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Compact piezoelectric micromotor with a single bulk lead zirconate titanate stator

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The advance of micro/nanotechnology promotes the development of micromotors in recent years. In this article, a compact piezoelectric ultrasonic micromotor with a single bulk lead zirconate titanate stator is proposed. A traveling wave is generated by superposition of bending modes with 90° phase difference excited by d_{15} inverse piezoelectric effects. The operating principle simplifies the system structure significantly, and provides a miniaturization solution. A research prototype with the size of $0.75 \times 0.75 \times 1.55$ mm is developed. It can produce start-up torque of $0.27 \mu\text{Nm}$ and maximum speed of 2760 r/min at 14_{RMS} . © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4799353>]

Micromotors are widely required as the power source of operation and propulsion across consumer industry,^{1,2} micro-robotics industry,³ and medical profession.^{4,5} Various driving approaches such as electromagnetic,⁶ electrostatic,⁷ thermal,⁸ osmotic,⁹ and electro-conjugate fluid,¹⁰ have been proposed for the development of micromotors by researchers. Generally, there are disadvantages of low torque, reduction necessary, slow response, or complex design.¹¹ Piezoelectric actuation is another potential driving approach, in which vibration in ultrasonic range is generated on the stator to move the rotor through friction in between them. Compared to its counterparts, ultrasonic motor has features that benefit size miniaturization. First, gearbox usually takes much space in electromagnetic micromotors, sometimes more than half of the total volume. However, it is no longer necessary in ultrasonic motors. Second, ultrasonic motor features high torque-to-mass ratio¹² and low torque-sensitive to size.¹¹ Energy density of conversion element, the piezoelectric material, in ultrasonic motors is high up to ~ 1000 times of static electricity field's.^{13,14} Therefore, it is possible to achieve high torque output for small size ultrasonic micromotors. Ultrasonic motors also have some other merits such as quick response, self-locking, and resistance to magnetic field disturbances.

So far, many ultrasonic motors in small/micro size have been developed by researchers. Various methods have been proposed to reduce the motor size, including manufacturing by silicon processing¹⁴ and electrochemical micromachining,¹³ cylindrical stators using bulk lead zirconate titanate (PZT)^{15–18} or thin film PZT¹⁹ as the energy conversion element, pretwisted beam stator,²⁰ and helical cut stator.^{21–23} However, there is always a structure limitation for most of them to be further miniaturized. For example, cylindrical motors usually have a hollow stator with a long rotor passing through. Although the transverse dimension is relatively small, the size in longitudinal direction is quite large.

Typically, the motor of Dong *et al.* is 1.5 mm in diameter and 7 mm in length.¹⁵ So, the overall size of cylindrical ultrasonic motors is not small enough. Although the helical cut motor^{21–23} has a diameter of sub-millimeter, the stator height is over 1 mm. In addition, machining of helical cut is very expensive and complicated.²⁴

In this article, we propose a compact piezoelectric ultrasonic micromotor with a single PZT stator in a shape of comparatively small length-to-width ratio, which provides a way to further reduce the size into sub-millimeter in all dimensions. The main part of the stator is a bulk PZT longitudinally polarized with an attached metal piece that aids for motion output, as shown in Fig. 1. A steel ball sitting atop the stator is employed as the rotor, serving for principle validation and output test. The construction of single-piece PZT stator simplifies the system significantly, and allows minimizing the overall size further. For actual implementations in small-sized systems such as microrobots, the rotor can be integrated with end-effector, so that the stator may produce torque to move the external loads directly.

FIG. 1. Structure of the proposed micromotor. All stator parts are bonded together. The rotor and stator contact with each other by gravity and friction. The PZT is C-203 by Fuji Ceramics Ltd., Tokyo, Japan. The rotor and the metal piece are made of low carbon steel (a soft magnetic material) and 304 stainless steel, respectively.

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The operating principle is somehow similar to that of cylindrical ultrasonic motor with bolted Langevin type transducer proposed by Kurosawa and Nakamura.²⁵ But different from that design, we employ a single tiny piece of bulk PZT as the stator, and the bending modes are excited by d_{15} inverse piezoelectric effects. A wobbling motion of the stator is generated through combination of two perpendicular bending vibrations in space with 90° out of phase, while a traveling wave forms on the top of the stator with displacement parallel to z axis. Therefore, the rotor can rotate around the z axis in one direction. If the phase difference is -90° instead, the direction is reversed. Four copper electrodes are plated on the center of four PZT sides (see Fig. 1) via vacuum deposition with a metal mask. As the location and size of the electrodes may influence mode frequencies and their degeneracy level, the metal mask needs high-precision machining and careful operation. Four polyurethane enameled copper wires of $50\ \mu\text{m}$ in diameter for power input are bonded to the electrodes with silver filled conductive epoxy (CHO-BOND-0584-29, Parker Hannifin Corp., USA). The metal piece and PZT are bonded together, forming the stator, and then mounted onto an alumina ceramic plate using the same epoxy. One hole is drilled at the center of the metal piece, through which the rotor could be braced and a friction pair is established between the stator and the rotor. As a preliminary step, the stator is machined to a size of $0.75\ \text{mm}$ both in length and width, and $1.55\ \text{mm}$ in height.

