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A novel single-mode linear piezoelectric ultrasonic motor based on asymmetric structure

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ABSTRACT

A novel single-mode linear piezoelectric ultrasonic motor based on asymmetric structure is proposed. The motor adopts the combination of the first longitudinal vibration and the asymmetric mechanical structure to produce the oblique movement on the driving foot; then, the linear output motion is obtained under the friction coupling between the driving foot and the runner. The motor is designed and its operation principle is illustrated in detail. The transient analysis is developed to verify the formed movement on the driving foot. A prototype is manufactured and its vibration characteristics are measured by a scanning laser Doppler vibrometer. An experimental system is established and the output performances of the motor are tested and discussed. The results indicate that the maximal no-load velocity of the motor is about 127.31 mm/s under the voltage of 150 $V_{p\text{-}p}$ and the preload of 30 N. The maximum thrust force is about 2.8 N when the voltage and preload are 150 $V_{p\text{-}p}$ and 40 N. The related works in this paper has verified the feasibility of the proposed single-mode ultrasonic motor based on asymmetric structure.

1. Introduction

As a new kind of micro actuators, the ultrasonic motors mainly take advantage of the inverse piezoelectric effect of the piezoelectric ceramics to excite the resonant status of the stator, and the input electric energy is transformed into the output mechanical energy under the friction coupling effect between the stator and the runner [1–7]. In contrast to the traditional electromagnetic motors, the ultrasonic motors exhibit a great many of unique features, such as low speed and large thrust force with simple construction, no bearing and lubrication, no electromagnetic interference, self-lock when power off, and so on [8–13]. Since the 1980s, the ultrasonic motors have long been investigated extensively by the scholars all over the world. Due to their excellent superiorities, the ultrasonic motors have been applied successfully in lots of fields like digital cameras, biomedical therapies and aerospace apparatus [14–16].

According to the number of the used vibration mode, the ultrasonic motors are generally divided into the multi-mode type, the double-mode type and the single-mode type [17–20]. The multi-mode ultrasonic motors usually make use of three or more vibration modes to achieve the output movements with multiple degrees of freedom like the multi-DOF motors proposed by Lu et al. [21], Shen et al. [22] and Yang et al [23]. For the double-mode type ultrasonic motors, two orthogonal vibrations both in space and in time are composed to form the elliptical trajectory vibration on the driving foot, and then the linear or rotary motions are acquired under the effect of friction coupling. For instance, Wan et al. [24] developed a linear motor using the longitudinal-bending mode and Liu et al. [25] presented a rotary ultrasonic motor utilized the composition of the third and fourth bending vibration modes. It is well known that the resonance frequencies between the multiple vibration modes should be as close to each other as possible for the double-mode and multi-mode ultrasonic motors mentioned above. The frequency degeneration between the multiple modes frequently leads to the complicated designing and fabricating processes. The single-mode ultrasonic motors utilize the combination of only one vibration mode and special mechanical structures to form the oblique vibration trajectory on the driving foot [26,27]. Thus, the single-mode ultrasonic motors always have flexible constructions as they can avoid the frequency degeneration problem. In addition, the single-mode motors only employ single-phase exciting signal, which makes the drive circuit simpler. The frog-shaped linear piezoelectric actuator proposed by Zhang et al. [28] is a representative one, which successfully verify the principle of the single-mode ultrasonic motor mentioned above. However, the frog-shaped structure has more sensitive dimensions impacted on vibrations, which leads to the complicated structure and is not easy to be manufactured.

In this paper, a novel single-mode linear piezoelectric ultrasonic motor based on asymmetric structure is designed and tested. The

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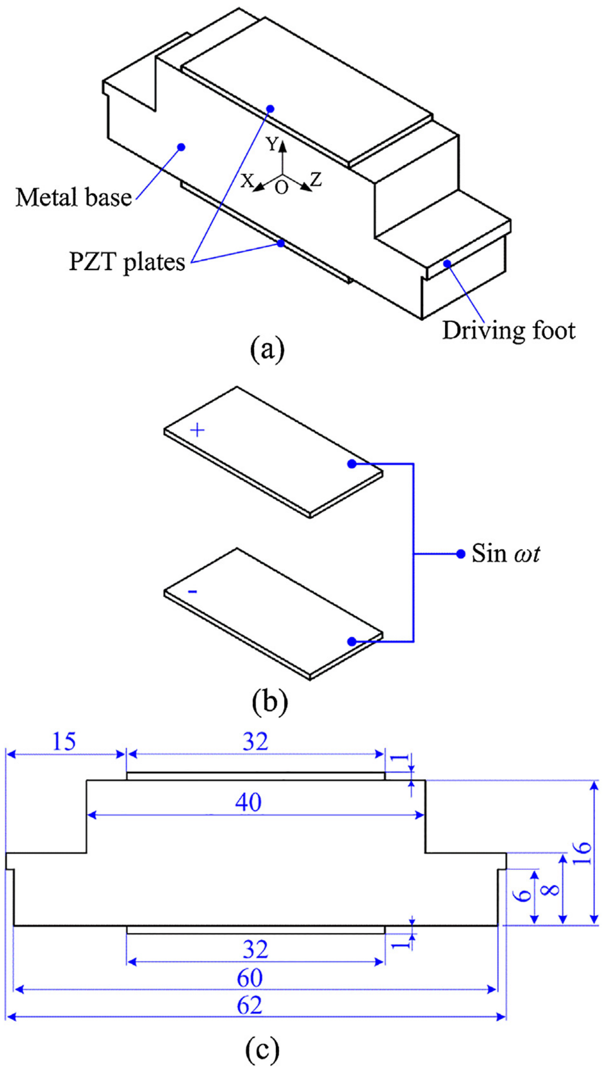

