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RESEARCH ARTICLE

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A 2-dimensional impact driven precise actuator using piezoelectric bimorphs

Abstract A new precise actuator is proposed, which is actuated by the impact force of an end-loaded piezoelectric bimorph cantilever, and bears two degrees of freedom for translation and rotation. The dynamic characteristics of the piezoelectric bimorph were analyzed by FEM, and are further proved by experimental tests. A new control system for the actuator was put forward and tested, which is called the fixed-frequency with adjustable voltage. In addition, the actuator’s performance of translation and rotation were both measured. The results demonstrate that the actuator is characterized by a simple structure, large movement range, strong driving ability and high positioning resolution. Its cost is estimated at only 1 % of the traditional impact actuators.

Keywords mechanical manufacturing engineering and equipment, precise actuator, impact drive, piezoelectric bimorph, cantilever, finite element

1 Introduction

In recent years, piezoelectric high-precision positioning actuators have been widely applied to some domains such as the assembly works of opto-electronic products, microfabrication of precise components, as well as the surface measurements in atom-sized scale. The impact drive mechanism (IDM) among these actuators, which utilize the dynamic characteristics of the piezoelectric element, has been developed into a kind of distinguished technology[1–3], e.g., in devices such as ultrahigh vacuum precise positioning systems, micro-robot arm, scanning tunneling microscope, and pencil-size electrical-discharge machine, where the IDM cannot be substituted. Moreover, some commercially available products based on the IDM principle have also been successfully developed, e.g., the automatic assembly of miniaturized products and micromanipulation for biological cell [4–8], etc. However, the present IDM generally adopts piezoelectric stack as the actuation element, which makes it costly and even 100 times higher than that of a piezoelectric bimorph. Furthermore, it has some disadvantages due to the stack’s inherent drawbacks. The piezoelectric stack holds less deformation and weak tensile strength compared with that of bimorphs, thus it cannot drive a heavier impact mass. In order to solve the problems mentioned, a new 2-degrees of freedom (2-DOF) IDM utilizing end-loaded piezoelectric cantilever bimorphs and controlled with a certain method is proposed. As we know, the bimorph will bend twice with much more displacement than the piezoelectric stack so the proposed IDM has such advantages. For example, the actuation performance is powerful and the positioning resolution is high. In addition, the mechanical structure of the IDM driven by a bimorph is simple and therefore the manufacturing cost is low.

2 Configuration and working principle of the actuator

Figure 1 is the schematic diagram of the configuration of the proposed 2-DOF IDM driven by a piezoelectric bimorph.

The mechanical structure can be separated into 2 main actuation modules: one is the rotational unit, which consists of a piece of piezoelectric bimorph and an impact mass, and the other is the translational unit, which also includes a piece of piezoelectric bimorph and an impact mass. For each actuation unit, the piezoelectric bimorph is employed like a cantilever beam, i.e., one end is fixed to the shaft while the other is free and joins a mass.

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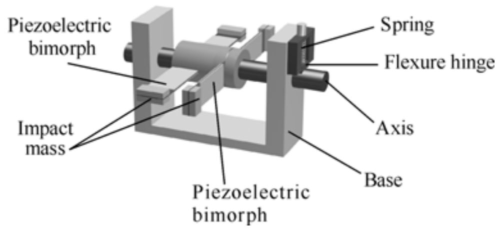

Fig. 1 Schematic diagram of the actuator configuration

Based on the converse piezoelectric effect, the piezoelectric bimorph will be bent under extra electric field. The deformation δ at the free end of the piezoelectric bimorph cantilever can be expressed in the following form:

$$\delta = \frac{3d_{31}V\sin\Omega L\sinh\Omega L}{4h^2\Omega^2(1+\cos\Omega L\cosh\Omega L)} \tag{1}$$

where d_{31} is a piezoelectric coefficient, V the voltage applied to piezoelectric bimorph, L the length of piezoelectric bimorph, h the thickness of piezoelectric bimorph, Ω a constant deduced from $\Omega = \sqrt{\omega / a}$ and $a = \sqrt{EI / \rho A}$, ω an angle speed of voltage. E, I, A, ρ are stiffness coefficient, moment of inertia, section area and density of piezoelectric bimorph, respectively.