One key issue of this study is vibration mechanism of the stator. To analyze the vibration mechanism, electrical state and vibration property should be investigated. Here, we discuss the electrical state first. To excite two perpendicular bending modes, an electric input pattern is designed, as shown in Fig. 2(a). The four electrodes are connected to four sinusoidal signals with stepping phase increments of 90° (or -90°) in a counterclockwise direction. Different from

FIG. 2. A view of (a) the electric input pattern in x - y plane and the electric field distribution at different phases: (b) $\theta = 0$, (c) $\theta = \pi/4$, and (d) $\theta = 3\pi/4$.

most ultrasonic motors, the PZT electric field distribution in this case cannot be considered as uniform in one direction, because the input pattern is a two-dimensional arrangement. It becomes non-uniform and time-varying in magnitude and direction. To facilitate the understanding, finite element method (FEM) is employed for the analysis. The electric field distribution at the phase of 0 , $\pi/4$, and $3\pi/4$ is presented in Figs. 2(b), 2(c), and 2(d), respectively. The directions of electric field strength (EFS) at different points are different, but an overall directionality appears clearly in the major region. We call this direction as “major direction,” and the EFS in this direction as “major EFS.” The major direction turns clockwise (or counterclockwise) as the phase increases with respect to time. The points with a significant component perpendicular to the major direction are always located at the periphery, and are almost symmetric about the axis passing through the center and parallel to the major direction. Therefore, the overall effect of the electric field is the same as that of the major EFS, and the effect in the other directions can be ignored. It is validated in the later harmonic analysis.

Besides the electrical state, the vibration property is also discussed. Modal analyses and further harmonic analyses of the stator are performed with ANSYS. Epoxy models with thickness of $10 - 20\ \mu\text{m}$ between stator parts are built to achieve more accurate results. The physical parameters of epoxy are obtained from Parker Hannifin Corp. and empirical data,²⁶ while those of PZT are from Fuji Ceramics Ltd. The SOLID5 and SOLID185 elements are used for meshing. In the postprocessor module, it shows that the stator has four modes, two of which perpendicular to each other belong to the first order, and the other two belong to the second order. The displacement and shear strain curves of the PZT corresponding to first-order and second-order bending modes of the stator are obtained as shown in Fig. 3. All data are picked up from those mapped on the longitudinal axis passing through the center of the cross section via path operations. As illustrated in the figure, the displacement curves are

FIG. 3. The displacement and shear strain curves of the PZT corresponding to (a) first-order and (b) second-order bending modes of the stator. The value in the horizontal axis is the height of PZT from the bottom to the top along z axis shown in Fig. 1. All data of the curves are picked up from those mapped on the longitudinal axis passing through the center of the cross section.

consistent with bending mode shapes of the standard constant cross-section beam with isotropic material. Shear strain appears as the stator is short. There is non-smooth part at the ends of the shear strain curves, a little different from the theoretical shape.²⁷ It is mainly caused by local stress, which is not taken into count in the theory. The first-order shear strain curve shows that the signs of all data are the same (positive as shown in the figure), which means that unidirectional d_{15} inverse piezoelectric effects can be made under the major EFS of the same direction in different heights. Meanwhile, the data signs of the second-order shear strain curve are not all the same, showing positive in the lower part and negative in the upper part. In spite of this, the electromechanical coupling effect in the lower location with larger strain is better than that in the upper location with smaller strain.¹² Furthermore, the lower part is longer than the upper one. Therefore, the overall coupling effect of the second-order bending mode is consistent with the lower part, and the second-order can be also excited by the electric signals.

The simulation result of stator vibration under the electric inputs in Fig. 2 is obtained with harmonic analysis module of ANSYS. It shows that the stator produces wobbling motions whether the signal frequency is near the first-order resonant frequency or the second-order one, and the first-order and the second-order modes are excited accordingly. The wobbling motion is generated in response to the rotation of the major EFS direction in Fig. 2. It can be explained as follows. The two perpendicular modes are excited at the same time under the time-varying electric field, and the vibrations under elastic deform meet the superposition principle. Therefore, the wobbling motion is formed by superposition of the two perpendicular vibrations.

