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Design and experimental evaluation of a novel stepping linear piezoelectric actuator

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ABSTRACT

A novel stepping piezoelectric actuator is proposed and tested in this work to achieve the linear driving with long stroke and high resolution. The proposed piezoelectric actuator contains four piezoelectric stacks located in U-shape: two of them are set horizontally, whereas the other two are placed vertically. The actuating principle of the U-shaped actuator is analyzed: two piezoelectric stacks are used to control the clamping state of the runner, while the linear stepping motion is achieved by the other two stacks. A double-level screws structure, which not only gives enough preload, but also protects the piezoelectric stacks from lateral forces, is proposed and used to make the piezoelectric stacks work under a reliable condition. An equivalent model is developed for the calculation of the clamping force of the piezoelectric actuator. The equivalent model is based on a concept of converting structures related to clamping forces into springs with certain elastic coefficients. Static analysis is performed by finite element method (FEM) to get the equivalent coefficients of the structures. A prototype is fabricated and the experimental studies are carried out to validate the actuating principle and obtain the mechanical output performances. Experimental results show that the maximum driving force of the prototype is 13.2 N and the maximum velocity is 47.6 μm/s.

1. Introduction

With the rapid developments of precision machining, robots, optical instruments, MEMS and cell manipulations, the researches of precision motion platforms have become more and more urgent [1–2]. A variety of new type actuators have been invented to meet different driving requirements of precision motion platforms, such as the piezoelectric actuators, shape memory alloy actuators, magnetostrictive actuators, electrostrictive actuators and so on [3–6]. The piezoelectric actuators have attracted a lot of attentions by their merits of simple structure, high power weight ratio, high displacement resolution, no electromagnetic interference, quick response within a few milliseconds, self-lock when power off, etc [7–8].

Piezoelectric actuators usually convert the electrical energies into the mechanical energies of the linear or rotary motions of the runners by the inverse piezoelectric effect of the ceramics [9–10]. They can be classified into four types by the drive mechanisms: ultrasonic piezoelectric actuators, micro-displacement piezoelectric actuators, inertial piezoelectric actuators and stepping piezoelectric actuators [11–16]. The ultrasonic piezoelectric actuators can achieve higher speeds by comparing with the other three types, but their displacement resolutions are in micrometer scale [17–19]. The micro-displacement piezoelectric actuators are very suitable for platforms with nanometer resolutions and short strokes [20–22]. The inertial piezoelectric actuators can produce long stroke motions with nanometer resolution by using the difference between the inertial force and the frictional force, but their thrust forces are usually smaller than the other three types [23–26].

The stepping piezoelectric actuators mainly imitate the movement of the inchworm in nature: they usually use the cycle of the clamping and pushing movements to drive the runner step-by-step and achieve a long travel range by accumulating single steps. They can obtain larger thrust forces by comparing with the inertial piezoelectric actuators. Furthermore, they are easy to obtain different stepping displacements by varying the amplitude of the exciting voltage as the output displacement of the piezoelectric element has an approximately linear relationship with the applied voltage. Therefore, the stepping piezoelectric actuators are very popular for applications in precision platforms with requirements of long stroke and high resolution, and it becomes the research hotspot in this field. Most of the previous designs of the stepping piezoelectric actuators have used the flexible hinge displacement amplification mechanisms to amplify the output displacements [27,28]. However, these hinges are always complicated in structures as they have

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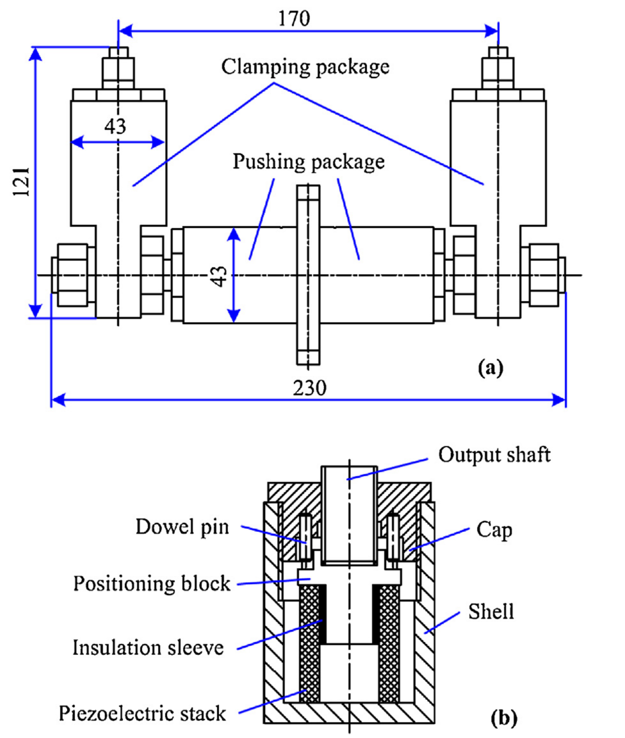

Fig. 1. The basic structure of the proposed stepping piezoelectric actuator: (a) the outline structure (unit: mm), (b) the section view of the package for the piezoelectric stack.

variable cross-sections, which make their fabrications difficult and expensive. Furthermore, the uses of these hinges will reduce the total stiffness of the actuator, and it will be sensitive to the low frequency noises from the environment.

