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A cylindrical traveling wave ultrasonic motor using longitudinal and bending composite transducer

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ABSTRACT

A cylindrical type traveling wave ultrasonic motor using longitudinal and bening composite transducer was proposed in this paper. A composite transducer is attached to the cylinder on its outer surface to excite two degenerate flexural vibration modes spatially and temporally orthogonal to each other in the cylinder. In this new design, a single transducer can excite a flexural traveling wave in the cylinder. Two cone type rotors are pressed in contact to the borders of the inner surface of teeth by means of a spring and nut system. The working principle of the motor was analyzed. The resonance frequencies of the two vibration modes of stator were tuned to be close to one another using finite element method. A prototype motor was fabricated and tested. Typical output of the prototype is no-load speed of 281 rpm and maximum torque of 1.2 N m at an exciting voltage of 200 V_{rms}.

1. Introduction

Ultrasonic motors (USMs) are based on the concept of driving the rotor by a mechanical vibration excited in the stator via piezoelectric effect. USM exhibit merits such as simple structure, quick response, quiet operation, self-locking when power off, nonelectromagnetic radiation and higher position accuracy [1,2]. According to the PZT working mode, USM can be classified into bonded type motors [3–8] and bolt-clamped type motors [9–15] up to the present. Theoretically speaking, the latter ones exhibit higher output power and efficiency than the former ones by adopting d_{33} working mode of PZT, which have higher transfer efficiency than d_{31} mode used by bonded type motors.

To obtain large mechanical output power, in a previous work, the authors have proposed, designed, and fabricated a cylindrical type traveling wave USM using longitudinal vibration transducers, see Fig. 1. The study results verified the feasibility of the excitation of a flexural traveling wave in the cylinder. The proposed design enables the traveling wave USM to operate under intense vibration at a high exciting voltage due to the bolt-clamped structure of the transducers. Typical output of the prototype is no-load speed of 290 rpm and maximum torque of 1.95 N m at an exciting voltage of 200 V_{rms}. However, two or more transducers must be used for the excitation of flexural traveling wave because the traveling wave is produced by two flexural vibration modes spatially and temporally orthogonal to each other in the cylinder. The differences among the vibration characteristics of the four transducers, which are inevitable, would reduce the output power and efficiency. And the adopting of four longitudinal transducers led to a low compact structure of the motor. Furthermore, two pyramidal faces were machined on the teeth, which made the heights of teeth decrease from the center to the ends and caused the decrease of vibration amplitude accordingly. The inconsistency among the vibration amplitudes of particles on the driving surfaces would also reduce the output power.

In this study, a cylindrical type traveling wave USM using longitudinal and bending composite transducer is proposed. In this new design, a single transducer can excite a flexural traveling wave in the cylinder. The structure is more compact compared with the previous design by decreasing the number of exciting transducers. The working principle and design method are introduced. After fabricating a prototype, the characteristics of the motor are investigated through experiments.

2. Structure of the USM

Fig. 2 shows the structure of proposed USM, where the longitudinal PZT and bending PZT are used to excite longitudinal and bending vibrations in the transducer, respectively. The stator is composed of one cylinder and one longitudinal and bending composite transducer located on the outer surface of the cylinder in radial direction. The transducer includes an exponential shape horn

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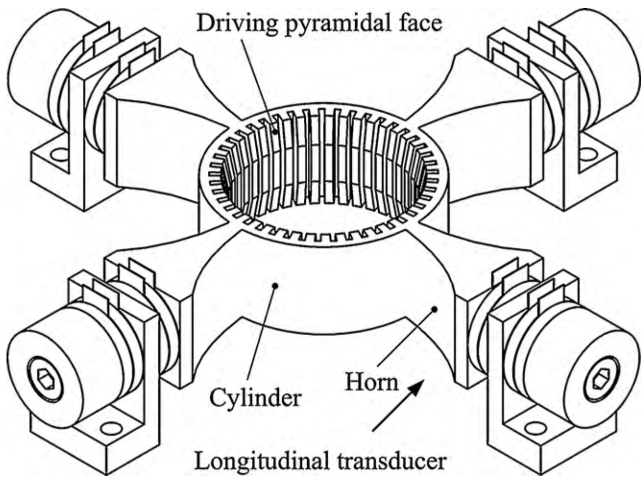

Fig. 1. Stator of the previous USM.

located on the leading end. The horn is designed as exponential shape to magnify vibration amplitude and velocity. One double head flange screw bolt fastens the horn, longitudinal PZT, bending PZT and end cap together to form the transducer. Beryllium bronze sheets are clamped to serve as electrodes. The polarization of PZT ceramics is shown in Fig. 2(a). The proposed motor belongs to the bolt-clamped type motors, and d_{33} working mode of PZT ceramics is adopted. Evenly distributed teeth are realized on the inner surface of the cylinder using linear cutting machine. Two cone type rotors are pressed in contact to the end rims of teeth, and the preload between the rotors and stator is accomplished by a spring and nut system, see Fig. 2(b).

