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Linear stepping ultrasonic motor

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Abstract A linear stepping ultrasonic motor, based on vibrators alternative driving and slider grooves positioning, is proposed in this paper. The step-by-step movements can be obtained by exciting two vibrators of stator by turns. The motor is capable of bi-direction stepping movements without accumulative position errors driven by an open-loop control circuit, which provides single-phase sinusoidal signal via a switch unit to the vibrators. Its step displacement is 1 mm. The speed without load in one step is 7.69~8.33 mm/s, and the blocking force is 0.12~0.35 N in operating frequency 30 kHz and operation voltage 300 Vpp.

Keywords Ultrasonic motor · Stepping · Alternative driving

1 Introduction

The ultrasonic motors (USMs) featuring high holding torque and high response characteristics are promised to be used as a precise and accurate positioning actuator [1]. In recent years, several stepping methods of ultrasonic motor have been proposed. They can be divided to two kinds. One obtains precise positioning by controlling their driving circuits [2, 3] . The other realizes stepping motion by special mechanical structure, such as mode conversion type stepping ultrasonic motors [4] and standing-wave type self-correct step ultrasonic motors [5–7]. The mode conversion type stepping ultrasonic motors are based on the phenomena that a small object on the vibrating body moves to the nodal position of vibration shape. A large torque is not easily obtained because of slipping friction on the contacting interface between the rotor (or slider) and the stator. The standing-wave type self-correct stepping ultrasonic motors are based on standing wave driving and self-correction positioning. It is necessary to ensure the rotor (or slider) to move into the self-correction area of goal position each step. The complete open-loop control could result in miss steps. In this paper, the new type linear stepping ultrasonic motor, based on vibrators alternately driving and slider grooves positioning, is capable of bi-direction stepping movements without accumulative position errors driven by an open-loop control circuit.

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2 Configuration

The linear stepping ultrasonic motor is shown as the Fig. 1, whose stator is composed of 2 Λ-shape vibrators bonded on the base of the motor and whose slider is a bar rectangular section with grooves uniformly distributed along the length in a side surface. The ends of two mutually perpendicular legs of each Λ-shape vibrator respectively fix piezoelectric ceramics.

3 Operating principle

The Λ-shape vibrator, whose dimension is shown as the Fig. 2, were made from bronze with elastic modulus 1.1×10^{11} N/m^2, density 8,800 kg/m^3, and Poisson ratio 0.33. Each piezoelement made from PZT8 has dimension $8\times 3.5\times 2$ m^3.

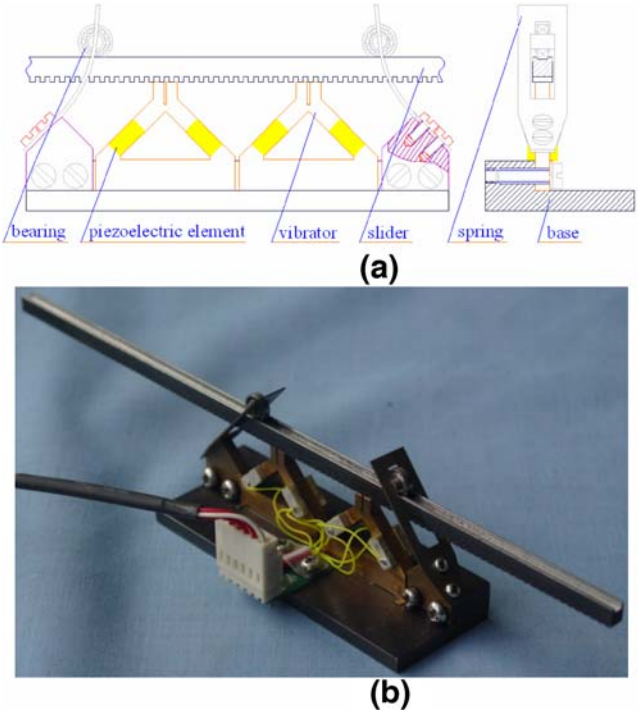

Fig. 1 (**a**) Structure of linear stepping ultrasonic motor. (**b**) Prototype of linear stepping ultrasonic motor

Analysis using ANSYS finite element method software illustrates the vibration shapes and frequencies of the vibrator. In which, the first-order longitudinal vibration with frequency 32.102 kHz was presented in the Fig. 3(a), and the second-order bending vibration with frequency 32.139 kHz was presented in the Fig. 3(b).

