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A 2 x 2 array of the multi-degree-of freedom ultrasonic actuators for a low profile two-dimensional sliding table

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Abstract: In this paper, we propose a configuration for the two dimensional array of multi-degree-of-freedom (MDOF) ultrasonic actuators suitable for two-dimensionally moving table. The MDOF motions of a ball rotor are achieved by the combination of two bending and one longitudinal vibrations excited on columns fixed on a substrate. A 2 x 2 array of MDOF column actuator is fabricated for two-dimensional movement of a plate placed on the array. Only one piezoelectric element is used for one column instead of a stack of different types of PZT elements to drive the vibrations. First, we describe the configuration of the actuator, an excitation method of each vibration, and the operating principle of the stage motion. Then, moving table operation was demonstrated and evaluated.

Keywords: microactuator, multi-degree-of-freedom, ultrasonic actuator

Classification: Ultrasonic electronics

References

[1] T. Amano, T. Ishii, K. Nakamura, and S. Ueha, "An Ultrasonic Actuator with Multi-Degree-of-Freedom Using Bending and Longitudinal Vibrations of a Single Stator," *Proc. IEEE Int. Ultrasonics Symp.*, pp. 667–670, 1998.

[2] K. Takemura, N. Kojima, and T. Maeno, "Development of a Bar-Shaped Ultrasonic Motor with Three Degrees of Freedom," *Proc. Fourth International Conference on Motion and Vibration Control*, vol. 1, pp. 195–200, 1998.

[3] M. Aoyagi, S. P. Beeby, and N. M. White, "A Novel Multi-Degree-of-Freedom Thick-Film Ultrasonic Motor," *IEEE Trans. Ultrason. Ferroelectr., & Freq. Control*, vol. 49, pp. 151–158, 2002.

[4] K. Otokawa, K. Takemura, and T. Maeno, "Development of a Multi-Degree-of-Freedom Ultrasonic Motor using Single Mode Vibrations," *Proc. Intl. Conf. Acoustics*, IV3231–3234, 2004.

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[5] C.-H. Yun, S. Niwano, J. R. Friend, K. Nakamura, and S. Ueha, "Support Mechanism for the Ball Rotor in the Three-Degree-of-Freedom Ultrasonic Actuator," *Jpn. J. Appl. Phys.*, vol. 42, pp. 3000–3001, 2003.
[6] S. Niwano, C.-H. Yun, J. R. Friend, K. Nakamura, S. Ueha, and T. Hirahata, "An Active Dummy Head Driven by a Multi-Degree-of-Freedom Ultrasonic Actuator," *Proc. of World Congress on Ultrasonics*, 2003.
[7] Y. Gohda, D. Koyama, K. Nakamura, and S. Ueha, "A Miniaturization of the Multi-Degree-of-Freedom Ultrasonic Actuator using A Small Cylinder Fixed on A Substrate," *Proc. 2nd International Workshop on Piezoelectric Materials and Applications in Actuators*, pp. 263–267, 2005.
[8] Y. Gouda, K. Nakamura, and S. Ueha, "A miniaturization of the multi-degree-of-freedom ultrasonic actuator using a small cylinder fixed on a substrate," *Ultrasonics*, vol. 44, supplement 1, pp. 617–620, 2006.

1 Introduction

Multi-degree-of-freedom (MDOF) actuator has been strongly demanded in robotics and multidimensional motion control for their miniaturization. Conventional MDOF actuator consists of several electromagnetic motors and gears or air pressure actuators. Use of electromagnetic actuator causes problems of complexity in structure, large volume and noise, and air pressure actuator has also problems of large volume and slow response. MDOF ultrasonic actuator, on the other hand, inherits the advantages of ultrasonic motor such as simplicity, silent operation, small size and having a holding force. In the ultrasonic actuator, the MDOF motion can be achieved by the combination of the two orthogonal bending vibrations and one longitudinal vibration of a rod [1]. A ball rotor pressed to the rod end is revolved in any directions by the friction force if an appropriate elliptical motion is formed at the end. Amano et al. and Takemura et al. independently introduced a MDOF ultrasonic actuator that consists of a bolt-clamped transducer with several piezoelectric elements [1, 2]. Resonant frequency of the longitudinal vibration is tuned to that of bending one, and each vibration is excited by different piezoelectric elements. The configuration of MDOF ultrasonic actuator was simplified by Aoyagi et al. [3]. The actuator consists of a cylindrical stator and a PZT ring fixed to a thin plate. The actuator is driven by single frequency, but the resonance frequency of the longitudinal vibration does not tuned to the bending one. MDOF ultrasonic actuator using single mode vibrations was proposed by Otokawa et al. [4]. The rotor touches pins attached to four vibrators, and the rotation of the rotor is controlled by the driving frequency. A large-sized ultrasonic MDOF actuator has many applications in robotics [5, 6]. On the other hand, miniaturized MDOF ultrasonic actuator and array of many MDOF ultrasonic actuators shall find new applications in micro devices. Previously, we proposed a simple configuration of the MDOF ultrasonic actuator using just a PZT ring and a cylindrical stator [7, 8]. We achieved the three-axes rotations of ball rotors with the maximum rotation speed of 15.8 rps and the maximum torque of 1 μNm. In this paper, we pro-

