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Study on the Piezoelectric Bender Actuator for Small Walking Robots

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Abstract: A linear piezoelectric actuator that utilizes the elliptical motion of the two tips of the actuator is proposed. This device is easy to fabricate owing to its simple structure, consisting of three piezo ceramic benders and is suitable for use in micro robotic applications. A π-shaped structure, which was composed of four piezo ceramic benders, was constructed. Two of the benders were positioned on the center of the actuator, and the joints were attached at the ends of the cantilever. The other two benders were positioned on the side of the actuator and were attached between the joint and the tips. The actuator structure was designed to obtain the first bending mode of the horizontal vibration and the vertical vibration at the same frequency, resulting in elliptical motions at the tips. When two sinusoidal wave voltages with a 90-degree phase difference were applied to the two pairs of the actuator benders, elliptical motions were obtained at the tips. The driving characteristics of the prototype actuator were then measured using a laser doppler vibrometer.

Keywords: Piezoelectric actuator, Finite element analysis, Cantilever

1. INTRODUCTION

Piezoelectric actuators are suitable for use in small-scale applications that require a high torque at a low speed. The inverse piezoelectric effect is described as the ability of certain materials to change their geometry in an electric field [1], and the first group of these consists of stacked piezoelectric elements that are integrated into a lever structure to provide a stroke enlargement [2]. The second group provides discrete steps as a sequence for clamping and pushing [3], sticking/slipping movements [4,5], or geared structures [6]. Finally, the third and largest group primarily uses the magnification of the amplitude at or near the resonant frequency of the oscillating structure [7,8].

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Micro-robotics applications are in need of ideal actuators that have a large force or torque, long strokes at a reasonable speed and a high response with precise positioning [9]. To meet these requirements, various actuators studied by many researchers. Of these, piezoelectric actuators have been found to satisfy these requirements the most. Recently, R. J. Wood introduced a micro air vehicle (MAVs), named Robobee, that takes design cues from biological system to achieve a small size, high maneuverability, and hovering ability with bimorph-type piezo ceramic cantilever structures. Several prototypes of robotic insects with flapping wings have shown promise, including the micromechanical flying insect [10] and the Harvard micro-robotic fly [11]. R. J. Full also suggested an animal-inspired micro-robot called RoACH that crawls autonomously as a hexapod. RoACH is capable of running at over 50 body-lengths per second, and it is capable of hexapedal, quadrupedal, and even bipedal locomotion [12], as well as high-speed climbing and rapid inversion [13]. Piezoelectric bending mode structures, such as bimorph and unimorph benders, can be used as both actuators and sensors in a wide range of applications. These simple structures as actuators are capable of producing large strokes under a low electric voltage [14,15]. In this work, we propose a linear piezoelectric actuator that utilizes elliptical motion on the tips using two orthogonal axis vibrations in the same frequency. this actuator is easy to fabricate because it has a simple structure assembled with four piezo ceramic benders, and it is suitable for use in micro robotic applications. This acturator may be used as a transporting platform for the micron scale precise positioning or manipulating system such as handling toxic chemicals or medical experiments for contagious diseases.

2. RESEARCH METHOD

2.1 Vibrations of a cantilever beam

A Cantilever beam fixed on left end is considered, as shown in Fig. 1. The bending vibrations of the beam are described with the following equation using the Euler-Bernoulli beam theory

$$EI\frac{\alpha^4 y}{\alpha x^4}+\rho A\frac{\alpha^2 y}{\alpha t^2}=0 \quad (1)$$

where E, I, ρ, and A are the Young's modulus, second moment of area of the cross section, density and cross section area of the beam, respectively, and L is the length of the beam.