The impact mass fixed on the free end can generate an inertial force to the shaft when it is driven by the piezoelectric bimorph. The force F_t caused by the translational actuating unit is parallel with the shaft while the force caused by the rotational actuating unit interleaves the shaft and generates moment T_t . They can be expressed in the following form:

$$F_t = ma_t = m\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} \tag{2}$$

$$T_t = ma_tL = mL\frac{\mathrm{d}^2\delta}{\mathrm{d}t^2} \tag{3}$$

where m is the mass of the impact block, a_t the tangential acceleration of the impact mass block.

The reciprocating movement of the free end of the bimorph also generates the centrifugal force F_r as follows:

$$F_r = ma_r = m\frac{v_n^2}{L} = \frac{m}{L}\left(\frac{\mathrm{d}\delta}{\mathrm{d}t}\right)^2 \tag{4}$$

where a_r is the normal acceleration of the impact mass block, v_n speed of the impact mass block.

To avoid the centrifugal effect and imbalance of the mass on the shaft, the actuating units are designed to consist of two symmetrical piezoelectric bimorphs with the same parameters. The two piezoelectric bimorphs in the translational unit have the same polarization direction while that of the rotational unit have reverse polarization direction, so that the centrifugal effect is counteracted and the inertial force or the inertial moment is increased.

As described in Fig. 1, the underpinning part includes the shaft, flexure hinge, spring and base. The shaft is sustained and oriented through the sliding bearings, and the frictional force between the shaft and bearings can be adjusted by the spring. The shaft length determines the movement range.

3 Actuating process and advantages of the actuator

3.1 Actuating process

The IDM achieves its precise movement through the initial force of the end-loaded bimorph driven by the applied electrical signal. The form of the electric voltage looks like a series of saw teeth, and is called a RAMP wave, which is shown in Fig. 2(a).

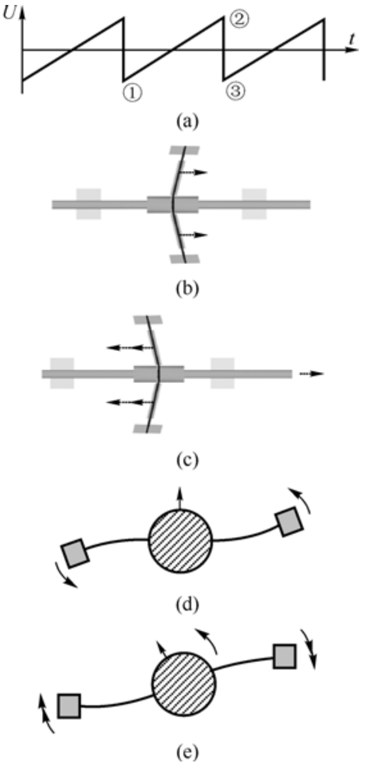

Fig. 2 The RAMP wave and driving process of the IDM

Figures 2(b)–(e) depicts the driving process in detail. Figures 2(b) and (c) is one translational step for the actuator along one direction, while Figs. 2(d) and (e) is one rotational step along the counterclockwise direction. When the applied voltage varies form ① to ② along the RAMP, the piezoelectric bimorph bends slowly, and the inertial force is generated by the impact mass of the translational unit. During this period, the inertial force is less than the frictional force between the shaft and the bearings, thus the shaft will remain motionless as shown in Fig. 2(b). Similarly, the inertial moment generated by the rotational unit is less than the friction moment between the shaft and the bearings, thus the shaft will also be in a motionless state as shown in Fig. 2(d). When the applied voltage varies from ② to ③, the inertial force or moment is more than the frictional force due to the rapid deformation of the piezoelectric bimorph. Then, the shaft will start to move or rotate one step as shown in Fig. 2(c) or Fig. 2(e). Thereafter, the next working cycle will start from ③ and the IDM will run step by step periodically.

The movement direction of the shaft can be shifted if the waveform of the applied voltage is reversed.

3.2 Advantages of the actuator

1) The cost is very low, approximately only 1 percent of the traditional IDM using piezoelectric stacks.

