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Development of a bi-directional standing wave linear piezoelectric actuator with four driving feet

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ABSTRACT

A bi-directional standing wave linear piezoelectric ultrasonic actuator with four driving feet is proposed in this work. Two sandwich type transducers operated in longitudinal-bending hybrid modes are set parallelly. The working mode of the transducer is not simple hybrid vibrations of a longitudinal one and a bending one, but a special coupling vibration mode contained both longitudinal and bending components. Two transducers with the same structure and unsymmetrical boundary conditions are set parallelly to accomplish the bi-directional driving: the first transducer can push the runner forward, while the other one produces the backward driving. In the experiments, two voltages with different amplitudes are applied on the two transducers, respectively: the one with higher voltage serves as the actuator, whereas the other one applied with lower voltage is used to reduce the frictional force. The prototype achieves maximum no-load speed and thrust force of 244 mm/s and 9.8 N. This work gives a new idea for the construction of standing wave piezoelectric ultrasonic actuator with bi-directional driving ability.

1. Introduction

Piezoelectric ultrasonic actuators (PUAs) have a number of advantages over the electromagnetic motors, such as high positioning accuracy, high resolution, simple structure, fast response, large force weight ratio, a lack of electromagnetic interference and easy realization of linear or multi-DOF driving [1,2]. According to the vibration modes, PUAs can be classified into travelling wave type [3,4], standing wave type [5,6] and mode-hybrid type [7,8] up to the present. The travelling wave PUAs operate by flexual travelling wave in a metal ring or cylinder, which is formed by the hybrid of two bending standing waves with the same frequency, the same amplitude, a spatial distance of a quarter wavelength and a temporal shift of 90 degree [9–11]. The mode-hybrid PUAs usually operate by the hybrid of two vibration modes, which can be classified into longitudinal-longitudinal modes hybrid type [12,13], bending-bending modes hybrid type [14,15], longitudinal-bending modes hybrid type [16,17] and longitudinal-torsional modes hybrid type [18,19]. The mode-hybrid PUAs require two vibration modes with very close resonance frequencies, which brings strict limitations on their structure dimensions.

The standing wave PUAs have merits of simple structure, simple driver circuit and simple control performance as they always work by single vibration mode. For example, He et al. did a lot of excellent works in designing PUAs operated under the standing wave [20–22]: a novel PUA using the bending mode of a plate had been proposed and tested [20], in which the 3rd and 4th bending modes of a plate were used for the generations of the forward and backward linear driving respectively; another PUA with size of 3.975 mm × 3.975 mm × 16 mm, maximum no-load speed of 1000 rpm and maximum torque of 0.37 mN·m was designed by using the bending mode of a tubular stator [22]. Zhang et al. proposed and tested a novel bi-directional linear PUA by using transducers worked under longitudinal vibration modes, the transducers were set obliquely to the runner; the driving tip vibrated with oblique linear trajectories, which contained both transverse and normal displacement components: the normal component overcame the preload, whereas the transverse displacement pushed the runner linearly [23]. Wang et al. designed and tested a novel standing wave PUA using a trapezoidal piezoceramic plate, their prototype achieved output force of 12.151 g under size of 22 mm × 8 mm × 1.5 mm [24]. Chen et al. proposed a novel standing wave linear PUA using the in-plane expanding and bending modes of a single Lead Zirconate Titanate (PZT) ceramic square plate, they obtained large improvement on the output power density [5]. Generally speaking, the standing wave PUAs are difficult to accomplish the bi-directional driving, or exhibit different mechanical output performances on the forward and backward motions.

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In this paper, a novel bi-directional standing wave PUA is proposed and tested. Two bolt-clamped transducers operated under longitudinal-bending coupling vibrations are used together to achieve the bi-directional driving: one transducer serves as the actuator, while the other one is used to reduce the frictional force between the interfaces; the exchanges of their roles can result in the reverse motion, and the proposed PUA can get the same output performances on the forward and backward motions. The operating principle of the proposed PUA is discussed, which is verified by calculating the motion trajectories of the driving tips. A prototype is designed and fabricated, and its output speed and thrust force are measured under different exciting voltages.

2. Structure and operating principle

The three-dimensional structure of the proposed bi-directional standing wave PUA is shown in Fig. 1, which can be seen as the combination of two parallel bolt-clamped transducers. Eight pieces of PZT ceramic plates, a flange and eight pieces of electrodes are clamped between two horns by a bolt to form a transducer. The PZT ceramic plates are polarized along their thickness directions, and placed reversely one by one. The horns are cone-shaped, and the cylindrical tips machined on the ends of the horns serve as the driving tips. The flange used in the transducer is designed for the clamping, whose structure can bring in unsymmetrical boundary conditions.