Effective electromechanical coupling factor (EECF) is an important parameter because it indicates the degree of electromechanical conversion. High value of EECF refers to strong ability to converse energy. Mode frequency is another important parameter. Theoretically speaking, a lower mode frequency is favorable because the vibration amplitude is higher and thus the motor performance is better when the mode frequency is far more than 20 kHz.¹⁵ The dependence of EECF and mode frequency on the PZT height is obtained and plotted in Fig. 4. As shown in the figure, small values of height result in better electromechanical coupling of the first order bending mode and yet larger mode frequencies. The situation is reversed when height is large. Meanwhile, the EECF of the second order bending mode is not sensitive to PZT height. Therefore, in order to balance the EECF and frequency, and achieve desirable torque output, a modest PZT height near the middle point is selected for our prototype. The final frequencies of first-order and second-order bending modes are thus determined at 131.4 kHz and 458.7 kHz, respectively. An impedance analyzer (1260, Solartron analytical, AMETEK, Inc., USA) is used to test the admittance characteristics of the developed research prototype. Several peaks within the range of 100–110 kHz and 400–430 kHz are found. The experimental values are a bit lower than FEA results, due to the uncertain thickness of the epoxy and the fact that the alumina ceramic plate cannot offer absolute clamping boundary condition in spite of its high elastic modulus and density. Because of the employment of ceramic

FIG. 4. Dependence of mode frequency and EECF on the PZT height.

plate, secondary bending modes appear, which in turn explains the existence of multiple peaks. This is validated in ANSYS by adding the alumina ceramic plate into the whole model. Experiments show that most vibrations near the peaks can drive the rotor to rotate, which indicates that the bending modes including secondary modes are effective for motion generation, as shown in video of Fig. 5.

A high speed video camera is utilized to capture the instant images of the rotor motions at starting point. Figure 5 shows an example of these images. The marks in black color on the rotor surface are tracked by image processing. The speed is then calculated by determining the pixels number between each frame of the video. As a result, the speed curves at the start moment with respect to time are obtained. Like most ultrasonic motors, the typical speed at the start moment is a curve in exponential form. From the speed data and the moment inertia of the rotor, the output performances of the motor are estimated using the method proposed by Nakamura *et al.*²⁸ The performance in Fig. 6 is obtained by using signals of 107.0 kHz and 412.3 kHz at a fixed voltage of 14_{RMS}. A NdFeB magnet is placed below alumina ceramic plate for increasing the preload by attracting the rotor of soft magnetic material. The preloads are different by changing the rotors in

FIG. 5. The instant images of the rotor when the motor started. The diameter of the rotor in the images is 4.78 mm (enhanced online) [URL: <http://dx.doi.org/10.1063/1.4799353.1>].

FIG. 6. The output performances at the signal frequencies of (a) 107.0 kHz and (b) 412.3 kHz. The preloads varied from 1.13 mN to 8.23 mN by changing the rotors in different diameters range from 2.5 mm to 4.78 mm. All data are acquired in the condition of 14_{RMS} signal voltage.

different diameters ranging from 2.5 to 4.78 mm. The values of the preloads are the sum of the gravity and magnetic force. The magnetic force is calculated by using electromagnetic field simulation software ANSYS MAXWELL (ANSYS, Inc., Canonsburg, PA, USA). Experimental results indicate that the motor performance is influenced by preloads. There is a critical point at 2.41 mN for 107.0 kHz, below which the maximum torque is stable while the no-load speed fluctuates when the preloads varied, and above which the maximum torque increases dramatically when the preloads are magnified. The critical preload for 412.3 kHz is 3.27 mN. Due to the constraint of the experimental facilities, a larger preload cannot be provided. It is possible to improve the motor torque further by increasing the preload. Under the above condition, the maximum torque and maximum no-load speed are 2760 r/min, respectively. Impressive ultrasonic motors have been proposed by Watson *et al.*,²¹ Kanda and Makino,¹⁷ Khoo *et al.*,²⁹ and Tjeung *et al.*³⁰ In terms of maximum torque per unit volume, our motor is relatively higher. Integrated thin-film piezoelectric using wafer scale MEMS fabrication techniques is reported recently.³¹ Its stator construction and fabrication process are relatively complex.

In summary, we have proposed a compact piezoelectric ultrasonic micromotor with a single bulk PZT stator. The construction is simple and propitious for miniaturization. The vibration mechanism of the stator is analyzed in detail. A research prototype with the size of 0.75 × 0.75 × 1.55 mm is developed. Experiments show that the micromotor can achieve impressive output performance. Future works will be conducted on further reducing the system size based on the similar operating principle to meet the requirement of smaller-space applications. Our preliminary simulation shows that a

micromotor with a 0.25 × 0.25 × 0.6 mm stator is possible while the first-order bending mode frequency is just over 300 kHz.

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