

LINEAR ULTRASONIC MOTOR USING LONGITUDINAL VIBRATION

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Abstract: A linear ultrasonic motor using longitudinal vibration of bar with varying section is proposed. The linear ultrasonic motor has two varying section bars connected by semi-circumferential structure. Elliptical trajectories of particles are formed on top of the semi-circumferential structure outer surface where a driving foot is located. And a mover is pushed to move linearly when the driving foot is pressed onto it. Finite element model of stator is built and results of harmonic analysis verify its principle. Moreover, design requirements of the motor are analyzed through finite element analysis and the results of sensitive analysis provide an efficient way to design the type of linear ultrasonic motor. Prototype test shows that the motor can afford load of 10 N at the speed of 100 mm/s.

Key words: linear ultrasonic motor; varying section; longitudinal vibration; minimization

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INTRODUCTION

Ultrasonic motors are energy transformation devices that transform electric energy into mechanical energy utilizing the inverse piezoelectric effect. In this process, alternating voltage signals with ultrasonic frequencies are applied to piezoelectric ceramics to excite certain vibration modes of stator, whose vibrating energy is cumulated to push a rotor or mover by friction. Their features such as fast response, high resolution, non magnetic, and low noise, make ultrasonic motors be good solutions for a large range of modern industry requirements^[1-2]. In linear ultrasonic motors (LUSM), vibrating energy of stator is directly transformed into motion energy of mover without any gear systems, so the application of LUSM makes a system smaller and simpler^[3].

The stator which is usually composed of elastic body and piezoelectric ceramics is the key component of a linear ultrasonic motor. Since the operation of stator utilizes resonance of elastic body

excited by piezoelectric ceramics, the construction type between the elastic body and the piezoelectric ceramics influences the performance of motor a lot. According to construction type of elastic body between piezoelectric ceramics, ultrasonic motor can be classified into sandwich type and sticking type. In the sticking type, piezoelectric ceramics are bond onto the surface of elastic body by thin layers of bond, where the d31 effect of piezoelectric ceramics is used and vibrating energy of piezoelectric ceramics is transferred by shear stress, so there is a problem of aging and shedding in the bond layer. Besides, the bonding layer consumes energy of vibrating piezoelectric ceramics, which lowers the efficiency of motor. In the sandwich type, piezoelectric ceramics are mechanically gripped by elastic body and the d33 effect of piezoelectric ceramics is utilized to transfer energy by normal stress. Since the piezoelectric constant d33 is bigger than d31, the sandwich type without bond layer has higher reliability and efficiency^[4-8].

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There are two typical sandwich type linear ultrasonic motors, V shape^[9-11] and shaking beam^[12-13]. Their common feature is that their stators have two longitudinal vibrators, so they have high thrust force. However, in the V shape LUSM, two longitudinal vibrators are connected at the end with a right angle, which inevitably causes bending vibration of vibrators and lowers the efficiency of transducer. Besides, the V shape structure enlarges lateral dimension of stator, which makes the minimization of LUSM difficult. Shaking beam LUSM forms the elliptical motion of driving foot by a shaking beam pushed by two parallel longitudinal vibrators. Its structure is smaller than V shape, but the bending mode of the beam is excited simultaneously. This also reduces the efficiency.

In order to find a solution to minimizing the structure of LUSM adopted two longitudinal vibrators and avoiding the decrease in efficiency caused by disturbing modes, LUSM with two longitudinal vibrators is proposed in this paper. The feature of LUSM is that a semi-circumferential structure is used to link two longitudinal vibrators with varying sections.

1 CONSTRUCTION OF STATOR

The structure of LUSM is shown in Fig. 1. The stator is composed of two longitudinal vibrators with varying section. These two vibrators are connected by a semi-circumferential structure whose middle driving foot is located. The stator is pressed onto the mover by a guiding spring system.

Dimensions of the stator and the polarization directions of piezoelectric ceramics are marked in Fig. 2. There are two groups of piezoelectric ceramics with four pieces in each group. All parts of the stator are fastened together by two bolts under proper pressure.

