A Multi-DOF Ultrasonic Motor Using In-plane Deformation of PZT Elements

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***Abstract*—A new multi degree-of-freedom (multi-DOF) ultrasonic motor using in-plane deformation of PZT elements is proposed in this paper. The stator of the motor consists of a hollow metal cylinder, whose outside surfaces are flattened on four sides at 90 degrees to each other. Four rectangular PZT plates polarized in thickness direction are bonded on them. By using the deformation of PZT plates in the plane perpendicular to the direction of polarization, the rotation around z-axis is generated by combining both bending vibration modes; whereas the rotation around x- or y-axis is generated by combining the longitudinal vibration mode and one of the above bending vibration modes. The stator geometry is designed in detail using the finite element method, and a prototype of the multi-DOF ultrasonic motor is produced. Admittance of the stator and load characteristics of the motor has been measured, respectively. The results confirm that the motor successfully provides the desired multi-DOF motion around orthogonal axes with a single stator using in-plane deformation of PZT elements.**

Keywords- multi-DOF actuator; ultrasonic motor; in-plane deformatiom

I. INTRODUCTION

Besides the excellent characteristics of ultrasonic motors, such as high torque at low speed, high stationary limiting torque, absence of electromagnetic radiation, less noise, and simplicity of design, multi-DOF ultrasonic motors can easily generate dexterous multi-DOF and also can reduce the volume and weight of the robots or devices greatly. And comparing to other multi-DOF actuators, multi-DOF ultrasonic motors can be easily miniaturized. So, multi-DOF ultrasonic motors with compact stator and simple driving circuit are very suitable for robot eye control, laser handling, and other applications [1].

Therefore, several multi-DOF ultrasonic motors have been proposed in the past. Toyama developed a spherical ultrasonic motor in which three or four ring-shaped vibrators are arranged around a spherical rotor [2]. Takfumi designed an ultrasonic actuator with multi-degree of freedom using bending and longitudinal vibration of a single stator, which has been applied in an auditory tele-existence robot [3], [4]. Takemura proposed a bar-shaped ultrasonic motor capable of generating three-DOF motion and a plate type multi-DOF ultrasonic motor whose rotor was larger in the size of volume [5], [6]. Otokawa constructed an arrayed-type multi-DOF ultrasonic motor based on a selection of reciprocating vibration modes [7]. Almost all these multi-DOF ultrasonic motors generate vibration by expanding and contracting with the coupling commonly associated with the piezoelectric d33 (strain) or e33, (stress) coefficients.

In this paper, a new multi-DOF ultrasonic motor is introduced, which generates vibration with the coupling associated with the piezoelectric d31 (strain) or e31, (stress) coefficients and the piezoelectric d15 (strain) or e15, (stress) coefficients. And experiments of the prototype motor have been conducted. The result confirms that the motor successfully provides the multi-DOF motion of rotor around orthogonal axes.

II. DESIGN AND ANALYSIS

A. Structure

Figure 1 illustrates the structure of the stator. As shown, the outside surface of a hollow metal cylinder is flattened on four sides at 90 degrees to each other and four rectangular piezoelectric plates are bonded onto these four flattened surfaces. The piezoelectric plate has five electrodes. Four of them are deposited on the top surface while the fifth one is deposited on the bottom surface of the PZT plates. On the top of PZT plates, two electrodes are connected across corners as one input.

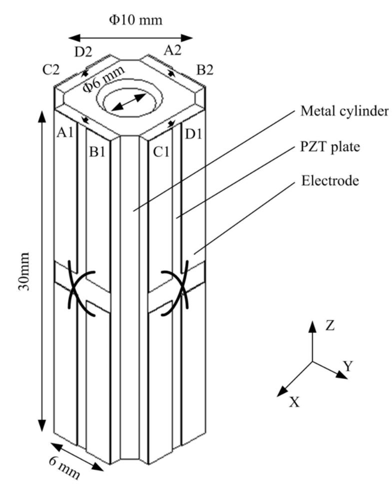

Figure 1. Structure of the stator

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And the bottoms of PZT plates are electroded uniformly and they are ground. The piezoelectric plates are poled in the thickness direction. With the application of an alternating current (AC) voltage potential across the thickness of the piezoelectric plate, the plate will expand and flex due to the coupling commonly associated with the piezoelectric d31(strain) or e31(stress) coefficients and the piezoelectric d15(strain) or e15, (stress) coefficients. With the configuration shown, the plate deforms in-plane and makes longitudinal and bending vibration of the base.