The solution for equation (1) can be written as a standing wave y(x, t) = w(x)u(t) separating the spatial and temporal component. This leads to the following characteristic equation that relates the circular frequency ω to the wave number k:

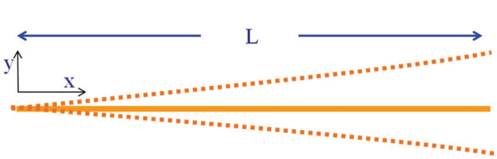

Fig. 1. Shape of the 1st bending mode for a cantilever beam.

$$\omega^2=\frac{EI}{\rho A}k^4 \quad (2)$$

The resonant frequency of the 1st bending vibration mode of cantilever beam can be written as:

$$Fr=\frac{1}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \quad (3)$$

2.2 Elliptical montion for the unltrasonic actuator

The elliptical displacement is realized by considering the horizontal and vertical displacements (u_x and u_y) of the multimodal vibration with intersecting perpendicular fields and by driving them by means of electrical signals with a phased difference, for example of 90-degree, as showen in Fig. 2. Hence, depending on the method for realizing such motion, different ultrasonic actuator forms arise, and various motor types can be constructed [16].

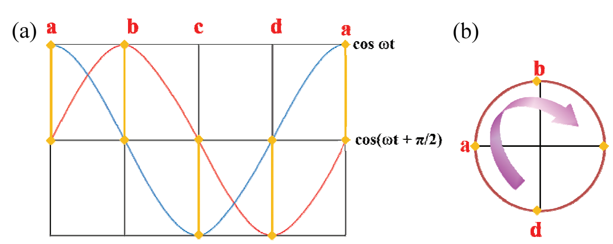

Fig. 2. Elliptical motions of actuator: (a) Driving signals and (b) elliptical motions at the tips.

2.3 Structure of actuator

The π-shaped structure shown in Fig. 3 is comprised of four piezo ceramic benders. Two of the benders are positioned on the center of the actuator and the joints are attached at the end of the cantilever. The other two benders were positioned on the side of the actuator and are attached between the joint and the tips. They can be named as body and legs respectively. The structure of the actuator was designed for the 1st bending mode of the horizontal vibration and the vertical vibration to have the same frequency in order to obtain elliptical motion at the

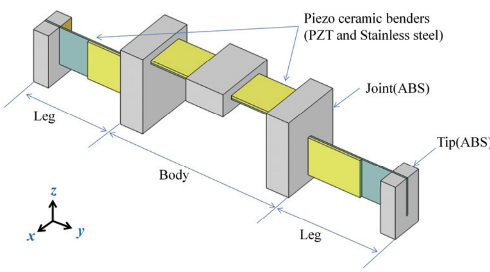

Fig. 3. Structure and materials of the actuator.

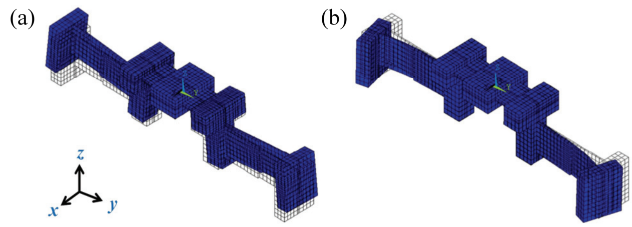

Fig. 4. Deformation shape of the actuator: (a) Vertical (z-axis) vibration and (b) horizontal (x-axis) vibration.

tips. This actuator can be classified as the multi-mode excitation-type actuators. Unlike single-mode excitation type where the motion at contact point is in oblique direction, the motion at the contact point of multi-mode excitation type motors is elliptical. The elliptical motion is generated by exciting two orthogonal mechanical resonance modes [17]. These orthogonal modes can be excited by multiple driving sources at the same frequenies with 90 degree phase difference. And it can be converted the directions by changing one of the phase of driving sources.

2.4 Design using finite element analysis

The ANSYS finite-element analysis program was used to analyze the vibration characteristics of the actuator. As in Fig. 3, which shows the structure and merterials of the actuator, the center body of the actuators, which is made of two unimorph piezo ceramic benders, was fixed on joints for vertical (z-axis) motion, and the leg actuators were fixed on joints for horizontal (x-axis) motions. We tuned the actuator geometries to produce vertical and horizontal motion with the same 1^{st} bending mode resonant frequency as shown in Fig. 4. After structural modeling, modal analysis was carried out to determine the vibration modes at the resonant frequencies. Among the modes, the 1^{st} bending vibration mode was utilized for the actuator. The resonant frequencies of the vertical and horizontal bending vibrations were examined by changing the thickness and length of the ceramics for the legs until both resonant frequencies reach almost the same point. Table 1 and Fig. 5 shows the sturctual parameters and the results of this analysis. At a thickness of 0.3 mm and length of 7 mm, both resonant frequencies became similar at around 880 Hz. A harmonic analysis

Table 1. Structual parameters and the results of analysis.

