Sensors and Actuators A 275 (2018) 11–18

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Development and experiment evaluation of an inertial piezoelectric actuator using bending-bending hybrid modes

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ARTICLE INFO

Article history:
Received 3 January 2018
Received in revised form 6 March 2018
Accepted 27 March 2018
Available online 28 March 2018

Keywords:
Piezoelectric actuator
Inertial driving
Linear driving
Bending-Bending modes
Step motion

ABSTRACT

An inertial driving piezoelectric actuator using bending-bending hybrid modes was proposed. In contrast to previous inertial driving piezoelectric actuators using PZT stacks, the proposed actuator used a piezoelectric transducer that could bend in the horizontal and vertical directions independently. The horizontal bending of the transducer was used to push the slider to move step-by-step. The vertical bending was used to change the normal force quickly to regulate the friction force in the driving process. The operating principle and inertial driving mechanism were planned, discussed and simulated by finite element analysis. The feasibility of the proposed mechanism was verified by experiments. The experimental results showed that the step distance was linearly related to the voltage of the horizontal excitation signal, and it was greatly improved by the vertical bending. The prototype achieved a maximum speed of 350 μm/s at a voltage of 400 $V_{p\text{-}p}$ and frequency of 250 Hz, and it achieved a maximum thrust force of 5.88 N at a preload of 63 N.

1. Introduction

Piezoelectric actuators exhibit merits of high resolution, rapid response, no electromagnetic radiation and compact structure [1]; thus, they can meet the requirements of many fields, e.g., bio medicine, robotics and semiconductor manufacturing. From their working principles, the piezoelectric actuators can be classified into four types: ultrasonic, direct driving, walking and inertial driving. The ultrasonic type actuators operate at their resonant modes with ultrasonic frequencies [2–6], and they have been used in some fields because of their merits of high output force and long stroke. However, the problems of high wear and accuracy reduction that accompany the ultrasonic actuators are difficult to address; thus, they are always used in fields with micrometer-scale positioning accuracy. The problems can be avoided by using other types of actuators that operate at low frequencies [7,8]. The direct driving type actuators that used PZT stacks to drive the slider directly usually have nanometer resolution [9–12]; however, their strokes are limited because the axial deformations of the PZT stacks are only approximately 0.1% of their total lengths. The long stroke driving has been achieved by the walking type actuators using the "clamp and feed" principle [13–16], in which the slider is moved step-by-step with a long stroke via the inchworm-like motions of several PZT stacks. However, the structures and control systems of the walking type actuators are complicated, which affects their scopes of application. Based on the stick-slip motions, the long stroke and nanometer resolution can be obtained by inertial driving type actuators with a simple structure and excitation signal; such actuators are easy to manufacture and control. Therefore, studies of inertial actuators have attracted many researchers.

According to the basic functional principles, the inertial driving actuators can be divided into the moving actuator type [17–19] and the fixed actuator type [20,21]. The moving actuator type is mainly used to transport a small load with nanometer accuracy as a micro-robot. The moving elements are attached to either side of the actuator, and they move together; they can thus achieve flexible movement with long strokes. However, the operated surface must be well machined, and the mass of the actuators must be relatively large so they can move by themselves, which makes the actuators heavy and limits the frequencies of the excitation signals. The fixed actuator type can solve these problems and function at high frequencies. The fixed actuator type typically uses a PZT stack as a stator to drive the moving element via the stick-slip principle to move an object with very small mass while not affecting the frequency characteristics of the actuators [22]. Thus, the fixed actuator type can be used to drive objects with different masses and widen the range of applications of inertial actuators. However, the dis-

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https://doi.org/10.1016/j.sna.2018.03.039
0924-4247/

placement is limited by the length of the rod. Moreover, rollback is inevitable for the actuators using the inertial driving mechanism because the friction force cannot be diminished in the rapid deformation stage, and the moving element is driven to move back in the driving process, which is unfavorable for improving the output speed.

Methods for changing the friction force in the driving process have been proposed by many scholars. The main ideas were to increase the static friction force in the slow deformation stage or reduce the sliding friction force in the rapid deformation stage, and the methods included two main types: designing proper excitation signals and exploring novel mechanical mechanisms. Cheng et al. proposed a method utilizing the ultrasonic friction reduction principle: a high-frequency sinusoidal signal was applied to the rapid deformation stage of the traditional saw-tooth wave [23], the sliding friction was reduced and the output speeds were improved. Wang et al. and Cheng et al. also used the similar method to investigate and improve the performance of the inertial actuators [24,25], and the validity of the method was verified by experiments. For the second method, Wen et al. presented an inertial rotary actuator based on changing the normal pressure through the use of a triangular block, which was used to change the friction force by adjusting the angle between the PZT stacks and the horizontal plane [26]. Li et al. proposed a linear inertial actuator that used a parallelogram-type flexure hinge mechanism and one piezoelectric stack to generate lateral motion to drive the slider via the inertial mechanism [27]; the static friction force in the slow deformation stage increased gradually, the sliding friction force in the rapid deformation stage decreased quickly, the rollback was suppressed and the output speed was raised. Next, Li et al. presented another inertial driving actuator that used a bridge-type flexure hinge mechanism [28] to improve the performance of the actuator; Cheng et al. also proposed a new design using right circular flexure hinge mechanism to drive the slider that enabled the friction force to be changed quickly [29]. As a result, the applications of the inertial actuators were clearly widened. However, the first method for designing proper excitation signals was based on the traditional moving actuator type, and the strokes of the slider were limited to the length of the rod. The structure of the actuators that used new flexure hinge mechanisms, as noted in the second method, was complex. Therefore, it is necessary to design an inertial actuator with simple structure and long stoke.