2 OPERATING PRINCIPLE

In LUSM, there are two energy converting procedures, including vibration exciting procedure and frictional driving procedure. In vibration

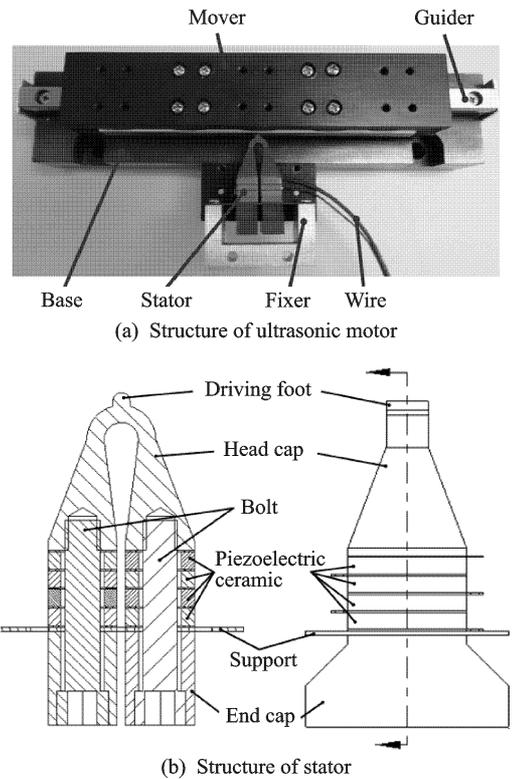


Fig. 1 Structure of LUSM

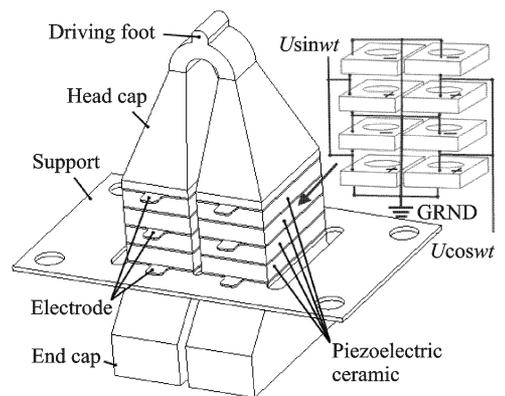


Fig. 2 Polarization of piezoelectric ceramics and its wire connection

exciting procedure, voltage signals with ultrasonic frequencies are applied to piezoelectric ceramics to excite vibration modes of stator, thus forming elliptical motion of driving foot. In the frictional driving procedure, vibration energy of stator is transferred to kinetic energy of the unidirectional motion of mover through frictional force between driving foot and mover^[14]. Thus it is important to choose proper vibration modes of stator to make

its driving foot vibrate elliptically.

The resonance of stator is used during the operation process of LUSM and the chosen two modes shown in Fig. 3 are excited simultaneously. One mode (called LL mode in the follows) in which two vibrators stretch and compress together causes the normal vibration of driving foot, while the other mode (called LS mode in the follows) in which two vibrators stretch and compress alternately causes the lateral vibration of driving foot.

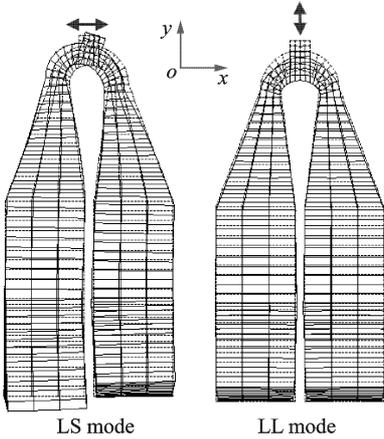


Fig. 3 Two working modes of ultrasonic motor

If the origin of coordinate system shown in Fig. 3 is moved to the top point of driving foot, when the LL mode is excited the motion trajectory of the particle on top of driving foot can be formulated as

$$x = A_x \sin \omega t \quad (1)$$

where A_x is the amplitude of vibration along x -axis and ω the vibration frequency. Likewise, when the LS mode is excited its motion trajectory can be formulated as

$$y = A_y \sin \omega t \quad (2)$$

where A_y is the amplitude of vibration along y -axis.

When the above two modes are excited with phase difference of $\pi/2$ simultaneously, the motion trajectory of the particle can be formulated as

$$\begin{cases} x = A_x \sin \omega t \\ y = A_y \cos \omega t \end{cases} \quad (3)$$

Eq. (3) can be simplified by substituting ωt , shown as

$$\frac{x^2}{A_x^2} + \frac{y^2}{A_y^2} = 1 \quad (4)$$

Eq. (4) is an ellipse equation, which states that when LL and LS modes are excited simultaneously the particles in driving foot elliptically vibrate.

When two groups of piezoelectric ceramics are applied with two sinuous voltage signals with the same frequency and a phase difference $\pi/2$ respectively (Fig. 2), the LL and LS modes of stator are excited with a vibration phase difference $\pi/2$. As a result, the normal and lateral vibration of driving foot has a phase difference of $\pi/2$, that is, the driving foot vibrates in an elliptical trajectory, as shown in Fig. 4. A mover is pushed to move linearly with the driving foot pressing onto its surface. If one of the voltage signal phases is reversed, the mover changes its motion direction.

