Ceramics International 43 (2017) S21–S26

Contents lists available at ScienceDirect

Ceramics International

journal homepage: www.elsevier.com/locate/ceramint

Developments of a piezoelectric actuator with nano-positioning ability operated in bending modes

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ARTICLE INFO

Keywords:
C. Mechanical properties
D. PZT
E. Actuators
Bending vibration

ABSTRACT

This paper proposed a new piezoelectric actuator operating in two working modes: the resonance working mode under alternating current (AC) signals and the non-resonance working mode under direct current (DC) signals. The AC resonance working mode used the hybrid of two resonance bending vibrations to produce high speed and large stroke linear motion, whereas the DC non-resonance working mode used the static horizontal bending movements to achieve linear driving with micrometer stroke and nanometer resolution. The working mechanism of the actuator was illustrated; then finite element analysis (FEA) method was utilized to finish the design and analyses; at last a prototype was manufactured to measure the performance. Under the resonance working mode, the proposed actuator achieved maximum output speed of 1750 mm/s and the maximum output thrust of 30 N under 500 $V_{p\text{-}p}$. Also, when working under the DC non-resonance working mode, the maximum output displacement was 2.62 μm. And the measurable minimum output displacement was 50 nm, which can reach smaller in theory. The correlation coefficient between the output displacement and the input DC voltage is 0.998, which was good for the control of the actuator under the non-resonance working mode. This piezoelectric actuator can accomplish linear position quickly and accurately in a large stroke with simple structure using bending modes.

1. Introduction

Piezoelectric actuators, as a new kind of actuator, have been researched from the 1980s, and they make use of the converse piezoelectric effect to convert the electric energy to mechanical energy by friction [1–3]. They have some special merits, such as simple structure as they have no coil and magnet, no need of reducer, quick response with few milliseconds, high displacement resolution, etc. [4–6]. Thus, piezoelectric actuators are used for ultra-precision positioning in many fields like MEMS, micro robots, optical instruments, biological equipment and precision machines [7–10].

From the vibration frequency viewpoint, the piezoelectric actuators can be divided into resonance type and non-resonance type. In general, the resonance type actuators have a relative high speed and large stroke. For example, Liu et al. proposed a composite bending vibration linear actuator with a no-load speed of 1527 mm/s [11]. Lu et al. proposed a linear ultrasonic actuator using friction reduction, and the no-load speed in the forward driving were 187 mm/s [12]. Asumi et al. proposed a V-shape transducer ultrasonic actuator with the no-load speed of 1.6 m/s [13]. Lee et al. proposed a butterfly-shape linear ultrasonic actuator with the no-load speed of 88 mm/s [14]. However, their positioning accuracies are in micrometer scale, which cannot meet the requirements in ultra-precision fields.

The non-resonance piezoelectric actuators can be classified into three types: the direct drive ones, the inertia ones and the inchworm ones. In addition, PZT stack is the most commonly used piezoelectric elements in the non-resonance actuators. However, the output axial displacement is only about 0.1% of its thickness. Driving the mover directly with the axial displacement of the PZT stack, the direct drive piezoelectric actuators usually have mechanical structures to amplify the deformation of the piezoelectric ceramics. And the resolution can reach nanometer or sub-nano scale. A diamond-shaped mechanical amplifier was used for a piezo actuator [15], a bridge-type amplifier structures were designed to accomplish enhanced displacement of the input translation by Juuti et al. [16], and compound parallelogram flexures and bridge-type displacement amplifiers were used in a XY stage by Li et al. [17]. Yao et al. designed, analyzed, fabricated and tested of a parallel-kinematic micropositioning XY stage, whose resolution was equal to the resolution of the position fiber optic sensors (about 20 nm) [18]. However the output displacements of the direct drive piezoelectric actuators are generally within 100 μm.

The inertia piezoelectric actuators have relative larger output

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http://dx.doi.org/10.1016/j.ceramint.2017.05.199

displacement than the direct drive ones; also the resolutions are usually within nanometer. Such as an impact drive mechanism that could provide X, Y and θ motions developed by Nomura et al. [19], the linear micro-stage proposed by Peng et al. [20], and the miniature X-Y stages dedicated to the manipulation of samples under a microscope introduced by Bergander et al. [21]. A motion mechanism of an XY micro-stage was designed and constructed for precision positioning by Shimizu et al., the travel range and the driving force were 1 mm and 6 mN respectively [22]. The driving forces of the inertia type actuators are relatively small for its working principle. Also the demands of the driving signals are strict.

A hybrid linear actuator under inchworm motion principle was developed by Kim et al. [23], a compact 2-DOF precision piezoelectric positioning platform based on inchworm principle was designed by Li et al. [24], and a fast inchworm type actuator was developed by Moon et al. [25]. Ma et al. designed a new piezo-electric linear actuator based on inchworm motion principle with a symmetry lever displacement amplification mechanism, Laser Doppler Interferometer (MCV-5005-S) with resolution of 1 nm was used for measuring displacement, the measured stroke, resolution and bearing capacity of the actuator is ± 25 mm, 60 nm and 11 N respectively [26]. The positioning accuracies of the inchworm actuators are usually nanometer level and the output speeds are usually less than 1 mm/s, also they have complex structures. In addition, all the non-resonance piezoelectric actuators make use of the axial displacements of the PZT stack which can only suffer positive voltage.