B. Working principle

Fig. 2 shows the driving principle of the multi-DOF ultrasonic motor. The rotor can rotate around three perpendicular axes. A longitudinal vibration and two bending vibrations of the stator are used as shown in Fig. 2. Fig. 2 (a) shows the natural vibration modes of the stator that are used when the rotor rotates around the z-axis. Figs. i and iii show the second bending mode of the stator in the x-z plane (mode A), and Figs. ii and iv show the second bending mode of the stator in the y-z plane (mode B). When these two natural vibration modes, A and B, are combined at a phase difference of 90° , the tip of the stator rotates around the z-axis. Then, the spherical rotor in contact with the stator's head also rotates around the z-axis by frictional force. The rotor will rotate around z-axis counterclockwise with electrodes A1 and C1 being excited simultaneously at a phase difference of 90° and rotate around z-axis clockwise with electrodes B1 and D1 being excited simultaneously at a phase difference of 90° .

Fig. 2 (b) shows the natural vibration modes used when the rotor rotates around the x-axis. Figs. i and iii show the first longitudinal mode of the stator along the z-axis (mode C), and Figs. ii and iv show the mode B. When a driving voltage is applied on electrodes A1 and A2, vibration modes B and C can be excited at the same time. Accordingly, the tip of the stator rotates around the x-axis counterclockwise. Then, the spherical rotor in contact with the stator's head also rotates around the x-axis counterclockwise by frictional force.

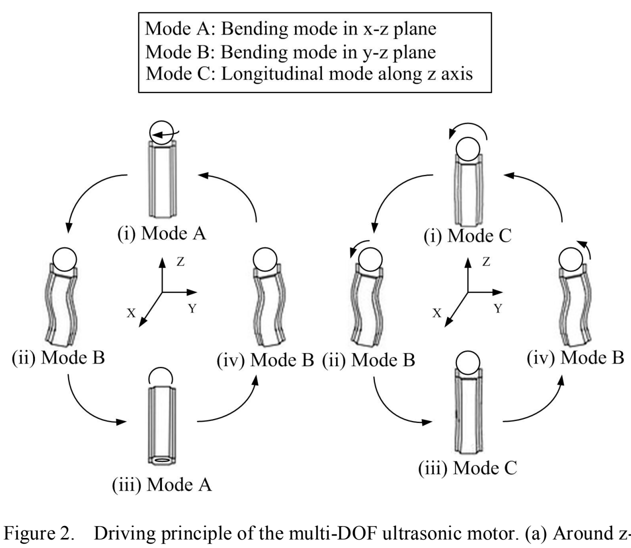
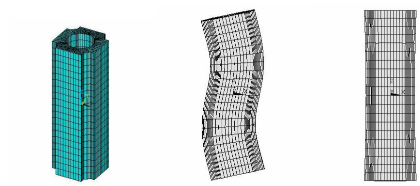


Figure 2. Driving principle of the multi-DOF ultrasonic motor. (a) Around z-axis; (b) Around x-axis

Similarly, the spherical rotor rotates around the x-axis clockwise, when a driving voltage is applied on electrodes B1 and B2. And the excitation on electrodes C1 and C2 will cause the counterclockwise rotation of the rotor and the excitation on electrodes D1 and D2 will cause the clockwise rotation of the rotor, as well.

C. Finite Element Analysis

Since the design is complicated, finite element analysis method is used to conduct modal and harmonic analysis of the ultrasonic motor, including the linearized piezoelectric material properties. In this way, a feasible design can be developed from the concept with reasonable assurance that the results of the analysis would resemble the behavior of an actual actuator. All the natural frequency nearly corresponds at 57 kHz, shown in Fig.3.



(a) (c) (d)

Figure 3. Finite element model and calculated natural modes of the stator. (a) Finite element model of the stator. (b) Longitudinal vibration mode (56.7 KHz). (c) Bending vibration mode (56.6 KHz).

III. EXPERIMENT

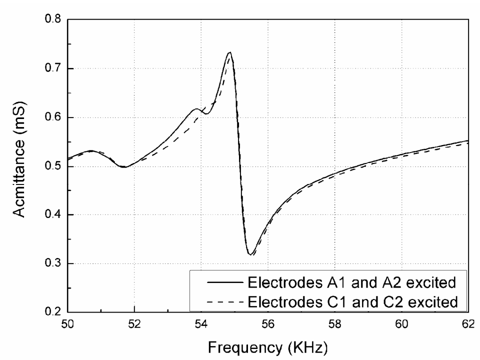
A. Fabrication

According to the results of finite element analysis, we designed the geometry of ultrasonic motor. The stator consists of a hollow metal tube (brass) with an outer diameter of 10 mm and inner diameter of 6 mm, length of 30 mm, and four rectangular piezoelectric plates with dimensions, 30 mm in length, 8 mm in width, and 1 mm in thickness. The outside surface of the metal cylinder is on four sides at 90 degrees to each other. The PZT plates, which are poled in the thickness direction, are bonded onto to the flat orthogonal surfaces of the cylinder using a conductive epoxy. The stator is held on the base with four screws. And the supporting points are on the nodal plane. The rotor is made of stainless steel. Fig. 4 shows the prototype of the ultrasonic motor.