The operating principle of the proposed PUA for the bi-directional driving is illustrated in Fig. 2. Specifically, two bolt-clamped transducers with the same structure and unsymmetrical boundary conditions are set parallelly to accomplish the bi-directional driving: the lower transducer can push the runner forward, while the upper one produces the backward driving. From the arrangement of the PZT ceramic plates and the polarizations, the intuitional understanding is that a longitudinal vibration will be generated in the transducer. It should be noted that the working mode of the transducer is not a longitudinal vibration along the axial direction, but a special coupling mode contained both longitudinal and bending vibration components. In other works, the end tip of the transducer will vibrate elliptically and obliquely under this longitudinal-bending coupling mode. When a runner is pressed on the end tip, the longitudinal component will overcome the preload, whereas the bending component produces the pushing effect by the frictional force between the interfaces.

Surely, the unsymmetrical boundary condition is the key factor for the generation of this longitudinal-bending coupling vibration, which can decide the oblique direction of the motion trajectory of the driving tip. The forward oblique movements are formed on the two end tips of the lower transducer, which can push the two runners forward, as shown in Fig. 2(a); the backward oblique movements are generated on the two end tips of the upper transducer, which are used to achieve the backward driving, as shown in Fig. 2(b). Each transducer can only achieve the unidirectional driving; thus, we need to switch the exciting signal between the two transducers for the bi-directional motions.

It should be noted that Fig. 2 is a schematic diagram for the operating principle, in which the driving tip is plotted to separate from the runner plate in some steps for the direct and visualized show of the principle. In fact, the preload applied between the runner and the transducer decides their contact state, and the increase of the preload may make them in contact state all the time. Therefore, there are static frictional forces in the interfaces since preload should be applied between the runners and the driving tips, which will bring in resisting effect if the transducer keeps still. Thus, two exciting signals will be used to overcome this resisting problem: one high voltage and one low voltage; the high voltage is applied on the transducer played the role of the actuator, whereas the other transducer applied low voltage is used to reduce the frictional force. We hope this special exciting method can improve the output performance since the ultrasonic vibration has been proved to be effective for anti-friction [25].

3. Longitudinal-bending coupling mode of the transducer

The above operating principle states that the desired vibration mode of the transducer is a longitudinal-bending coupling one, whose vibration shape is shown in Fig. 3. Finite element method (FEM) was used to accomplish the design and analysis of the proposed PUA. The FEM model of one transducer was built by ANSYS software, modal analysis was accomplished by applying fixed boundary on the end of the flange. The vibration shape shown in Fig. 3 illustrates that the two driving tips will vibrate obliquely and forward under a resonance frequency of 28.887 kHz. Usually, the longitudinal and bending vibrations of a transducer occur separately under different resonance frequencies as the independence of different vibration modes; but the unsymmetrical boundary condition caused by the flange breaks this limitation and leads to a new coupling mode. The end tips will vibration obliquely under this coupling vibration mode, which means that horizontal and vertical displacements can be produced synchronously on the driving tips. This special movement can produce linear driving effect when a runner is pressed on the end tip, as shown in Fig. 2.

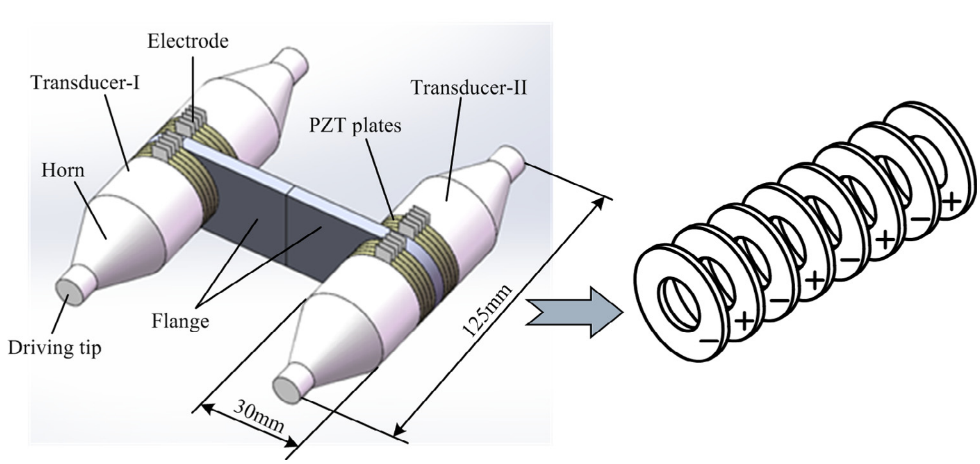

Fig. 1. Structure of the proposed bi-directional standing wave linear PUA.