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A novel standing wave linear piezoelectric actuator using the longitudinal-bending coupling mode

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ABSTRACT

A novel standing wave linear piezoelectric actuator is proposed and tested by using a sandwich transducer operated in longitudinal-bending coupling mode. The vibration mode used in this work is neither longitudinal mode nor bending mode, but a longitudinal-bending hybrid one, which is generated simultaneously by only one group of PZT ceramic elements. The exciting principle of this coupling mode is discussed, and then realized by designing a standing wave piezoelectric actuator. When the 1 st longitudinal and 3rd bending modes of the transducer have colse resonance frequencies and unsymmetrical boundary condition is applied, the desired longitudinal-bending coupling mode can be generated by a sine signal, which finally produces oblique elliptical movement on the end tip of the transducer. The design and analysis work is accomplished by finite elements method (FEM), and verified by a scanning laser Doppler vibrometer after the fabrication of a prototype. The proposed standing wave linear piezoelectric actuator achieves maximum no-load speed and thrust force of about 891.3 mm/s and 39.2 N under voltage of 400 V_{P-P} and working frequency of 29.4 kHz.

1. Introduction

Piezoelectric actuators usually push the runners by the resonant movements on the surface particles; these movements should have transverse and normal components simultaneously: the normal one is used to overcome the preload between the interface, whereas the driving force is produced by the transverse vibration [1–3]. According to the vibration mode utilized, piezoelectric actuators can be classified into travelling wave ones [4–6], standing wave ones [7–9] and mode-hybrid ones [10–15] up to the present.

For the travelling wave piezoelectric actuators, two flexual standing waves with the same resonance frequency, a temporal shift of 90° and a spatial distance of quarter wavelength should be generated in a ring or a disk to compose the travelling wave, which means that they need two phase of exciting signals to produce the two independent standing waves. Most of the mode-hybrid piezoelectric actuators also need two phase of exciting signals as they operate by the hybrid of two different vibration modes. Theoretically speaking, the standing wave piezoelectric actuators have merits of simple structure and simple control performance as they only need one exciting signal.

For example, a novel standing wave piezoelectric actuator using the bending mode of a plate had been proposed and tested by He et al.; the 3rd and 4th bending modes of the plate were used for the rightward and leftward linear driving, respectively [16]. Chen et al. proposed a linear standing wave piezoelectric actuator using a sandwich type bending transducer; their prototype achieved maximum speed and thrust force of 180 mm/s and 14 N, respectively [17]. Park et al. proposed a standing wave square tubular piezoelectric actuator, their prototype achieved the no-load speed of 1000 rpm and the maximum torque of 0.37 mN m under a size of 3.975 mm × 3.975 mm × 16 mm[18]. In these works, the driving tips of the actuator moved with oblique linear trajectories, which had both transverse and normal components. Genernally speaking, the standing wave piezoelectric actuator only use one vibration mode to obtain the desired oblique linear movements.

In this paper, a novel standing wave linear piezoelectric actuator is proposed and tested, in which a new longitudinal-bending coupling mode is generated in a sandwich transducer to produce oblique elliptical movement on the driving tip. In this new design, the longitudinal and bending modes are generated simultaneously by only one group of PZT ceramic elements; in other words, the vibration mode used by the proposed actuator is neither pure longitudinal mode nor pure bending mode, but a longitudinal-bending

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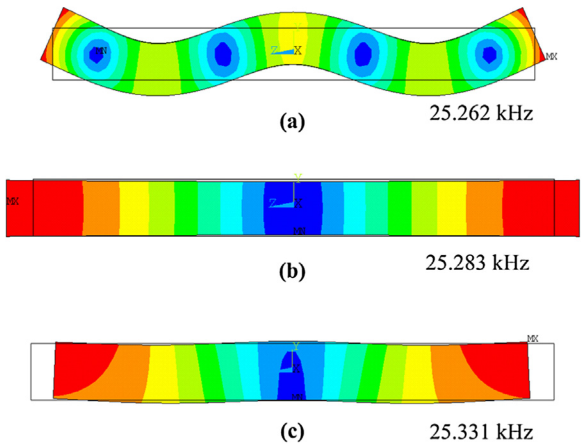

Fig 1. Longitudinal-bending coupling mode of a square beam: (a) the longitudinal mode under free boundary condition, (b) the bending mode under free boundary condition, (c) the longitudinal-bending coupling mode under partial fixed boundary condition.

