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A linear piezoelectric actuator using the first-order bending modes

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Abstract

A linear piezoelectric actuator using the first-order bending modes is proposed, designed, fabricated and tested in this study. The proposed actuator contains two exponential shape horns located on the two leading ends. Two groups of PZT elements are clamped between the two horns by a bolt to excite two first-order bending modes of the actuator. These two bending vibrations are orthogonal in space, which can produce elliptical movements on the horns' tip ends when they have the same resonance frequency and a phase shift in time of $\pi/2$. The structure and working principle of the proposed actuator are introduced. The input impedance characteristics of the proposed actuator are calculated and discussed. After the fabrication of a prototype, its vibration modes are tested using a scanning laser Doppler vibrometer. Finally, the mechanical ability of the prototype is tested. This study verifies that the bending mode with lower order can help a lot in improving the power density.

Keywords: C. Impedance; D. PZT; E. Actuators; Piezoelectric actuator

1. Introduction

Piezoelectric actuators (can also be called as ultrasonic motors) are special-type actuators that produce a linear or rotary motion by their resonance vibrations excited via converse piezoelectric effect of the PZT elements. Compared with electromagnetic ones, piezoelectric actuators exhibit merits such as simple structure, quick response, quiet operation, self-locking when powered off, non-electromagnetic radiation and higher position accuracy [1,2].

According to the vibration type, piezoelectric actuators can be classified into traveling wave actuators [3–5], standing wave actuators [6,7] and composite vibration modes type actuators [8–10] up to the present. For the composite vibration modes type actuators, elliptical movements are produced on the driving tips by the superimposing of different vibrations. Since most of them have bolt-clamped structures, high exciting voltage can be applied to obtain large output power.

In this study, a linear piezoelectric actuator with double driving feet, belonging to the composite vibration modes type, is proposed. Two orthogonal first-order bending modes are utilized in the new design to produce elliptical movements on the driving tips. The input impedance characteristics are calculated and discussed. After the fabrication of a prototype, its vibration characteristics and output ability are investigated through experiments.

2. Structures and working principle

Fig. 1 shows the structure of the proposed piezoelectric actuator. Two groups of PZT elements, named as bending PZT-V and bending PZT-H, are clamped between two horns by a bolt. The tip ends of the horns serve as the driving feet. Thin beams and setting holders are machined on the two sides of each horn to accomplish the elastic supporting. It can be understood that for the excitation of the first-order bending modes of the actuator, the PZT elements are arranged and polarized as Fig. 1(c) shows.

Bending PZT-V are set in the middle of the actuator while bending PZT-H are symmetrically arranged on the two sides of bending PZT-V. This symmetrical allocation of the PZT elements can result in uniform vibration characteristics on the two driving feet. The PZT elements are located at the wave loop of the first-order bending mode, which favors excitation of the flexural modes of the

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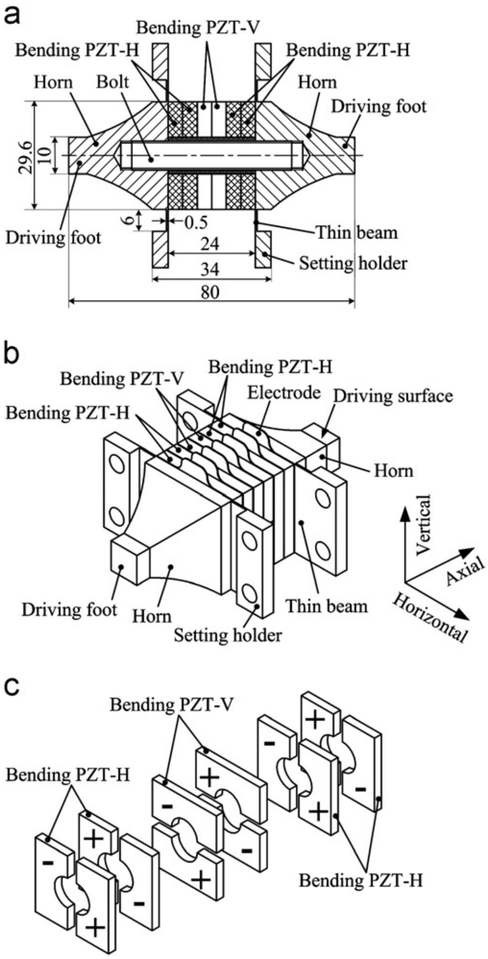

Fig. 1. Structures of the proposed actuator: (a) section view of the actuator (unit: mm); (b) three-dimensional model of the actuator; and (c) PZT polarization.