2) The actuating ability of the bimorph type IDM is powerful. Compared with piezoelectric stacks, the bimorph can drive a heavier end-mass easily because its deformation magnitude in the free-end is more than 10 times the piezoelectric stack. Hence, the heavy-load driving ability of the actuator is increased.

3) The mechanical structure of the actuator is simple and its working range is theoretically unlimited. The translational range is only limited by the span of the shaft; it can move at a centimeter order or more. The rotational range is only limited by the wire, so it can reach from 180 degrees to more than 360 degrees.

4) It is hardly affected by the nonlinearity and the hysteresis of the piezoelectric materials.

4 Dynamic characteristics and controlling manner of the actuating unit

In order to obtain the performance and control characteristics of the bimorph type IDM, the mode and dynamic responses of the end-loaded bimorph cantilever are analyzed by FEM and the experiments.

4.1 Finite element analysis of the bimorph's vibration mode

Since the actuating unit consists of two bimorphs with the same parameters, the analysis is only made on one of them as a representation. The FEA software adopts ANSYS 8.1.

Figure 3 shows the three order vibration modes. From the FEM results shown in Table 1, it can be seen that the deformation of the bimorph's free-end in the first mode is maximal, and therefore is optimum to meet the requirements of the impact driving actuator. Therefore, the frequency of the applied voltage should be lower than that of the first mode of the bimorph vibrator.

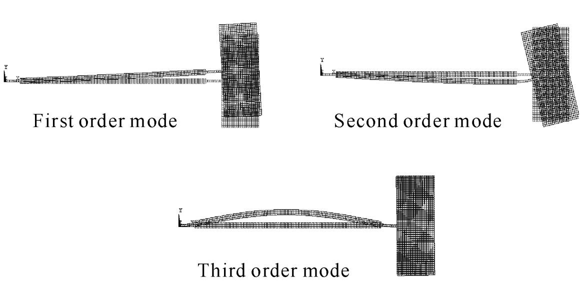

Fig. 3 Piezoelectric bimorph modes of vibration

Table 1 FEA modal analysis results of piezoelectric bimorph

Vibration mode order	Resonance frequency /Hz	Deformation of free-end /μm
1	39.4	78.56
2	227	10.69
3	1 538	4.33

4.2 Dynamic response test and analysis to the bimorph vibrator

The test system consists of a four-channel programmable signal generator AG1200, a non-contacted laser precise position tester LC2400A, a multifunctional FFT analyzer CF5200, adjustable power amplifier and the precise air-spring vibration insulation stage. The experimental objective is to obtain the dynamic responses of the bimorph's free-end driven by the RAMP voltage. The test results show that the first order frequency of the bimorph is 38.9 Hz.

The responses of the piezoelectric bimorph's free-end driven by RAMP voltage is shown in Fig. 4. It was compounded with two vibration waveforms, of which the frequencies are respectively that of the RAMP voltage and the bimorph's first order. Their frequency ratio has the notable effect to the positioning response waveform of the bimorph's free end. For certain vibrator bimorphs, since the first mode frequency is constant, the positioning responses of the free-end of the bimorph are remarkably different with the change of the frequency of the driving voltage signal.

Figure 4(a) shows the responding curve of the piezoelectric bimorph's free end to the applied RAMP voltage at 11 Hz. When the response to the pulse of the driving voltage signal is inphase with the first mode vibration of the bimorph, the changes of the speed of the impact mass and the inertial force from that is little, therefore, the impact effect is relatively feeble. Figure 4(b) is that of the responding curve at 10 Hz. When the response to the pulse of the driving voltage signal is outphase with the first mode vibration of the bimorph, the change of the speed of the bimorph end-loaded impact mass and the inertial force from that is much more, then the impact effect is relatively powerful.

Because the bimorph's responses change notably with the variety of frequency of the RAMP voltage, a certain frequency predetermined for the RAMP voltage is vital. In such a fixed frequency, the actuation ability of the bimorph type IDM is the most powerful.

