Sensors and Actuators A 235 (2015) 158–164

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Miniaturized piezoelectric actuator operating in bending hybrid modes

Yingxiang Liu [a,b,*], Dongmei Xu [a], Xiaohui Yang [a], Weishan Chen [a]

[a] State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001,Heilongjiang Province, China
[b] State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science & Technology, Wuhan 430074, Hubei Province, China

ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form
28 September 2015
Accepted 1 October 2015
Available online 9 October 2015

Keywords:
Piezoelectric actuator
Bending hybrid
Elliptical movement
Vibration characteristic

ABSTRACT

A novel miniaturized piezoelectric actuator operating in bending hybrid modes is reported in this work. It provides a way to reduce the size of piezoelectric actuator and shows potential application in small system. We use two orthogonal 1st bending modes of a symmetrical beam to produce elliptical movements on two driving feet; therefore, the design and fabrication process of the proposed piezoelectric actuator is quite easy. The side surfaces of the end tips are selected as the driving parts as the bending vibration can generate higher transverse displacement, which means that the axial movement of the end tip is unused as its lower amplitude. Parameters of the prototype is as follow: length of 34 mm, cross section of 10.5 mm × 10.5 mm, weight of 7.0 g, working frequency of 54.2 kHz, maximum no-load speed of 392 mm/s and maximum thrust of 1.2 N.

1. Introduction

Piezoelectric actuators have attracted a lot of attentions in the past years as their merits of simple structure without coils, quick response at millisecond, high precision and resolution at nanometer, low speed without reducer, self-locking in the power-off state and absence of electromagnetic radiation, etc., which makes them good candidates for precise actuating system, such as aerospace mechanism, micro robot, micro electromechanical system and optical instrument [1–5].

Recently, piezoelectric actuators with small sizes have become the research focus as they can accomplish precise driving demands in small system easier than the conventional electromagnetic motors. Most previous piezoelectric actuators achieve linear or rotary actuating by the elliptical movements of their driving tips. This special Lissajous trajectory vibration can be generated by a traveling wave of a ring [6–8], or be produced by the hybrid of two vibration modes with the same resonance frequency [9–11]. The hybrid of two vibration modes, such as longitudinal–longitudinal (L–L) [12,13], longitudinal–bending (L–B) [14,15], longitudinal–torsional (L–T) [16,17] and bending–bending (B–B) [18–20], have been studied and reported to design various piezoelectric actuators. To achieve small size, the linear piezoelectric actuators using L–B modes is a good choice; the one operated in the hybrid of the 1st longitudinal and 2nd bending modes of a rectangular PZT plate is a good example [21], which has been commercialized by Nanomotion Company. However, the dimensions of this piezoelectric actuator cannot be adjusted optionally as it will make the resonance frequency of the 1st longitudinal mode away from that of the 2nd bending mode.

In this study, a new type of piezoelectric actuator operated in the hybrid of two 1st bending modes is proposed. The proposed actuator can satisfy the frequency degeneration requirement by a symmetrical structure as the two 1st bending modes always have the same resonance frequency. Therefore, its dimensions can be adjusted easily to satisfy different requirements for space and weight. Compared with the previous L–B hybrid piezoelectric actuator, the proposed B–B hybrid one has flexibility on size design and miniaturization. It is also more suitable for precise actuating in small system.

2. Structure and operating principle

The proposed piezoelectric actuator is illustrated in Fig. 1, in which four pieces of PZT plates are bonded on the four side-surfaces of a square-shaped beam separately. The two ends of the beam are cutting into cone-shaped horns to magnify the bending vibration

* Corresponding author. Fax: +86 451 86416119.
E-mail addresses: liuyingxiang868@hit.edu.cn (Y. Liu), dongmeixu@hit.edu.cn (D. Xu), youngsme@hit.edu.cn (X. Yang), cws@hit.edu.cn (W. Chen).

http://dx.doi.org/10.1016/j.sna.2015.10.002
0924-4247/

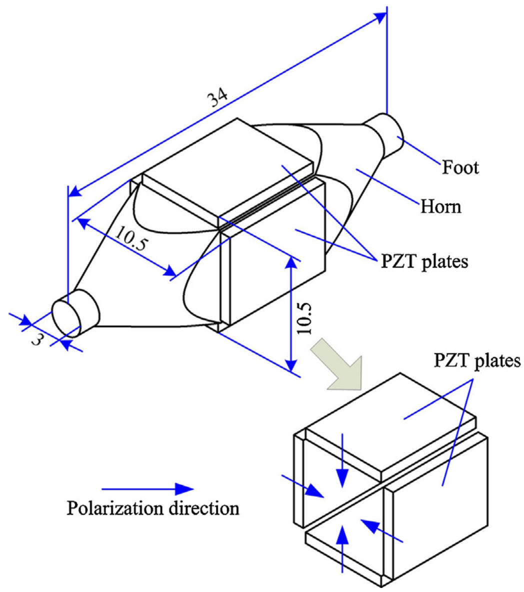

Fig. 1. Structure of the proposed piezoelectric actuator (unit: mm).

amplitude and velocity; the tip ends of the two horns are machined to cylinders to sever as the driving feet. The dimensions of the proposed piezoelectric actuator and the polarizations of the PZT elements are also listed in Fig. 1.

