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The design and experiment of a novel ultrasonic motor based on the combination of bending modes

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ABSTRACT

This paper presents a new-type linear ultrasonic motor which takes advantage of the combination of two orthogonal bending vibration modes. The proposed ultrasonic motor consists of eight pieces of PZT ceramic plates and a metal beam that includes two cone-shaped horns and a cylindrical driving foot. The finite element analyses were finished to verify the working principle of the proposed motor. The mode shapes of the motor were obtained by modal analysis; the elliptical trajectories of nodes on the driving foot were obtained by time-domain analysis. Based on the analyses, a prototype of the proposed motor was fabricated and measured. The mechanical output characteristics were obtained by experiments. The maximal velocity of the proposed motor is 735 mm/s and the maximal thrust is 1.1 N.

1. Introduction

Ultrasonic motors (USM) are based on the working principle that electric energy is converted into mechanical vibration via converse piezoelectric effect of the ceramic element, elliptical or oblique movements are created on the driving feet of stators, then rotary or linear motions of runners are generated by frictional coupling on the interfaces of stators and runners. The working principle permits ultrasonic motors to exhibit many merits such as quick response, simple structure, large torque or force under low speed, self-locking under power off state, nonelectromagnetic radiation and higher position accuracy [1–5]. It is much difficult for traditional electromagnetic motors to absolutely satisfy various practical demands. Therefore, traditional electromagnetic motors have been replaced by ultrasonic motors in many fields.

According to the mode of the output movement, USM can be classified into linear, rotary and multi-DOF ones, whose driving principles are manifold. Many of them use the hybrid of two vibration modes. When motors use the combination of a longitudinal and a bending vibrations [6–12], a longitudinal and a torsional vibrations [13–15], two longitudinal vibrations [16–19] or two different order bending vibrations [20], modal degeneration is needed to tune the resonance frequencies of two vibrations as close as possible. Usually, the process of modal degeneration brings in many restrictions on the structural dimensions of the ultrasonic motors, which makes it hard to adjust these structural dimensions to satisfy various demands from practical applications.

The proposed motor in this paper takes advantage of two third bending vibrations. Their resonance frequencies will be equal when the structure of the ultrasonic motor keeps symmetrical. Therefore, the parameters of the proposed ultrasonic motor can be adjusted freely to satisfy different demands such as space and weight. The proposed ultrasonic motor has bonded type structure, which is easier to be processed and assembled compared with the bolt-clamped type ones [21,22]. Theoretically speaking, the proposed motor can realize miniaturization more simply. Furthermore, the motor can be fixed on the base by both sides as there is only one driving foot located in the middle part, which can improve the stiffness of supporting. This paper is divided into three sections: the actuator concept is presented in the first section, the second section presents the results of modal and transient analyses by finite element method (FEM), the experiment results are presented and analyzed in the last section.

2. Actuator concept

In this paper, the proposed ultrasonic motor is designed to realize linear driving. This section will present the mode selection, geometry and working principle of the proposed ultrasonic motor.

2.1. Mode selection

The proposed motor has a single driving foot. In order to obtain good driving capacity, it's better to locate the driving foot at the

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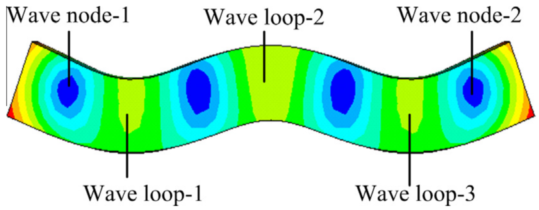

Fig. 1. The third bending mode of a beam.

middle part and bond the piezoelectric ceramics at the two ends. The process of degeneration can be avoided by using two bending vibrations of same order and a symmetrical structure. Furthermore, it must be odd order bending vibration that can make driving foot locate at a wave loop. Generally speaking, with the equal input energy, the amplitude of vibration is lower when the order of vibration is higher. Therefore, the third bending vibration is selected, as shown in Fig. 1. There are three wave loops that are labeled. The wave loop-2 is used to lay the driving foot. The wave loop-1 and wave loop-3 are used to lay the piezoelectric ceramic plates. The two wave nodes can be used to fix the ultrasonic motor.