A U-shaped stepping piezoelectric actuator is proposed in this work, in which a double-level screws structure is used to make the piezoelectric stacks work in a reliable condition. The proposed actuator has the similar operating principle with the previous stepping piezoelectric actuators operated by inchworm-like motions, and the runner is pushed step-by-step by the alternating motions of several piezoelectric stacks. But the elements in this actuator are easy to be fabricated and low cost by comparing with the flexible hinge, and the stiffness of the actuator will also be improved. The basic structure of the proposed U-shaped stepping piezoelectric actuator is discussed in Section 2. Section 3 gives the detail explanation about the actuating principle. An equivalent model is developed for the calculation of the clamping force in Section 4. A prototype is fabricated and tested in Section 5, which is followed by a conclusion in Section 6.

2. Structure of the proposed actuator

The basic structure of the proposed U-shaped stepping piezoelectric actuator is shown in Fig. 1; it consists of four similar piezoelectric stack packages, which are divided into two groups according to their functions: the two clamping packages and the two pushing packages. The two pushing packages are set horizontally and coaxially, whereas the two clamping packages are placed vertically and parallel, and they are located in U-shape. The two end tips of the two clamping packages are used as the driving feet. There are certain differences in the structures of shells and displacement output shafts between the clamping packages and the pushing packages, but these four packages have exactly the same internal structure, as shown in Fig. 1(b). The two pushing packages have a total length of 230 mm, the clamping package has a length of 121 mm and the distance between the two axes of the two clamping packages is about 170 mm. Four piezoelectric stacks, with outer diameter of 25 mm, inner diameter of 15 mm and length of 30 mm are set in the four packages separately.

The assembly of the piezoelectric stack package is realized by the double-level screws among the output shaft, the cap and the shell. The double-level screws structure not only applies preload on the piezoelectric stack, but also can reduce the effects caused by the lateral forces by transmitting them to the shell. Therefore, these packages with double-level screws structures can protect the piezoelectric stacks from shear forces, which is very likely to damage the piezoelectric stacks. Meanwhile, the packages can provide reliable preloads on the piezoelectric stacks, which will ensure the piezoelectric elements work under effective and safe states. Moreover, the deformations of the double-level screws ensure that the output shaft will have large displacement when the piezoelectric stack is energized. Generally speaking, the proposed double-level screws structure has merits of simple structure and low cost by comparing with the flexible hinges used in the previous inchworm piezoelectric actuators. The total stiffness of the piezoelectric actuator can be improved since there is no thin beam like the flexible hinges, which means that it will be less sensitive to the low frequency noises from the environment.

3. Actuating principle

The actuating principle of the U-shaped stepping piezoelectric actuator is shown in Fig. 2, in which arrows in are used to illustrate the motion of the four stacks and the runner. There are six sub-steps in each actuating cycle. The four piezoelectric stacks in the actuator are named as stack-a, stack-b, stack-c and stack-d for the identification, respectively. The operating sequences of the stepping piezoelectric actuator can be described as follows.

(1) Stack-a is energized, stack-b, stack-c and stack-d are de-energized. Due to the elongation of the piezoelectric stack caused by voltage, the output shaft connected with stack-a is pushed forward. The frictional force f_1 between the left foot and the runner increases, and it will exceed the frictional force f_2 between the right foot and the runner. The action of the left clamping package is called "clamping".
(2) Stack-b and stack-c are energized, while the status of stack-a and stack-d are maintained as sub-step (1). The output shafts connected with stack-b and stack-c are pushed forward, which result that the left foot is moved leftward and the right foot is moved rightward. The runner will be moved leftward by the left foot for one step as the f_1 is bigger than f_2. The action of the left pushing package is called "pushing".
(3) Stack-d is energized and the status of stack-a, stack-b and stack-c are maintained as sub-step (2). The right clamping package clamps the runner, which is a preparation for the switch to the next sub-step.
(4) Stack-a is de-energized, while the status of stack-b, stack-c and stack-d are maintained as sub-step (3). The left foot departs from the runner and the f_1 becomes smaller than f_2.
(5) Stack-b and stack-c are de-energized, the left foot is moved rightward and the right foot is moved leftward. The right foot pushes the runner leftward for another step.
(6) Stack-a is energized and the left clamping package clamps the runner again, which is a preparation for the switching to sub-step (1) in the next cycle.

According to the actuating principle, the signals applied on the four piezoelectric stacks are plotted in Fig. 3. T is the period; a, b, c and d represent the actuating signals applied on the corresponding