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An asymmetrical inertial piezoelectric rotary actuator with the bias unit

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ABSTRACT

A novel piezoelectric inertial rotary actuator with a bias unit that is based on asymmetrical clamping structures was presented in this paper. Under the same circumstance, the designed actuator with symmetrical electrical signals produced a relatively larger inertial driving moment difference because of the existence of the bias unit. Mechanical analysis was derived and the simulation model of the bias unit was built to ascertain the influence of structural parameters on output performance. A prototype with a bias unit, a carrying device and a friction adjusting device was fabricated and an experimental system was built to evaluate the performance in terms of output displacement, angular velocity, driving moment and bearing capacity. Both simulation and experimental results indicated that the bias unit improved angular velocity and output force to some extent. Compared with the actuator without a bias unit, the actuator with the offset distance of 15 mm enhanced the maximum angular velocity by approximately 54.88% from 3.48 rad/s to 5.39 rad/s under 100 V, 23 Hz and the highest driving moment by 50.2% from 2.41 N mm to 3.62 N mm. Angular displacement resolution reached 14.3 μrad under 15 V, 1 Hz and heavy bearing capacity attained 1300 g under 100 V, 4 Hz. In general, the proposed actuator can achieve larger angular velocity and higher carrying capacity than those in literature.

1. Introduction

The interests in precision actuators are rapidly increasing [1–3] due to a variety of potential applications, such as ultra-precision manufacturing [4], semiconductor industry [5], aerospace [6], adaptive optics [7] and composite material [8]. Among these applications, the demands for the motion range and the resolution are typically at micrometer level and nanoscale, respectively. Piezoelectric precision actuators, under precision actuators type, meet these needs owing to their superior characteristics such as high precision, rapid response and long stroke.

Previous designed piezoelectric inertial actuators by using piezoelectric bimorph usually have a relatively low output force, angular velocity and bearing capacity. As a result of these defects, sustaining large loads and achieving quick position are difficult. Chen and Liu proposed a two-degree-of freedom precise actuator for translational and rotational motions with the maximum rotational speed of 3.72 rad/s and driving force of 2.32 mN [9]. An inertial impact piezoelectric ultrasonic motor by Paik et al. enhanced the output force to 110 mN [10]. Moreover, Sharp et al. improved the driven force to 348 mN [11]. A multi-degree-of-freedom miniature actuator using piezoelectric pusher element studied by Shen et al. could sustain a load of nearly 360 gf [12]. Zeng et al. presented a new inertial linear actuator to increase the bearing capacity to 1 kg [13], and developed a bi-directional inertial rotary actuator with the maximum angular speed of 5.23 rad/s [14]. Cheng et al. presented a piezoelectric inertial rotary actuator based on asymmetrical clamping structures and optimized the output performance through introducing the magnetic field, the maximum angular velocity and output force reached 4.02 rad/s and 0.98 N, respectively [15]. The aforementioned piezoelectric actuators commonly possess superiority in one aspect and there is still large potential to improve output performance from other perspectives.

According to current research status, instead of utilizing the magnetic force to assist to realize optimization indirectly in reference [15], this paper proposes an innovative piezoelectric inertial rotary actuator with improved angular velocity, carrying capacity and output force through structural optimization to alter the driving moment directly. A bias unit was defined and designed to optimize output performance as output force and rotary speed. Asymmetrical clamping structures were utilized to obtain asym-

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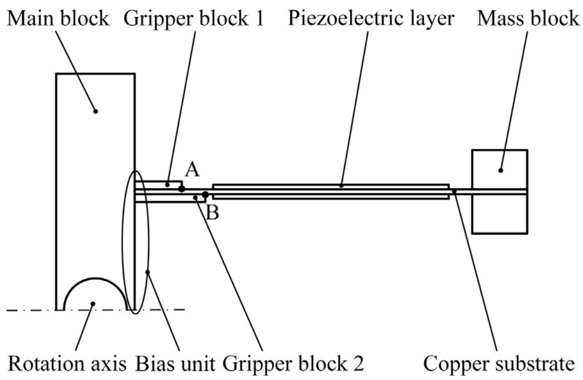

Fig. 1. Major elements of main motion body.

metrical inertial impact force. A carrying device was also adopted to realize a stable output performance and to test the bearing capability. More details about the working principle, structural design and analysis, simulation, experiments, and conclusions will be introduced in subsequent sections.