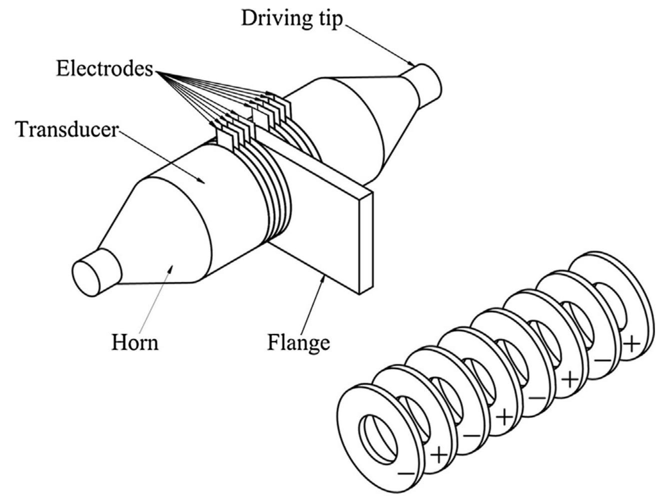

Fig. 2. The structure of the proposed standing wave linear piezoelectric actuator.

hybrid one. Section 2 explains the principle of the longitudinal-bending coupling mode, Section 3 describes the operating principle of the proposed standing wave piezoelectric actuator, Section 4 shows the design process by finite element method (FEM), Section 5 shows the experimental testing and results, which is followed by a summary in Section 6.

2. Longitudinal-bending coupling mode of a beam

Generally speaking, an elastic beam has three types of basic vibration modes, which are longitudinal mode, bending mode and torsional mode. Therefore, sandwich type piezoelectric transducer can operate under these three modes separately or their hybrid. Usually, these vibration modes are generated by separated PZT elements as the problem of the independence of vibration modes: longitudinal mode is excited by whole pieces of PZT plates vibrate in axial direction, bending mode is always generated by half pieces of PZT plates with reverse polarizations, whereas PZT elements deform in circumferential direction are needed for the excitation of the torsional mode. Thus, for the generation of a hybrid vibration in a beam, can either be longitudinal-bending hybrid or longitudinal-torsional hybrid, two separated groups of PZT elements are necessary.

However, the longitudinal-bending coupling vibration mode propose in this work is different with the traditional hybrid vibration as the longitudinal and bending vibrations are generated simultaneously by only one group of PZT elements; in other words, we can see this coupling vibration as a particular type of mode that contains of both longitudinal and bending components. Fig. 1 gives a specific illustration of the longitudinal-bending coupling mode of a square beam, which is obtained by FEM modal analysis.

A duralumin alloy square beam with cross-section of 10.8mm × 10.8 mm and length of 100 mm is analyzed, whose vibration shapes of longitudinal and bending modes under free boundary condition are shown by Fig. 1(a) and (b); and these two modes can produce axial and transverse displacements on the beam end, respectively. On the other side, Fig. 1(c) gives the vibration shape of the desired longitudinal-bending coupling mode, which is obtained under fixed boundary condition on the middle part of the downside surface. This coupling mode is a superposition of the longitudinal and bending ones, which can produce axial and transverse displacements on the beam end synchronously.

In summary, there are two necessary conditions for the generating of the longitudinal-bending coupling mode: the first one is that the longitudinal mode must have close resonance frequency with the bending mode, whereas the other one is that unsymmetrical boundary condition must be applied. Under these conditions, we

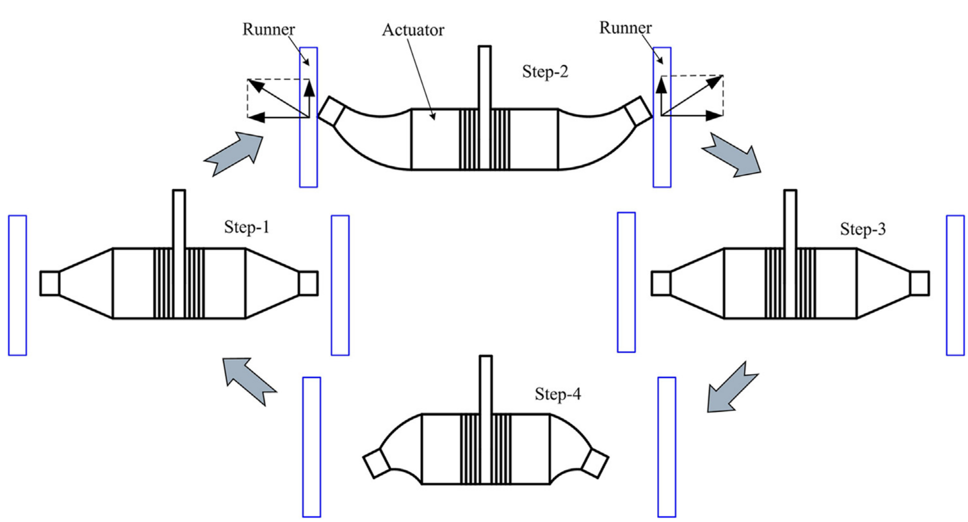

Fig. 3. The operating sequence of the transducer in one circle.