Fig. 1. Configuration of the proposed single-mode piezoelectric ultrasonic motor: (a) the three-dimensional model, (b) the polarizations and arrangements of the PZT plates, (c) the main structure dimensions (unit: mm).

proposed motor utilizes the first longitudinal vibration to stimulate the stator with asymmetric structure to generate oblique vibration on the driving foot. Firstly, the structure of the motor is designed and its principle is illustrated. The movements of the driving foot are analyzed and the driving principle of the motor is verified by means of simulation analyses. The vibration characteristics and output performances of the prototype are tested, which is followed by the conclusion in the last section.

2. Configuration of the motor

The single-mode linear piezoelectric ultrasonic motor based on asymmetric structure adopts bonded-type configuration, which can simplify the fabricating and assembling processes, and its three-dimensional model is shown in Fig. 1(a). This proposed motor has a very simple structure and it only consists of two pieces of PZT plates and a metal base with two driving feet. The distinctive feature of this novel proposal is that the metal base has the asymmetric structures at its both ends about the XOZ plane, while the metal base is symmetric about the XOY and YOZ planes (the coordinate system is plotted in Fig. 1(a)). The motor utilizes the first longitudinal vibration and the asymmetric mechanical structure to generate the desired and reciprocating oblique trajectory vibrations on the driving feet. Two PZT plates polarized reversely along their thickness directions are attached to the middle positions on the upside and downside surfaces of the metal base, which are used to stimulate the motor to generate the first longitudinal vibration by applying only one exciting signal. The polarizations of the PZT plates are marked with the symbols of "+" and "−", as shown in Fig. 1(b). Moreover, the main structure dimensions of the proposed motor are determined, as shown in Fig. 1(c). The total length of the motor is 62 mm and its cross-sectional area is 16 mm × 16 mm. The sizes of the two PZT plate are 32 mm × 16 mm × 1 mm (length × width × thickness).

3. Principle of the motor

Based on the determination of the structure and its dimensions, the modal analysis of the motor was carried out by the finite element software ANSYS 10.0. During the simulation, SILID227 element was used for the meshing of the motor. The material of the metal base was aluminum and its properties of the mass density ρ, the young modulus E and the poisson ratio σ were set as 2810 kg/m^3, 72 × 109 N/m^2 and 0.33, respectively. The materials of the PZT plates were PZT-4, whose mass density ρ was 7600 kg/m^3. The Block Lanczos method is used to extract the modal analysis results and the calculated vibration mode of the motor is shown in Fig. 2. The simulated result states that the resonance frequency of the first longitudinal vibration mode is 46.924 kHz.

The vibration mode shape in Fig. 2 clearly indicates that the two driving feet generate composite deformations consisted of longitudinal and transverse deformations in OZ and OY directions, which is caused by the asymmetric structure at both ends of the metal base. The longitudinal deformation is used to overcome the preload between the driving foot and runner, while the transverse deformation can push the runner linearly. Then, the operation process of the motor in one cycle is illustrated in Fig. 3. Here, the point P represents the center point of one driving foot and T is the period of the exciting signal. The operation principle of the motor is analyzed in detail as follows.

At the initial moment (t = 0), no deformation is generated in the motor and the driving foot maintains the original position P_0. When t = 1/4T, the motor generates the maximum elongation deformation and the driving foot extends to its extreme position P_1. When t = 2/4T, the motor is excited to return at its initial status and the driving foot moves at its original position P_0. When t = 3/4T, the motor generates maximum shortening deformation and the driving foot is moved to the minimum extreme position P_2. Thus, an oblique trajectory movement of the driving foot from P_1 to P_2 is formed based on such operation orders. The driving foot can push the runner linearly with a large stroke by repeating the operation process in principle.

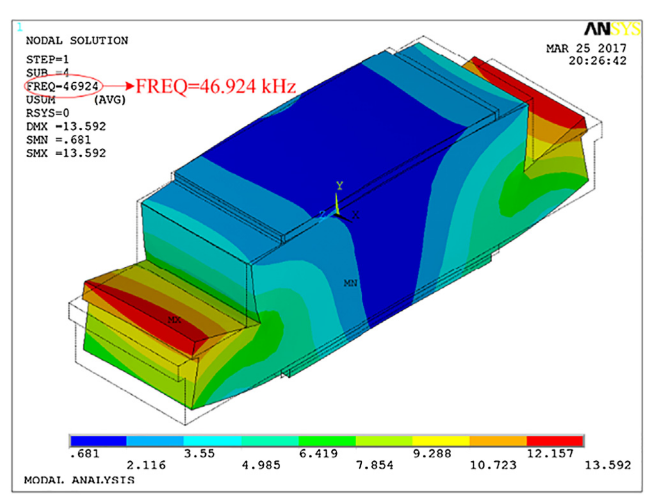

Fig. 2. Vibration mode of the proposed motor.