Sensors and Actuators A 223 (2015) 125–133

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Piezoelectric inertial rotary actuators based on asymmetrically clamping structures

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ARTICLE INFO

Article history:
Received 26 September 2014
Received in revised form 7 January 2015
Accepted 7 January 2015
Available online 15 January 2015

Keywords:
Piezoelectric bimorph
Actuator
Inertia
Magnetic force

ABSTRACT

This paper presents innovative piezoelectric inertial rotary actuators based on asymmetrically clamping structures, which apply magnetic force to improve driving performance. By using a pretightening force control device, the designed actuators can realize high accuracy and stability. To test the influence of magnetic force on the driving property, two types of actuators are fabricated and investigated. Piezoelectric-driven force is the only driving source of the first actuator type, whereas magnetic force is applied to the second actuator type. An experimental system is built to test the performance of the actuators under different frequencies, voltages, and pretightening torques. Experimental results indicate that the stable minimum output stepping angle is 0.85 μrad under a square signal of 20 V, 6 Hz and a pretightening torque of 2.475 N mm. Under the condition of 8 Hz and 100 V, the maximum angle velocity and output force can reach 4.02 rad/s and 0.98 N, respectively. The proposed actuators not only achieve a stable and accurate rotary motion but also realize a large output force and a fast velocity, thus contributing to the application of pretightening force control device and magnetic force.

1. Introduction

With the rapid development of nanotechnology, precision actuators have become increasingly significant in a variety of technical fields, such as ultra-precision manufacturing [1], precision measurements [2], aerospace [3], optical [4], and medical engineering [5,6]. According to driving principles, traditional actuators can be mainly classified into electromagnetic [7], hydraulic [8], and pneumatic actuators [9]. The types of precision actuators include magnetostrictive [10], electrostrictive or piezoelectric [11], electrostatic [12], shape memory alloy [13], and artificial muscle actuators [14]. This actuator has recently been in high demand in application for precise positioning because of its superior characteristics, such as small size, nanoscale resolution, rapid response, and long stroke [15].

Many novel piezoelectric actuators have been developed, including ultrasonic [16,17], direct drive [18,19], inchworm [20,21], and inertial types [22,23]. The inertial actuator is a new type of micro-actuator that is commonly driven by only one active component. This micro-actuator has superior performance, a simple mechanical structure, high response, and high movement speed. Thus, considerable attention has been given to inertial actuators [24].

In terms of inertial actuators, two common control approaches to 1-DOF motion are used, namely, signal-control type [25] and friction-control type [26]. The former type usually utilizes an asymmetrical waveform excitation signal to generate unequal impact forces in contrary direction. The latter type enables the actuator to achieve motion by changing the friction force on the surface between the moving body and supporting base under a symmetrical waveform excitation signal. However, inertial actuators based on an asymmetrical signal generally depend on a complex and precise signal-control system to produce specific waveforms, thus increasing the difficulty of the simplification and integration of the actuator [27]. For friction-control-type inertial actuators, the complicated friction force results in drawbacks of low precision and nonlinearity though this type of actuators could overcome the complex circuit drawback. These actuators usually require high-precise friction-control methods [28]. These disadvantages limit the functionality of available inertial actuators to practical applications.

To overcome existing problems, an innovative inertial-rotated stepping actuator based on an asymmetrically clamping structure is presented to achieve 1-DOF rotation. This actuator also applies the effect of permanent magnets to improve performance. The control type of this actuator depends on a specific mechanical structure, namely, asymmetrically clamping bimorph piezoelectric vibrators

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http://dx.doi.org/10.1016/j.sna.2015.01.007
0924-4247/

(mechanism-control type [29]). Compared with the control methods of other actuators, the special control strategy of actuator not only simplifies the design of circuit control system and miniaturizes the electric structure, but also reduces the requirements for high-precise friction control methods. This is due to the fact that the signal and the friction of this actuator are both symmetrical. If the actuator is designed as a product in the future, obviously, it will be much easier to establish a symmetrical signal (such as square wave) circuit control system than an asymmetrical signal (such as sawtooth wave) circuit control system. Therefore the asymmetrically clamping structure is proposed in this work to mainly exploit the advantage of circuit miniaturization. The working principle, motion process, and structure are introduced and expounded in detail. Moreover, the inertial impact driving principle is analyzed on the basis of asymmetrical clamping. A prototype is designed and manufactured to validate the driving principle and test the working performance. The pretightening torque characteristics, frequency characteristics, voltage characteristics, and effect of magnetic force on the property of this actuator are observed and recorded in a series of experiments. The average output stepping angle, velocity, and output force of two types of actuators under different conditions are provided in this paper.

2. Working principle and motion process

2.1. Inertial impact driving principle on the basis of asymmetrical clamping

A pair of bimorph piezoelectric vibrators with an asymmetrical clamping difference serves as the driving source in the innovative actuator. Each bimorph piezoelectric vibrator consists of a non-piezoelectric layer, two piezoelectric layers, two mass blocks with the same size and weight at the vibrating side, and two main blocks of different sizes at the clamping side (Fig. 1(a)). The poling direction of each piezoelectric layer and voltage application of the vibrator are designated in the figure. The inertial impact driving principle based on the asymmetrically clamping structure is illustrated in Fig. 1(b). Under a periodic symmetrical exciting signal, the bimorph piezoelectric vibrator will vibrate up and down. When the vibrator vibrates to the upside, point A is the clamping location and l_1 is the length of long clamping arm. However, when the vibrator vibrates to the downside, point B is the clamping location and l_2 is the length of short clamping arm. The distance Δx between points A and B is defined as the clamping difference, which can be adjusted by matching the size of main blocks 1 and 2. The equivalent stiffness of the bimorph piezoelectric vibrator on one side is different from the other side because of the clamping difference.