In this paper, a novel piezoelectric actuator working in two working modes is proposed. When working under the resonance mode, the actuator is regarded as an ultrasonic actuator, which can provide high speed moving and large stroke. When direct current is applied to the actuator, the non-resonance working mode is inspired. Under the non-resonance driving, the actuator exhibits high positioning resolution. The proposed actuator operates in bending vibrations, which can suffer both positive and negative voltages. In addition, the actuator has simple structure and large output thrust force.

2. Structure and operating principle

2.1. Structure of the actuator

The structure of the actuator is shown in Fig. 1, which is composed of 32 pieces of piezoelectric ceramics, two driving feet and one double-head flange bolt. The piezoelectric ceramics are divided into two groups, which are named as PZT-A and PZT-B respectively. The polarization directions of the piezoelectric ceramics set at the left side of the flange bolt are shown in Fig. 1(b); and those set at the right side of the flange bolt are symmetrical with the left side. The “+” and “−” are used to illustrate the polarization directions. Beryllium bronze sheets are clamped between the PZT ceramic plates to serve as the electrodes.

2.2. Operating principle

2.2.1. Working under the alternating current (AC) working mode

When working under the AC working mode, the actuator is regarded as an ultrasonic actuator which works at the resonance frequency. Two orthogonal bending vibration modes of the cantilever beam, as shown in Fig. 2, are generated to form the elliptical movements at the driving feet. Every piece of piezoelectric ceramic has two inverse polarized partitions. When sine signal is applied to PZT-A, the PZT ceramics will expand-contract along the axial direction, which would cause the vertical displacement of the driving feet; similarly when cosine signal is applied to PZT-B, the horizontal displacement of the driving feet will be generated. Thus when the sine and cosine voltages are applied to the PZT-A and PZT-B simultaneously, two designed bending vibrations will be excited, and the driving foot would move in the elliptical trajectory to drive the mover.

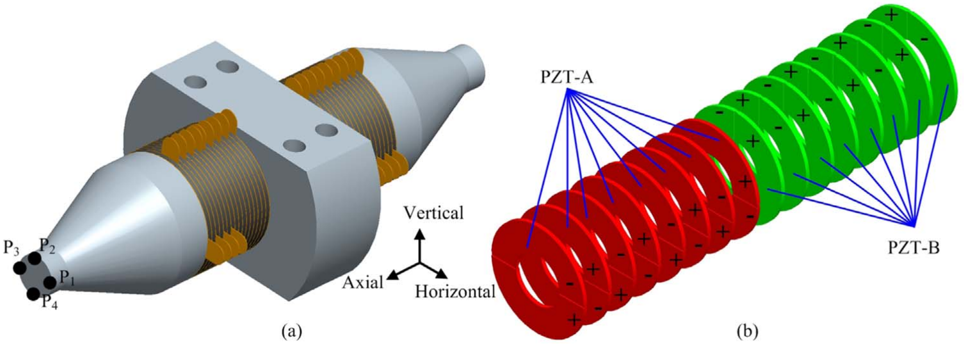
2.2.2. Working under the direct current (DC) working mode

When working under the DC working mode, the actuator makes use of the displacement of the driving feet under the DC voltage. The principle diagram of the movement is shown in Fig. 3. The driving foot can produce displacement with micro-scale under the static friction force between the driving foot and the mover. And the output displacement of the mover can be varied by changing the value of the DC voltage, which even can reach nano-scale in theory.

3. Optimal design and simulation analysis

The dimensions, as shown in Fig. 4, are optimized by the FEA software ANSYS 10.0. The material of the double-head flange bolt is steel with density of 7800 kg/m^3, Poisson ratio of 0.3 and Young modulus of 206 GPa. Two driving feet are made of aluminum with density of 2810 kg/m^3, Poisson ratio of 0.33 and Young modulus of 72 GPa. The piezoelectric ceramic is set as PZT4. The resonance frequencies of the bending vibration modes are designed to ultrasonic scale by the modal analysis. The frequencies of the bending vibrations in horizontal and vertical directions are calculated to be 22.41 kHz and 23.11 kHz respectively with a discrepancy of 0.70 kHz, which is mainly caused by the unsymmetrical structure of the flange.

Transient analysis is utilized to get the response characteristics. Two sine voltages with 90 degree phase difference under 500 $V_{p\text{-}p}$ and frequencies of 23.0 kHz are applied to the horizontal and vertical piezoelectric ceramics respectively. The driving trajectories of the driving feet are shown in Fig. 5. P_1, P_2, P_3 and P_4 are points selected from the left driving feet as shown in Fig. 1; T_1, T_2, T_3 and T_4 are points at the same location of the right driving feet. The trajectories of the eight points are ellipses with the maximum displacements of 9.54 μm in horizontal direction and 16.60 μm in vertical direction. In addition, the eight ellipse trajectories are consistent with each other.



(a) (b)

Fig. 1. (a) Structure of the proposed actuator, (b) arrangement and polarization directions of the PZT ceramics at the left side of the flange.