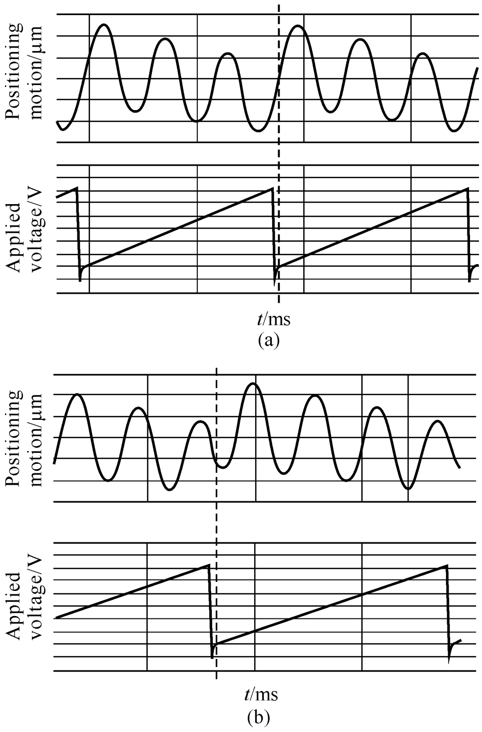

Fig. 4 Response of piezoelectric bimorph driven by RAMP signal. (a) RAMP signal 11 Hz; (b) RAMP signal 10Hz

4.3 The frequency choice of the fixed-frequency voltage signal

The frequency of the driving voltage signal should be less than that of the first order of bimorph. However, when the pulse of the RAMP voltage waveform is in superposition with the latter half period of the first mode vibration waveform of the bimorph, the response to the pulse of the driving voltage signal is outphase with the first mode vibration of the bimorph. The change of the speed of the bimorph's end-loaded impact mass and the inertial force from that is much more, then the ability of impact is relatively powerful. Thus, the fraction of the ratio of the driving voltage frequency (f_R) and the first mode frequency (f_B) of the bimorph should be within the range of (0.5, 1). The certain frequencies of the fixed-frequency RAMP voltage are described as follows:

$$\begin{cases} f_R < f_B \\ \left[\dfrac{f_B}{f_R} - \mathrm{int}\left(\dfrac{f_B}{f_R}\right)\right] \in (0.5, 1) \end{cases} \tag{5}$$

where f_R is the frequency of the applied voltage, f_B the first order resonance frequency of the bimorph.

5 Experimental analysis of the actuator

The prototype of the proposed actuator is fabricated and its performance is also tested in different driving conditions. The testing system is the same with that used for bimorph test mentioned.

5.1 The parameters of the actuator prototype

The prototype of the 2-DOF IDM is shown in Fig. 5.

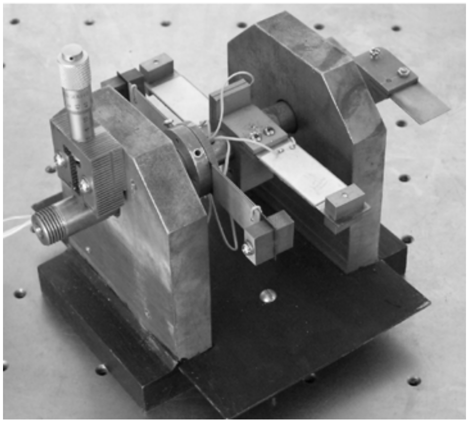

Fig. 5 Photograph of the positioning device

The parameters of the translational actuating unit are as follows: the base of the bimorph size is 55 mm × 20 mm × 0.4 mm and is made of beryllium copper; the piezoelectric plate size is 40 mm×20 mm×0.4 mm and the impact block is 18 mm×10 mm×10 mm with a mass of 9 g×4.

The parameters of the rotational actuating unit are as follows: the base of the bimorph is 60 mm× 20 mm× 0.4 mm made of beryllium copper; the piezoelectric plate is 40 mm× 20 mm×0.4 mm, and the impact block is 18 mm× 10 mm× 10 mm with a mass of 8 g×4.

The parameters of the supporting unit are as follows: the diameter of the shaft is 16 mm, and is made of 45# steel and a mass of 180 g; the base of the stage part is 45# steel and the sliding bearings are SF-10 self-lubricated bearings.