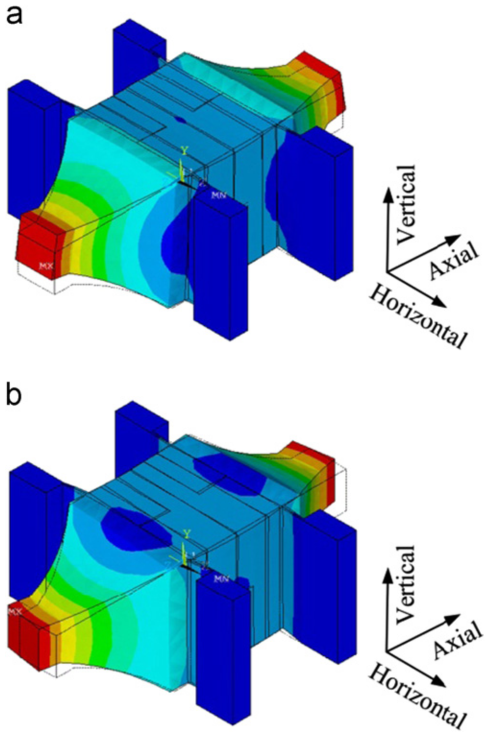

Fig. 2. Bending modes of the actuator: (a) vertical bending mode and (b) horizontal bending mode.

actuator by their stretching vibrations. By applying alternating voltages at the resonance frequency of the first-order bending mode, the stretching vibrations of bending PZT-V can generate one flexural vibration of the actuator and result in vertical displacements on the driving feet, see Fig. 2(a); another flexural vibration, excited by bending PZT-H, can produce horizontal movements of the driving feet, see Fig. 2(b). When these two vibrations have a phase shift in time of $\pi/2$, elliptical movements can be produced at the driving surfaces. The horizontal movements of the feet will push the runner into motion by frictional forces while the vertical ones will overcome the preload.

3. Input impedance characteristics

In this study, we intend to utilize the first-order bending modes to improve the vibration intensity. The input impedance characteristics of the proposed actuator are obtained to verify this original intention. Harmonic analysis (ANSYS software was used) was developed to gain the input impedances of the two modes, see Fig. 3. The series and parallel resonance frequencies can be obtained from the impedance curves. For each vibration mode, its electromechanical coupling factor k can be calculated by the following equation:

$$k = \sqrt{\frac{f_p^2 - f_s^2}{f_p^2}} \tag{1}$$

where f_s and f_p are the series resonance frequency and the parallel resonance frequency, respectively.

Fig. 3 indicates that the f_s and f_p of the vertical bending mode are 23.264 kHz and 24.480 kHz respectively, while the two resonance frequencies of the horizontal bending mode are 23.318 kHz and 25.099 kHz. By Eq. (1), the electromechanical coupling factors of the two bending modes are calculated to be 31.1% and 37.0% correspondingly. The PZT elements adopted for the generation of the horizontal bending are two times of the ones for the vertical vibration; this makes the proposed actuator presents two different factors. The high electromechanical coupling factors of the proposed actuator prove that more electric energy can be changed to the mechanical vibration energy of the actuator, which can improve its vibration intensity remarkably. Adopting the first-order bending mode is the direct reason that results in these high factors.

4. Vibration and mechanical output characteristic experiments

According to the structural parameters listed in Fig. 1, a prototype actuator was fabricated, see Fig. 4. The initial

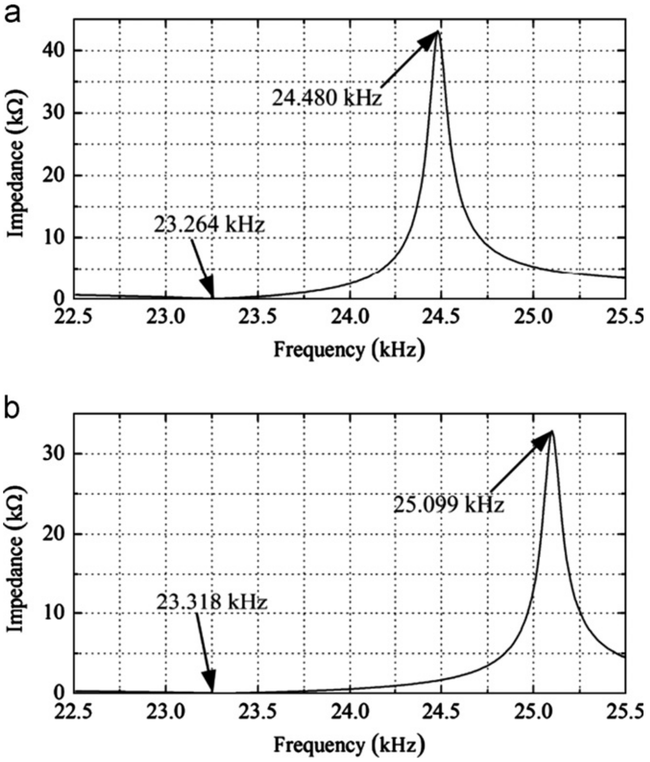

Fig. 3. Input impedance of the proposed actuator: (a) vertical bending mode and (b) Horizontal bending mode.