3. Working principle

The proposed motor forms elliptical trajectories at teeth by exciting a flexural traveling wave in the cylinder. Applying alternating voltages on longitudinal PZT and bending PZT with resonance frequencies can excite two vibration modes of stator, see Fig. 3. Take $B(m,n)$ to describe the bending vibration modal of cylinder, where m and n indicate nodal circles and diameters, respectively. $B(0,8)$ bending vibration mode of cylinder was selected in this study. Mode-A is the vibration mode excited by longitudinal vibration of the transducer while Mode-B is the vibration mode excited by bending vibration of the transducer. Thus, two bending standing waves are generated in the cylinder, which have a spatial phase difference of $\pi/2$. When the amplitudes of two bending standing waves are equal, and their temporal phase difference is $\pi/2$, a flexural traveling wave can be excited in the cylinder. Thus, elliptical trajectories are achieved at the particles on the teeth. And the driving force is the frictional force between the rotors and the teeth. The direction of traveling wave can be changed by alternating the temporal phase difference of the exciting voltages, which will change the rotary direction of the rotors.

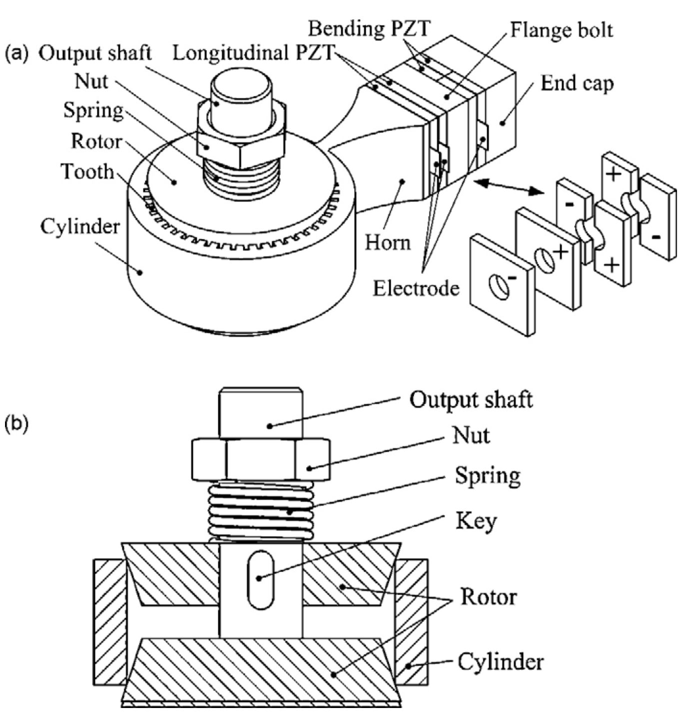

Fig. 2. Structure of the USM. (a) Three-dimensional model of motor. (b) Section view of motor.

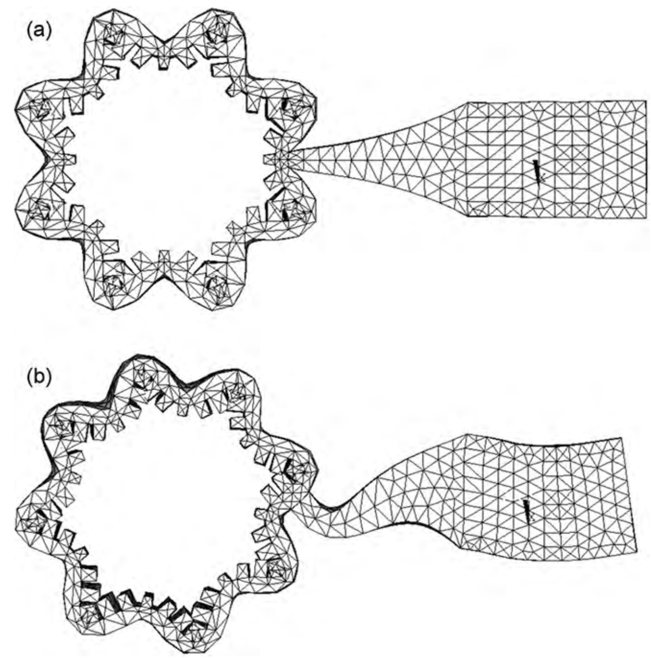

Fig. 3. Vibration modes of stator. (a) Mode-A. (b) Mode-B.

4. Design and analysis

The working principle of the proposed motor indicates that the key to form a traveling wave in the cylinder is tuning the resonance frequencies of two vibration modes of the stator to be the same. Some previous studies on bolt-clamped type USM also focus on superimposing different types of vibration modes in the elastic body of the motor and generating elliptical trajectories at the driving tips. For example, by changing the length of bolt, the resonance frequency of longitudinal vibration of transducer can be tuned to that of the bending vibration [12]. The matching between the longitudinal vibration of transducer and bending vibration of cylinder can be realized by modifying the length of the end cap [11]. By changing the length of transducer, the bending resonance frequency of transducer can be tuned to the bending resonance frequency of a ring [16].

To the USM using a composite transducer in this study, the tuning process is more complicated as three different vibration modes are involved. To realize the excitation of Mode-A, the longitudinal resonance frequency of the transducer should be tuned to the bending resonance frequency of the cylinder. And the bending res-