5.2 The relation of the positioning step of the actuator and the frequency of RAMP voltage

The step of the translational movement and the rotational movement was tested when the actuator prototype was applied a different voltage frequency and amplitude. The experimental results are shown in Fig. 6.

Figure 6(a) shows that the actuating ability changes notably with the frequency variety of the applied voltage, which corresponds with the analysis results of the bimorph vibration. It is therefore necessary that the bimorph type IDM should adopt a driving manner called fixed-frequency actuation. Figure 6(b) shows the well-defined linear relationship between the movement step and the applied voltage amplitude. Therefore, the motion step and speed can be controlled by adjusting the voltage amplitude when the voltage frequency is fixed, namely fixed-frequency and adjustable-amplitude voltage.

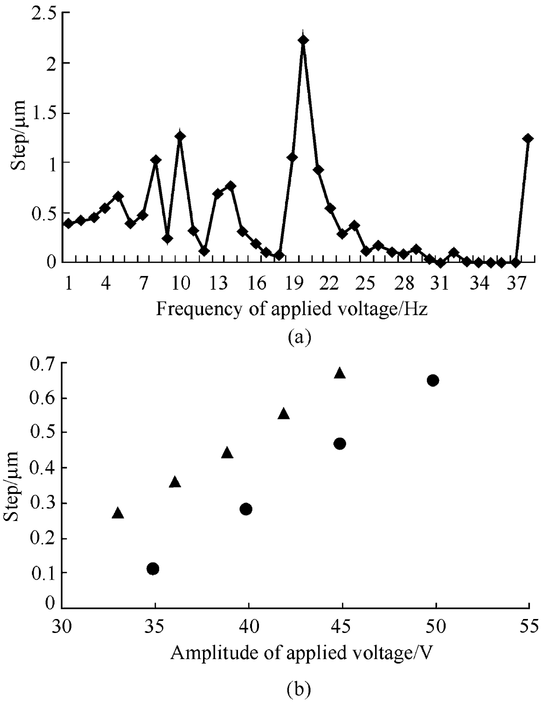

Fig. 6 Movement step affected by the applied voltage frequency and amplitude. (a) Relation between motion step and the applied voltage frequency; (b) Relation between movement step and the applied voltage amplitude

The relationship of the rotational step and the applied voltage for the rotational part is identical with that of the translational part.

5.3 Testing results of the actuator driven with the fixed-frequency and adjustable-amplitude voltage

Driven by fixed-frequency and adjustable-amplitude voltage, the performance of the actuator, such as moving range, positioning resolution and speed, as well as load-bearing ability are tested, with the frequency of the translational RAMP voltage at 13 Hz and the frequency of the rotational RAMP voltage at 11 Hz. The testing results are shown in Table 2.

Table 2 Experimental results of the positioning device

Motion form	Translation	Rotation
Frequency of applied voltage	13 Hz	11 Hz
Movement range	35 mm	180º
Resolution (applied voltage)	0.08 μm (30 v)	1 μrad (30 v)
Maximum speed (applied voltage)	5 mm/min (90 v)	0.2 rad/min (90 v)
Driving ability	2 N (90 v)	0.02 Nm (90 v)

6 Conclusions

1) We have presented a new precise IDM with 2 degrees of freedom for translational and rotational motions actuated by end-loaded piezoelectric bimorph cantilevers. The main performance index of the actuator has been tested. Translational motion ranged at 35 mm, resolution was 0.08 μ, the maximum speed was 5 mm/min, the maximum actuating force was 2 N, and the rotational motion is that range 180 degree, resolution of 1 μ rad, the maximum rotational speed 0.2 μ rad /min, the maximum actuating moment was 0.02 Nm. The actuator is characterized by a large movement range, high positioning resolution, simple mechanical structure and low cost.

2) The performance index of the actuator such as the positioning step and the actuating force or moment, etc. changes with different driving frequencies of the voltage nonlinearly. Nevertheless, they change with the amplitude of the driving voltage linearly. It is therefore very important that the bimorph type IDM should have fixed frequency voltage and adjustable amplitude, i.e., adopting a driving manner called the fixed-frequency and adjustable-amplitude voltage.

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