2.2. Geometry

The geometry and parameters of proposed motor are shown in Fig. 2(a). The proposed motor consists of one metal beam and eight pieces of piezoelectric ceramic plates. The cylindrical driving foot is arranged at the middle of the metal beam and the horns are cone-shaped. These eight pieces of piezoelectric ceramic plates are polarized along their thickness directions and divided into two groups: group-A and group-B, as shown in Fig. 2(b). Ceramics of group-A are used to excite the third bending vibration in *X* direction, as shown in Fig. 2(c); while the other third bending in *Y* direction is excited by group-B, see Fig. 2(d).

2.3. Driving principle

Elliptical movements on the driving feet of proposed motor are formed by the superposition of two third bending vibrations. Two alternating signals are used and the phase shift between them is 90 deg. When a sine exciting voltage is applied on PZT ceramics of group-A and a cosine exciting voltage is applied on PZT ceramics of group-B, the driving foot will move as the trajectory shown in Fig. 3. When the phase shift of the exciting voltages applied on ceramics is changed to −90 deg, the driving foot will move reversely.

3. FEM analyses

After presenting the actuator concept, this section is devoted to accomplish the modal and transient analyses. The material of the proposed motor's metal base is beryllium bronze (mass density

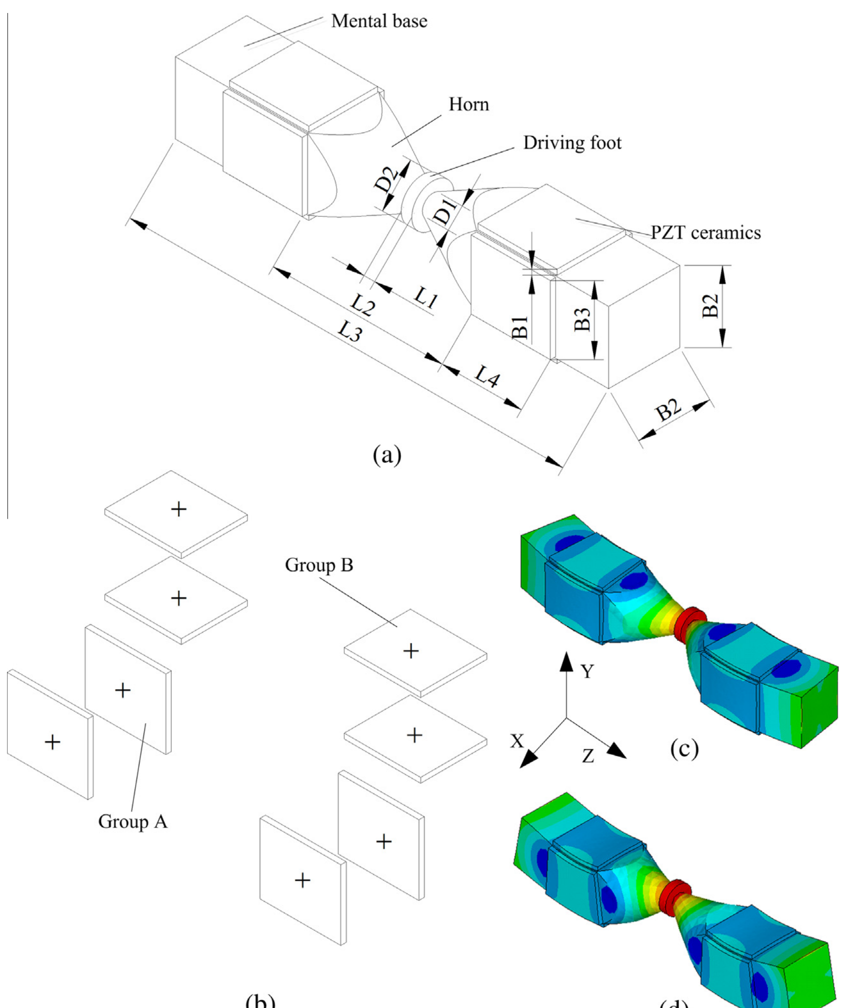

Fig. 2. Structure and modes of the proposed USM: (a) the three-dimensional model and parameter of the proposed motor, (b) the polarizations of PZT ceramics, (c) the third bending vibration mode in *X* direction, (d) the third bending vibration in *Y* direction.