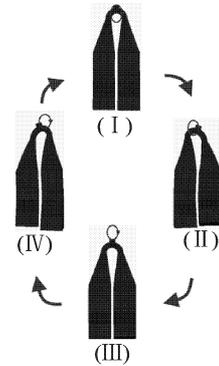


Fig. 4 Operation of stator in one period

3 STRUCTURE DESIGN

According to the operation principle, the LL and LS modes must be excited simultaneously at the same frequency. This can be realized by adjusting structure parameters and this process is called mode degeneration. To decrease the influence of support on the vibration modes, the support is located at longitudinal vibration nodes of transducer, which is a thin plate sandwiched by stator components as shown in Fig. 2. In this design, eight piezoelectric ceramics with 14 mm length, 8 mm width and 2 mm thickness are used to excite longitudinal vibration of stator. In the center of each piezoelectric ceramic plate, there is a hole with diameter of 5 mm for the convenience

of assemblage.

Parametric finite element model of stator is built using commercial FEA software ANSYS. Dimensions of stator are shown in Fig. 5. Bounce is chosen to be the material of elastic body and element type solid 45 is selected to simulate the elastic body. Some simplifications such as the neglect of electrodes and the support are made.

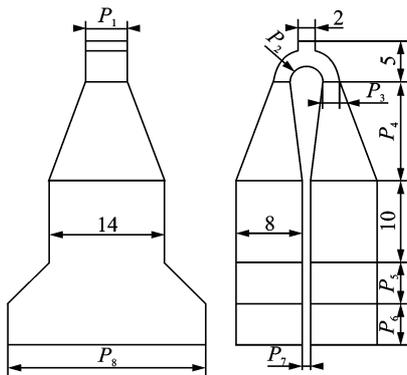


Fig. 5 Parametric model of stator

Sensitive analysis is conducted to find sensitive structure parameters to degenerate operation modes of stator. By modifying the parameters of finite element model with 0.1 mm increase, changes of two mode frequencies are obtained as shown in Fig. 6.

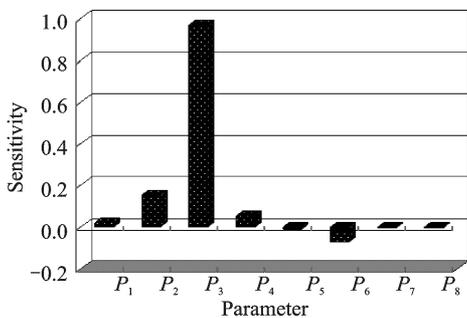


Fig. 6 Sensitive results of parameters

From Fig. 6, parameters P_2 , P_3 and P_6 are more sensitive. Therefore it is available to eliminate the frequency difference of two operation modes by adjusting these parameters.

4 MEASUREMENTS AND ANALYSIS

Using finite element analysis, dimensions

and materials of the stator are selected. A prototype with bounce (QSn6.5-0.4) elastic body and PZT8 of 14 mm×8 mm×1 mm is fabricated. The mover is a linear slider coated with Al_2O_3 ceramic, as shown in Fig. 7.

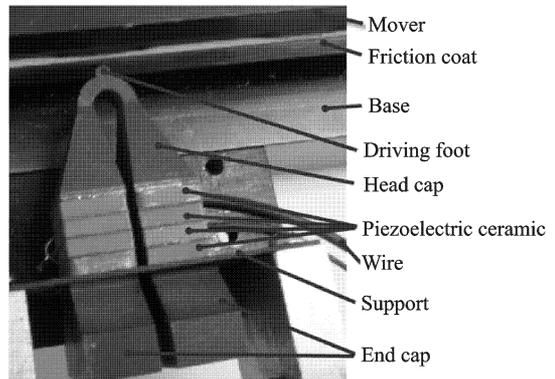


Fig. 7 Prototype picture

Modal test of stator is conducted using the laser Doppler vibrometer, which can obtain the shape of vibrating surface. To identify two operation modes, the laser beam is pointed on the two end cap surfaces. In LL mode, two end cap surfaces vibrate with the same pace while in LS mode they vibrate reversely, as shown in Fig. 8. Two operation modes are found at 48.69, 48.90 kHz, as shown in Fig. 9.

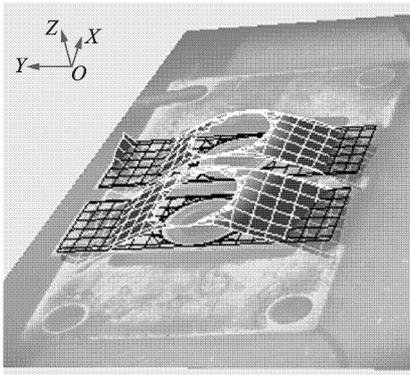
Performance test set is shown in Fig. 10. The relations between speed and frequency, speed and thrust are studied.