This work aims to provide an inertial piezoelectric actuator with a simple structure. The actuator uses a piezoelectric transducer operating in bending-bending hybrid modes, and the horizontal bending mode is used to drive the slider to achieve a long stroke via the inertial driving mechanism. While the vertical bending is used to change the normal force quickly in the driving process and the friction force can be increased in the slow deformation stage and reduced in the rapid deformation stage, the rollback can be suppressed to improve the step distance. The rest of this paper is organized as follows. In Section 2, the configuration of the inertial actuator and its operating principle are planned and discussed. In Section 3, simulation and analyses of the actuator are conducted. In Section 4, experiments are designed and performed. The performances of the actuator are investigated. A discussion of the results and conclusions is given in Section 5.

2. Actuator configuration and operating principle

The structure of the proposed piezoelectric actuator is shown in Fig. 1(a). The structure consists of a piezoelectric transducer operating in bending-bending modes that is clamped onto the end cap with a bolt. The transducer is composed of a group of PZT elements and a horn with a driving tip. The group of the PZT elements is divided into four zones, as shown in Fig. 1(b). They are all polarized along their thickness direction, and the polarized directions of the two regions at the diagonal direction are opposite. The two pairs of diagonal zones are named horizontal and vertical PZT elements. The horizontal PZT elements are used to generate the bending motion of the transducer along the horizontal direction and drive the slider to achieve a linear motion by the inertial driving principle. The vertical PZT elements are used to produce the bending motion along the vertical direction and change the normal force quickly during the driving process.

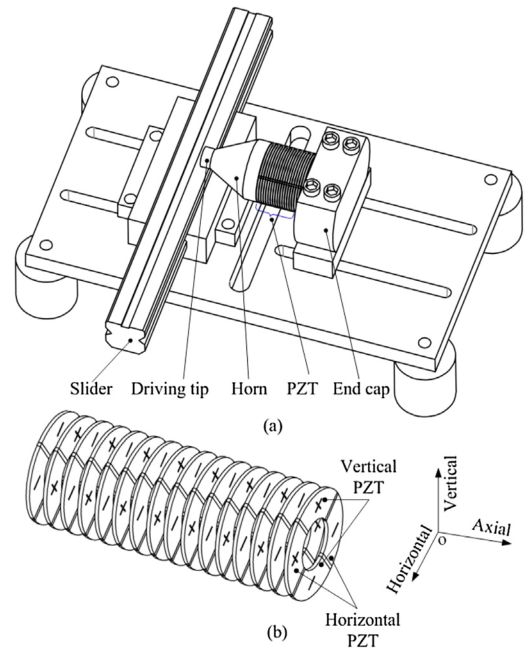

Fig. 1. Structure of the proposed piezoelectric actuator: (a) the three-dimensional model, (b) the arrangement of the PZT elements.

The operating principle of the actuator is based on the stick-slip motion, as illustrated in Fig. 2. A trapezoidal-wave signal is selected as the input voltage signal to achieve the inertial driving, as shown in Fig. 2(d). A square-wave signal is selected to change the normal force, as shown in Fig. 2(e). By applying the trapezoidal-wave and square-wave voltage signals on the horizontal and vertical PZT elements, respectively, the slider will be moved along the horizontal direction step-by-step. In total, the proposed actuator can operate in two stages in one cycle as follows.

(1) Slow bending stage: a positive DC voltage is applied on the vertical PZT elements to move the driving tip to the lower extreme, and then the tip presses tightly on the slider. Next, a signal with a slowly increasing voltage is applied on the horizontal PZT elements in time period t_1, and the transducer bends slowly to its positive extreme along the horizontal direction, as shown in Fig. 2(b). The slider is moved for one step by the friction force.
(2) Fast bending stage: a negative DC voltage is applied on the vertical PZT elements, and the driving tip moves to the upper extreme and leaves from the slider. Next, the excitation voltage signal applied on horizontal PZT elements decreases rapidly in time period t_2. The transducer bends rapidly to its negative extreme along the negative direction of the horizontal axis, as shown in Fig. 2(c), and the slider remains still via the inertial force.

The slider can be moved along the positive direction of the horizontal axis step-by-step when periodic excitation signals are applied to the horizontal and vertical PZT elements, as shown in