Parameters			Results	
Piezo ceramic of leg			Resonance [Hz]	
Thick-ness (α) [mm]	Length (β) [mm]	Simbols (Fig. 5)	Vertical	Horizontal
0.2	5	A	917	645
	7	B	901	753
	9	C	880	833
0.3	5	D	904	708
	7	**E**	**880**	**882**
	9	F	852	1,047
0.4	5	G	891	743
	7	H	862	969
	9	I	826	1,219

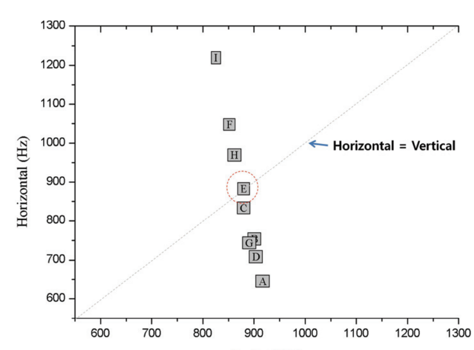

Fig. 5. Results of analysis: The resonant frequency of vertical and horizontal vibration, regarding the modelling parameters in Table 1.

was carried out to approximate the configuration of the actuator tip movement. As shown in Fig. 6, the elliptical configuration was verified, the maximum displacements were obtained when 50 Vrms / 880 Hz were applied, with 108 mm in the vertical axis and 102 mm in the horizontal axis.

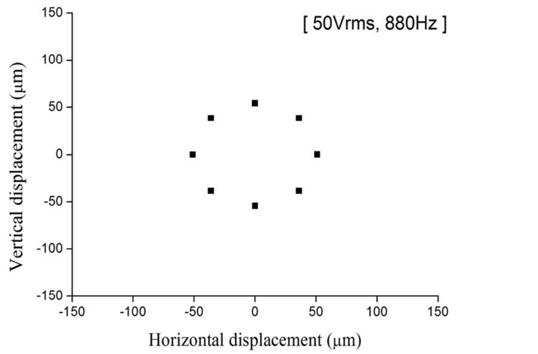

Fig. 6. Configuration of the actuator tip movement through the analysis.

2.5 Fabrication and experiments

2.5.1 Fabrication

The body, joints, and tips were made with ABS resin material (ReFila, allthat3D) on a 3D printer (ALMOND, OPENCREATORS). The piezo ceramic benders were made of 0.3 mm-thick rectangular piezo ceramics (SJC4040018, Samjeon co. Ltd) that were bonded on the surfaces of 0.2 mm-thick elastic stainless steels using an plate epoxy bond (EPO-TEK® 353ND) at a temperature of 150˚C for 1 hour. Electric wires with a 0.18 mm diameter were soldered on the piezo ceramics and the elastic plate. Figure 7 shows the dimensions of the actuator and the fabricated actuator weighed 1.74 g.

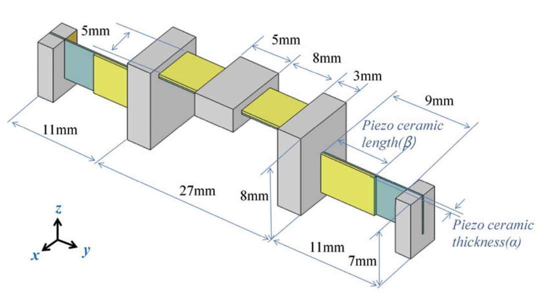

Fig. 7. Dimensions and FEA parameters (α and β) of the actuator.