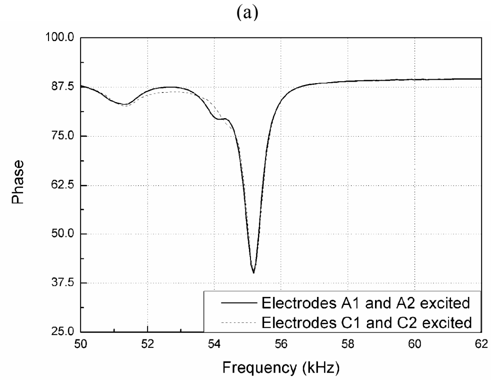
Figure 4. Prototype of multi-DOF ultrasonic motor

B. Admittance Measurement

To clarify the behavior of the stator, the admittance spectra of the free stator are measured, using a standard impedance analyzer (HP4192A) in conjunction with a data acquisition computer. Fig. 5 (a) and (b) show the magnitude and phase of the free stator when electrodes A1 and A2 or electrodes C1 and C2 are excited. When electrodes A1 and A2 or electrodes C1 and C2 are excited while short circuiting the other electrodes to the ground, the stator has the bending mode resonance frequencies around 54.8 kHz. When electrodes B1 and B2 or electrodes D1 and D2 are excited, the stator shows a similar behavior.



(a)



(b)

Figure 5. Magnitude and phase of the transducer when electrodes A1 and A2 and electrodes C1 and C2 are excited

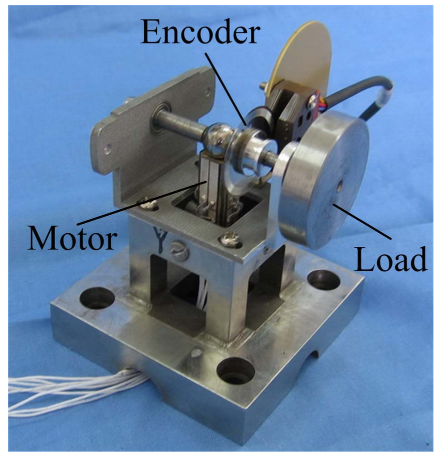
C. Motor Performance

The transient characterization method is used to measure the performance of the motor, which was initially proposed by Nakamura *et al* [8]. A disk load, whose moment of inertia is known, is mounted onto the motor. After running the motor, the transient speed is obtained as a function of time. The transient torque T (t) can be described as followed:

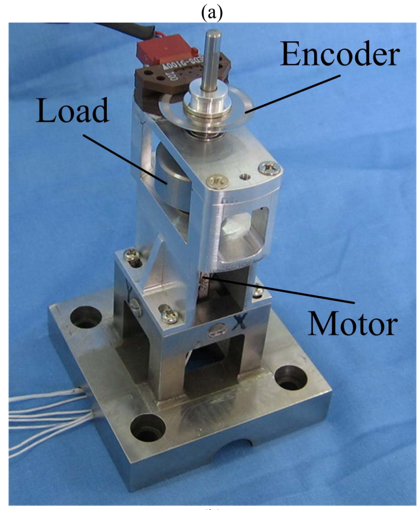
$$T(t) = J\frac{d\varpi(t)}{dt} \tag{1}$$

where ω (t) is the transient speed and J is the moment of inertia of the load. By differentiate the transient speed, the transient angular acceleration can be calculated and then the transient torque is obtained by multiplying the acceleration and the moment of inertia. The torque/speed curve is plotted with the transient data of torque and speed at the same time. Using this method, it is possible to determine the torque/speed curve for a particular configuration based on only a single run.

The actuation characteristics are measured using the experimental systems shown in Fig. 6. Two independent systems are used to measure the horizontal characteristics and the vertical characteristics, respectively. The load, a metal disk with the moment of inertia (2.5 kg • mm2) is mounted onto the horizontal test system as shown in Fig. 6 (a), whereas another load a metal disk with the moment of inertia (1.3 kg • mm2) is mounted onto the vertical test system as shown in Fig. 6 (b). The position of the rotating disk is detected through an optical encoder (US Digital, HEDS-9100-I00), and the transient position data are obtained using a motion control card (Leadshine Corp., DMC-3000).