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pose an arrayed structure using four of the MDOF ultrasonic actuators and explain the design of the resonance frequencies of the actuator. A 2 x 2 array actuator is applied to a sliding table.

2 Structure and the operating principle

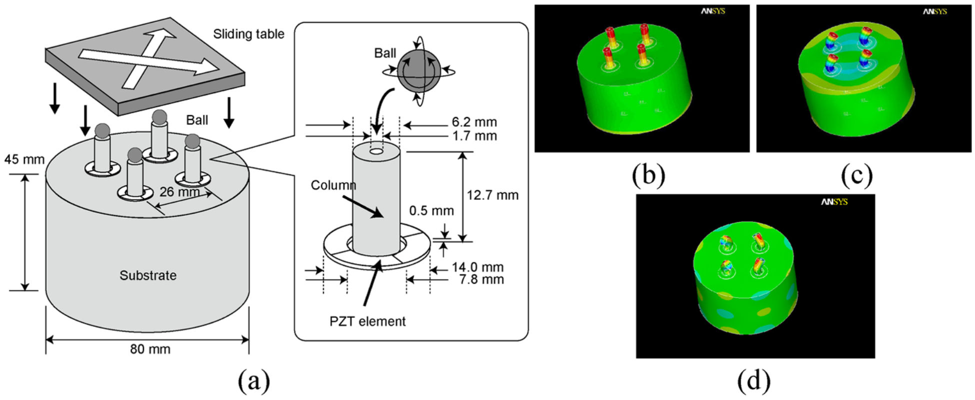

Fig. 1. (a) Arrayed ultrasonic actuator with MDOF. Element actuators are located with the spacing of 26 mm. The height, the inner diameter, and the outer diameter are decided so that the longitudinal resonance frequency of the cylinder matches the bending one. (b) is the longitudinal mode at 82.314 kHz, (c) is the bending mode at 87.840 kHz, and (d) is another bending mode at 90.120 kHz.

The element actuator consists of a cylinder fixed on a substrate and a PZT ring glued to the substrate at the cylinder bottom as shown in Fig. 1 (a). The PZT ring is uniformly polarized in thickness direction, and its electrode is divided into four parts. We can excite two orthogonal bending vibrations and one longitudinal vibration by selecting the electrodes. A metal ball placed on the top of the cylinder rotates in the required direction because of an elliptical motion composed at the top edge by the combination of the three vibrations. The X-bending vibration is excited when voltages with the phase difference of 180 degrees are applied to two electrodes that are diagonally located each other. The Y-bending vibration is excited in the same way as the X-bending vibration but the 90°-rotated electrodes are selected. Longitudinal vibration in the Z-axis direction is excited when the same voltage is applied to all the electrodes. The X-axis rotation is obtained using the Y-bending vibration and the Z-longitudinal vibration, while the Y-axis rotation is obtained using the X-bending vibration and the Z-longitudinal vibration. The phase difference between the longitudinal and bending vibrations should be 90° to have elliptical motions at the top of the cylinder. The Z-axis rotation is achieved by the combination of the X-bending and Y-bending vibrations with 90° phase difference. Four element actuators are fabricated on the same substrate at the point symmetric positions. According to the fi-

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nite element analysis, there are three vibration modes as shown in Fig. 1 (b): longitudinal mode at 82.314 kHz and bending mode at 87.840 kHz. In these modes, the vibrations are in phase. In another bending mode at 90.120 kHz, vibrations with orthogonal directions and anti-phase are obtained. Though every actuator has its own electrode to excite the necessary vibrations, four columns vibrate synchronously to some extent due to elastic coupling via the substrate. This nature is suitable for operation of a sliding table.