2. Working principle

2.1. Inertial impact driving principle

Fig. 1 illustrates the major components of the main motion body. Each piezoelectric vibrator is composed of a beryllium bronze substrate, two piezoelectric layers, two mass blocks and an asymmetrical clamping structure [13,15,16] with two gripper blocks in different length. In addition, the offset distance is defined as the perpendicular distance between the mid-plane of copper substrate and the axes of rotation axis. The bias unit, which is generated due to the offset distance, is applied to enhance output force and angular velocity to realize large load-bearing capacity and quick positioning. The piezoelectric vibrators equipped with asymmetrical clamping structures serve as the driving source in the actuator. Under a periodic symmetrical square wave signal, the vibrators will vibrate up and down. Meanwhile, the length of the effective clamping arm and the equivalent stiffness differ on both sides. When the vibrator vibrates to the upside, point A is effective clamping point. On the contrary, it turns to point B downside. In addition, the equivalent stiffness of the vibrator in the upside is smaller than that in the downside. Thus, distinguishing tip resultant force appears, and the driving moment, produced in both sides, will eventually enable the actuator to rotate clockwise in this case. However, when short gripper block 1 and long gripper block 2 are exchanged initially, the actuator can achieve reversed rotation.

2.2. Motion process

The motion process of the target actuator with asymmetrical clamping structures and bias unit under a symmetrical square wave signal is shown in Fig. 2.

(a) The actuator remains original state without motions when the driving voltage is null.
(b) When the signal varies from "0" to "*a*", the vibrators deform rapidly in the counter clockwise. Meanwhile, if the inertia moments, generated by two maximum impact forces on both sides, are larger than the maximum static friction torque, then the actuator will rotate β_1 clockwise. The vibrators keep deforming counter clockwise with no extra motions as the signal goes from "*a*" to "*b*".
(c) The vibrators bend to the opposite direction as signal varies from "*b*" to "*c*." The inertia moments, generated by two maximum impact forces on both sides, if larger than the maximum static friction torque, will make the actuator rotate in counter clockwise direction by a step angle of β_2. The actuator keeps still under the constant voltage from "*c*" to "*d*".
(d) Eventually, the vibrators generate no deformation and return to the initial state when the signal varies from "*d*" to "*e*." β_3, which is believed as the angular displacement of the actuator in one cycle of the excitation signal, ultimately appears.

The actuator can achieve continuous movements by repeating four steps discussed above under a periodic excitation signal.

3. Design and analysis

3.1. Structure design

The massive structure of the designed actuator is shown in Fig. 3. The actuator consists of a carrying device, a pointer, a rotation axis, a beam, two bearings, two support frames, a main motion body, a friction adjusting device, and a base. The bias unit is adopted to gain a better output manifestation, and offset distance is adjusted from 0 mm to 30 mm to test its influences. To measure the ability of practical application and to achieve stable output performance, a carrying device is designed. The pointer under the carrying device acts as the measuring point of the motion. The friction adjusting device can change the movements by controlling a swiveling

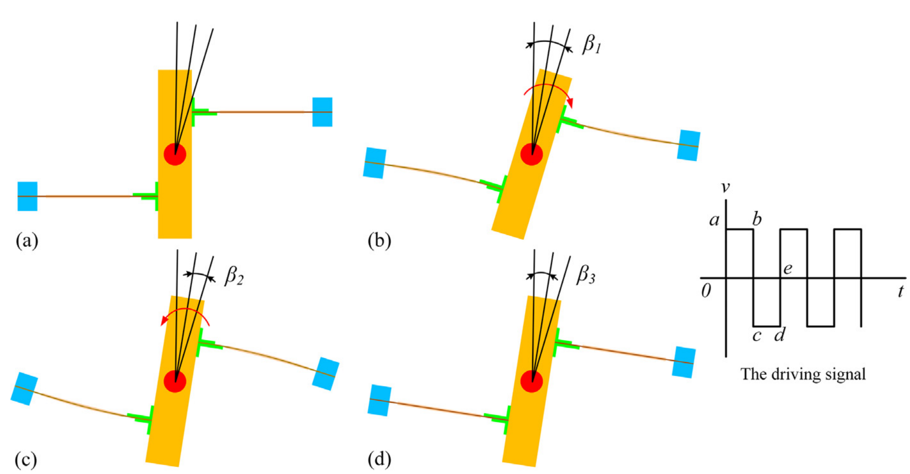

Fig. 2. Driving process of the target actuator under a symmetrical square signal.