The first-order longitudinal vibration of one leg on the Λ-shape vibrator is excited by the piezoelectric elements bonded on the leg, and the second-order bending vibration of the other leg is induced in the same time. The harmonic response analysis by ANSYS was illustrated in the Fig. 4. The exciting frequency is 32.120 kHz.

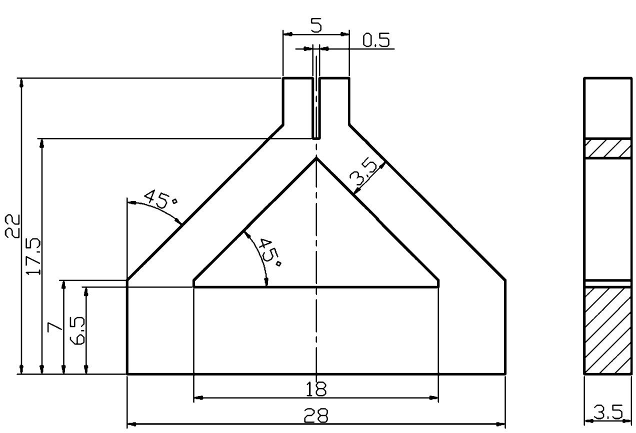

Fig. 2 Λ-shape vibrator

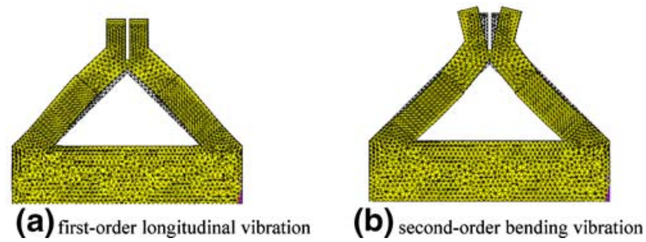

Fig. 3 Modal analysis of the Λ-shape vibrator

There are two surfaces on the top of the Λ-shape vibrator. Because the left surface has larger vertical displacement than the right in exciting the right leg, the right surface only contact the slider at the vibrating equilibrium location. In this case, the tangential component of the left surface can drive the slider pressed on the top of the Λ-shape vibrator, as shown in the Fig. 5(a). When the left surface located a groove on the slider, as shown as the Fig. 5(b), its vibration can not drive the slider but obstruct motion of the slider. Therefore, the slider only move from a tooth to the adjoining groove when any leg of the Λ-shape vibrators is excited continuously.

The stepping principle is illustrated in Fig. 6. The grooves uniformly distributed on the slider are used as positioning. The slider is pushed by driving end when the driving end is located at one of teeth on the slider, as shown in Fig. 6(a). Its does not push the slider when it is located at one of grooves on the slider (Fig. 6(b)). Hence, the slider can automatically stop at a certain position. The next step is realized by exciting another vibrator, whose driving end is at a tooth of the slider when the former is at the groove of the slider (see Fig. 6(c,d)). By this way, stepping motion can be realized by supplying the driving signal the two legs alternately in an interval, which can be determined experimentally. The stepping number is equal to the switching times of the power. The step is equal to half of the distance between the adjoining grooves. The position error of each step was determined by manufacture accurate of the gooves on the slider, and was not influenced by previous steps.

The stepping procedure is described as following. See Fig. 6 (1) exciting the piezoelectric element on the leg 3, the slider moving (Fig. 6(a)); (2) the slider stop when the driving end is at a groove (Fig. 6(b)); (3) switch off the

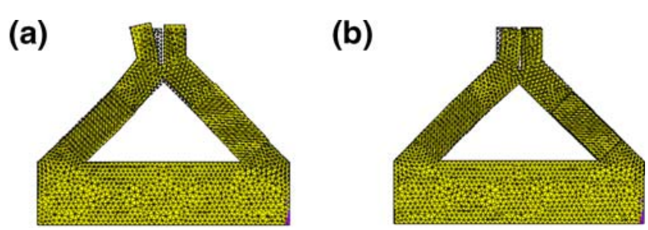

Fig. 4 Harmonic response of the Λ-shape vibrator

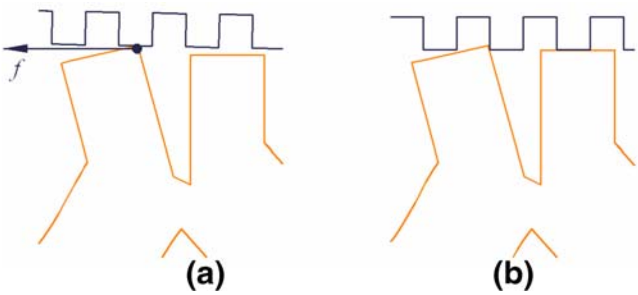

Fig. 5 Driving principle of linear stepping ultrasonic motor

Table 1 Frequencies & amplitudes.