The external force exerted at the vibrator end, which is usually called the equivalent bending force, can lead to the equal tip deflection induced by the electric field. Assuming that the increase in the effect of rigidity caused by the piezoelectric layers and connective seam layers is ignored, the maximum equivalent bending force F_{bi} can be obtained as follows [30]:

$$F_{bi} = \frac{3\varepsilon\varepsilon_0 S_C V}{h_C d_{31} l_i^2}(l_i - a_i)(h_M + h_C + 2h_S), \quad (i = 1 \text{ or } 2) \tag{1}$$

where ε is the relative dielectric permeability, ε_0 is the dielectric constant, S_C is the transverse sectional area of the piezoelectric elements, V is the driving voltage, d_{31} is the piezoelectric constant, a is the length from the center of the piezoelectric layer to the clamping point of the main block on the same side, h_M is the thickness of the non-piezoelectric layer using elastic metal, h_C is the thickness of the piezoelectric layer, and h_S is the thickness of the connective seam.

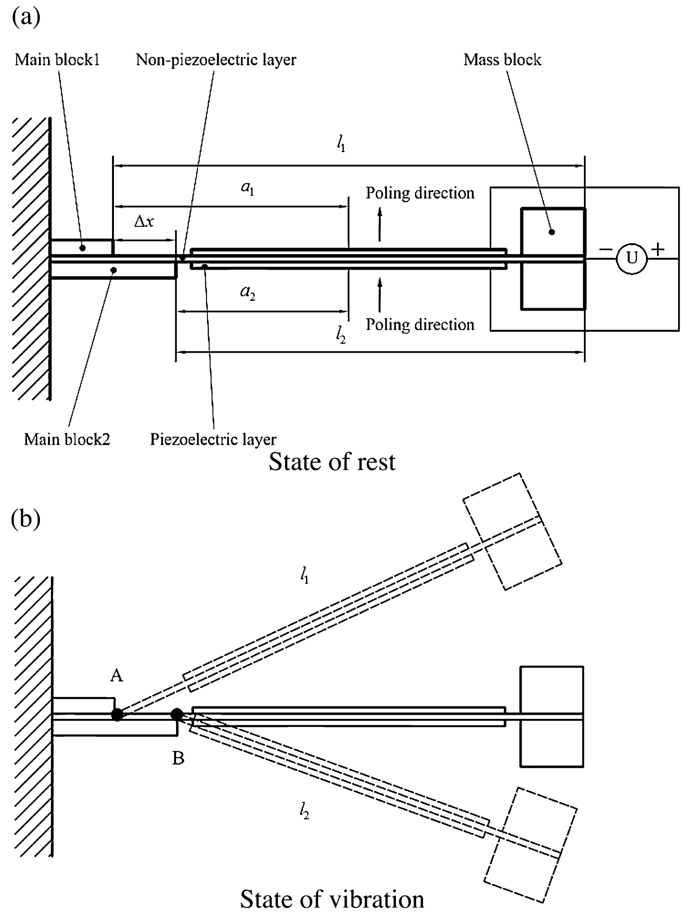

Fig. 1. Inertial impact driving principle based on asymmetrically clamping structure: (a) State of rest (b) State of vibration.

In this novel actuator, the maximum impact force F_i, which is considered the driving source when the bimorph piezoelectric vibrators swing up and down, is equal to the value and opposite in direction to the maximum equivalent bending force F_{bi}. The limit position of each side is described by superscripts U and D (Fig. 1(b)). The maximum impact force generated in both bending directions can be written as follows:

$$\begin{cases} F_i^{(U)} = \dfrac{3\varepsilon\varepsilon_0 S_C V}{h_C d_{31} l_1^2}(l_1 - a_1)(h_M + h_C + 2h_S) \\ F_i^{(D)} = \dfrac{3\varepsilon\varepsilon_0 S_C V}{h_C d_{31} {l_2}^2}(l_2 - a_2)(h_M + h_C + 2h_S) \end{cases} \tag{2}$$

By using $A = \left(3\varepsilon\varepsilon_0 S_C V / h_C d_{31}\right)(h_M + h_C + 2h_S)$, we can simplify Eq. (2) as follows:

$$\begin{cases} F_i^{(U)} = A \times \dfrac{(l_1 - a_1)}{l_1^2} \\ F_i^{(D)} = A \times \dfrac{(l_2 - a_2)}{{l_2}^2} \end{cases} \tag{3}$$

If $M_i^{(U)}$ is the maximum impact torque generated in the upside bending direction and $M_i^{(D)}$ is the maximum impact torque generated in the downside bending direction, the difference between the two torques can be deduced using Eq. (3) and calculated as follows:

$$M_d = M_i^{(U)} - M_i^{(D)} = A \times \frac{(l_1 - a_1)}{l_1^2} \times l - A \times \frac{(l_2 - a_2)}{l_2^2} \times l \tag{4}$$

where l is the distance from the point of the maximum impact torque to the rotation center of the actuator, and M_d is the