(a)



(b)

Figure 6. Measuring device for the characteristics of motor. (a) Around the x- and y-axis. (b) Around z-axis.

When the motor is driven to rotate around horizontal x- and y-axis with an AC voltage of 180 V at 54.8 kHz, the transient speed of the motor under loaded condition is shown in Fig. 7. The steady state speed reaches 161 rpm around x-axis and 155 rpm around y-axis in 0.1 sec. The load characteristics of the motor are obtained by plotting the transient speed as a function of transient torque, shown in Fig. 8 (a). At 180 Volt, the starting torque around x-axis and the starting torque around y-axis are 3.3 mNm and 5.1 mNm, respectively. The maximum power of 18.8 mW is obtained at a speed of 11.8 rad/s and a torque of 1.6 mNm when rotating around x-axis, whereas the maximum power of 24.4 mW is obtained at a speed of 7.9 rad/sec and a torque of 3.1 mNm when rotating around y-axis. The difference between the performance of rotating around x-axis and y-axis is due to the asymmetric assembling and diversity of PZT plates.

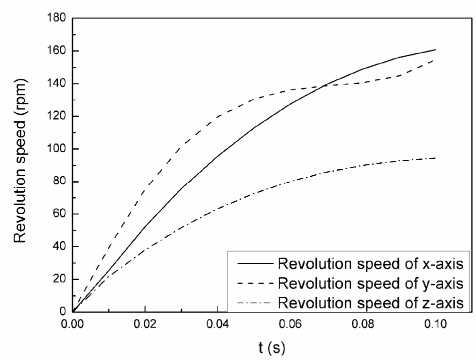


Figure 7. Transient response of motor at 180V

When the motor is driven to rotate around z-axis with required AC excitations of 180 V at 54.8 kHz, the transient speed of the motor under loaded condition is shown in Fig. 7. The steady state speed reached 95 rpm in 0.1 sec and the starting torque is 0.24 mNm. The maximum power of 0.76 mW is obtained at a speed of 6.6 rad/s and a torque of 0.11 mNm, shown in Fig. 8 (b). Since all the experiments are conducted with only the weight of rotor as preload, the output torque and the power of the motor will be reduced. And the small frictional coefficient between the rotor and the stator (stainless steel and brass) also causes the small output torque and the low power of the motor.

IV. CONCLUSION

This paper presented the design of a new multi-DOF ultrasonic motor using in-plane deformation of piezoelectric elements. By exciting any two of the vibration modes of a hollow cylinder, the rotation around x-, y-, or z-axis takes place. The structure of the stator is analyzed by using the ANSYS finite element code. Motor characteristics are measured and the results demonstrate that the motor can provide the multi-DOF rotation around orthogonal axes.

Significant advantages of our multi-DOF motors are lower manufacturing cost and higher scalability. Actually, the size of the stator will be reduced and the power of the motor will be improved in the further, so that the motor will be applied in microrobotics and microsurgery applications as an actuator.

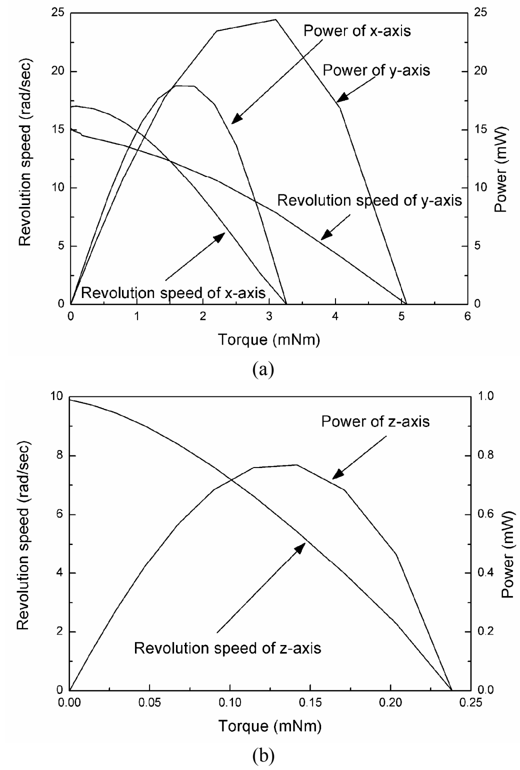


Figure 8. Load characteristics of motor. (a) Around x- and y- axis. (b) Around z-axis.

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