The proposed piezoelectric actuator operates under bending hybrid modes; concretely speaking, it produces elliptical trajectory movements on the two driving feet by the superimposing of two 1st bending vibrations: a horizontal one in XOZ plane and a vertical one in YOZ plane, as shown in Fig. 2. The symmetrical structure of the actuator makes these two bending have the same resonance frequency. Under this condition, the actuator will vibrate as shown in Fig. 2 if the two 1st bending vibrations have a temporal shift of 90°. Some previous piezoelectric actuators also operate under the similar principle as they all use the hybrid of two bending modes to generate elliptical movements on the driving parts. But our actuator works with a different actuating mode.

It can be easily understood that the hybrid of two orthogonal bending modes can forms three-dimensional motions on the beam ends, which contains OX displacement, OY one and OZ one. In previous works, the axial displacement along OZ direction was commonly used to overcome the preload between the actuator and the rotor. However, our actuator gives up this actuating mode, but uses the transverse displacement along OY direction to accomplish this task. For the bending of a beam, the transverse displacements, which contain the OX one and the OY one, are usually larger than the axial one along OZ direction. Thus, we hope this new actuating mode can improve the mechanical output performance. Furthermore, this new mode is applicative for both linear and rotary driving. The schematic diagrams for the linear and rotary driving are shown in Fig. 2(b) and (c), respectively. When the proposed piezoelectric actuator is pressed on two runners limited by two guiders, the same direction linear movements can be realized synchronously; the rotation movements can be achieved by placing two disk-shaped rotors upside. It should be noted that the outer surfaces of the two cylindrical driving feet serve as the driving parts.

3. Harmonic and transient analysis of the actuator

First, harmonic analysis was accomplished by using finite element method (Ansys software) to gain the input impedance characteristic of the proposed piezoelectric actuator. As its symmetrical structure, the two 1st bending vibration modes must have the same input impedance performance. Thus, only the horizontal bending mode in XOZ plane was calculated, which was shown in Fig. 3. During the harmonic calculation, a damping factor of 0.003 was adopted, and the frequency was set from 55.7 kHz to 56.5 kHz. The two frequencies with minimum and maximum impedances are got by this curve, which are 55.922 kHz and 56.336 kHz respectively. Thus, the electromechanical coupling factor k of the 1st bending mode can be calculated by the following equation:

$$k = \sqrt{\frac{f_{max}^2 - f_{min}^2}{f_{max}^2}} \quad (1)$$

where f_{max} and f_{min} are the two frequencies with maximum and minimum impedances separately. The electromechanical coupling factor is calculated to be about 12.1%.

Then, transient analysis was developed to get the motion characteristic of the actuator in time domain. To accomplish the simulation, sine and cosine voltages with value of 140 $V_{0\text{-}P}$ and frequency of 55.922 kHz were applied on the two groups of PZT plates for about 5.36 ms. Eight particles on the two outer rims were selected, and their movements were extracted and plotted, as shown in Fig. 4.

The two displacement response curves state that the proposed piezoelectric actuator can reach the steady vibration state after about 3.5 ms. The steady OX and OZ displacements of the driving tip are about 3.3 μm and 0.6 μm, which means that the maximum transverse vibration velocity of the feet is about 1160 mm/s. Another FEM model was also established and calculated, in which in the horns were deleted and a square-shaped uniform beam with length of 34 mm was used; the steady OX and OZ displacements of the driving tip were calculated to be about 2.1 μm and 1.0 μm under 1st bending resonance frequency of 33.610 kHz. This comparison states that the cone-shape horns used in the proposed actuator help a lot in improving the transverse amplitude and downing the axial one, and also cause obvious increase on the resonance frequency.

Fig. 4 also states that the movement trajectories of the two driving feet are three-dimensional ellipses as the displacements along OX, OY and OZ directions are generated synchronously. The movement trajectory of the foot is a two-dimensional ellipse in the XOY plane, as shown in Fig. 4(d), and the eight particles vibrate under overlapped circles in XOY plane. But their motions in XOZ plane have bad uniformity: some particles vibrate under ellipses and the other ones have oblique linear trajectories, see Fig. 4(e). The displacement along OZ direction is useless for the driving of the runner, as shown in Fig. 2. Therefore, we are more interested in the elliptical movement in XOY plane as it is used to push the runner. Concretely speaking, the combination of OX, OY and OZ displacements make the two tips vibrate in three-dimensional ellipses, and it is a better way to actuate the runner with the outer circles of the cylindrical feet as these parts have more intensive and uniform motions.

4. Fabrication and measurement

A prototype was fabricated under the dimensions listed in Fig. 1, as shown in Fig. 5. The four pieces of PZT plates were bonded on the four side-surfaces of the beam by epoxy adhesive. Precise flat tongs was used to clamp the PZT plates on the square-shaped beam for about 12 h to accomplish the solidification process. To fix the prototype, two clampers were also machined, which griped the actuator by screws. The contact parts for the clamping located near the wave nodes of the 1st bending modes.

First, the input impedance characteristic of the prototype was measured by Precision Impedance Analyzer (4294A). The measured frequency region was set from 52 kHz to 54 kHz. The curves of the impedance versus the frequency were tested, and the equiv-