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A novel inchworm type piezoelectric rotary actuator with large output torque: Design, analysis and experimental performance

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A B S T R A C T

A novel inchworm type piezoelectric rotary actuator based on wedge block clamping is presented in this paper. With the help of only one piezo-stack and two clamping blocks, the proposed actuator can imitate the walking mode of inchworm to deliver stable long range rotary motion accompanying with high driving resolution. Owing to the advantages of the distinctive clamping principle, the output torque of the actuator can be up to 7168.7 Nmm. The mechanical structure and the working principle of the actuator are introduced in detail. As a key component of the actuator, the clamping block is well designed and the curve function of its working surface is deduced. We manufacture an actuator prototype and establish a set of experimental system and conduct a series of experiments to test the performance of the prototype. The experimental results indicate that the prototype can output stable angular displacements step by step under various driving voltages and frequencies and all steps have high reproducibility. The driving resolution of the actuator is 0.567 μrad and the designed motion range is 5°. We can obtain a satisfactory driving velocity by choosing a proper driving voltage and frequency for the actuator. Under driving frequency of 1 Hz, the maximum velocity is 511.7 μrad s^{-1} when the driving voltage is 150 V and under driving voltage of 90 V, the velocity can reach to 42959.5 μrad s^{-1} when the driving frequency is 128 Hz.

1. Introduction

With the rapid development of optical systems, ultraprecision machining, micro/nano manipulation and so on, the demand for high-accuracy positioners with nanometer resolution and millimeter range has been gradually increasing in various technical fields [1–7]. Although several means of precision positioning exist, many are either unsuitable or do not readily lend themselves to ultra-precision application [8–10]. So they can hardly satisfy the continuous increasing functional demands, which motivate researchers to develop new driving methods, principles and technologies.

Piezoelectric actuators are a kind of non-traditional actuator operated by the inverse piezoelectric effect of the ceramic element and the frictional coupling between the interfaces [11–13]. They exhibit merits of simple structures with no coil and magnet, high power under small weight, high precision locating in nanometer and so on [12,13]. While having so many advantages, piezoelectric actuators suffer from small motion range, which seriously limits their applications [6–13]. The development of piezoelectric actuator with high active-passive performance has been a challenging topic in many smart structural applications, and attracted the attention of numerous researchers in the last decades [14].

Many methods have been utilized to obtain long motion ranges of the piezoelectric actuators [15–23]. Due to the simplified structure and high resolution, the flexure hinge amplification mechanism is one of the common methods [17,18]. Nevertheless, the working range of the flexure hinge amplification mechanism is generally less than dozens to hundreds of micrometers, which is still not enough for the cross-scale system. Thereupon, the stepping type motion principles are developed [19–29]. These types of piezoelectric actuators can work step by step and their working range can reach to millimeters, even infinite. So far, the stepping type piezoelectric actuators mainly consist of stick-slip type actuators [19–22], ultrasonic type actuators [23–25], and inchworm type actuators [26–29].

A stick-slip actuator is equipped with a friction element that can move forward slowly and backward rapidly. When the friction element moves forward slowly, the rotor/mover can be driven by the frictional force. But when the friction element moves backward rapidly, the rotor/mover cannot follow the fast motion of the friction element and remains in place due to its inertia. Therefore, the rotor/mover can produce an unlimited displacement by continuously repeating this operation [19–22]. An ultrasonic actuator is powered by the ultrasonic

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Table 1
Performance of piezoelectric actuators.

Reference	Year	Type	Velocity	Output	Resolution
[19]	2017	Stick-slip	1165 μrad s^{-1}	70.6 Nmm	1.83 μrad
[20]	2015	Stick-slip	32000 μrad s^{-1}	152.9 Nmm	1.54 μrad
[23]	2016	Ultrasonic	1.65×10^7 μrad s^{-1}	53 Nmm	N/A
[24]	2016	Ultrasonic	3.58×10^7 μrad s^{-1}	6.26 Nmm	N/A
[26]	2013	Inchworm	6508.5 μrad s^{-1}	93.1 Nmm	4.95 μrad
[27]	2014	Inchworm	71300 μrad s^{-1}	19.6 Nmm	25 μrad

vibration excited at resonance. The stator can produce elliptical driving trajectories on the frictional contact surfaces by this vibration energy. The rotor/mover, placed against the stator, can be then driven by using the elliptical driving trajectories [23–25]. An inchworm actuator which usually consists of one feeding module and two clamping modules is a type of bionic device which imitates the movement of the inchworm in nature. It can deliver nanometer-precision positioning over a long motion range [26–29]. Although having been applied in many fields, the existing stepping type piezoelectric actuators usually suffer from small output capacity. Table 1 summarizes the performance data of the reviewed piezoelectric actuators.

This study proposes a novel inchworm type piezoelectric unidirectional rotary actuator based on wedge block clamping. With the help of two clamping blocks, the proposed actuator can deliver stable long range rotary motion with high driving resolution. Comparing with general piezoelectric actuators, the actuator discussed in this paper possesses the following three characteristics: (1) it is equipped with only one piezo-stack; (2) owing to the advantages of its distinctive clamping principle, the proposed actuator can deliver long range rotary motion with large output torque; (3) the actuator is provided with the self-locking ability under power-off state.

