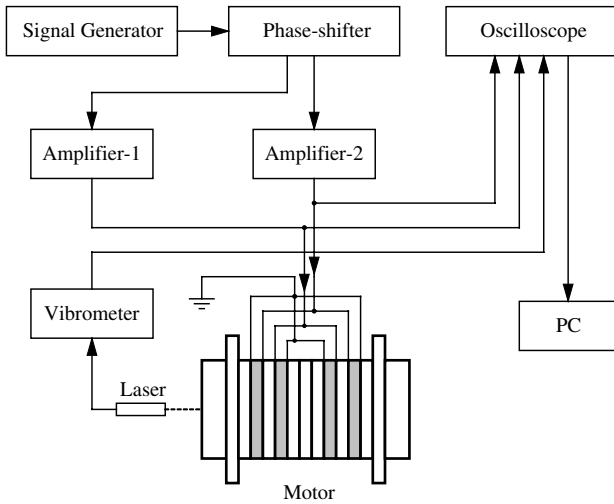


Fig. 9. The scheme of experimental setup.

of the rotor. In experiments, the eigenfrequencies of longitudinal vibration and torsional vibration are excited by two voltages with 90 degrees temporal phase shift between the two vibrations. The eigenfrequencies and eigenforms of these two vibration modes are measured by laser vibrometer that are 19.48 KHz and 17.64 KHz

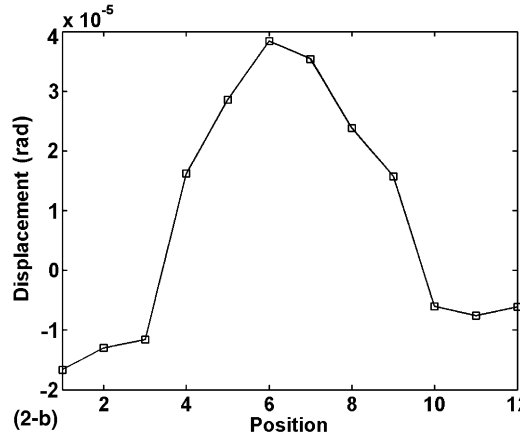
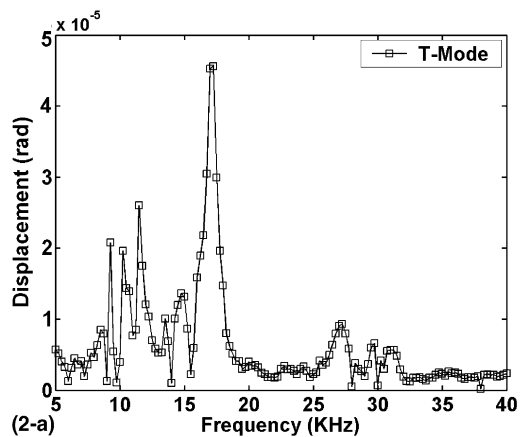
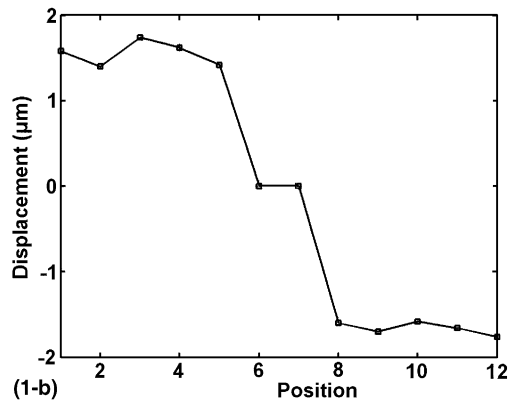
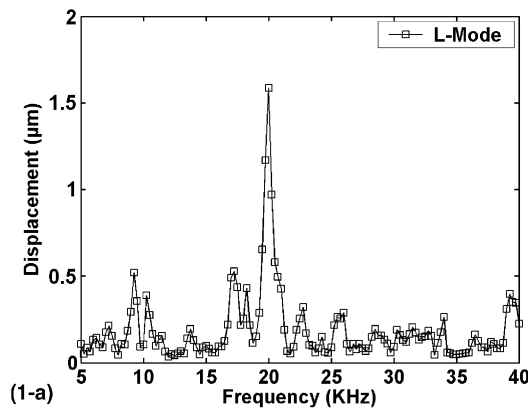


Fig. 10. The measured first-order eigenfrequency of two vibration modes. (1) Longitudinal vibration mode: (1-a) Eigenfrequency and (1-b) eigenform. (2) Torsional mode: (2-a) Eigenfrequency and (2-b) eigenform.

respectively when the ring is placed at the end of the stators (see Fig. 10).

The load characteristic of the present motor was measured under three different exciting voltages for two transducers (see Fig. 11). The rotary speed decreases greatly with the load increasing. Under no load condition, the motor behaves as the theoretical predictions

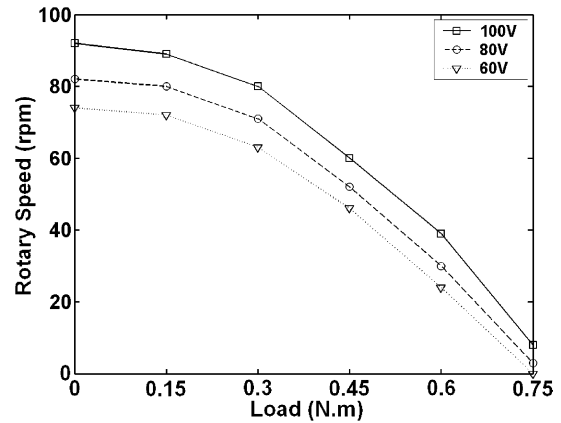


Fig. 11. Rotary speed versus load for the motor under different exciting voltages.

and the speed of rotor reaches the maximum 92 rpm at the working frequency 19.0 KHz. Compared with the FE analytical value 20.75 KHz, the experiment value 19.0 KHz has about 8.4% error. Considering the glue used to stick the PZT is neglected in FE model, this error could be acceptable. To obtain excellent characteristics, the present motor should be improved in the future.

5. Conclusions

A new longitudinal and torsional piezoelectric ultrasonic motor with two stators is developed in this paper. The symmetrical structure of the present motor as well as two adjusting rings on the stator can be utilized to match the resonance frequencies of longitudinal and torsional vibrations to obtain large output torque. A FE model of stator is proposed and the analytical results show that through changing the position of the rings the first-order resonance frequency of longitudinal vibration is coincided with that of torsional vibration. In the experiment the present motor behaves as the theoretical predictions and the measured first-order eigenfrequencies of longitudinal and torsional vibrations are 19.48 KHz and 17.64 KHz, respectively. The speed of rotor reaches the maximum 92 rpm at the working frequency 19.0 KHz.

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