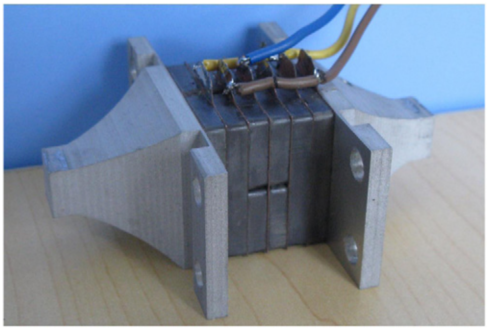

Fig. 4. Prototype of the proposed actuator.

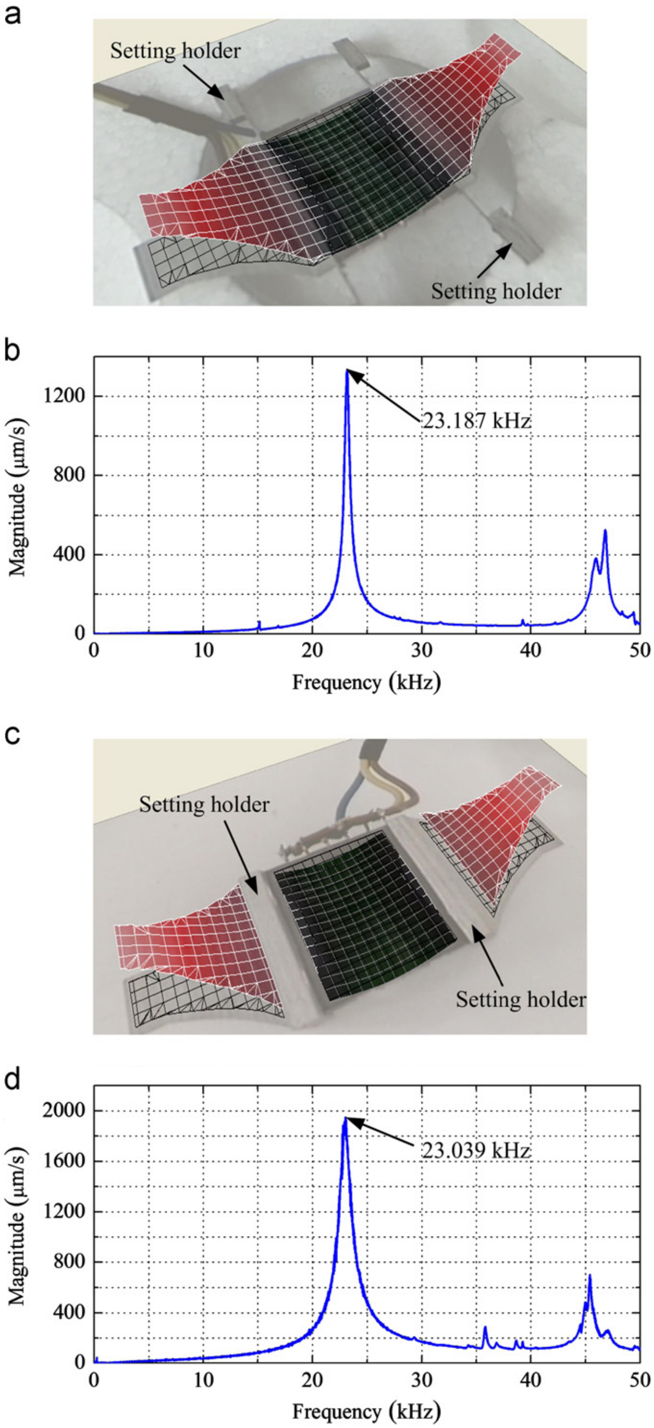

Fig. 5. Vibration scanning results of the actuator. (a) vertical bending vibration shape (under bending PZT-V excitation); (b) vibration velocity response spectrum under bending PZT-V excitation; (c) horizontal bending vibration shape (under bending PZT-H excitation); and (d)vibration velocity response spectrum under bending PZT-H excitation.

cross sections of the horns are circles with diameter of 70 mm. After the assembling, the horns with thin beams and setting holders were cut to design shapes by using a linear cutting machine.