2. Configuration and working principle

2.1. Configuration of the actuator

The structure of the designed piezoelectric actuator with specific dimensions of 120 mm × 75 mm × 18 mm is illustrated in Fig. 1. It mainly consists of a stator, a rotor, a piezo-stack, a spindle, a balance spring, two clamping blocks and two clamping springs. As a significant component of the actuator, the rotor including a bearing hole, a piezo-stack installing groove, a set of flexure hinges and two clamping surfaces is shown in Fig. 2. The piezo-stack which is preloaded by a shim and an adjusting bolt is nested inside the piezo-stack installing groove of the rotor. The clamping springs are two extension springs which can

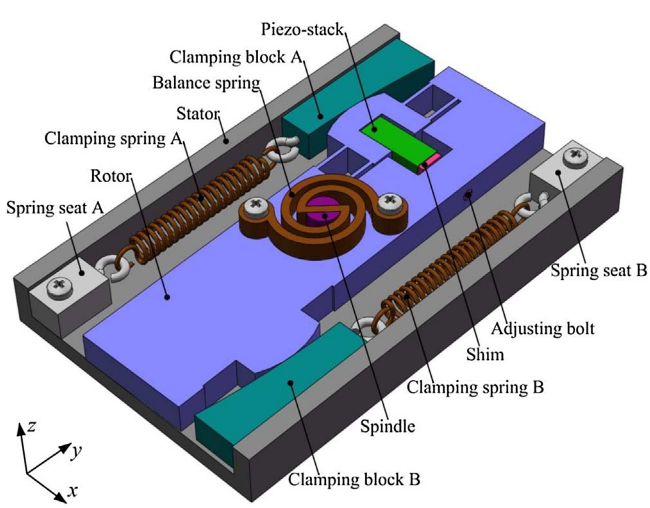

Fig. 1. Model of the actuator.

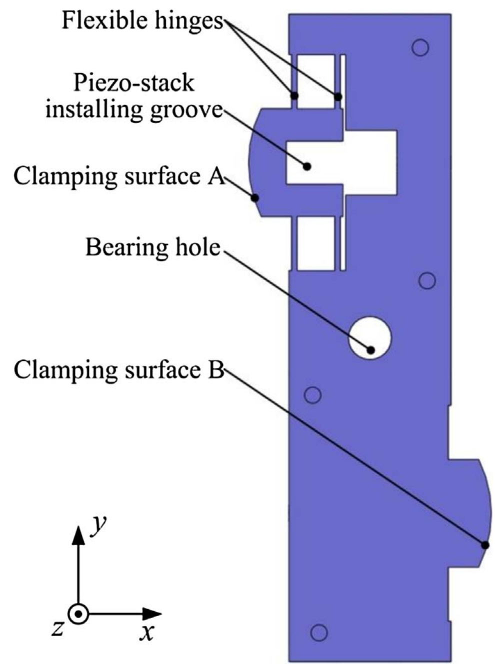

Fig. 2. Structure of the rotor.

provide traction forces for the clamping blocks to produce their clamping motions. There is a hook to connect the clamping spring and the clamping block and the hook is in threaded connection with the clamping block. So the clamping force can be adjusted by the threaded connection. The balance spring is a torsion spring which is utilized to counteract the moments from the clamping blocks and hold the position of the rotor. In order to obtain good elastic properties of the flexure hinges, the whole rotor is made of 65 Mn (ASTM1566).

2.2. Working principle

As shown in Fig. 1, the piezo-stack is nested inside the piezo-stack installing groove of the rotor. When the positive driving voltage is applied, the extension of the piezo-stack drives the elastic deformations of the flexure hinges and micro motion of the clamping surface A. In this study, the sinusoidal wave signal voltage illustrated in Fig. 3 is applied to the piezo-stack.

Fig. 4 presents the working process of the actuator in one working cycle, which can be divided into five steps. They are described as follows:

(a) As shown in Fig. 4, at time 0, the piezo-stack is not deformed by applying zero voltage to it. The clamping block A presses the clamping surface A tightly under the force of the clamping spring A. Similarly, the clamping block B presses the clamping surface B tightly under the force

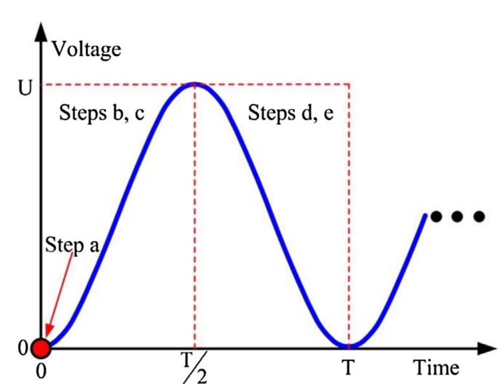

Fig. 3. Input voltage signal.