3 Stage operation of the actuator

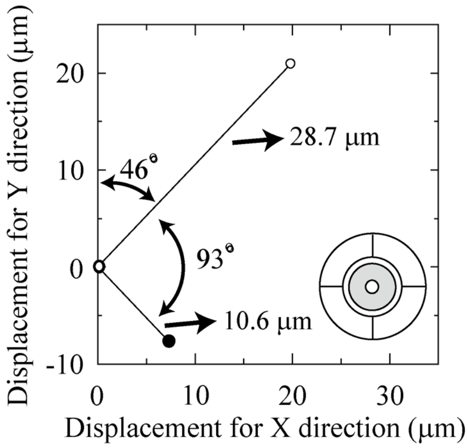

Fig. 2. Moving direction and displacement of the stator for 1000-cycle burst-drive.

Four element actuators whose outer diameter of 6.2 mm, inner diameter of 1.7 mm and height of 12.7 mm are placed in two by two arrangements with spacing of 26 mm as shown in Fig. 1. Both cylindrical stators and the substrate are made of stainless steel (SUS 304). Four PZT rings whose outer diameter of 14.0 mm, inner diameter of 7.8 mm, and thickness of 0.5 mm are glued to the substrate around each stator. Resonance frequencies of the actuators are 84.0-84.3 kHz. Ball rotors made of steel with the diameter of 6.0 mm are used.

We placed an acrylic board (90 x 90 mm, 20 g) on the four ball rotors for the stage operation. We confirmed X and Y translation motions at 88.735 kHz and 88.724 kHz, as well as the rotation at 84.430 kHz. Two orthogonal motions of the acrylic stage were obtained by changing the driving frequency. Fig. 2 shows the moving direction and distance of the acrylic stage for a 1000-cycle burst drive. The board moved to the required direction though the distance was differ 2.7 times. The moving directions are almost parallel to the diagonal lines of the each faced-electrode. We measured the relationship between the burst duration of the input voltage and the moving displacement of the stage for three materials: duralumin, acrylic, and rubber. All the materials show the same gradient, but the rubber stage made the smallest step of 0.19 μm/50 cycles as shown in Fig. 3 (a). The maximum error at the 50 cycles was 0.04 μm. Fig. 3 (b) shows the comparison between the

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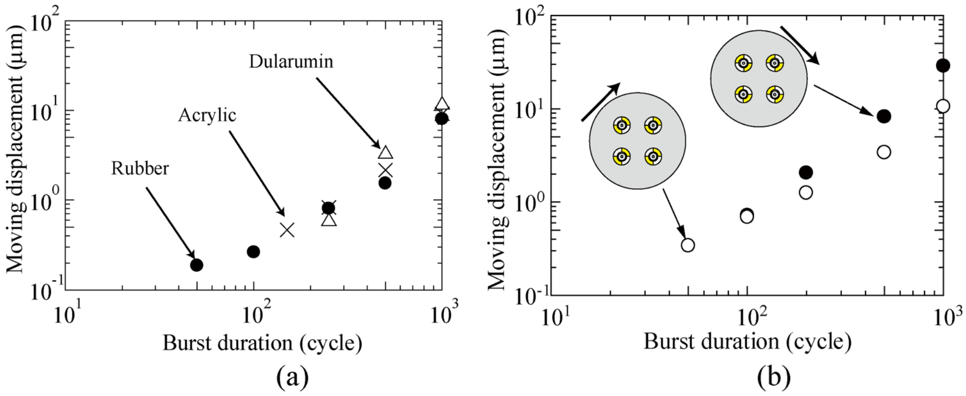

Fig. 3. (a) Moving displacement of the stator vs. burst duration for three materials of the plate. The weights of the rubber and the acrylic plates are adjusted to that of the duralumin as 0.238 kg. The driving frequency is 86.4 kHz. The surface of the duralumin plate is polished by #2000 sandpaper. The moving displacements are measured using the digital microscope. (b) shows the comparison of the moving displacement between two orthogonal directions.

two orthogonal directions. For the relatively short burst duration, the error between the directions is small.

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