According to Fig. 10, it is concluded that the closer exciting frequency is to mode frequency, the faster mover moves. When the exciting frequency is lower than mode frequency, the speed can increase very fast. Then the speed decreases slowly with the increase of exciting frequency.

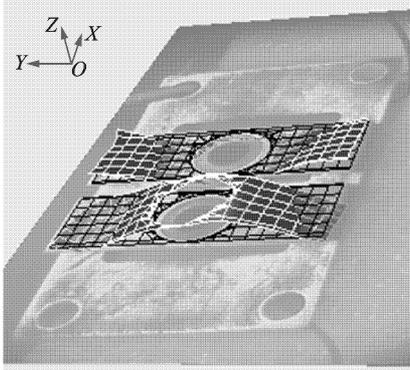
5 CONCLUSIONS

(1) A novel sandwich type linear ultrasonic motor utilizing longitudinal vibration is proposed in this paper. Its operation principle is analyzed and the motion trajectories of driving tip are formulated as an ellipse equation.

(2) According to sensitive analysis results obtained by means of finite element method, the



(a) LL mode shape



(b) LS mode shape

Fig. 8 Two mode shapes of stator

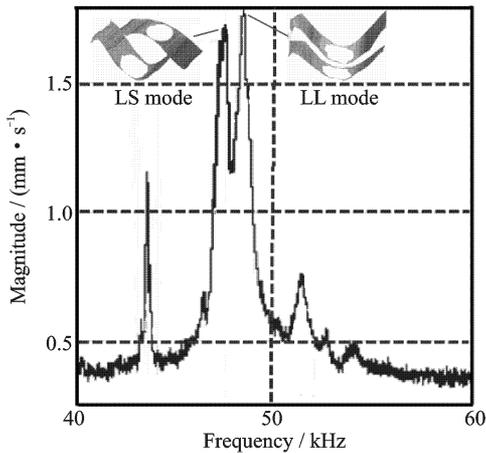
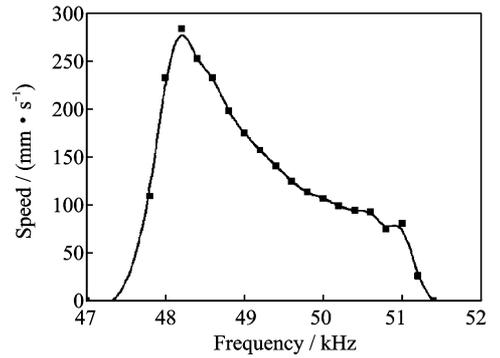


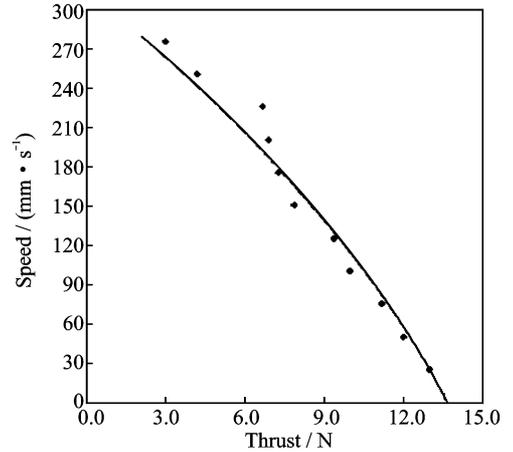
Fig. 9 Harmonic response of stator

structure of motor is designed and its prototype is fabricated. Prototype test and performance statistics of motor show that the motor can afford load of 10 N at the speed of 100 mm/s.

(3) Since the friction pair of stator and mover can be optimized and frequency difference between two working modes can be further decreased, motor performance is improved.



(a) Relation between speed and frequency



(b) Relation between speed and thrust

Fig. 10 Performance test results

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一种利用纵振的直线超声电机

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摘要:设计了一种利用变截面杆纵振模态工作的直线超声电机,该超声电机的特点是具有两个变截面杆状并由一半圆环连接。位于圆环中间驱动足顶部质点以椭圆轨迹运动,当驱动足以一定预压力接触动子时,动子将输出直线运动。通过建立定子的有限元模型并对其进行谐响应分析验证了原理的可行性。提出了电机结构设计的要求,并通过有限

元方法进行了结构参数灵敏度分析,为该类电机结构的设计提供了高效的方法。样机试验表明,该电机在100 mm/s的运行速度下可以推动10 N的负载。

关键词:直线超声电机;变截面;纵振;小型化

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