After the fabrication of the actuator, its vibration characteristics were measured using a scanning laser Doppler vibrometer (PSV-400-M2, Polytec, Germany). Fig. 5 shows the vibration mode shapes and vibration velocity response spectrums under bending PZT-V and bending PZT-H excitations. To test the vertical bending mode, the upper surface of the actuator is selected as the test region, while the side surface is selected for the measurement of the horizontal bending mode.

In Fig. 5(a) and (c), the setting holders are marked to give a clear view of the bending modes. The two tested vibration modes are flexural ones with two wave nodes, which are in a good agreement with the vibration shapes shown in Fig. 2. The two vibration velocity average response spectrums shown in Fig. 5 state that the series resonance frequencies of the two first-order bending modes are 23.187 kHz and 23.039 kHz, which are different from the results obtained by the FEM harmonic analysis with discrepancies of 0.077 kHz and

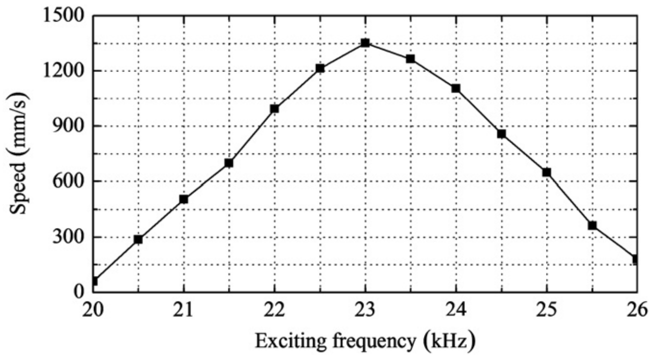

Fig. 6. Plot of the speed versus exciting frequency.

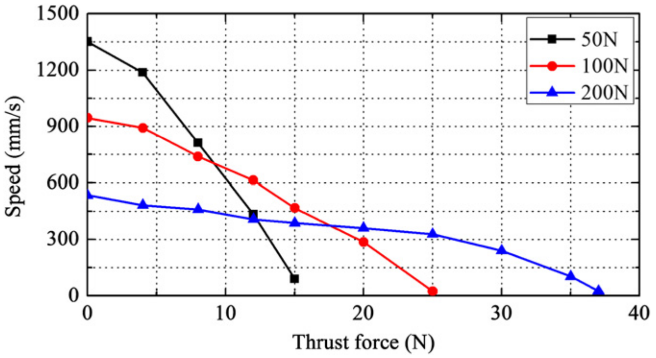

Fig. 7. Plot of the thrust force versus speed.

0.279 kHz respectively. It can be clearly seen that there are no other natural vibration modes in the ambient frequency range of bending vibration mode obviously excited, which is very favorable for the operation stability of the actuator.

Finally, the mechanical output characteristics of the prototype were tested. The actuator was set on an experiment platform, in which the two driving feet are pressed on two runners; the two runners were linked together at their tip ends to increase the output thrust force. To increase the frictional forces between the driving feet and the runners, two copper-based powder metallurgy plates with thickness of 1 mm were bonded on the driving surfaces of the two feet.

During the measurement, two phases of excitation voltages that have a phase shift in time of $\pi/2$ are applied on bending PZT-V and bending PZT-H to excite the corresponding modes. Fig. 6 gives the plot of the speed versus frequency of exciting voltage (the effective value of exciting voltage is 200 V, the thrust force is zero and the preload is 50 N). The actuator achieves a maximum speed of 1351 mm/s as the exciting frequency is about 23.0 kHz.

Then, a fixed excitation frequency of 23.0 kHz was adopted during the following test; Fig. 7 gives the plot of the speed versus the thrust force under different preloads (the effective value of exciting voltage is 200 V). The actuator achieves a maximum thrust force of 37 N and a maximum output power of 8.2 W, which are high values considering the fact that its weight is only 0.23 kg.

5. Conclusion

A linear piezoelectric actuator, with a bolt-clamped transducer structure, forming elliptical movements on its two leading ends by the superimposition of two orthogonal first-order bending modes, was proposed and tested in this study. The square cross-section structure favors the two bending modes to have the same resonance frequency. The symmetrical arrangement of the PZT elements makes the two feet have uniform movements. The vibration characteristic test results of the prototype verify that the two bending resonance frequencies are very close. The mechanical output test shows that the prototype achieves large speed and thrust force. Compared with actuators using different vibration modes, the proposed actuator has overcome the problem of modal degeneration, which makes its design work quite flexible. This merit can help a lot in broadening its application areas of linear and rotary driving.

Acknowledgments

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