Leg	Frequency (kHz)	Amplitude of driving end (μm)
1	31.516	2.2
2	29.875	2.3
3	31.010	2.6
4	30.224	2.4

power for the piezoelectric element on the leg 3, the first step is finished; (4) feeding the piezoelectric element on the leg 1 instead, driving the slider (Fig. 6(c)); (5) the slider stop again when the driving end is at a groove (Fig. 6(d)); (6) switch off the power for the piezoelectric element on the leg1, the second step is over.

In this way, the slider moves step by step along the direction denoted in the Fig. 5 by supplying power for the two piezoelectric elements(1, 3) by turns. By the same principle, the other two legs (2, 4) can have the slider move in the opposite direction.

The vibrating frequencies and longitudinal amplitudes of vibrators investigated by the Laser Doppler Vibrometer are presented in the Table 1.

When operation frequency $\omega/(2\pi)$ is 30 kHz and operation voltage A is 300 Vpp, the duration Δt of runs for one step without load is about 0.12~0.13 s, so the speed without load in one step can be calculated,

$$\overline{\nu} = \frac{1}{\Delta t} = 7.69 \sim 8.33 \text{ mm/s}$$

The blocking force measured by suspending weights is in 0.12~0.35 N.

4 Conclusion

A new type linear stepping ultrasonic motor, based on vibrators alternately driving and slider grooves positioning, is proposed in this paper. Its stepping movements is obtained by exciting two vibrators of the stator by turns, and is capable of bi-direction moving driven by an open-loop control circuit, which provides single-phase sinusoidal signal via a switch unit to the vibrators. There are not accumulative position errors in the operation of the motor. Its operation can be controlled by a certain impulse sequence. The step displacement is 1mm, when the distance between two adjoining grooves is 2 mm. The speed without load in one step is 7.69~8.33 mm/s, and the blocking force is 0.12~0.35 N in operating frequency 30 kHz and operation voltage 300 Vpp.

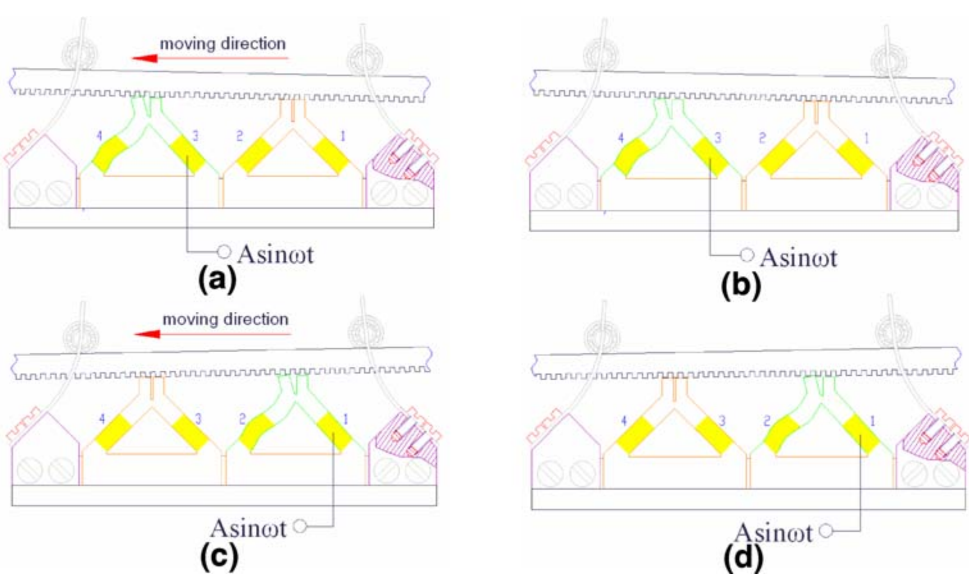

Fig. 6 Stepping principle of linear stepping ultrasonic motor

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