2.5.2 Experiments

Figure 8 shows the experimental setup used to drive the actuator and measure its driving characteristics. Signals from the function generator (33120A, Agilent) were amplified using a power amplifier (HSA4051, NF) that was applied to the actuator clamped on the center of the body. An oscilloscope (GDS-2204, PW instek) was used to monitor the output signals. The vibration characteristics of the actuator were measured using a laser Doppler vibrometer (OVF-5000, Polytec). When sinusoidal wave voltages at the resonant frequencies with a 90-degree phase difference were applied to the body and leg benders, the tips of the actuator exhibited elliptical motion driven by the two successive motions of the vertical movement by the body benders and horizontal movement by the leg benders.

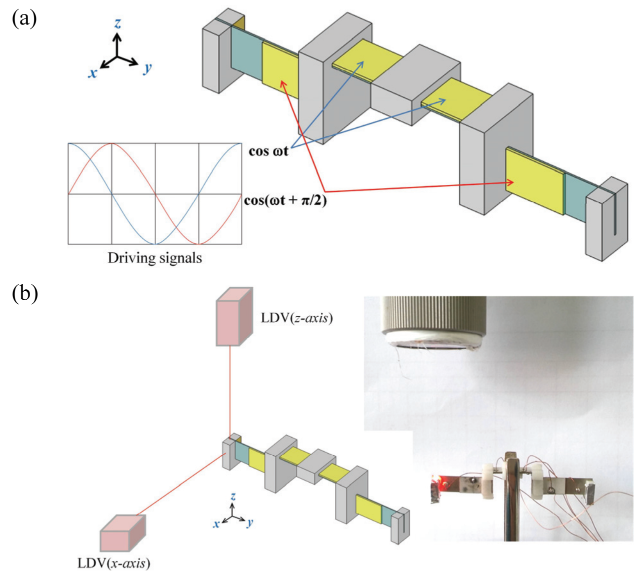

Fig. 8. (a) Input signals and (b) experimental setup and measurement of displacement at the tip of actuator.

3. RESULT AND DISCUSSION

Figure 9 shows the elliptical configuration at the tip of leg. The maximum displacements were acquired when 50 Vrms / 830 Hz were applied, with 182 μm in the vertical axis and 90 μm in the horizontal axis.

There were acceptable difference of the maximum displacements at resonant frequency between FEA and experiments. But we will study more on the bonding conditions between elastic plate, POM and piezo ceramic for reducing the gap. Since the purpose of this study was to embody the elliptical motion on the tips at the

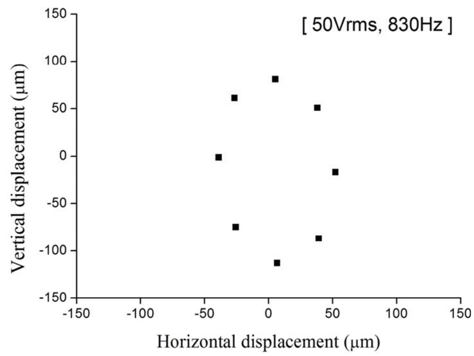

Fig. 9. Configuration of the actuator tip movement obtained through experiments.

same frequency, evaluation of the actuator characteristics such as the speed, optimum preload value and the output force characteristics, were not carried out. Those measurements will be tested as part of an ongoing study. In addition, we will proceed further miniaturization and assembling two or three actuators for future work.

4. CONCLUSION

A linear piezoelectric actuator was developed by applying elliptical motion tips. An FEA simulation (ANSYS) optimized the actuator structure by tuning at the same 1st bending resonant frequency of the vertically and horizontally moving parts. A π-shaped actuator (8×39×10 mm) was fabricated using four piezo ceramic benders, and its performance was tested. Elliptical motion was obtained at the tips of legs when sinusoidal wave voltages were applied to the actuator at the same resonant frequency, with a 90 degree phase difference between the leg and body benders to produce two successive vertical and horizontal motions. The driving displacements of the prototype actuator were measured using a laser Doppler vibrometer. At a resonant frequency of 830 Hz, we verified the elliptical motion on the tips of the actuator with a vertical displacement of 182 μm and horizontal. displacement of 90 μm.

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